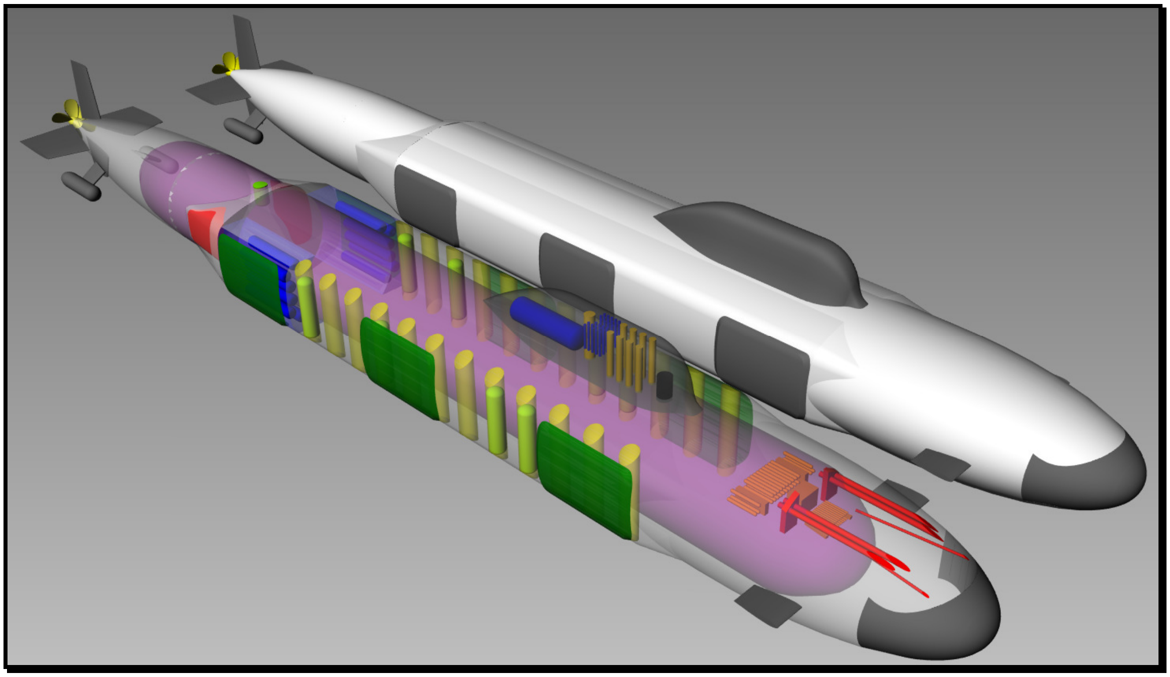
PERSISTENT INTELLIGENCE, SURVEILLANCE AND RECONAISSANCE (PISR) SUBMARINE



2.705: PROJECTS IN NEW CONCEPT NAVAL SHIP DESIGN

FINAL REPORT

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1.0 Project Overview

1.1 Study Objectives

The purpose of this design study was to examine the feasibility of a clean-sheet submarine design with the primary mission of conducting Intelligence, Surveillance, and Reconnaissance (ISR) operations. This study also considered the incorporation of potential submarine design features and technologies into a conceptual design. Particular design features and technologies of interest were:

1. Integrated Power Systems (IPS)
2. Air Independent Backup Power Generation (Non Diesel Emergency Power Generation)
3. Novel Construction Methods
    a. Double Hulled Construction
    b. Non-Body of Revolution Outboard Profiles
    c. Advanced Sail Designs (Faired/Shaped Sail)
    d. Expansion of Non-Pressure Hull Ballast Tanks
4. Outboard Placement of Payload(s)
5. Advanced Submarine Escape Technologies
6. Enhanced Habitability

1.2 Stakeholder Requirements

Specific stakeholder requirements with thresholds and goals, where appropriate, are shown in Table 2of Section 2.2. General stakeholder requirements are given below. Stakeholder did not establish any initial requirements for program cost or risk.

- Displace less than 15k LT submerged
- Stay on station for 90 days at a time
- Store and retrieve UUVs
- Be manned to a level commensurate with current submarines
- Be capable of hosting (not employing) SOF
- Accommodate multiple manned/unmanned surface and underwater vehicles; launch and recovery
- Have an Extremely Large Reconfigurable wet/dry space (e.g. payload bay) – greater than or equal to D5 tube
- Possess quiet launch capability
- Shoot the following weapons: CVLWT, Mk-54, Tomahawk
- Deploy from CONUS or Hawaii

1.3 Major Assumptions

The following assumptions were used in this concept design study:

- Margin lead – 13% of A-1 weight (retain 5% of A-1 weight for service life allowance)
- Service life – 30 years
- Ships in the class – 20-ship class

- Integrated Power System
- Operating Profile – PISR will be homeported in CONUS and during peacetime will deploy for up to 8 months to support two high endurance missions (90-120 days). PISR will operate in littoral and deep sea environments and against ASW, ASuW, and AAW threats. Similar to current fast-attack submarine manning, the PISR will have a single crew and will have a nominal two year deployment schedule.
- Risk level commensurate with current ship designs as determined by the project team

1.4 Information Resources

The stakeholders for this project consisted of: MIT Naval Construction and Engineering Faculty, NAVSEA05U6, and various technical points of contact in the Naval Ship Design Enterprise. The primary sponsor for this study was the Technical Warrant Holder for New Concept Submarine Designs (NAVSEA 05U6). Additional direction and guidance was provided by the Design Review Board comprised of faculty members of the Naval Construction and Engineering program. This design also leveraged work performed to date on Next Generation IPS (NGIPS) by the Electric Ship Office. In order to maximize commonality for IPS architecture, NGIPS work done to support 2.705 surface ship projects was also examined.

1.5 Process Overview

- Develop stakeholder requirements and constraints – using the PISR study guide and Initial Capabilities Document (ICD), the requirements and constraints for the concept were identified and employed to guide later design decisions
- Adopt a design philosophy for the concept design – an overarching design philosophy prioritized the design effort and guided design tradeoffs
- Analyze mission performance drivers and requirements – identifying the mission requirements for the ship (beyond those directly from the stakeholder) permitted a focus on specific capabilities the concept design needed (identifying the key performance parameters of the concept design)
- Set key parameter goals/thresholds – using the insights generated from analyzing the mission areas, a list of threshold and goal values for each parameter to satisfy mission requirements was established
- Identify architectural features of interest – to ensure that the study objective of evaluating new and novel design features was satisfied, the study of the trade space was organized by potential combinations of architectural design features of interest
- Develop trade space of variants – using all reasonable combinations of the identified architectural features, a slate of concept variants for comparison was generated
- Evaluate relative risk and capability – lacking the direct capability for cost modeling of a large trade space of variants, a relative ranking for risk and capability for each of the architectural design features studied was made; this permitted a comparison of different variants according to risk versus capability
- Select final variant – through a comparison of the most attractive variants identified by the risk to capability analysis, a single final variant was selected
- Model and refine concept design – with the final variant selected, the refinement and feasibility of the concept was performed starting with the larger systems

(propulsion, combat system, command and control) and progressing toward smaller components
- Analyze concept design performance – with arrangement of components within the design complete, several analyses to validate the performance of the concept against the stakeholder requirements, constraints , key parameters, goals and thresholds were conducted; within these analyses a detailed ‘deep dive’ analysis of the ship’s structural and hydrodynamic performance was completed
- Model concept cost – with the final ship modeled using the tools of this study, estimates of the acquisition and life cycle costs of the ship using the MIT 2N weight based cost model were made

The following design and analysis tools were used in the performance of the persistent ISR submarine project:

- Spreadsheets for the production of graphs and reports - Microsoft Excel
- Spreadsheets for weight estimation - Microsoft Excel
- CAD for sketches and drawing – Rhino
- Parametric models for concept selection – MIT 2N Math Model and Paramarine
- Hydrodynamic models for powering, resistance and seakeeping – Paramarine
- Structure models for evaluating structural requirements – Paramarine

Work Assignments are:
- Jerod Ketcham
    - Developing parametric submarine model in Paramarine
    - Ship refinement and Paramarine Analyses
    - Cost modeling
    - Structural optimization and analysis of final ship
    - Propeller design
- Jon Gibbs
    - Initial analytical decision framework used to select variants for conceptual design
    - IPS configuration
    - Propulsion plant arrangement and weight estimation
    - Analyses outside of Paramarine
    - General arrangements
    - Resistance and maneuvering analysis of final ship design

2.0 Design Decision Framework

2.1 Design Philosophy

The persistent intelligence, surveillance and reconnaissance (PISR) submarine's primary mission is to perform high endurance intelligence, surveillance and reconnaissance missions in support of national tasking. Persistent ISR was given priority over other mission areas however the submarine is also capable of the following additional missions:

Secondary Missions
Anti-Submarine Warfare (ASW)
Anti-Surface Warfare (ASuW)
Anti-Air Warfare (AAW) – Self-Defensive

Tertiary Missions (limited capability)
Special Operations Forces (SOF)
Mine Warfare (MIW)
Land Attack

Table 1: Secondary and Tertiary Mission Sets for PISR SSN

To facilitate the required mission capabilities, PISR required the following enabling design features:

1. Extremely high on-station endurance (including AAW self defense) and operational availability
2. High surge to theater capability (from domestic basing)
3. Sophisticated and upgradable sensor suite
4. Large, reconfigurable payload capacity with payload-flexible ship-sea interfaces
5. Precision maneuvering and station keeping (e.g. periscope depth, hovering in support of UUVs)
6. State of the art signature reduction
7. Habitability (specifically: the removal of hot racking on station)

The design of the PISR must also include consideration of:

1. Lead-ship and lifecycle cost
2. Technical risk
3. Manning / crew concept
4. Maintenance and operational philosophy
5. Propulsion plant and engineering space size and weight reduction

A moderate tolerance for risk was accepted in the selection of a highly capable concept design. Additionally, one of the study objectives for this concept work was to evaluate potential attractive technologies and features that are not currently fielded on U.S. submarines. This drove the development of the trade space according to architectural features identified in chapter 3.

The initial effort concentrated on development of a well defined baseline set of weapons that is consistent across all subsequent design variants. A baseline weapon set followed the requirements in the Initial Capabilities Document (ICD) for the persistent ISR submarine. Using the baseline weapon set, several possible hull configurations and machinery configurations were developed in order to perform a trade off study and select the optimum hull and machinery configuration to meet mission and cost requirements.

A significant design constraint was to incorporate an Integrated Power System (IPS) and use electric motor propulsion. The IPS architecture is required to be common with surface ship variants of IPS in order to increase commonality and reduce total ship ownership costs to the U.S. Navy (USN). Groups from Naval Postgraduate School (NPS) assisted in providing details of weapons systems volume, weight and powering requirements. Surface ship project groups in the Naval Construction and Engineering program at the Massachusetts Institute of Technology (MIT) defined the general architecture of an IPS ship.

Other desirable goals of the persistent ISR submarine project were to:
1. Eliminate the diesel engine
2. Eliminate a standard torpedo room that is inboard to the pressure hull
3. Maximize the use of external weapons

2.2 Design Objectives, Constraints, and Standards

To support these required mission capabilities, key design parameters were identified. Table 2, below, identifies these design parameters, their basis and threshold and goal values. These parameters are a combination of the requirements given directly by the stakeholder and derived requirements implemented by the design team. These, in addition to the constraints and requirements provided by the stakeholder in section 1.2, served to guide the evaluation of concept variants and design decisions throughout the project.

Parameter	Description	Threshold	Goal	Basis	Parameter Justification
Maximum Sustained Speed	Speed required to reach nominal operating area from homeport in a total time less than 10% of on station duration	25 kts	35 kts	Tactical repositioning and survivability	Operational Availability, Surge to Theater Capability
Endurance, Time on Station	Time that ship can stay on station without support	90 days	120 days	Enhanced endurance for long-duration missions	Operational Availability
Max Draft	Maximum Allowable Draft	36’	29’	No additional infrastructure will be created to support this ship in port. Numbers based on *Ohio* and *Virginia* Class drafts	Operability
Max Beam	Maximum Allowable Beam	50’	< 50’	No additional infrastructure will be created to support this ship in port. Numbers based on *Ohio* and *Virginia* Class beam and maximum allowable beam at current shipyard dry docks	Producibility
Max Pressure Hull Beam	Maximum Allowable Beam of Pressure Hull	43’ 4”	< 43’ 4”	Ability to fabricate a right circular cylinder with current industrial capitalization (fixtures)	

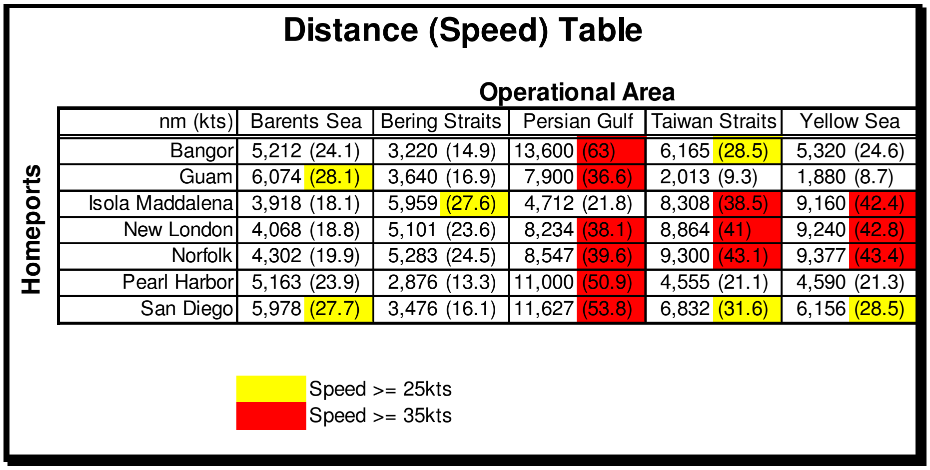
Table 2: Desired Submarine Specifications

Parameter	Description	Threshold	Goal	Basis	Parameter Justification
Payload Weight Fraction	Ratio of payload-related weight groups to submerged displacement	4%	8%	Goal is to maximize mission capability of ship	Payload Capacity
Payload Volume Fraction	Ratio of payload-related volume to total envelope volume	2%	4%	Goal is to maximize mission capability of ship	
Cost	Full Life Cycle Cost using MIT Cost Model; Use appropriate costs as basis for design decisions and variant selections	2x “Average SSN” Lead-ship Cost	”Average SSN” Lead-ship Cost	If ship costs approximately what an “Average SSN” does it will likely be funded. Greater than twice an “Average SSN”	Producibility
Risk	Qualitative/subjective assessment of technical risks/uncertainties (e.g. Technology Risk Level indications)	Moderate Risk (as determined by engineering judgment)			Producibility

Table 2: Desired Submarine Specifications (Continued)

The payload weight and volume fractions are presented as a measure of the mission capability of the submarine. By comparing these ratios to similar ratios for current submarines a rough estimation of this submarine’s mission capability can be made. Submarines typically have lower payload fractions than other naval weapon platforms and including this parameter is an attempt to ensure that the design process makes a deliberate effort to accommodate a maximum amount of ordnance.

Figures 1-4 show the analysis performed to identify the thresholds and goals for endurance (time on station), and maximum sustained speed. Each figure displays the distance between a homeport and operating area and the average transit speed required to surge to theater in the time listed in the figure caption. This analysis resulted in the selection of threshold speed of 25 knots, a threshold on-station endurance of 90 days, a goal speed of 35 knots, a goal on-station endurance of 120 days.

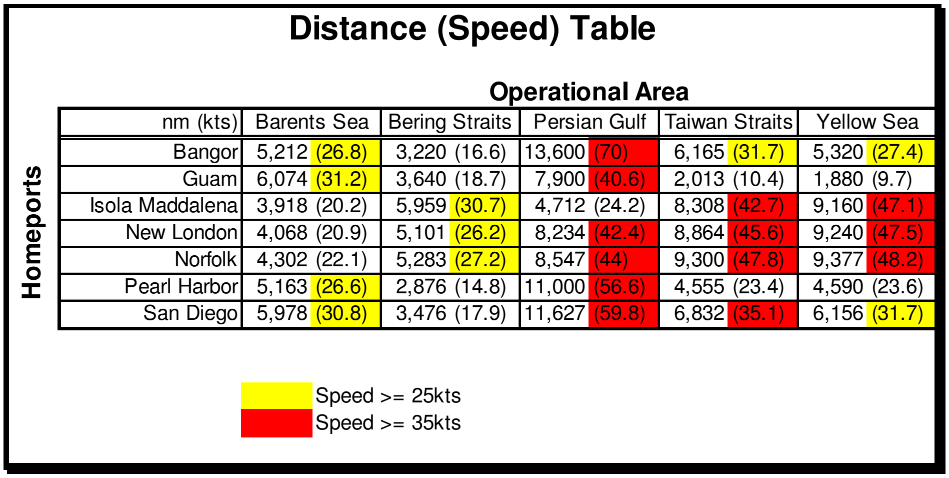


Distance (Speed) Table

		Operational Area				
	nm (kts)	Barents Sea	Bering Straits	Persian Gulf	Taiwan Straits	Yellow Sea
Homeports	Bangor	5,212 (24.1)	3,220 (14.9)	13,600 (63)	6,165 (28.5)	5,320 (24.6)
	Guam	6,074 (28.1)	3,640 (16.9)	7,900 (36.6)	2,013 (9.3)	1,880 (8.7)
	Isola Maddalena	3,918 (18.1)	5,959 (27.6)	4,712 (21.8)	8,308 (38.5)	9,160 (42.4)
	New London	4,068 (18.8)	5,101 (23.6)	8,234 (38.1)	8,864 (41)	9,240 (42.8)
	Norfolk	4,302 (19.9)	5,283 (24.5)	8,547 (39.6)	9,300 (43.1)	9,377 (43.4)
	Pearl Harbor	5,163 (23.9)	2,876 (13.3)	11,000 (50.9)	4,555 (21.1)	4,590 (21.3)
	San Diego	5,978 (27.7)	3,476 (16.1)	11,627 (53.8)	6,832 (31.6)	6,156 (28.5)

🟨 Speed >= 25kts
🟥 Speed >= 35kts

Figure 1: Speed Analysis – Time on Station = 90 Days; Surge to Theater = 9 Days



Distance (Speed) Table

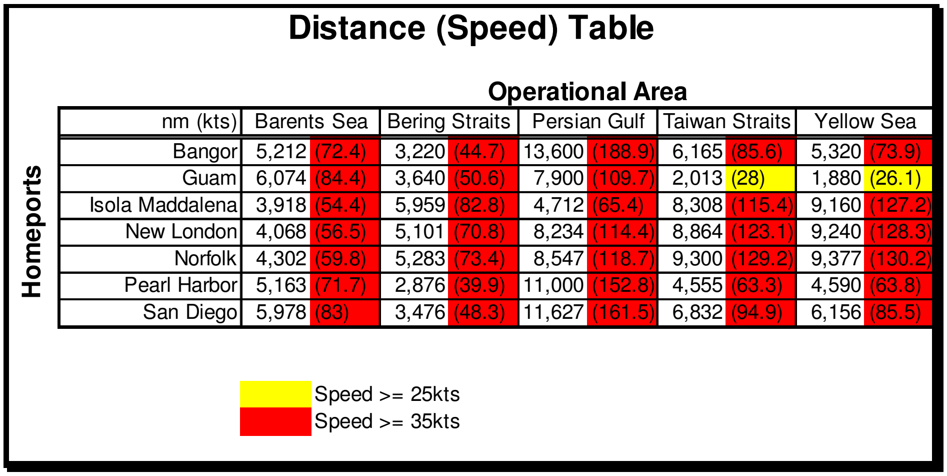
Operational Area

Homeports

nm (kts)	Barents Sea	Bering Straits	Persian Gulf	Taiwan Straits	Yellow Sea
Bangor	5,212 (26.8)	3,220 (16.6)	13,600 (70)	6,165 (31.7)	5,320 (27.4)
Guam	6,074 (31.2)	3,640 (18.7)	7,900 (40.6)	2,013 (10.4)	1,880 (9.7)
Isola Maddalena	3,918 (20.2)	5,959 (30.7)	4,712 (24.2)	8,308 (42.7)	9,160 (47.1)
New London	4,068 (20.9)	5,101 (26.2)	8,234 (42.4)	8,864 (45.6)	9,240 (47.5)
Norfolk	4,302 (22.1)	5,283 (27.2)	8,547 (44)	9,300 (47.8)	9,377 (48.2)
Pearl Harbor	5,163 (26.6)	2,876 (14.8)	11,000 (56.6)	4,555 (23.4)	4,590 (23.6)
San Diego	5,978 (30.8)	3,476 (17.9)	11,627 (59.8)	6,832 (35.1)	6,156 (31.7)

🟨 Speed >= 25kts
🟥 Speed >= 35kts

Figure 2: Speed Analysis – Time on Station = 90 Days; Surge to Theater = 8.1 Days



Distance (Speed) Table

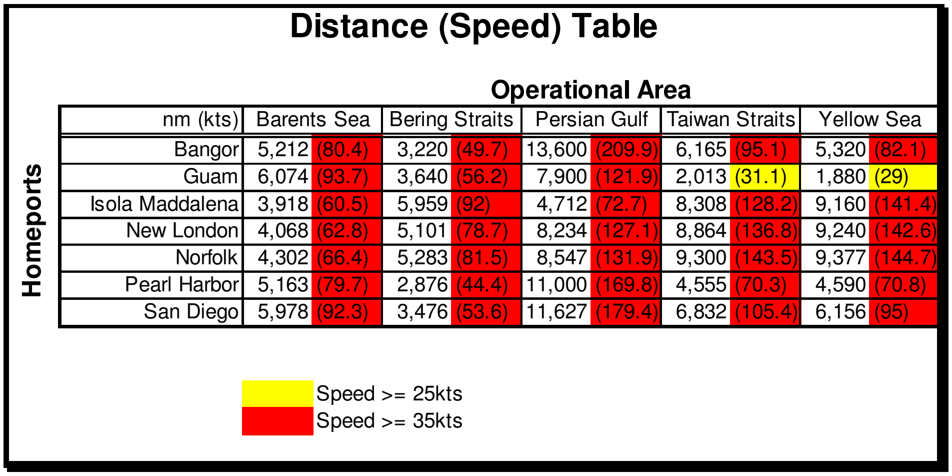
Operational Area

Homeports

nm (kts)	Barents Sea	Bering Straits	Persian Gulf	Taiwan Straits	Yellow Sea
Bangor	5,212 (72.4)	3,220 (44.7)	13,600 (188.9)	6,165 (85.6)	5,320 (73.9)
Guam	6,074 (84.4)	3,640 (50.6)	7,900 (109.7)	2,013 (28)	1,880 (26.1)
Isola Maddalena	3,918 (54.4)	5,959 (82.8)	4,712 (65.4)	8,308 (115.4)	9,160 (127.2)
New London	4,068 (56.5)	5,101 (70.8)	8,234 (114.4)	8,864 (123.1)	9,240 (128.3)
Norfolk	4,302 (59.8)	5,283 (73.4)	8,547 (118.7)	9,300 (129.2)	9,377 (130.2)
Pearl Harbor	5,163 (71.7)	2,876 (39.9)	11,000 (152.8)	4,555 (63.3)	4,590 (63.8)
San Diego	5,978 (83)	3,476 (48.3)	11,627 (161.5)	6,832 (94.9)	6,156 (85.5)

🟨 Speed >= 25kts
🟥 Speed >= 35kts

Figure 3: Speed Analysis – Time on Station = 30 Days; Surge to Theater = 3 Days



Distance (Speed) Table

Operational Area

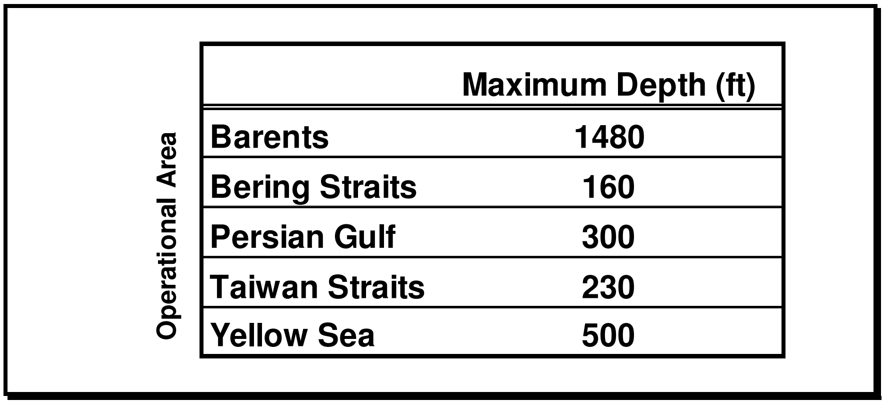
Homeports

nm (kts)	Barents Sea	Bering Straits	Persian Gulf	Taiwan Straits	Yellow Sea
Bangor	5,212 (80.4)	3,220 (49.7)	13,600 (209.9)	6,165 (95.1)	5,320 (82.1)
Guam	6,074 (93.7)	3,640 (56.2)	7,900 (121.9)	2,013 (31.1)	1,880 (29)
Isola Maddalena	3,918 (60.5)	5,959 (92)	4,712 (72.7)	8,308 (128.2)	9,160 (141.4)
New London	4,068 (62.8)	5,101 (78.7)	8,234 (127.1)	8,864 (136.8)	9,240 (142.6)
Norfolk	4,302 (66.4)	5,283 (81.5)	8,547 (131.9)	9,300 (143.5)	9,377 (144.7)
Pearl Harbor	5,163 (79.7)	2,876 (44.4)	11,000 (169.8)	4,555 (70.3)	4,590 (70.8)
San Diego	5,978 (92.3)	3,476 (53.6)	11,627 (179.4)	6,832 (105.4)	6,156 (95)

🟨 Speed >= 25kts
🟥 Speed >= 35kts

Figure 4: Speed Analysis – Time on Station = 30 Days; Surge to Theater = 2.7 Days

In order to establish a threshold requirement for maximum operating depth, the maximum charted water depth in various operating areas was examined. These results are shown in Figure 5. These data support a 600’ threshold and 2000’ goal for maximum operating depth.



Operational Area	Maximum Depth (ft)
Barents	1480
Bering Straits	160
Persian Gulf	300
Taiwan Straits	230
Yellow Sea	500

Figure 5: Operating Area Depth

The initial effort concentrated on specifying a baseline set of weapons to be consistent across all design variants. The baseline weapon set was developed around the requirements of the Initial Capabilities Document (ICD). Using the baseline weapon set and an Integrated Power System (IPS), several possible architectures were identified for further analysis.

Weapon	Quantity
Mk-54 Lightweight Torpedo	24
Common Very Lightweight Torpedo	12
Tomahawk Land Attack Missile	12 (Vertical)
AIM-9X	12

Table 3: Minimum Weapon Set for PISR

2.3 Evaluation and Decision Framework

As demonstrated in chapter 3, a trade space of variants was developed featuring variants with a slate of the architectural features of interest. For each feature, a relative capability multiplier and risk multiplier were identified using the best judgment of the team members. All of the variants generated were scored according to a risk and capability comparison to identify those most promising. From this handful of variants, a final variant was selected that was not only promising from a trade-off consideration, but also contained novel architectural and technological features and presented many interesting topics for additional study.

3.0 Concept Exploration and Selection

3.1 Concept Exploration Approach

The concept exploration evaluated the relative risk and capability of numerous potential PISR variants that each uniquely incorporated architectural and technological design features of interest. These features were identified and a relative risk associated with each was developed. For features that represented readily fielded architectures (i.e. a reference feature), a unit score for risk and capability was designated. A unit score represents the reference design architecture. The capability scores were normalized to permit a one-to-one comparison of the multiplicative capability score with that of the reference design. The scale used for capability scores is 1 – 1.5. In contrast, the risk scores are purely relative in their weights against one another and range from 1 – 10. For each variant, all of the risk scores are multiplied together to obtain a composite relative risk score, similar to the capability score. These scores are used to identify variants of interest and, ultimately, to select the final variant used in this concept design study.

3.2 Technology and System Evaluation and Selection

In order to identify potential design solutions for the PISR submarine, the impact of several architectural options were surveyed. These are:

- External placement of (horizontally launched) weapons systems – by eliminating the requirement for a torpedo room within the pressure hull, arrangeable volume and area within the pressure hull are made available and a significant stack length driver for the ship is removed
- External placement of propulsion motors – by placing the propulsion motors external to the pressure hull, the hull penetration by the shaft is eliminated and the propulsion plant no longer need be located aft of the RC
- Use of non-traditional (AIP) emergency power generation / storage – by eliminating the emergency diesel generator (and/or main storage battery) from the design, acoustic signature may be improved and the requirement to snorkel for emergency power eliminated
- Use of enhanced submarine escape systems – the addition of escape capsules to the design would eliminate the need for fly-away deep water rescue capability and enhance crew survivability
- Use of a non-body of revolution external shape – allowing for non-body of revolution designs permits the enhanced arrangement of outboard spaces
- Shaped sail (with UUV access capability) – the inclusion of a shaped sail in the design promises to improve hydrodynamics and provide additional outboard arrangeable volume
- Pressure hull size – increasing the pressure hull size may allow for superior length to diameter ratios and reduced packing factors
- Configuration of payload and ship-sea interfaces (forward or aft Main Ballast Tanks / plug / wraparound non-pressure hull)

- Large Main Ballast Tanks (MBTs) – current submarine construction methods would be employed (forward and aft non-pressure hull sections) however these tanks would be enlarged (lengthened) to accommodate additional payload storage (potentially increasing reserve buoyancy and/or allowing margin for growth of future outboard systems).
- Plug section – additional pressure hull section(s) is incorporated into the design to facilitate dedicated space for payload stowage and ship-sea interfaces.
- Double Hull (wraparound non-pressure hull) – additional volume for stowage of payload is achieved through incorporating a non-pressure hull around the pressure hull along the parallel mid-body (as well as forward and aft of the pressure hull).

The values of and justification for the risk and capability scores are as follows:

Architecture Feature	Risk Score And Justification		Capability Score And Justification	
External Weapons (Horizontal Launch)	5	Moderate technical risks exist in moving all weapons outboard of the pressure hull, particularly with weapon launching and rating support systems to test depth	1.05	The addition of external weapons will free up some arrangeable area and volume within the pressure hull and alleviate some stack length requirements for the operations compartment: minor capability enhancement
External Motors	10	Significant technical and operational risk exists in placing motors outboard of the pressure vessel (such as rating to test depth, inaccessibility of propulsion bearings, and acoustic isolation)	1.10	Significantly eases the arrangement requirements of a motor room at the stern of the pressure hull and eliminates the SUBSAFE shaft seals boundary; also frees up arrangeable volume or removes stack length requirement from the pressure hull: moderate capability enhancement
AIP Backup Power	9	Despite the use of AIP systems aboard foreign submarines, the operational endurance required for this design will place significant demands on the long term storage of oxidizer for multi-month missions	1.15	Operationally removes the requirement for snorkeling for use of backup power; potential weight and space savings over diesel and battery (especially with external banks); would require additional atmosphere exchange capability over a low-pressure blower (for casualty recovery): moderate capability enhancement
Escape Capsules	3	While the U.S. Navy has employed a philosophy of free ascent or submarine rescue, incorporation of escape capsule technology presents low to moderate risk with moderate impact to ship architecture but relatively simple structure and systems	1.20	Removes the requirement for flyaway submarine rescue capability, potentially improves morale and crew survivability: moderate capability enhancement

Table 4: Risk and Capability Score Justification

Architecture Feature	Risk Score And Justification		Capability Score And Justification	
Non-Body of Revolution	4	The U.S. has focused entirely on hydrodynamics of bodies of revolution since the 1960's; a departure from this construction technique will require significant testing and modeling for surfaced and submerged dynamic performance	1.25	Permits larger aperture hull arrays (if beam is extended), permits use of planar flank arrays, increases outboard volume significantly: moderate capability enhancement
Shaped Sail (with UUV Tube)	3	Moderate risk assessment given the overall impact on the ship design and the maturity of construction techniques	1.35	Maintenance access for UUV's without need for payload plug, enhanced hydrodynamic performance, addition of outboard volume: significant capability enhancement
40' Pressure Hull	1	Current infrastructure supports construction of pressure hulls of this size and familiarity from *Seawolf* class submarines mitigates risk levels; may additionally provide for modularity, reduced packing fractions over smaller pressure hulls	1.30	Enhanced modularity and upgradability over life of ship (design margin), improved L/D for resistance and powering: moderate capability enhancement
Payload MBTs	2	Extending the forward and aft MBTs to accommodate additional payload would require additional structural considerations but leverages current ballast tank arrangements	1.05	Additional payload capacity and ship-sea interfaces over baseline design, additional reserve buoyancy: minor capability enhancement
Double Hull Construction	8	U.S. submarine construction has largely avoided double hull construction and there is large uncertainty in the fabrication and maintenance processes required to support this architecture	1.45	Significant additional reserve buoyancy and external payload capacity, signature reduction potential, weapons effects standoff for improved shock rating: significant capability enhancement
Payload Plug Section	3	The addition of a payload plug would require increased SUBSAFE boundaries for ship-sea interfaces; also increases length to diameter ratio and increases friction drag	1.30	Moderately increased payload capacity and potential for complete backhaul of off board sensors/UUV's, additional of arrangeable volume and area: moderate capability enhancement

Table 4: Risk and Capability Score Justification (Continued)

3.3 Ship Concept Variants Description, Evaluation, and Selection

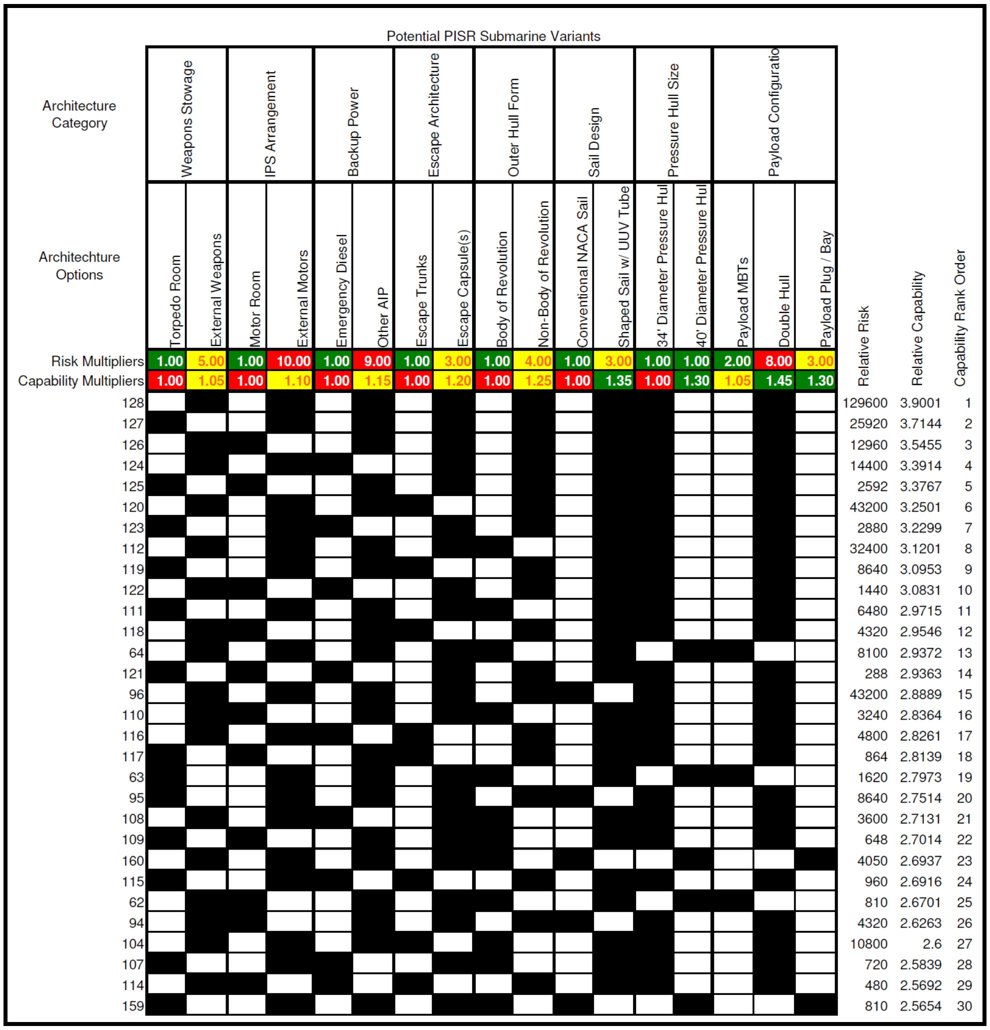
A full exploration of these architectural options produces 384 potential variants. Due to the dependent nature of some of these options, the trade space was reduced to 160 variants. The eliminated designs featured:

- Non-body of revolution designs that were not double hulled – it was anticipated that the costs and technical risks of fabricating non-uniaxially symmetric pressure hulls would be prohibitive (128 variants eliminated)
- Double hull designs combined with a 40' pressure hull – Adding an external non-pressure hull around a 40' pressure hull would likely exceed threshold beam requirements (64 variants eliminated)
- Shaped sail with UUV tube combined with plug section – IPS architecture enables offsetting the propulsion plant from the main motor(s) which allows for a plug section/payload bay in the engine room for UUV handling. With an engine room

plug section/payload bay, incorporation of a UUV tube into the sail would be unnecessary (32 variants eliminated).

Across these architectural options, all potential variants (160 combinations) were ranked according to potential technical risk and capability of each incorporated architectural feature. Five design architectures for concept exploration were selected. A partial listing of this survey (the 30 most capable variants) is shown in Figure 6, below.

The left most column lists identification numbers for each variant. For each 'exotic' architectural feature, a relativistic risk factor (shown in green, yellow and red) and a relativistic capability factor were developed for the purpose of comparison. By multiplying all of a variant's risk factors together and all of the capability factors together, a relative risk score and a relative capability score for the variant was obtained. A green risk score represents a feature that is incorporated into current submarines or is thought to be sufficiently developed that it does not represent additional risk if incorporated into a new design. Yellow risk ranks represents a moderate risk because that feature is not currently employed and therefore represents a moderate degree of uncertainty. Red risk represents high risk and is intended to indicate that, if a problem were to develop in one of these areas during construction, it could place the entire program in jeopardy. The colors used for capability are reversed from risk (green is higher capability than yellow which is higher than red). The capability scores are designed to be normalized against the least capable or baseline architecture so that the most capable ship should be on the order of four times as capable as the least capable ship. The risk scores, however, are intended only to produce a ranking on a relative scale. Thus the variant with the highest total risk score is not intended to be a 129,600 times as risky as the least risky variant.



Potential PISR Submarine Variants

Architecture Category	Weapons Stowage		IPS Arrangement		Backup Power		Escape Architecture		Outer Hull Form		Sail Design		Pressure Hull Size		Payload Configuratio					
Architechture Options	Torpedo Room	External Weapons	Motor Room	External Motors	Emergency Diesel	Other AIP	Escape Trunks	Escape Capsule(s)	Body of Revolution	Non-Body of Revolution	Conventional NACA Sail	Shaped Sail w/ UUV Tube	34' Diameter Pressure Hul	40' Diameter Pressure Hul	Payload MBTs	Double Hull	Payload Plug / Bay	Relative Risk	Relative Capability	Capability Rank Order
Risk Multipliers	1.00	5.00	1.00	10.00	1.00	9.00	1.00	3.00	1.00	4.00	1.00	3.00	1.00	1.00	2.00	8.00	3.00			
Capability Multipliers	1.00	1.05	1.00	1.10	1.00	1.15	1.00	1.20	1.00	1.25	1.00	1.35	1.00	1.30	1.05	1.45	1.30			
128	□	■	□	■	□	■	□	■	□	■	□	■	■	□	□	■	□	129600	3.9001	1
127	■	□	□	■	□	■	□	■	□	■	□	■	■	□	□	■	□	25920	3.7144	2
126	□	■	■	□	□	■	□	■	□	■	□	■	■	□	□	■	□	12960	3.5455	3
124	□	■	□	■	■	□	□	■	□	■	□	■	■	□	□	■	□	14400	3.3914	4
125	■	□	■	□	□	■	□	■	□	■	□	■	■	□	□	■	□	2592	3.3767	5
120	□	■	□	■	□	■	■	□	□	■	□	■	■	□	□	■	□	43200	3.2501	6
123	■	□	□	■	■	□	□	■	□	■	□	■	■	□	□	■	□	2880	3.2299	7
112	□	■	□	■	□	■	□	■	■	□	□	■	■	□	□	■	□	32400	3.1201	8
119	■	□	□	■	□	■	■	□	□	■	□	■	■	□	□	■	□	8640	3.0953	9
122	□	■	■	□	■	□	□	■	□	■	□	■	■	□	□	■	□	1440	3.0831	10
111	■	□	□	■	□	■	□	■	■	□	□	■	■	□	□	■	□	6480	2.9715	11
118	□	■	■	□	□	■	■	□	□	■	□	■	■	□	□	■	□	4320	2.9546	12
64	□	■	□	■	□	■	□	■	■	□	□	■	□	■	■	□	□	8100	2.9372	13
121	■	□	■	□	■	□	□	■	□	■	□	■	■	□	□	■	□	288	2.9363	14
96	□	■	□	■	□	■	□	■	□	■	■	□	■	□	□	■	□	43200	2.8889	15
110	□	■	■	□	□	■	□	■	■	□	□	■	■	□	□	■	□	3240	2.8364	16
116	□	■	□	■	■	□	■	□	□	■	□	■	■	□	□	■	□	4800	2.8261	17
117	■	□	■	□	□	■	■	□	□	■	□	■	■	□	□	■	□	864	2.8139	18
63	■	□	□	■	□	■	□	■	■	□	□	■	□	■	■	□	□	1620	2.7973	19
95	■	□	□	■	□	■	□	■	□	■	■	□	■	□	□	■	□	8640	2.7514	20
108	□	■	□	■	■	□	□	■	■	□	□	■	■	□	□	■	□	3600	2.7131	21
109	■	□	■	□	□	■	□	■	■	□	□	■	■	□	□	■	□	648	2.7014	22
160	□	■	□	■	□	■	□	■	■	□	■	□	□	■	□	□	■	4050	2.6937	23
115	■	□	□	■	■	□	■	□	□	■	□	■	■	□	□	■	□	960	2.6916	24
62	□	■	■	□	□	■	□	■	■	□	□	■	□	■	■	□	□	810	2.6701	25
94	□	■	■	□	□	■	□	■	□	■	■	□	■	□	□	■	□	4320	2.6263	26
104	□	■	□	■	□	■	■	□	■	□	□	■	■	□	□	■	□	10800	2.6	27
107	■	□	□	■	■	□	□	■	■	□	□	■	■	□	□	■	□	720	2.5839	28
114	□	■	■	□	■	□	■	□	□	■	□	■	■	□	□	■	□	480	2.5692	29
159	■	□	□	■	□	■	□	■	■	□	■	□	□	■	□	□	■	810	2.5654	30

Figure 6: Partial Listing of Potential Variants (in Order of Capability: High to Low)

By plotting the combined relative risk score and the relative capability score for each variant, can characterize the trade space by risk versus capability. This plot is shown in Figure 7.

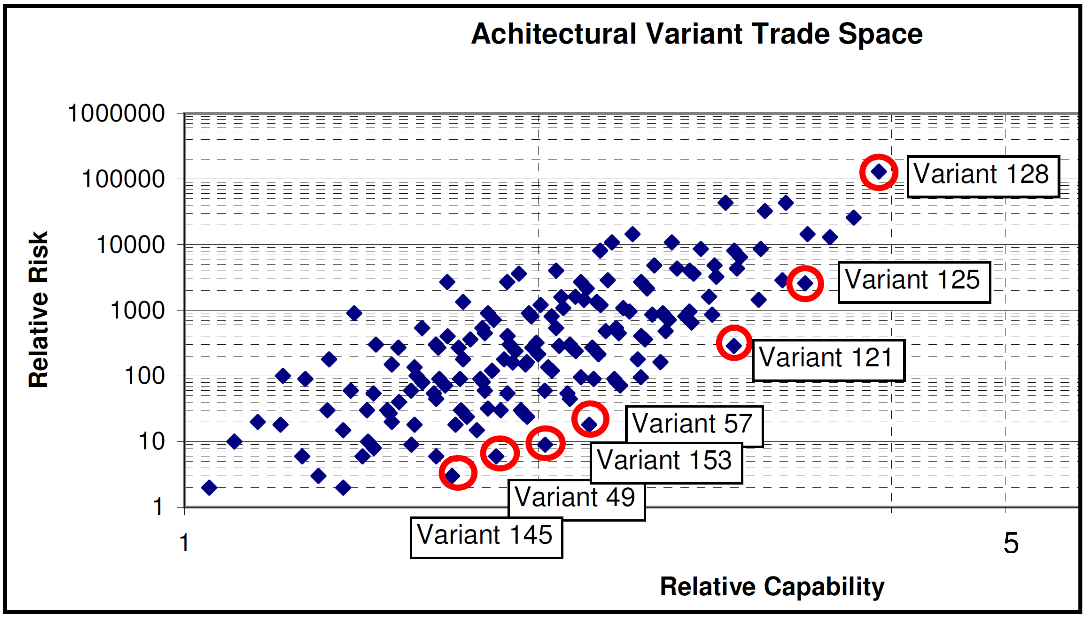
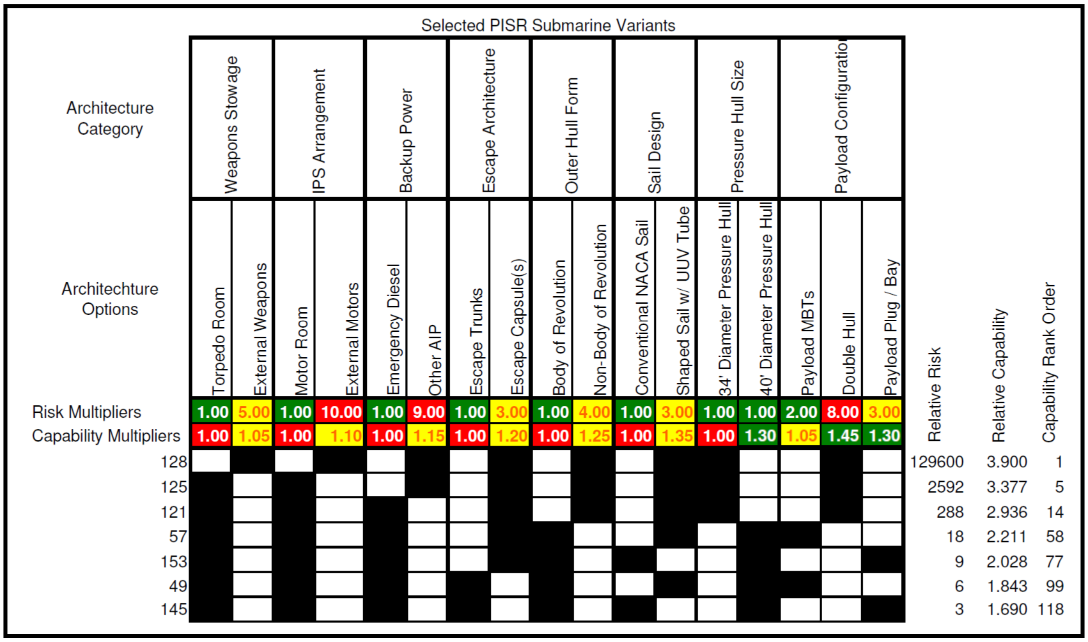


Figure 7: Variants Selected for Final Comparison

With all 160 variants plotted showing the potential trade space solutions, 7 variants were selected for further study which are circled in Figure 7. These variants generally represent the trade space frontier of high capability with low risk. The architecture of these variants is shown in Figure 8 below:



Selected PISR Submarine Variants

Architecture Category	Weapons Stowage		IPS Arrangement		Backup Power		Escape Architecture		Outer Hull Form		Sail Design		Pressure Hull Size		Payload Configuratio					
Architechture Options	Torpedo Room	External Weapons	Motor Room	External Motors	Emergency Diesel	Other AIP	Escape Trunks	Escape Capsule(s)	Body of Revolution	Non-Body of Revolution	Conventional NACA Sail	Shaped Sail w/ UUV Tube	34' Diameter Pressure Hull	40' Diameter Pressure Hull	Payload MBTs	Double Hull	Payload Plug / Bay	Relative Risk	Relative Capability	Capability Rank Order
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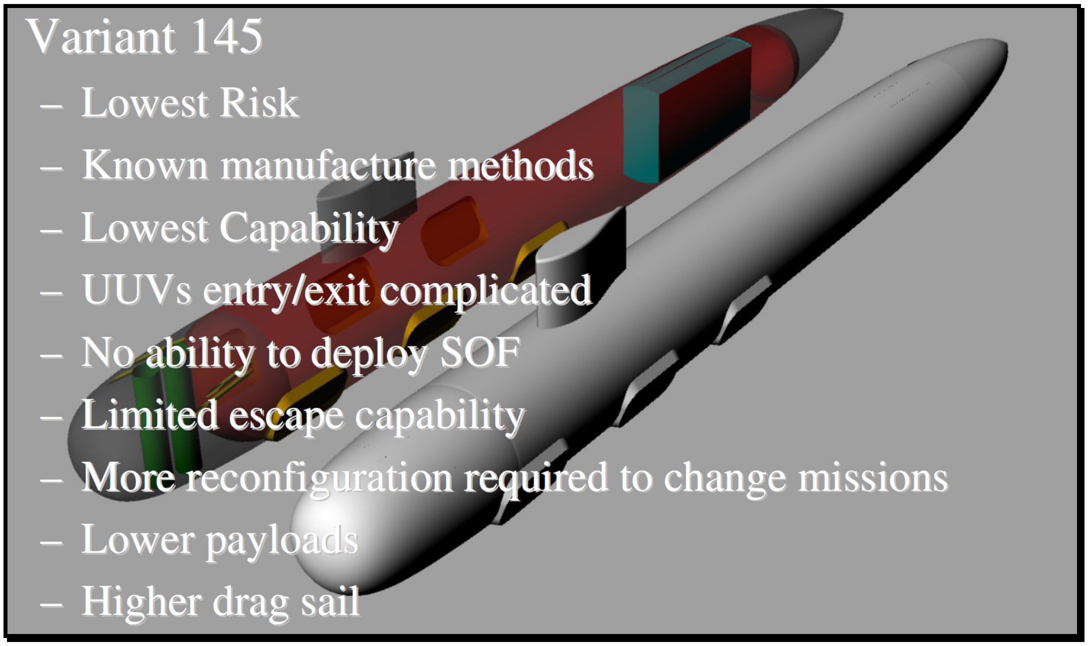
Capability Multipliers	1.00	1.05	1.00	1.10	1.00	1.15	1.00	1.20	1.00	1.25	1.00	1.35	1.00	1.30	1.05	1.45	1.30			
128	□	■	□	■	□	■	□	■	□	■	□	■	■	□	□	■	□	129600	3.900	1
125	■	□	■	□	□	■	□	■	□	■	□	■	■	□	□	■	□	2592	3.377	5
121	■	□	■	□	■	□	□	■	□	■	□	■	■	□	□	■	□	288	2.936	14
57	■	□	■	□	■	□	□	■	■	□	□	■	□	■	■	□	□	18	2.211	58
153	■	□	■	□	■	□	□	■	■	□	■	□	□	■	□	□	■	9	2.028	77
49	■	□	■	□	■	□	■	□	■	□	□	■	□	■	■	□	□	6	1.843	99
145	■	□	■	□	■	□	■	□	■	□	■	□	□	■	□	□	■	3	1.690	118

Figure 8: Variant Trade Space (Risk vs. Capability)

Across these 7 all architectural options were included. This allowed and examination of the impact of each technology on variant cost and performance.

For each of these 7 variants, a concept sketch (or cartoon) was developed using Rhino, a computer aided design program. For each variant, a list of relative advantages and disadvantages was developed. Figures 9-15 show the cartoons of several variants overlaid with the relative advantages and disadvantages of the variant's architectural / technological features. The pressure hull is shown in red, sonar systems in orange, UUV storage and backhaul in teal, external torpedoes, torpedo tubes and VLS tubes in yellow, and MAC tubes in green. Escape chambers are represented by spheres.



Variant 145

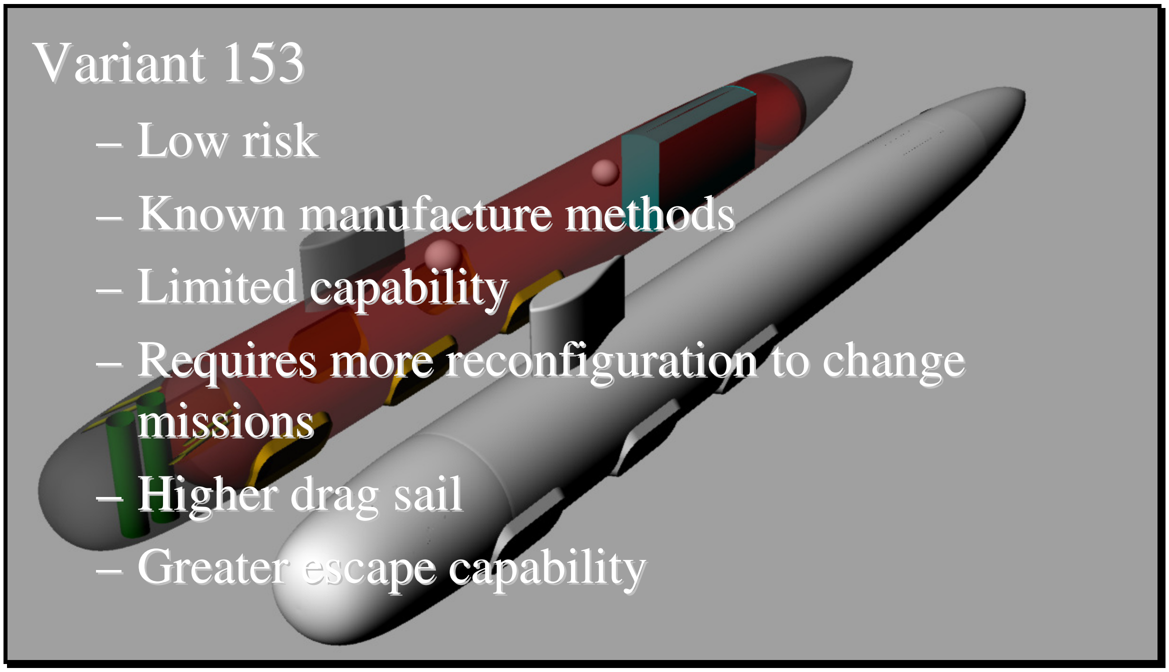
- Lowest Risk
- Known manufacture methods
- Lowest Capability
- UUVs entry/exit complicated
- No ability to deploy SOF
- Limited escape capability
- More reconfiguration required to change missions
- Lower payloads
- Higher drag sail

Figure 9: Variant 145 Cartoon and Characteristics

Variant 49

- Low risk
- Limited capability
- Limited reconfigurability
- UUVs enter/exit more easily
- Greater reserve buoyancy likely (Payload MBTs)

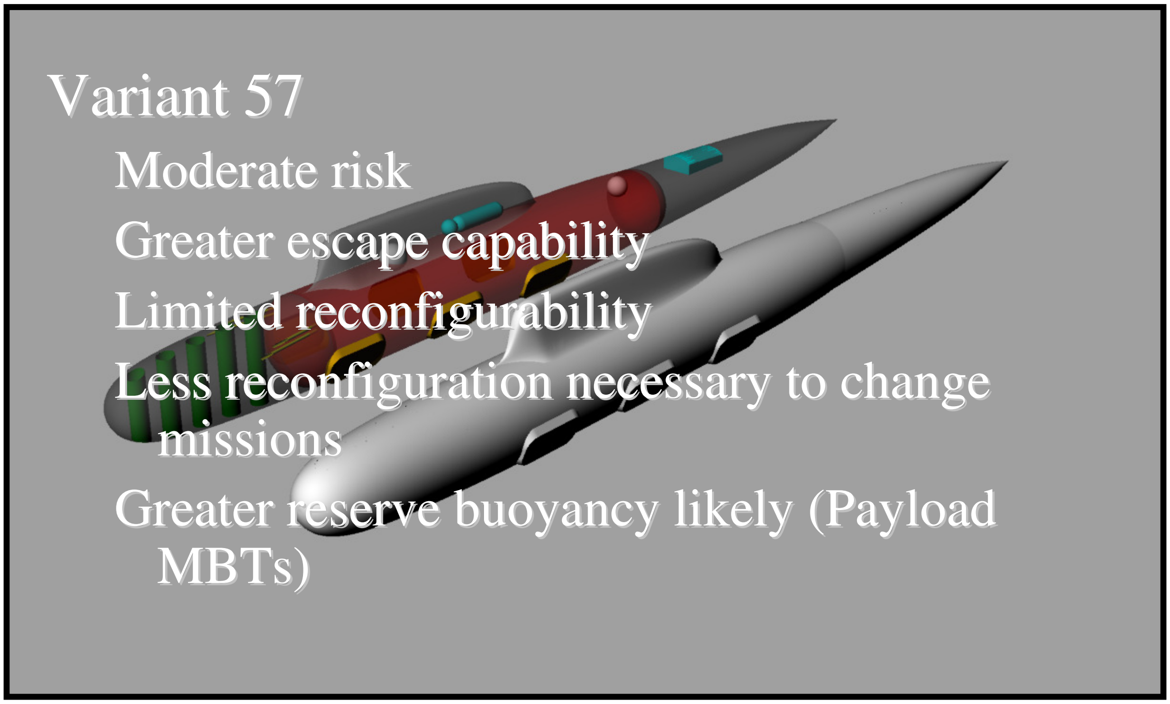
Figure 10: Variant 49 Cartoon and Characteristics



Variant 153

- Low risk
- Known manufacture methods
- Limited capability
- Requires more reconfiguration to change missions
- Higher drag sail
- Greater escape capability

Figure 11: Variant 153 Cartoon and Characteristics



Variant 57

Moderate risk

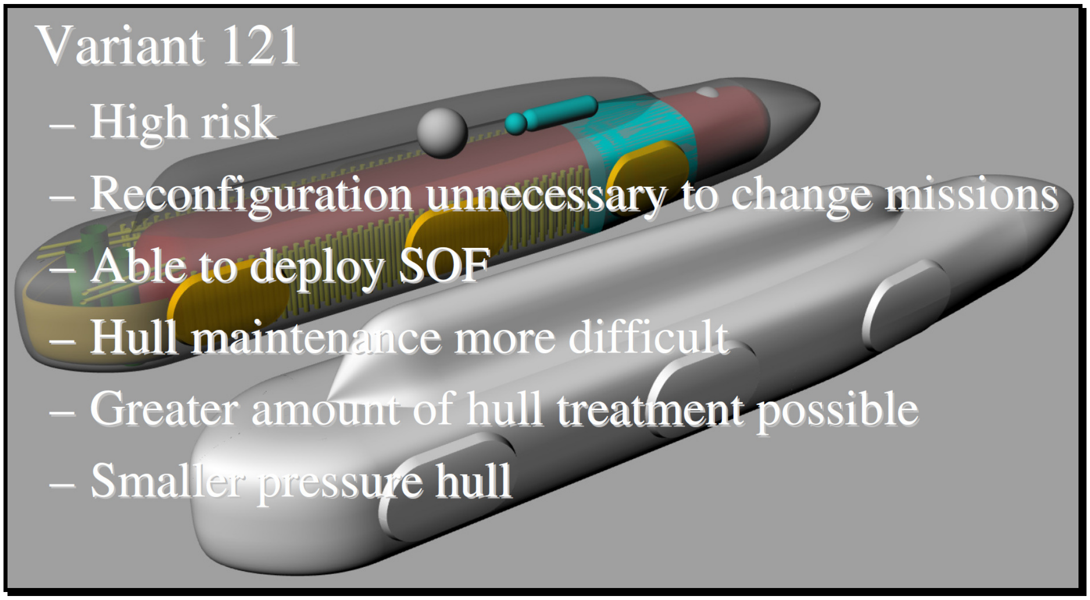
Greater escape capability

Limited reconfigurability

Less reconfiguration necessary to change missions

Greater reserve buoyancy likely (Payload MBTs)

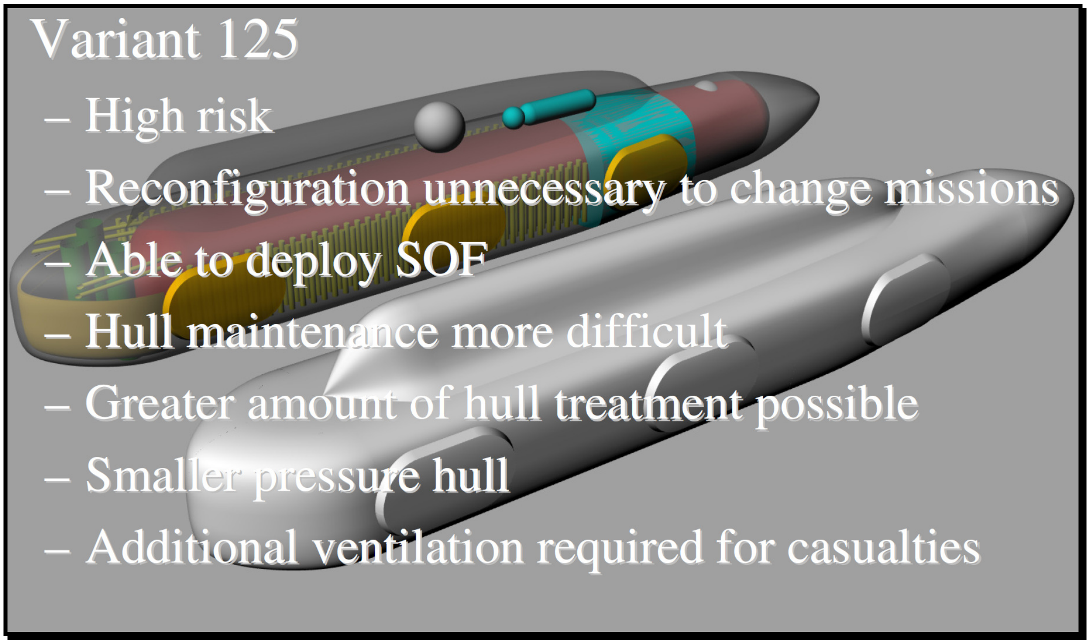
Figure 12: Variant 57 Cartoon and Characteristics



Variant 121

- High risk
- Reconfiguration unnecessary to change missions
- Able to deploy SOF
- Hull maintenance more difficult
- Greater amount of hull treatment possible
- Smaller pressure hull

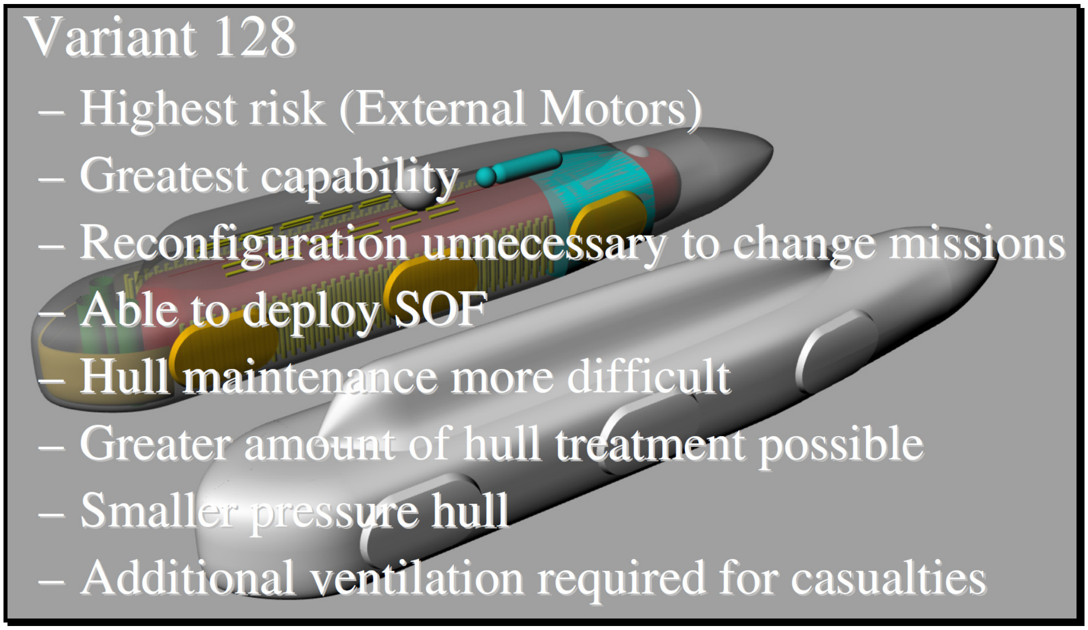
Figure 13: Variant 121 Cartoon and Characteristics



Variant 125

- High risk
- Reconfiguration unnecessary to change missions
- Able to deploy SOF
- Hull maintenance more difficult
- Greater amount of hull treatment possible
- Smaller pressure hull
- Additional ventilation required for casualties

Figure 14: Variant 125 Cartoon and Characteristics



Variant 128

- Highest risk (External Motors)
- Greatest capability
- Reconfiguration unnecessary to change missions
- Able to deploy SOF
- Hull maintenance more difficult
- Greater amount of hull treatment possible
- Smaller pressure hull
- Additional ventilation required for casualties

Figure 15: Variant 128 Cartoon and Characteristics

After considering the relative advantages, disadvantages, risk, and capability as well as opportunity for study of novel architectures and technologies, variant 121 was chosen for final refinement and feasibility study.

3.4 Final "Preferred" Concept Design

Figure 16 and Figure 17, below, show the cartoon arrangement of the final variant. The level of detail developed at this point in the design only permitted very gross estimates of ship characteristics.

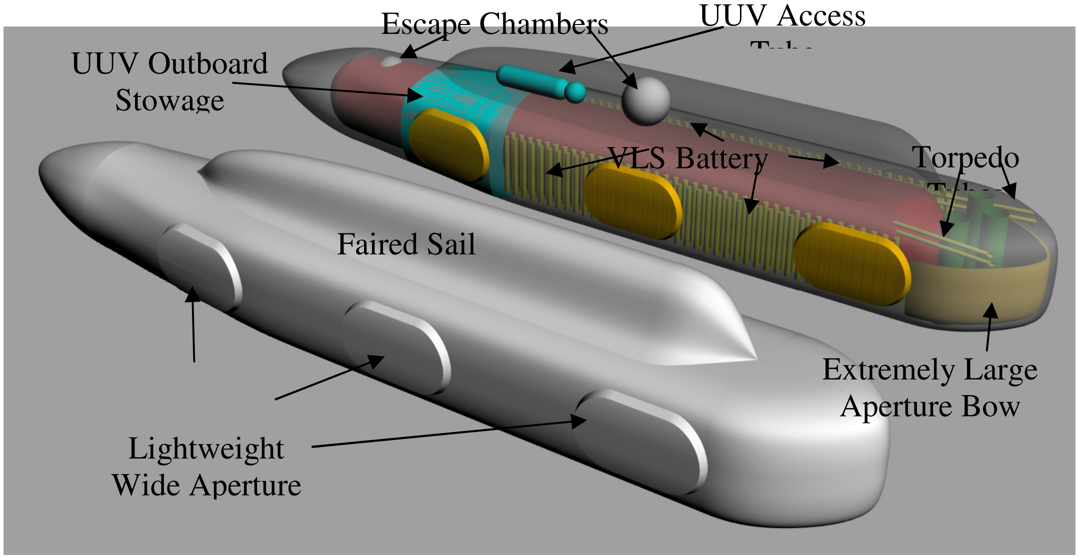


Figure 16: Final Variant Cartoon (Perspective View)

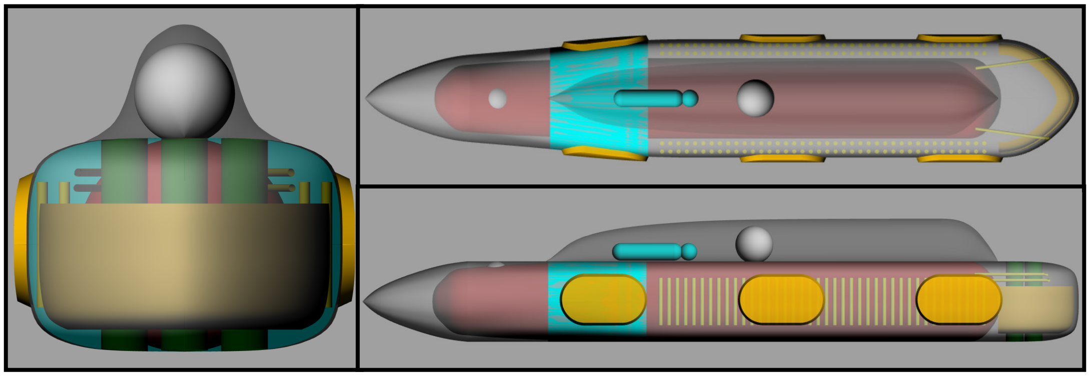


Figure 17: Final Variant Cartoon (Section, Plan, and Profile Views)

Table 5**Error! Reference source not found.** lists the architectural features incorporated in the final variant design. Table 6 lists the estimates for the notional ship performance parameters of the concept design based on the concept cartoon shown in Figure 17.

Variant 121 Architectural Features
Double Hulled Construction
Escape Chamber(s)
Torpedo Room
Shaped Sail with UUV Tube
Motor Room (Inside Pressure Hull)
34' Pressure Hull
Emergency Diesel Generator
Non-Body of Revolution

Table 5: Final Variant Architectural Characteristics

Length Overall	303 ft
Length of Pressure Hull	240 ft
Beam	50 ft
Displacement	~12,500 LT
Pressure Hull Diameter	34'
Motor Rating	36.5 MW / 48,947 HP
Crew Complement	135 Persons
Endurance	120 days + 10 days transit
Sustained Speed	27 kts
Draft / Trim	29'
Weapons / Payload	26 – Mk-54 12 – CVLWT 160 – AIM-9X or 160 – TLAM or 160 – AUV's
UUV Capability	8 – high endurance UUV's

Table 6: Predicted Variant Performance Parameters

This final design for the PISR concept features several attractive capabilities, in particular:

- Large apertures for sonar arrays (Wide Aperture Array and Bow Array)
- Double hull allows for vast increase in payload capacity (VLS stowage)
- Escape capability will significantly exceed that of current fleet submarines
- Wet handling and stowage of UUV’s with capability to backhaul for maintenance without requiring complicated sea interface (can maintain double isolation from sea)

4.0 Feasibility Analysis and Refinement

4.1 Design Definition

Designing this submarine involved completing a design spiral three times.
The first time through the spiral consisted of the following steps:

1. Determining engine room, reactor compartment and operations compartment volumes using the parametrics contained in Ref 4 and 5.
2. Initial sizing of variable ballast tank
3. Estimating single digit weights from parametrics and comparative naval architecture
4. Balancing submarine (Weight = Buoyancy, BG > 1ft)
5. Creating initial arrangement drawings
6. Estimating power and resistance

At the conclusion of the first design spiral the submarine was balanced and a notional location of all components had been determined.

The second time through the spiral involved:

1. Performing pressure hull structural optimization and analysis
2. Estimating the weight of the non-pressure hull structure
3. Updating group 100 weights
4. Completing an electric plant layout
5. Completing the arrangement drawings for the engine room
6. Updating group 200 and 300 weights
7. Rebalancing the submarine
8. Creating an equilibrium polygon

The third time through the design spiral added the following:

1. Layout of the payload tubes
2. Establishing final group 700 weights
3. Adding volume as a result of step 2
4. Rebalancing the submarine
5. Performing a power and resistance analysis
6. Performing a maneuvering analysis
7. Completing a parametric propeller analysis
8. Designing and adding a propeller
9. Completing final arrangement drawings
10. Updating the equilibrium polygon

4.1.1 Design Margins and Service Life Allowances

The PISR Design SWBS group weight estimates include an 8% design margin and the final concept design includes a Service Life Weight Allowance of 446 LT of lead located along the centerline of the pressure hull, 193.5' aft of the forward extent of the non-pressure hull. This allowance represents 6.1% of the A-1 weight and should provide for adequate modification of the ship over its 30 year service life. No additional allowance is included in the BG for service life as the service life lead and stability lead may both be impacted by future weight additions based on the VCG of the weight addition.

The PISR electric plant is configured with a capacity of 10 MW for electrical loads in addition to 36.5MW for propulsion . A conservative analysis of required electrical capacity indicates that this represents an electrical power service life allowance of 25%. Furthermore, the IPS infrastructure will permit back fitting of higher electrical distribution capacity at the expense of top speed propulsive power.

4.1.2 Ship Geometry / Hull Form

The PISR pressure hull form is a body of revolution hull. The non pressure hull form is structure added at the beams of the pressure hull to create volume for the accommodation of a vertical launch system and UUVs. Near the stern of the submarine, the hull shape transitions to a body of revolution shape. The plan view of the submarine shows how the non-pressure hull beam greatly exceeds the diamter of the pressure hull. In the elevation view the submarine appears to more closely resemble a body of revolution hull form. A plan, elevation and perspective view of the hull are shown below:

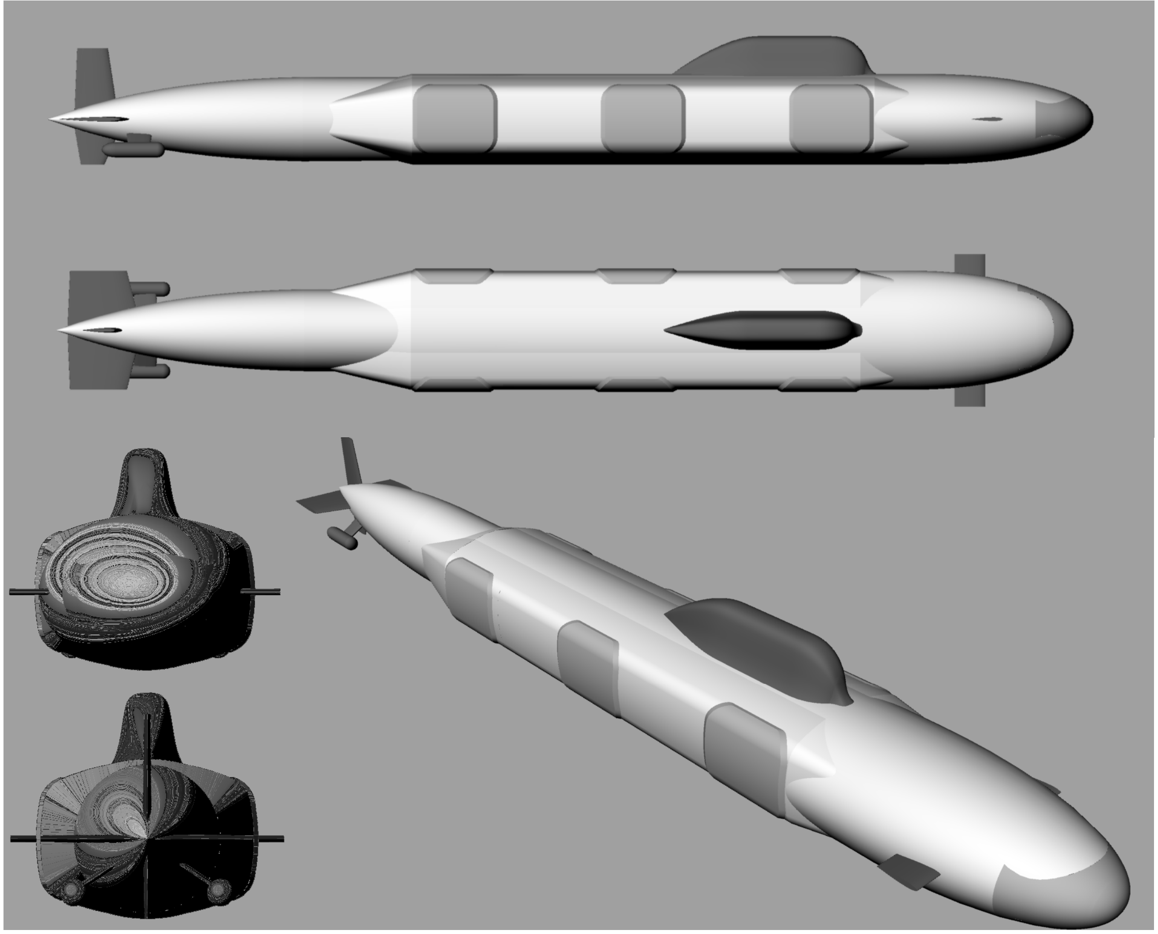


Figure 18: PISR Hull Configuration

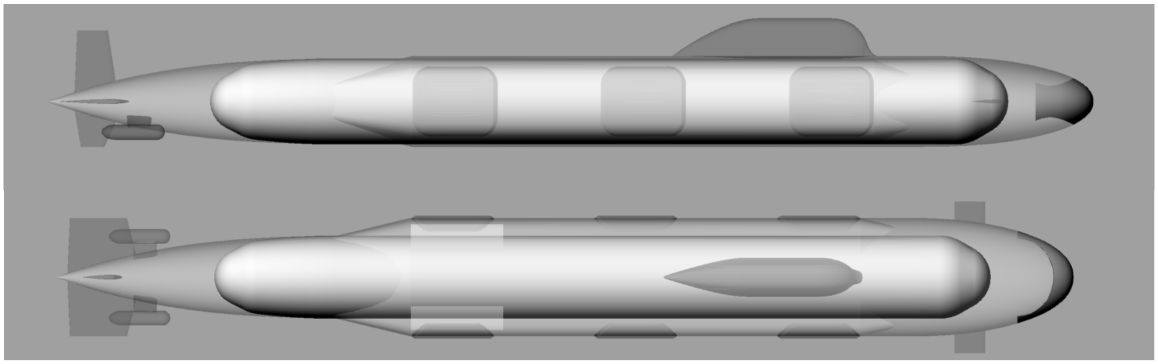


Figure 18: PISR Hull Configuration (Continued)

4.1.3 Mission/Combat Systems Payload

This submarine has three missions:

Primary: Persistent Intelligence, Surveillance and Reconnaissance
Secondary: Anti-Submarine, Surface and Air Warfare
Tertiary: SOF and Mine

The primary mission is accomplished by the incorporation of UUVs, UAVs, bow array, wide aperture flank arrays, towed arrays and masts and antennas. Table 7 shows the specific number and size of each of the primary combat systems is shown below:

Primary Combat Systems			
System	**Number**	**Size**	**Notes**
Bow Array	1	786ft^2, 32ft beam	This is a conformal array
Thin Line	1	Standard	
Fat Line	1	Standard	
WAA Panels	6	959ft^2, 77.3 ft spacing	Three WAA panels per side at spacing listed
UUV	12	4ft Diameter	Number is size diameter dependent
UAV	28	10in dia x 7.8 ft long	UAVs will require collapseable/foldable wings

Table 7: Primary Systems

The secondary missions are accomplished by the incorporation of cruise missiles, surface to air missiles and torpedoes. Table 8 shows the specific number and size of each of the secondary combat systems.

Secondary Combat Systems			
System	**Number**	**Size**	**Notes**
Payload Tubes	16	65"dia x 22.5' long	
Tomahawk	64 max	Standard	Number actually carried depends on load out configuration but is four per payload tube
AIM-9X	48 max	Standard	Number actually carried depends on load out configuration but is three per payload tube
Mk-54	26	Standard	
CVLWT	20	Standard	

Table 8: Secondary Systems

Tertiary missions include the ability to deploy mines and host, but not deploy, Special Forces. Mines can be deployed from any of the 4 main torpedo tubes; however, these small diameter tubes cannot accommodate standard-sized submarine launched mines. The ability to host Special Forces is demonstrated in the number of berths which were designed into the submarine. The normal crew compliment is 145 but the number of accommodations designed into the submarine is 165 (+1 for a Senior Embarked Rider in the XO State Room).

A major goal of the PISR design was to significantly shift payload outboard of the pressure hull. This is achieved in several features. The largest of these is a battery of 16-65" (ID) vertical payload tubes. These are able to support multiple missions including Anti-Air Warfare/Self Defense (AIM-9X), Strike (TLAM), ASuW and ISR (additional UUV or large size UAV's). ASW capability could be enhanced by adding bottom opening hatches and torpedoes that drop out. This feature is not part of PISR but there is sufficient margin and stability lead present in the submarine to be able to incorporate this capability in the future.

Figure 19 illustrates the arrangement of these payload tubes (shown in yellow).

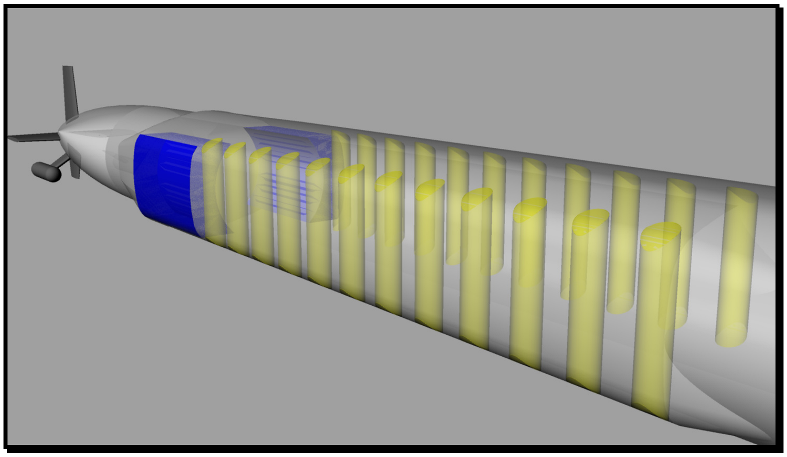


Figure 19: Payload and Escape Tubes and UUV Outboard Stowage Arrangement (Bow Right)

Sail Removed for Clarity

Also visible in Figure 19 is the UUV outboard stowage space, shaded in blue. The concept for UUV deployment could take several forms that need to be further examined. Aft of this area is the portion of the non-pressure hull that tapers back down into a body of revolution. This presents an ideal geometry for UUVs to enter and leave the outboard stowage. The UUVs would be deployed and retrieved with the submarine in a hovering or near hovering (< 1.5 kts) operational condition and either the area immediately abaft of the UUV stows would include a large hydraulic door in the non-pressure hull that would pivot inboard, or the entire UUV stowage assembly would pivot outboard so that UUVs could address the stows at an angle with respect to the longitudinal axis of the ship. These two concepts are shown in Figure 20 and Figure 21:

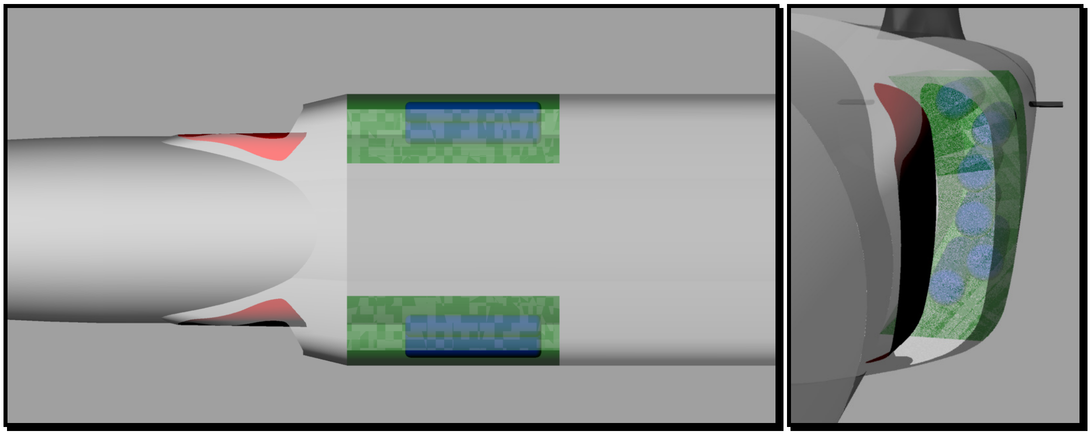


Figure 20: Pivoting In Door Concept for UUV Access
Plan View Left, Perspective Right, Bow Right

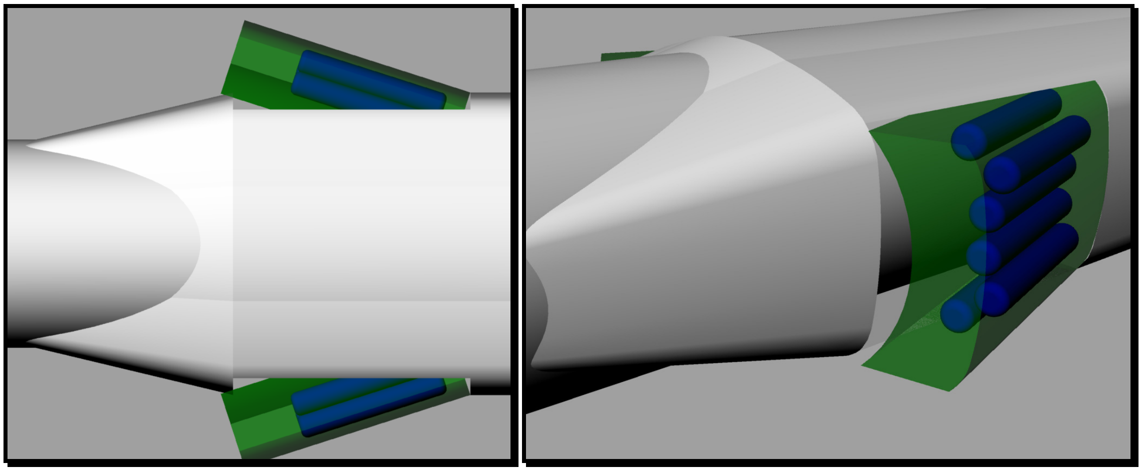


Figure 21: Pivoting Out Carriage Concept for UUV Access

The pivoting concept carries increased technical risk as this would impact the aftmost pair of WAA panels and the challenge of fairing the door for hydroacoustics would be exacerbated by the requirement to maintain the array panel in alignment with the rest of the array. The large size of the outboard stowage volume for UUVs ensures flexibility in the payload carried. Figure 22 shows how the configuration of the UUV stowage differs for UUVs ranging from 4-6' in diameter.

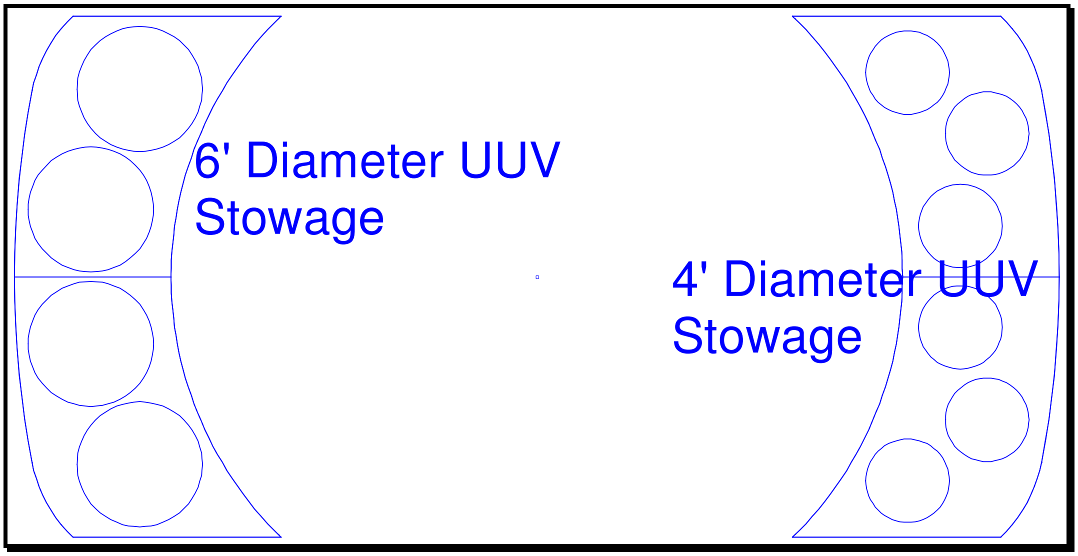


Figure 22: Section View of Potential UUV Outboard Stowage Configurations

This payload volume can easily accommodate large UUVs and has the flexibility to embark non-cylindrical UUVs as well. 24' long UUVs are modeled in this concept.

Additional mission payloads are stowed outboard in the sail. The sail includes bridge access, 8 modular mast locations, snorkel induction mast and an 87" x 27' UUV access tube in which UUVs can be accessed and maintained without the need for a complete backhaul capability into the pressure hull. This concept does require that the UUV be able to pilot itself into the UUV access tube. The sail also holds outboard stowage for 28 UAVs in vertical launch tubes. As currently modeled, each UAV tube is provided with a holding enclosure and hatch. In future refinements, these payloads should be grouped into larger tubes to reduce the total number of hatches and therefore the system weight and complexity. Figure 23 shows the sail configuration of the PISR. The UUV access tube is in blue, masts in gold, UAV tubes in green, and bridge access trunk in black. The sail design incorporates doors on the aft end (not shown) that swing outward to allow full access to the UUV tube in the rear.

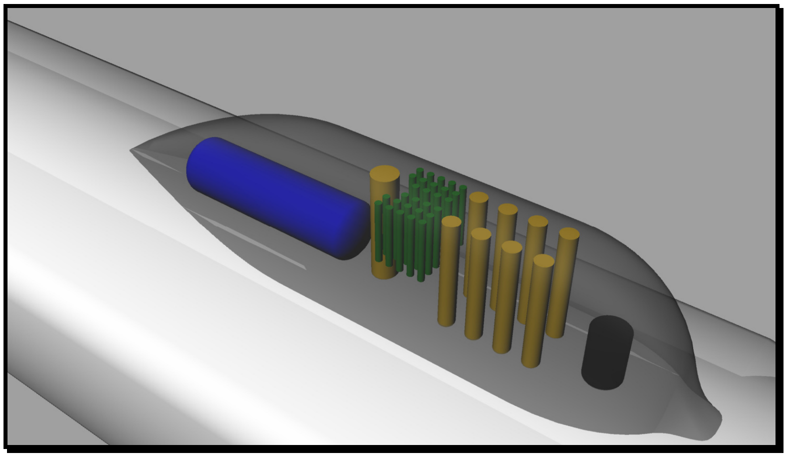


Figure 23: PISR Sail Outboard Arrangement

4.1.4 Command, Control and Communications

The PISR features C4I systems comparable to those found aboard modern US fleet SSNs such as the USS VIRGINIA. Similar to VIRGINIA, the Command and Control function is located in the middle level of the operations compartment. This permits a large, open control and attack center that is removed from major passageways and includes segregated spaces for navigation systems, radio room, ESM room and a dedicated space for sensitive operations using off board sensors and autonomous vehicles. All of these rooms communicate with the control room. The electronics to support the C4I systems are located in a large CSES/SES room just forward of the attack center. The communications suite for the PISR concept includes 6 Universal Modular Mast (UMM) bays in the sail, and two photonics masts.

4.1.5 Propulsion, Electrical and Auxiliaries

A major consideration in the overall concept design was the customer requirement of installing an IPS architecture aboard the PISR SSN. Figure 24 shows the overall configuration of the IPS system.

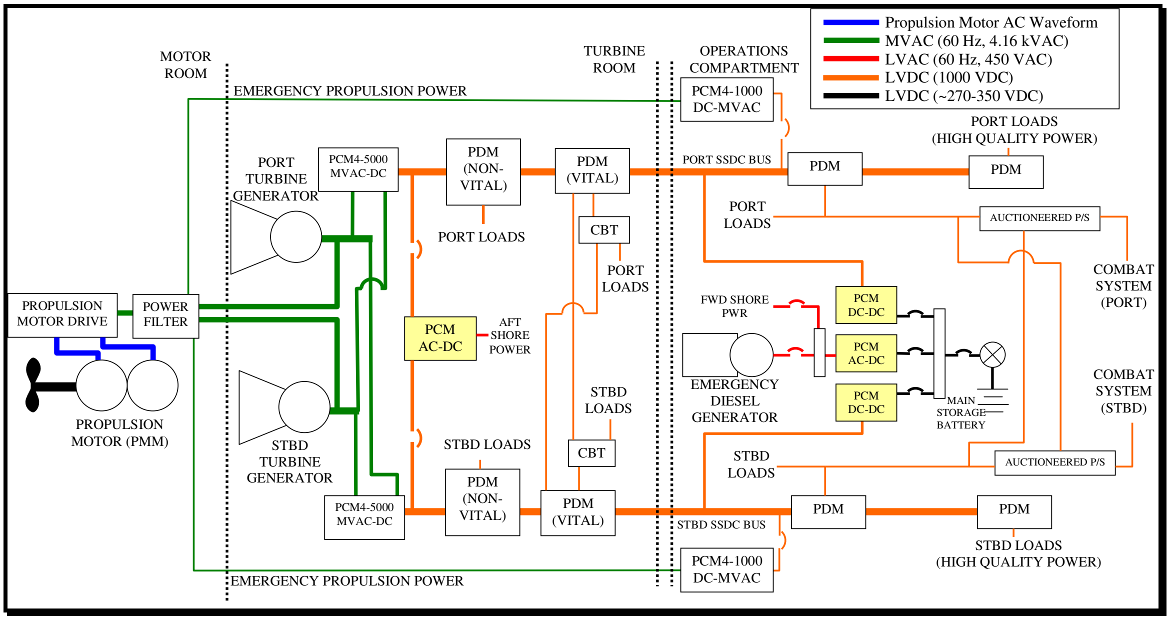


Figure 24: Integrated Power System Layout

Primary service power is provided throughout the ship using 1000VDC Port and Starboard busses. In order to maximize commonality with the work being done with other IPS design teams and the Electric Ship Office, a 4.16kV Medium Voltage AC was selected as the output from the two 25 MW turbine generators as well as an IPS certified Propulsion Motor Module in the form of a 36.5 MW Permanent Magnet Motor. While promising technologies are being developed such as the High Temperature Super Conducting motor, the technical risk in using a new motor design was not warranted. Table 9 and Table 10 summarize the propulsion plant ratings and the IPS components selected.

Propulsion Summary	
Reactor & Steam Plant Thermal Efficiency	30%
Generator Efficiency	98%
Electrical Conversion Efficiency	98%
Motor Efficiency	97%
Propulsion Motor	
Propulsion Motor Rating	36.5 MW
Electrical Load	
Installed Ship's Electric Power	10 MW
Electrical Generation	
Required Generator Capacity	49.2 MW
Individual Generator Selection	25.0 MW
Reactor	
Reactor Plant Required Rating	167.5 MWth

Table 9: Propulsion Plant Summary

IPS COMPONENTS	Qty	Length (ft)	Width (ft)	Height (ft)	Diameter (ft)	Weight (LT)	LCG (ft from FP)	VCG (ft above PH base)	TCG (ft from CL)	Power Required (kW)	Power Rating (MW)	Total Capacity (KWhr)
Propulsion												
Propulsion Motor	1	16.07	17.85	15.25		108.53	324.84	17.50	0.00			
Motor Drive / Propulsion Converter	1	22.97	4.92	9.84		18.01	299.69	12.92	-10.41			
Power Filter	1	19.69	5.91	7.87		28.15	299.85	11.94	9.85			
Dynamic Braking Resistors	2	14.44	5.91	7.55		24.58	305.10	19.53	0.00			
Motor / Shaft Lube Oil System	1	11.81	5.74	8.20		5.25	312.30	5.53	0.00	32		
Power Generation												
Turbine Generator	2	4.56			5.49	3.87	260.26	24.68	0.00		25	
Generator Pull Space	2	3.80	4.17	4.17		0.00	265.26	24.68	0.00			
Diesel Generator	1	3.00	3.00	3.00		1.00	180.38	8.50	0.00		1	
Main Storage Battery (/cell)	126	1.17	1.17	4.58		0.58	128.25	3.00	0.00			1150
Power Conversion and Distribution												
PCM4-5000 (4.16kVAC - 1000 VDC)	2	18.77	4.49	6.40		4.97	299.81	17.77	0.00		5	
PCM4-1000 (1000 VDC - 4.16kVAC)	2	5.41	4.49	6.40		4.97	310.10	19.15	0.00		1	
AFT SP PCM (450VAC - 1000 VDC)	1	5.41	4.49	6.40		4.97	295.64	20.05	-3.21		1	
FWD SP PCM (450VAC - ~270-350 VDC)	1	5.41	4.49	6.40		4.97	182.62	27.00	-8.00		1	
BATTERY PCM (~270-350 VDC - 1000 VDC, BI-DIRECTIONAL)	2	5.41	4.49	6.40		4.97	131.09	-6.50	-2.23		2	
AFT PDMs	4	2.50	3.50	6.40		1.5	294.38	20.05	3.41			
FWD PDMs	4	2.50	3.50	6.40		1.5	183.00	9.50	-8.50			

Table 10: PISR IPS Component Summary

One opportunity that this concept takes advantage of is the architectural impact of the IPS configuration on the Engine Room. With an eye toward enhanced damage control and the desire to counteract the addition of a heavy propulsion motor and drives aft, the steam plant was placed as close to the RC bulkhead as feasible. This ultimately permitted the segregation of engineering systems into a Motor Room, a Turbine Room, an Auxiliary Machinery Room, and a Reactor Compartment (inaccessible during power operations). Table 11 shows the division of systems into these spaces.

Auxiliary Machinery Room	Reactor Compartment	Turbine Room	Motor Room
Emergency Diesel Generator	Reactor	Turbine Generators	Maneuvering
CO_2 Scrubbers	Reactor Cooling	Main Condensors	Propulsion Motor
CO-H_2 Burners	Steam Generating	Condensate & Feed	Propulsion Drives/Filters
ILPE Oxygen Generator	Reactor Shielding	Reactor Aux Systems	Propulsion PCMs/PDMs
External Hydraulics		Drain Station	Ships Service Hydraulics
Trim Pumps		Propulsion Plant Fresh Water	Steering and Diving Hydraulics
Distilled Water		Reactor Plant Pure Water	Main Lube Oil
R-134 Refrigeration Plant		Reverse Osmosis Units	Shaft Seals
Electronics Fresh Water		Main Steam	High Pressure Compressors
		Nucleonics Lab	Low Pressure Compressor
		TG Lube Oil	Reactor I&C
		Main Sea Water	R-134 AC Plants
		Auxilliary Steam	Chill Water

Table 11: PISR Engineering Function & System Breakdown

By subdividing the engine room with a non-holding bulkhead (rated to a notional 40 psid), most of the high energy systems (steam, seawater, reactor plant, etc.) were effectively segregated from the main engineering control station (Maneuvering) and the major electrical components in the IPS. Note the integration of the RFT into the engine room bulkhead in Figure 25. Furthermore, placing all of the engine room switchgear in the Motor Room limits the spread of smoke from an electrical fire in the switchboards to the adjacent engineering space (the turbine room). Figure 25 shows the subdivision of the aft engineering spaces.

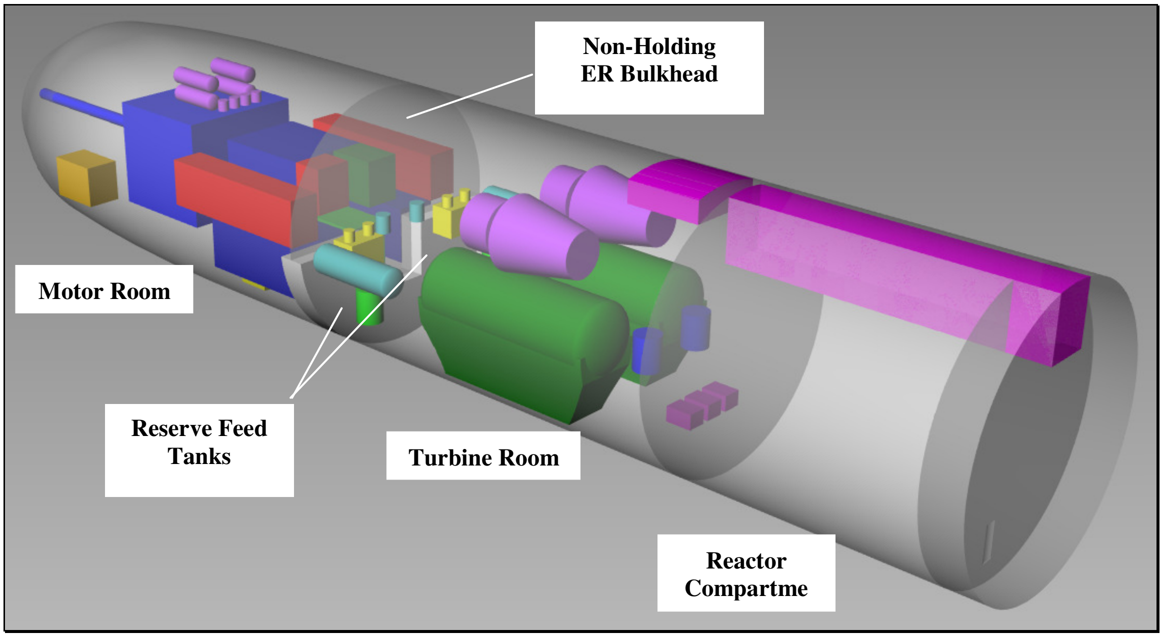


Figure 25: Engine Room Subdivision

4.1.6 Survivability and Signatures

Survivability and the signatures of this submarine are expected to be commensurate with or an improvement on current US Navy submarines. Some features of this submarine which will likely impact survivability and signatures are:

1. Double hull design
2. Large doors for UUV access to outboard stowage
3. Large doors for UUV access tube
4. Unique sail design
5. Large bow array
6. Electric Propulsion Motor

4.1.6.1 Double Hull Design

Overall the double hull design is expected to improve the submarine's survivability and reduce its signature. The double hull design will improve survivability by increasing the minimum standoff to pressure hull for a weapon that detonates near the beam of the ship. The non-pressure hull will also increase the moment of inertia of the submarine hull girder which will make the hull less susceptible to hull whipping in the event of weapon detonation near the keel. Additionally, the double hull design enables a high reserve buoyancy of 15.3%. The submarine's signature might also be improved by the presence of the non-pressure hull which will provide additional surfaces for treatment. However, care should be taken when producing a detailed design for and constructing the non-pressure hull to prevent the generation of transients through non-pressure hull hydrodynamic induced vibrations or flexure.

4.1.6.2 Large Doors

Large doors, necessary to fair the UUV access tube into the sail and to fair the UUV outboard stowage location into the transition from pressure hull to non-pressure hull, are a ship signature concern. Doors which do not fair properly into the rest of the hull have the ability to generate flow tonals which will increase the ship's signature. These doors will also require proper stiffening to prevent the doors from vibrating and acting as a sound board. The actuator and actuator attachment points for these doors will also require some design attention to prevent transients while the doors are being opened or closed. Both sets of doors are intended to only be operated while hovering which should lessen some of the difficulty in designing this structure.

4.1.6.3 Unique Sail Design

In order to accommodate the UUV access tube, UAV vehicle stowage and the usual complement of submarine masts and antennas, a unique sail shape is presented on this submarine. The effect of this sail design on the submarine's survivability and signature is unknown but could significantly alter the flow into the propulsor which raises a concern for the signature emanating from both the sail and propulsor. It is possible that the faired sail form will result in a smaller wake when compared with a standard hydro-foil shaped design and that this could significantly improve both the hydro acoustics and hydrodynamics of the hull performance, but additional study is needed in this area.

4.1.6.4 Large Bow Array

Since the principal mission of this submarine is ISR, large sonar arrays have been used. These arrays will improve the survivability of PISR against other ASW threats such as surface ships and other submarines. Large bow arrays will allow PISR to remain outside of a counter detection range while still performing its own mission. Specifically, the bow array aperture on this submarine is much larger than typical bow arrays. This array will improve ship safety and allow PISR to remain outside of the detection range of other submarines.

4.1.6.5 Electric Propulsion Motor

This submarine is electrically driven and incorporates a single permanent magnet motor (PMM) for propulsion. While the signature of the motor itself is not known, it is expected that the incorporation of an electric propulsion motor will reduce the acoustic signature of the ship because it enables increased isolation of the steam turbines from water surrounding the hull and precludes the need for reductions gears. The effect of an electric propulsion motor on non-acoustic ship signatures is unknown but should be given consideration in the evaluation of the advantages and disadvantages of this type of propulsion.

Total ship signature and survivability for this submarine should outperform or be comparable to current submarines if each of the features listed above is properly designed and built.

4.1.7 Manning and Automation

This submarine design did not make any specific effort to reduce manning or incorporate automation. The total manning level of PISR is commensurate with a submarine which has multi-mission capability. In fact the crew size is somewhat larger than a traditional fast attack submarine in order to support the longer deployment capability and to support the operation of UUVs. The manning break down for this submarine is

Personnel	
Officers	14
Chiefs	15
Crew	116
Total	145

Table 12: Manning

Automation in some areas is less than that used on some current submarines. The torpedo room is one area where automation was not used. In fact, the forward end of the torpedo room which is reserved for the lightweight weapons does not have hydraulics for weapon movement but will instead be moved manually on the racks and into the tubes. In other areas of the submarine the level automation is similar to what is currently used in the fleet.

4.1.8 Space and Arrangements

Figure 26 shows the overall arrangement of the PISR submarine. Sonar hull arrays are shown in green (WAA and Large Bow Array), large Payload Tubes in yellow, UUV and UAV Handling in blue, masts in gold, bridge access in black, torpedo handing in orange, and torpedo ejection and tubes in red.

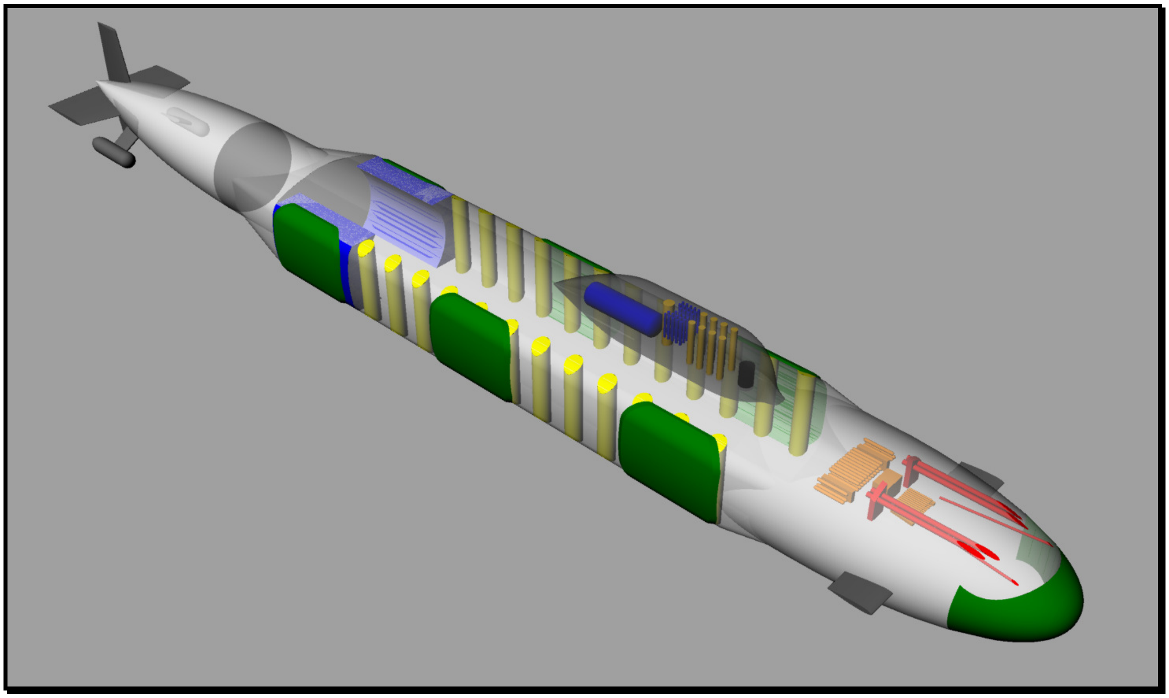


Figure 26: PISR SSN Outboard Arrangements

4.1.8.1 Topside

In the topside drawings shown below it can be seen that this submarine has five access points: one in the engine room and four in the operations compartment. Engine room access is via a logistics escape trunk (LET), just aft to of the engine room subdivision bulkhead, that can be removed to pass larger components. There is a removable plug trunk aft of the sail that allows access to the aft end of the operations compartment; this trunk is expected to be the normal means of ingress/egress for the ship and the trunk that would be used for stores load. It is also possible to access the submarine via the UUV tube in the aft portion of the sail. This access point might be used for personnel transfers at sea during foul weather to prevent waves from entering an open hatch. Immediately forward of the sail is another plug hatch which facilitates stores loads directly into the lower level of the ship convenient to the large general stores room in the forward portion of the Operations Compartment.

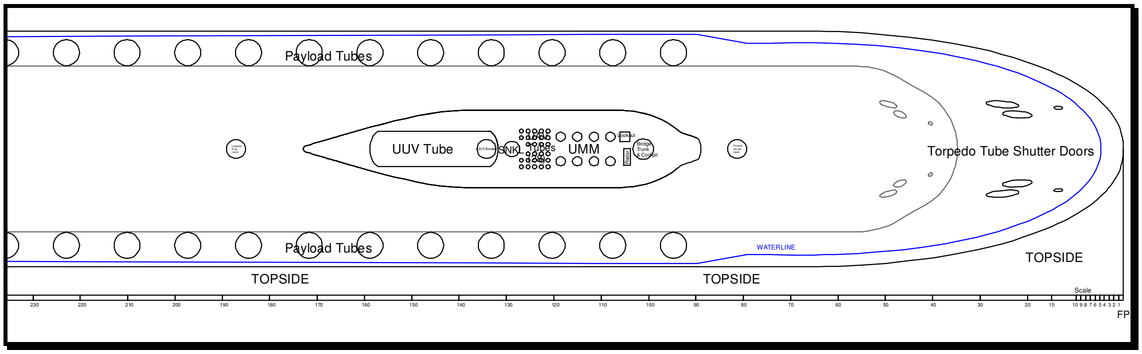


Figure 27: Topside Arrangements in Plan View (FWD Portion)

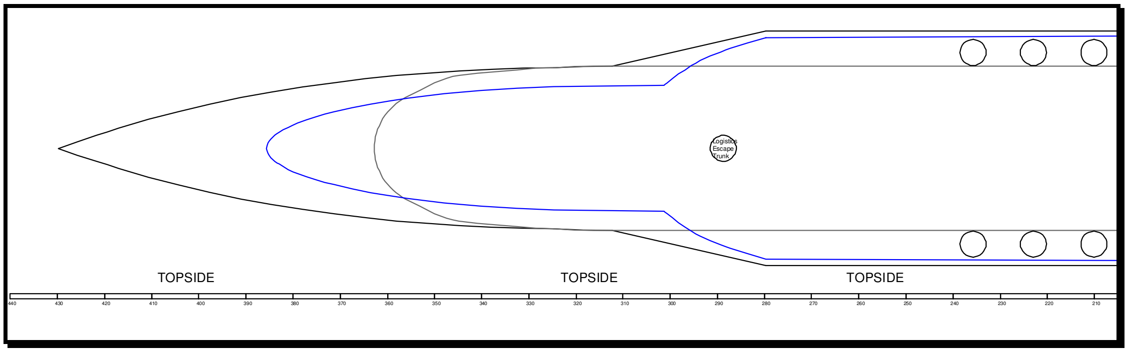


Figure 28: Topside Arrangements in Plan View (AFT Portion)

4.1.8.2 Internal

Internal arrangements are as shown in the figures below. The internal arrangements drawings show several beneficial features: the access trunk in the aft end of the operations compartment and the mid engine room bulkhead. In the aft end of the operations compartment there is access to all decks via removable deck plates. This was done to facilitate stores load and to allow large components from the AMR to be lifted out of the submarine. A similar loading capacity is provided in the forward logistics hatch. The mid engine room bulkhead was included to minimize the impact of a casualty in one half of the engine room on the other half of the engine room. This bulkhead is not a holding bulkhead (rated at 40 psid) but would limit the water communication between ends of the engine room in the event of a flooding casualty.

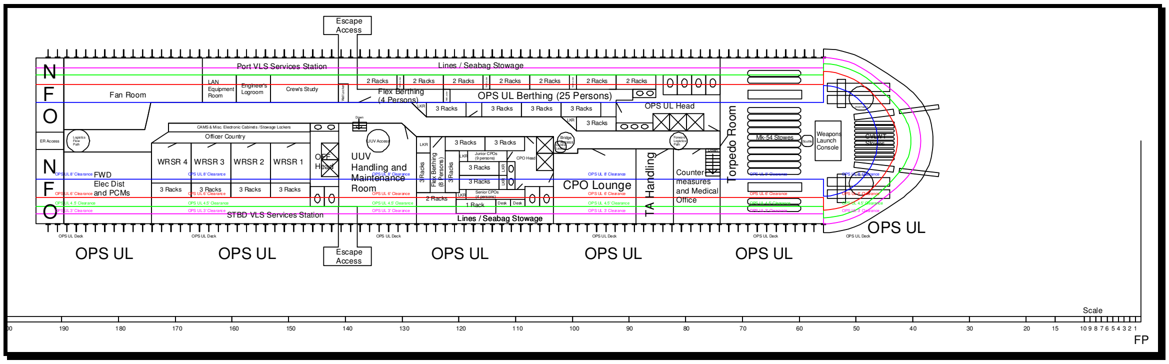


Figure 29: Operations Compartment Upper Level Arrangements in Plan View

The upper level of the Operations Compartment features a longitudinal passageway from the Torpedo Room all the way aft to the Reactor Compartment Shielded Tunnel. The Torpedo Room takes full advantage of the small sized ordnance by keeping torpedo stows low to the platform deck and using the entire breadth of the space. Access to the capstan and MBT Vent Operators is located between the small diameter tubes forward of the CVLWT stowage racks.

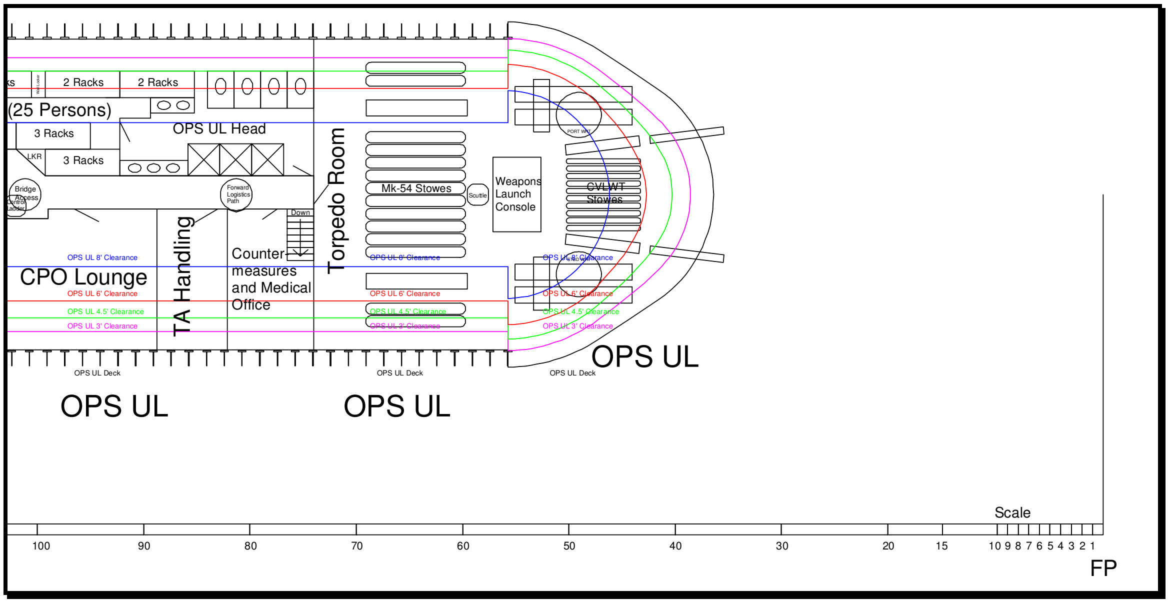


Figure 30: Detailed Arrangements of Operations Compartment, FWD Upper Level

Moving aft from the Torpedo Room, the bulk of Operations Compartment Upper Level (OPSUL) contains habitability space for crew, CPOs and officers. Additional space is provided for fat line towed array handling, countermeasures and medical supplies and access to 4 of the 8 submarine escape capsules.

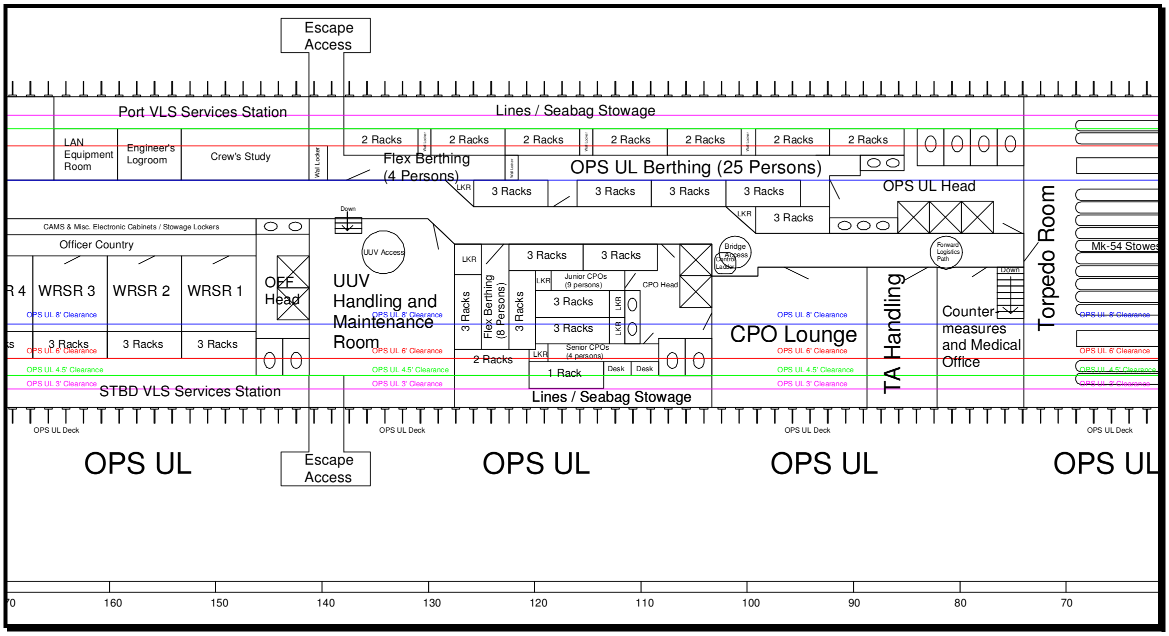


Figure 31: Detailed Arrangements of Operations Compartment, MID Upper Level

Further aft lie office spaces for the ship's LAN, the Engineering Log Room, the Crew's Study, the forward Electrical Room (forward PCMs and PDMs with the exception of the Battery PCMs in OPSLL) and the fan room.

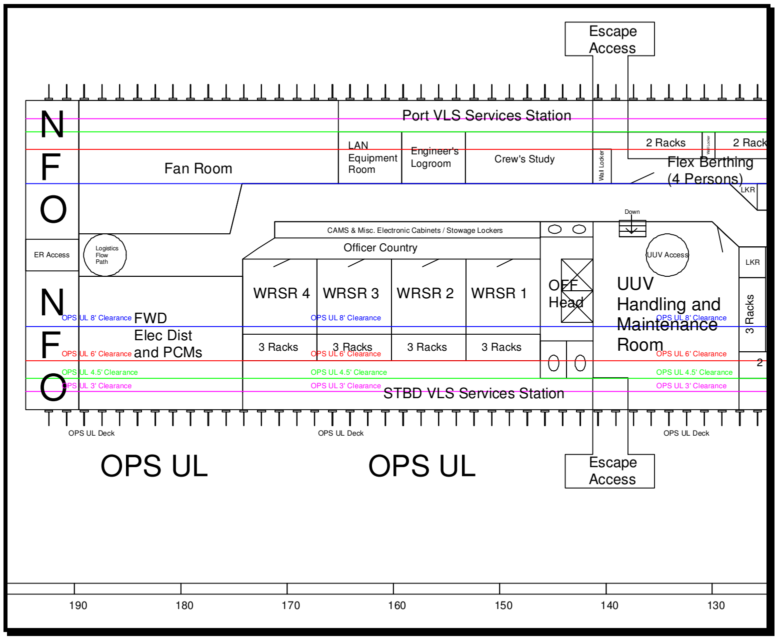


Figure 32: Detailed Arrangements of Operations Compartment, AFT Upper Level

OPSML is divided fore and aft between command and control / combat system spaces and messing and galley spaces. As the function of these spaces is greatly enhanced by maintaining them inviolate, no passageways pass through them. Excellent communication with OPSUL and OPSLL is achieved through double non-vertical ladders in the aft of CSES/SES and just forward of the mess decks.

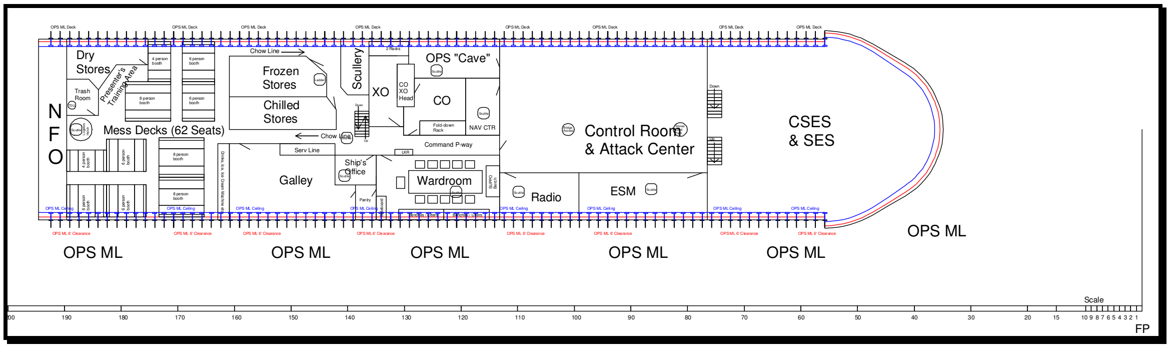


Figure 33: Operations Compartment Middle Level Arrangements in Plan View

The extreme forward of OPSML features a large combat system / sonar equipment space. This space is more than adequate to operate the entire combat system.

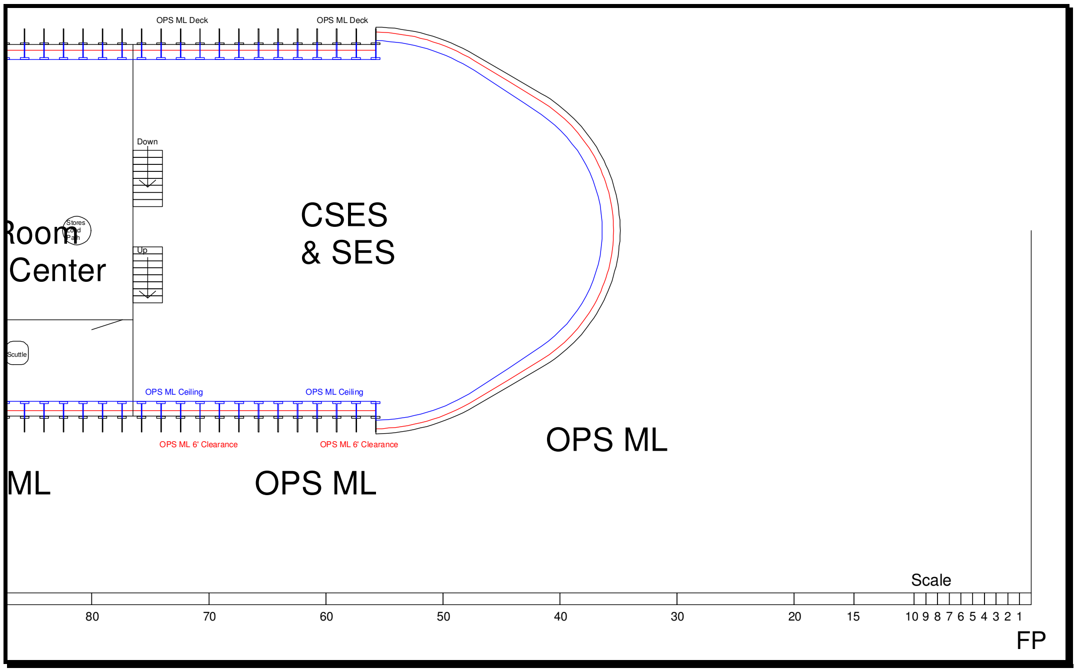


Figure 34: Detailed Arrangements of Operations Compartment, FWD Middle Level

The middle portion of OPSML includes the large Attack Center, operational spaces surrounding it (OPS Cave, Radio, ESM, Nav Center), CO/XO staterooms, and the Ship's Office. A large Wardroom can sit 13 at meals and easily accommodate 25+ for training or briefings. Aft of the command passage is the galley, chilled and frozen storerooms, and scullery. To aid in the high endurance of the ship, the Frozen Storeroom is two decks tall. These spaces are also isolated from the mess decks so that breakouts need not disrupt training there. The configuration of the ladder and serving line provides an efficient chow line where crew wait (in OPSUL for CPOs, in OPSLL for crew) to queue via the ladder, pass through the serving line, eat, bus their trays back past the scullery to the ladder without disruption of the serving line.

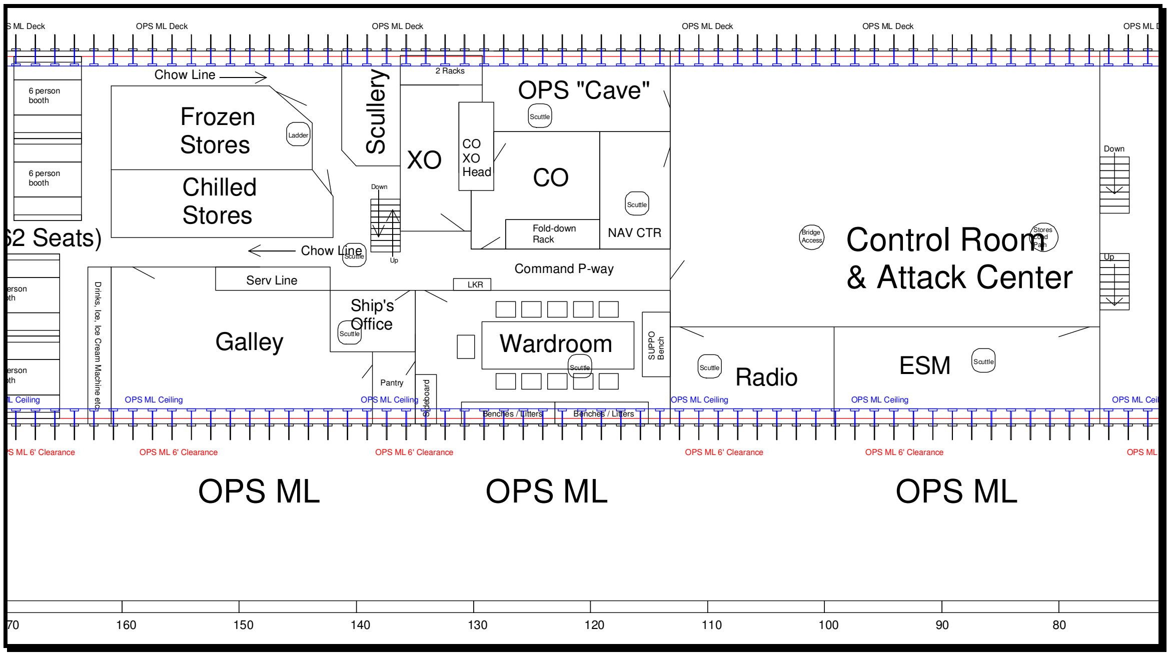


Figure 35: Detailed Arrangements of Operations Compartment, MID Middle Level

The After portion of OPSML is the Mess Decks. The crew's mess features seating for 62, and nearly every one of these seats is oriented so as to maximize training visibility toward a presenter's corner. The trash room and dry stores rooms are located on the aft bulkhead.

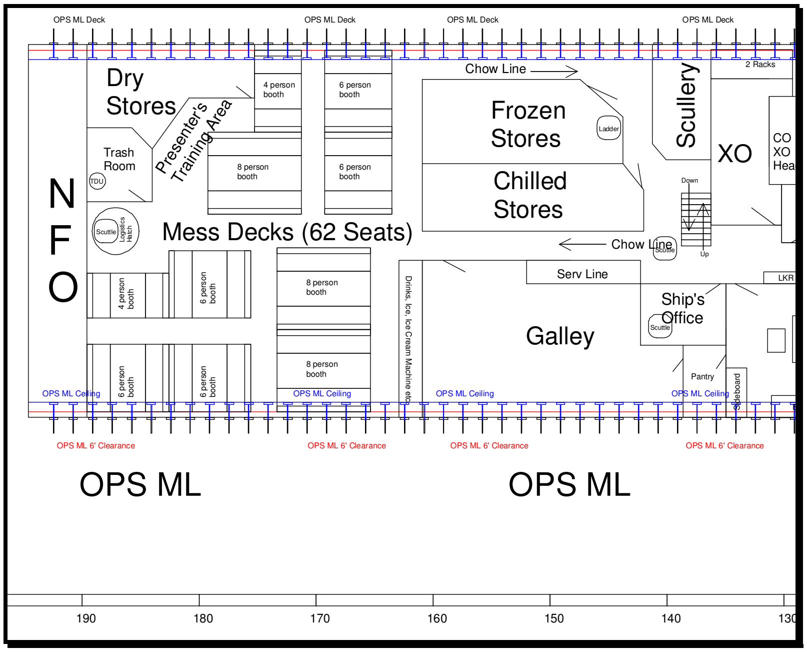


Figure 36: Detailed Arrangements of Operations Compartment, AFT Middle Level

The OPSLL contains the bulk of the enlisted berthing, secondary fore-aft passage, stores and the supply office, a reconfigurable mission space, and the Auxiliary Machinery Room.

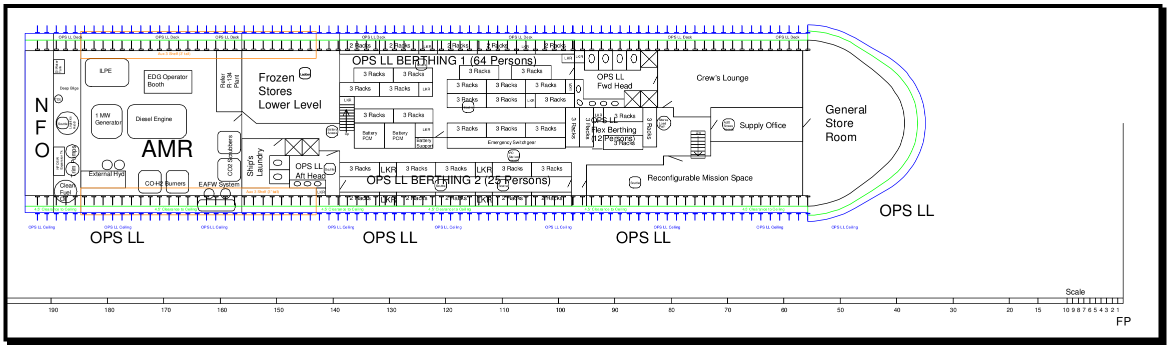


Figure 37: Operations Compartment Lower Level Arrangements in Plan View

The forward portion of OPSLL is dominated by a large store room and the supply office. Additional space is designated as a crew's lounge and a reconfigurable mission space. The forward logistics hatch allows the direct loading of stores all the way into OPSLL.

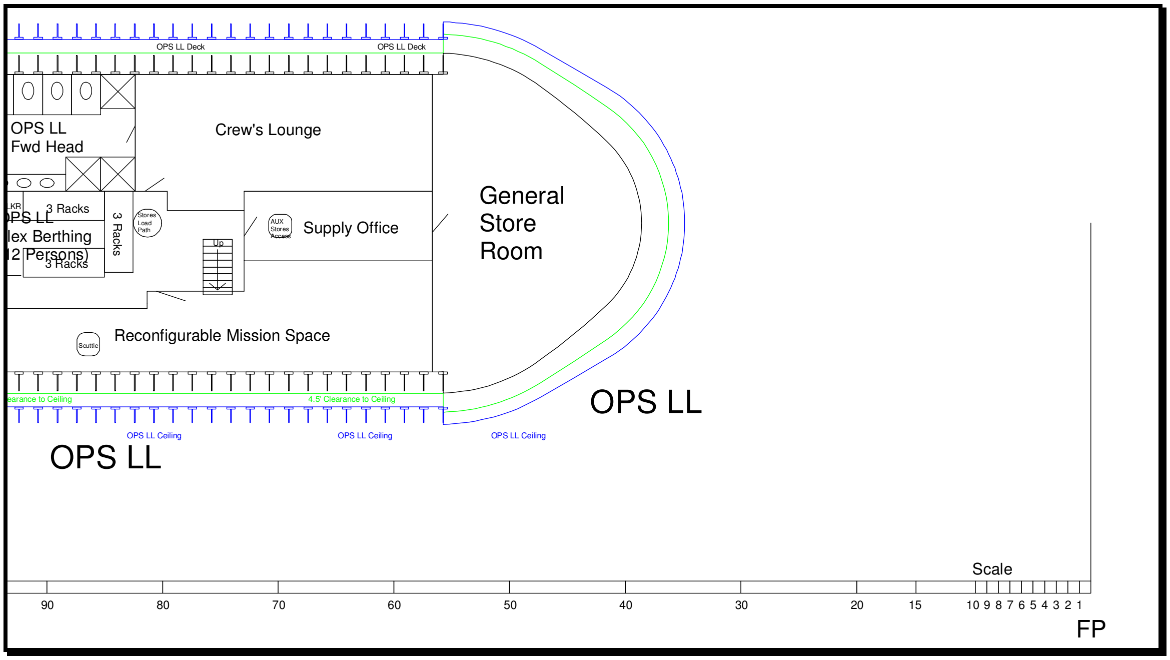


Figure 38: Detailed Arrangements of Operations Compartment, FWD Lower Level

The mid portion of OPSLL is dominated by two large berthing rooms, a smaller flex berthing room, two crew's heads, battery support gear and emergency distribution switchgear.

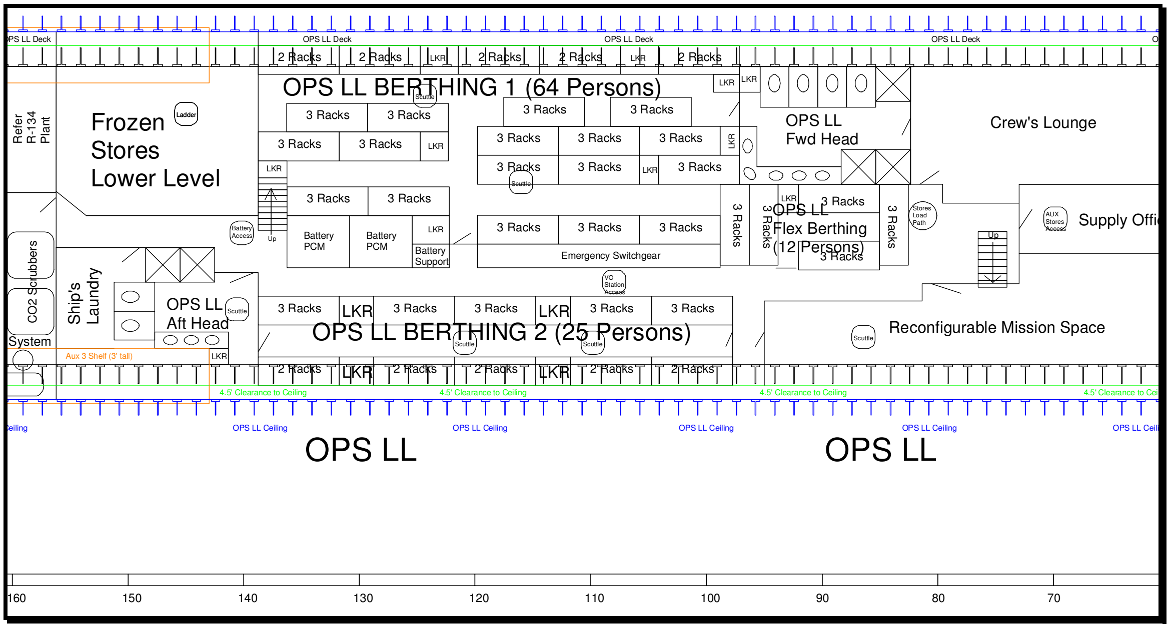


Figure 39: Detailed Arrangements of Operations Compartment, MID Lower Level

The aft portion of OPSLL features the Auxiliary Machinery Room, Lower level of the Frozen Stores Room, and Ship's laundry. The outline of the Aux 3&4 tanks is shown in orange. As shown in the tank arrangement 3-D pictures, these tanks extend 3ft above the lower level deck forming a shelf above which additional equipment is mounted.

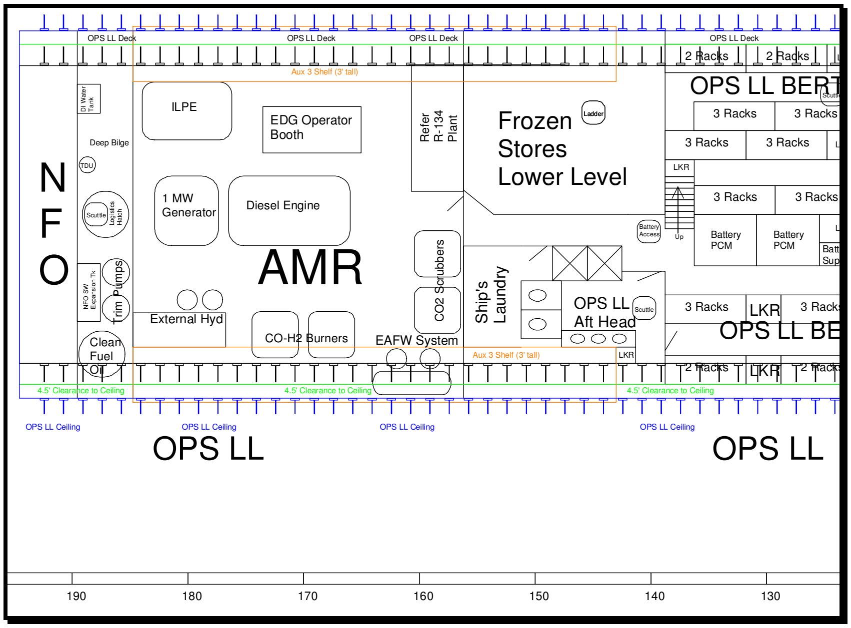


Figure 40: Detailed Arrangements of Operations Compartment, AFT Lower Level

Figure 41 shows the Operations Compartment Tanks including the Main Storage Battery Well and deep bilge, and forward valve operating station.

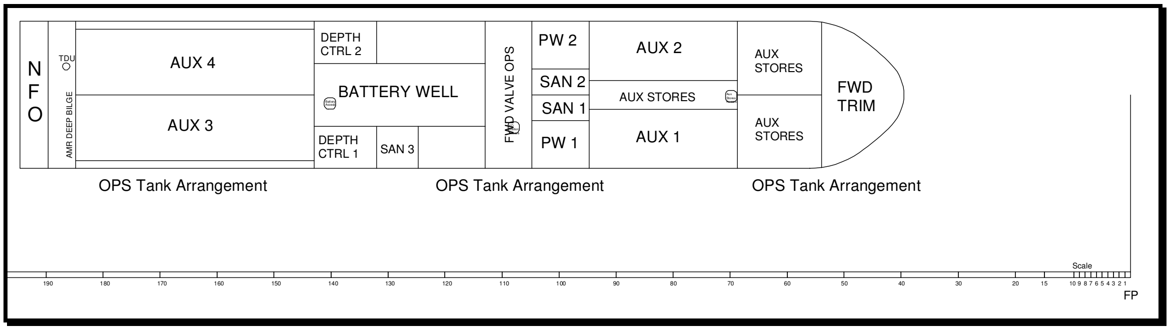


Figure 41: Operations Compartment Tank Arrangements in Plan View

Figure 42 shows the tanks as modeled in the PISR concept. Trim system tanks (including the hovering / depth control tanks) are shown in green; lube oil, fuel oil and hydraulic tanks in yellow; pure and fresh water tanks in blue; battery well in red; torpedo impulse and water round tanks in purple; sanitary tanks in brown; stores and operating stations in light brown.

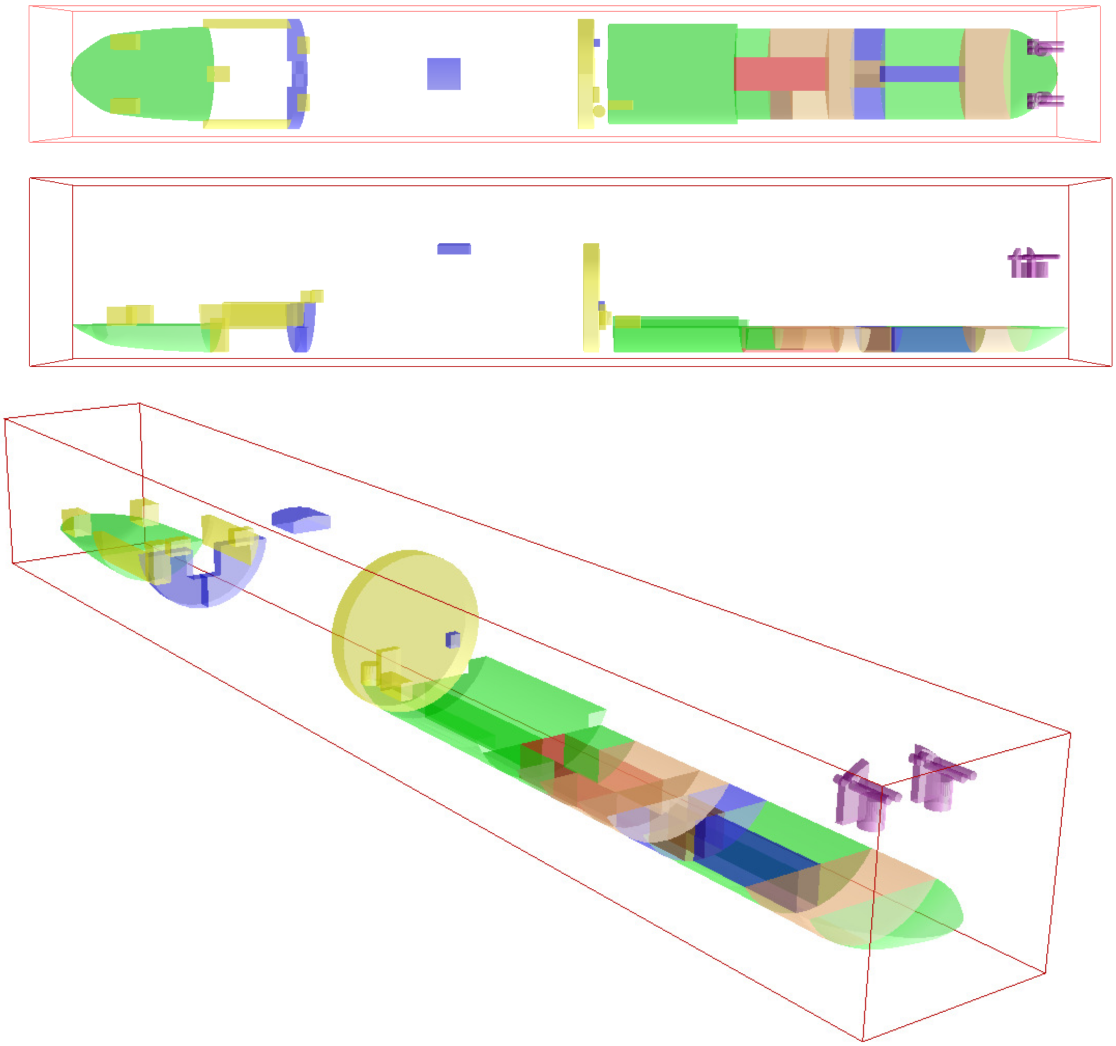


Figure 42: Tank Arrangements as Modeled Using Paramarine

Figure 43 shows a partial arrangements drawing of the Engineering Spaces. The Turbine Room is dominated by the large main condensers and generators. The Motor Room features the large propulsion motor, 2 levels of power electronics, and the Maneuvering Room.

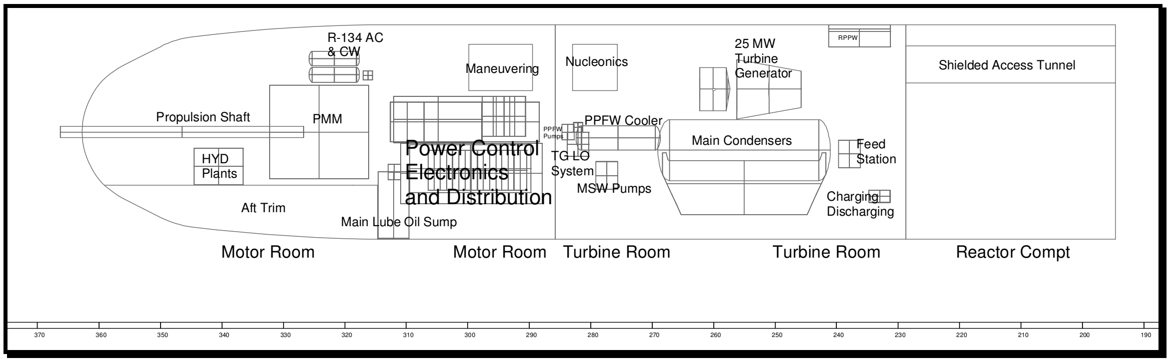


Figure 43: Engineering Space Arrangements in Profile View

Figure 44 and Figure 45 show the 3-D arrangement of the Motor Room. R-134 AC units are shown in lavender, PMM and shaft in blue, hydraulic plants in gold, PCMs in red, PDMs and load controllers in green, and PMM motor drives, resistors, and filters in deep blue.

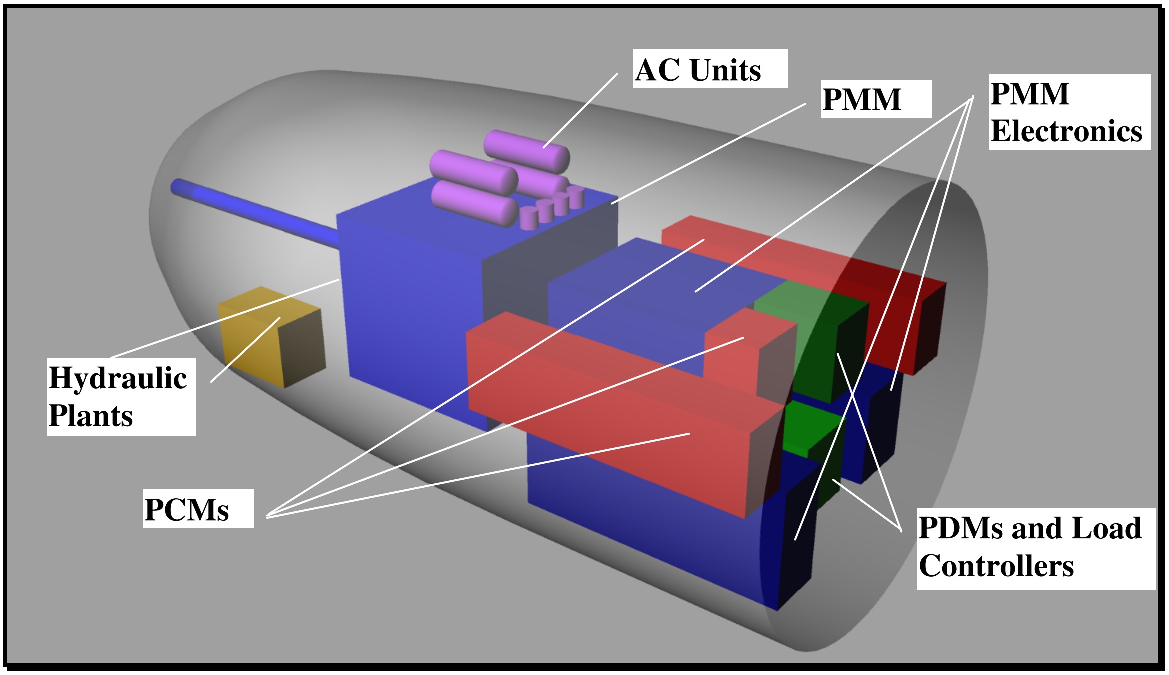


Figure 44: Motor Room Arrangements in Perspective View (Bow Right)

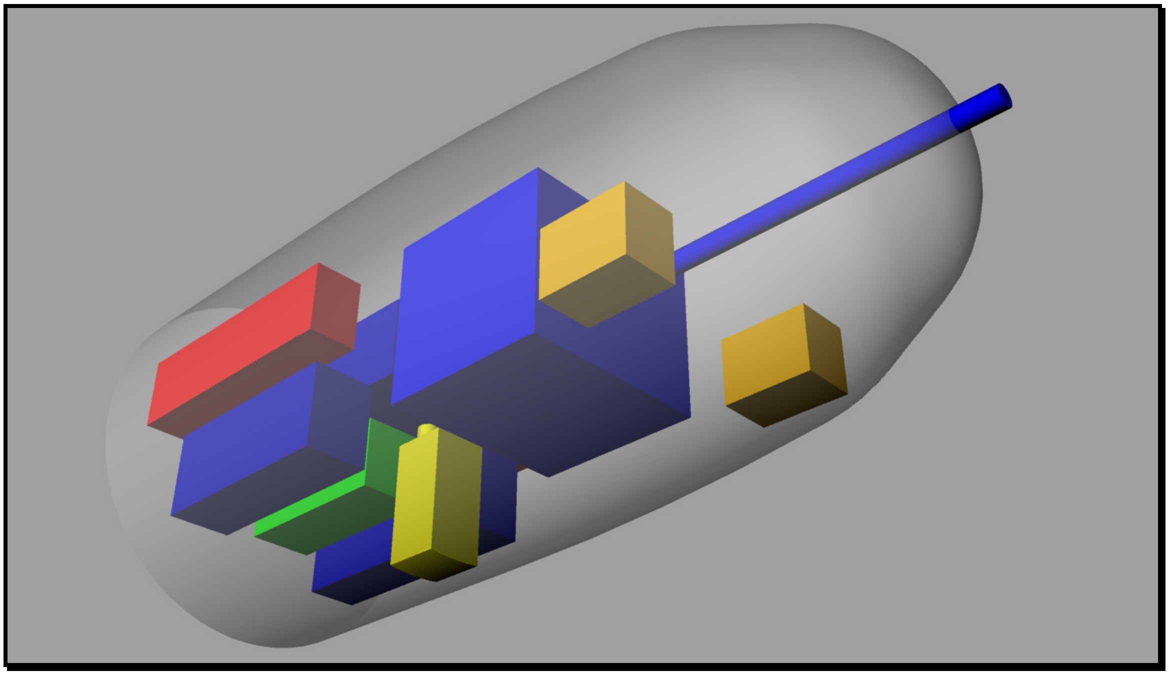


Figure 45: Motor Room Arrangements in Perspective View (Bow Left)

Figure 46 and Figure 47 show the 3-D arrangement of the turbine room. Main condensers are shown in green, turbine generators in lavender, reactor auxiliaries in magenta, turbine lube oil in yellow, main seawater pumps in green, and propulsion plant fresh water in cyan.

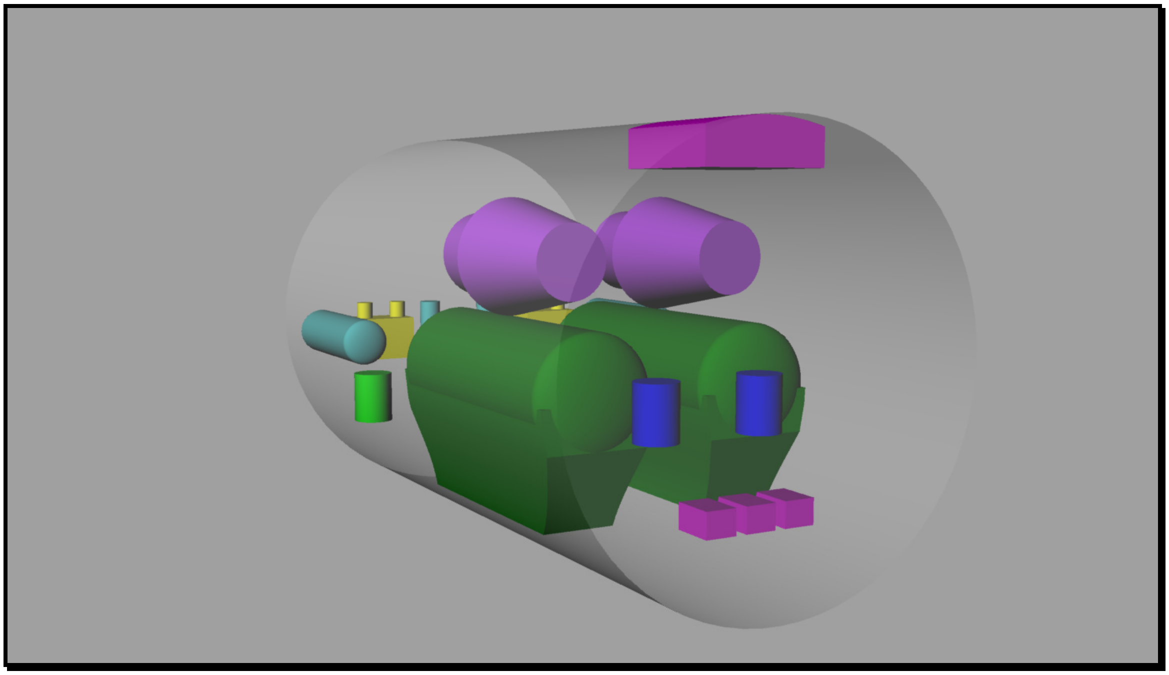


Figure 46: Turbine Room Arrangements in Perspective View (Bow Right)

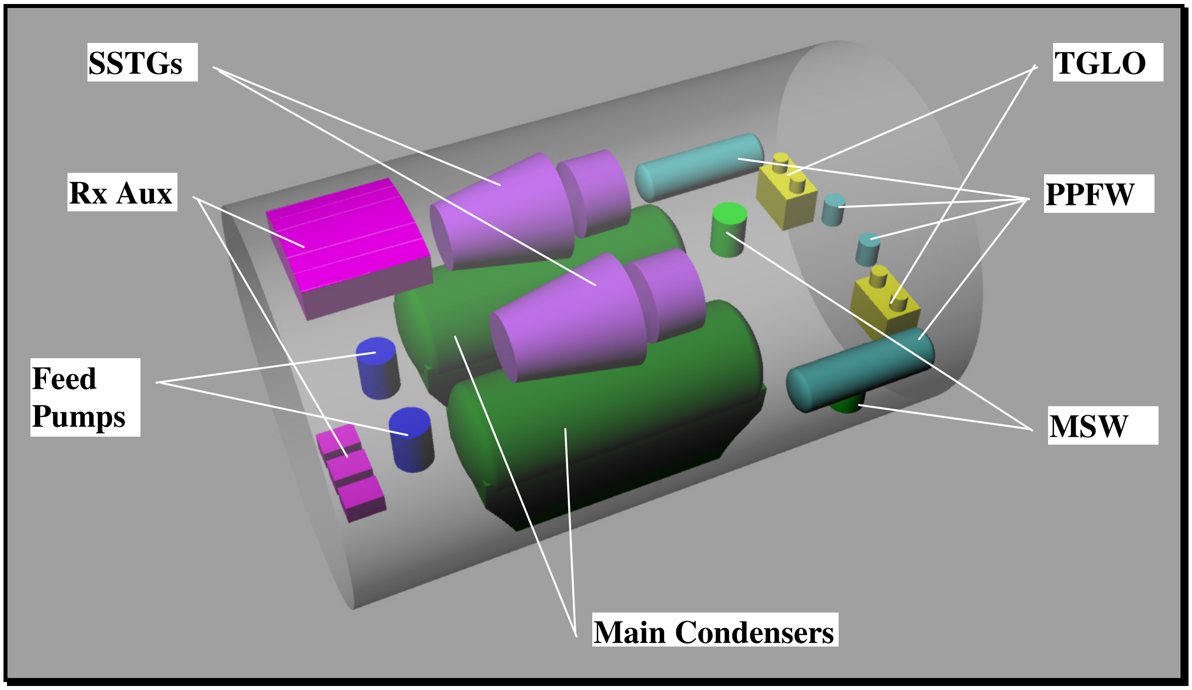


Figure 47: Turbine Room Arrangements in Perspective View (Bow Left)

4.1.8.3 Area/Volume Balance

The PISR design relied heavily on parametric relationships developed in Ref 4 and 5. Using these parametrics, required areas and volumes for the PISR submarine were developed. Table 13, below, compares the required area and volumes to those achieved in the concept design.

Volume and Area Balance							
Parametric Demand			**PISR Supply**			**Supply / Demand**	
Space	**Volume (ft^3)**	**Area (ft^2)**	**Space**	**Volume (ft^3)**	**Area (ft^2)**	**Volume**	**Area**
Engine Room	123,183		Turbine Room & Motor Room	117,297		95.22%	
Reactor Compartment	32,723		Reactor Compartment	32,862		100.42%	
Operations Compartment	82,803		Operations Compartment	95,379	13,053	115.19%	
Auxiliaries	13,163		Auxiliary Machinery Room	6,430	860	106.97%	
			PW, Sanitaries, Depth Control, NFO Tanks	7,650			
Variable Ballast	16,322		Trim System	18,358		112.47%	
Command & Control		800	Control Room & Attack Center, Radio Room, Nav Ctr, ESM, and OPS Cave	10,591	1,293		161.61%
Torpedo Room		600	Torpedo Room	5,970	1,001		166.83%

Table 13: Area/Volume Demand and Supply Comparison

It is appropriate to take some credit for the unique configuration advantages of an IPS engine room (elimination of reduction gearing, shortened turbines and condensers). Accordingly, allocation of 95% of the demanded volume to the engine room spaces was made in the arrangement drawings. The remaining spaces, particularly command and control and operations compartment, are significantly better accommodated in the PISR concept design than was required.

Table 14 lists and Table 15 summarizes the spaces in the concept design.

Space and Area Summary				
Compartment & Platform	Space	Max Deck Height (ft)	Deck Area (ft^2)	Volume (ft^3)
OPS UL	Passageway	8.00	433.54	3,468.30
OPS UL	Fan Room	8.00	262.08	1,516.16
OPS UL	VLS Services	8.00	216.49	673.15
OPS UL	FWD Electrics	8.00	194.30	1,188.06
OPS UL	Officer Country	8.00	479.25	3,349.24
OPS UL	LAN Room	8.00	29.07	188.44
OPS UL	Engineer's Logroom	8.00	29.07	188.44
OPS UL	Crew's Study	8.00	58.14	376.89
OPS UL	UUV Handling and Maintenance	8.00	236.88	1,568.29
OPS UL	Stowage	8.00	272.74	715.42
OPS UL	CPO Berthing	8.00	137.72	980.55
OPS UL	CPO Head	8.00	84.17	633.50
OPS UL	CPO Lounge	8.00	189.17	1,166.40
OPS UL	TA Handling	8.00	87.04	539.77
OPS UL	Medical / Countermeasures	8.00	95.77	571.98
OPS UL	Flex-Berthing (4)	8.00	89.46	580.62
OPS UL	Flex-Berthing (8)	8.00	85.93	635.06
OPS UL	OPS UL Berthing (25)	8.00	272.27	1,909.11
OPS UL	OPS UL Head	8.00	156.54	1,163.40
OPS UL	Torpedo Room	8.00	1,000.97	5,969.59
OPS ML	Trash Room	8.25	33.69	277.92
OPS ML	Dry Stores	8.25	81.06	656.75
OPS ML	Mess Decks	8.25	769.67	6,313.89
OPS ML	Passageway	8.25	274.24	1,930.41
OPS ML	Chill/Frozen Stores	8.25	224.47	1,851.87
OPS ML	Galley/Pantry	8.25	282.50	2,308.99
OPS ML	Scullery	8.25	46.08	375.59
OPS ML	Ship's Office	8.25	38.29	315.92
OPS ML	CO/XO Staterooms & Head	8.25	209.44	1,720.79
OPS ML	OPS Cave	8.25	100.64	816.85
OPS ML	Wardroom	8.25	237.47	1,940.98
OPS ML	NAV Center	8.25	60.00	495.00
OPS ML	Radio Room	8.25	109.25	889.66
OPS ML	ESM	8.25	177.15	1,442.51
OPS ML	Control Room & Attack Center	8.25	845.81	6,947.31
OPS ML	CSES / SES	8.25	1,155.76	9,497.00
OPS LL	AMR	7.75	860.01	6,429.58
OPS LL	Frozen Stores II	7.75	274.87	1,887.05
OPS LL	OPS LL Berthing (25)	7.75	317.75	2,350.25
OPS LL	OPS LL Berthing (64)	7.75	680.00	5,156.02
OPS LL	Battery PCMs and Services	7.75	54.94	425.80
OPS LL	Switchgear	7.75	42.00	325.50
OPS LL	OPS LL Head AFT	7.75	95.93	743.47
OPS LL	Crew's Laundry	7.75	72.43	506.90
OPS LL	OPS LL Head FWD	7.75	149.78	1,160.79
OPS LL	Reconfigurable Mission Space	7.75	290.20	2,249.01
OPS LL	Flex Berthing (12)	7.75	99.54	771.45
OPS LL	Crew's Lounge	7.75	271.60	2,104.88
OPS LL	Supply Office	7.75	97.84	758.23
OPS LL	General Store Room	7.75	394.20	3,055.06
OPS LL	Passageway	7.75	295.67	2,291.41
RC	Reactor Compt	N/A	N/A	32,861.79
ER	Turbine Room	N/A	N/A	54,840.20
ER	Motor Room	N/A	N/A	62,456.80

Table 14: PISR Space and Area Summary

Space and Area Summary		
Space Category	**Deck Area (ft^2)**	**Volume (ft^3)**
Engineering Spaces	N/A	158,527.73
Habitability Spaces (Berthing)	2,608.84	19,394.06
Habitability Spaces (Non-Berthing)	2,209.70	17,132.63
Combat System, Command & Control and Mission Spaces	4,443.33	32,164.49
Passageways	1,003.44	7,690.12
Stores and Stowage	1,345.17	8,924.39
	13,052.87	245,538.03

Table 15: PISR Space and Area Summary by Space Category

Table 16 details the accommodations onboard the PISR. The concept accommodates mixed gender crews of various ratios by incorporating 24 berths in several flex rooms. Additionally, the 25-person bunk room in OPSLL and the after OPSLL head are intended to accommodate female crew. The CPO Lounge is separated from the male CPO berthing and head to allow for female CPOs to have equal access to the space. Officer staterooms should provide sufficient flexibility to allow 3 female officers to share a stateroom.

Accommodations				
Category	**Space**	**Berths**	**Area/Berth (ft^2)**	**Berths per Category**
Officer	CO	1	104.72	14
	XO	2*		
	WRSR	12	39.94	
CPO	Junior	9	10.59	13
	Senior	4		
Flex	OPS UL 1	4	22.37	24
	OPS UL 2	8	10.74	
	OPS LL	12	8.30	
Enlisted	OPS UL	25	10.89	114
	OPS LL 1	64	10.63	
	OPS LL 2	25	12.71	
Total Berths		165	15.81	
*- Senior Rider Rack in XOSR is not included in Berths Tally				

Table 16: PISR Accommodations Summary

Table 17 outlines the sanitary accommodations onboard PISR to ensure that adequate facilities are provided to meet Navy Habitability Standards.

Sanitary Facilities Feasibility				
Crew Category	**Total Accom**	**Lavatories / Accom/Lavatory**	**Water Closets / Accom/Water Closet**	**Showers / Accom/Showers**
Crew Fixtures (Total)	117	10/14.6	10/11.7	7/16.7
Crew Fixtures (Male)	91	7/13.0	8/11.4	5/18.2
Crew Fixtures (Female incl CPO)	26	3/8.7	2/13.0	2/13.0
CPO Fixtures (Male)	13	2/6.5	2/6.5	2/6.5
Officer Fixtures (excl CO/XO)	12	6/2.0	2/6.0	2/6.0

Table 17: Sanitary Facilities

Table 18 shows the requirements for community sanitary spaces in submarines from the Shipboard Habitability Design Criteria Manual, Reference 1. Together Tables 17 and 18 demonstrate that the sanitary facilities in the PISR SSN meet or exceed the standard.

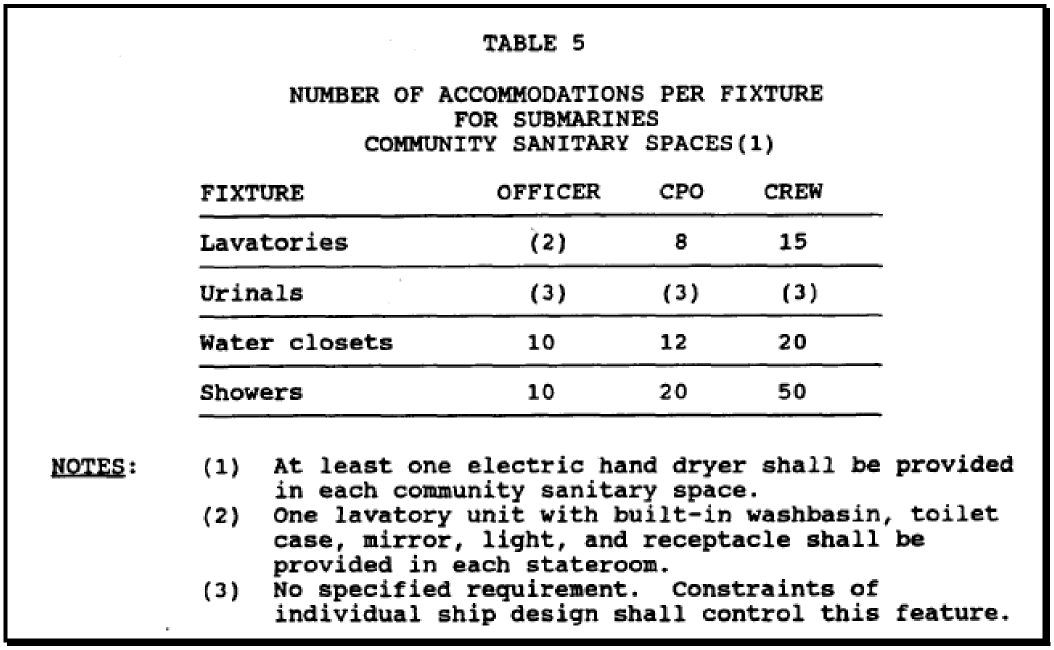


TABLE 5

NUMBER OF ACCOMMODATIONS PER FIXTURE
FOR SUBMARINES
COMMUNITY SANITARY SPACES(1)

FIXTURE	OFFICER	CPO	CREW
Lavatories	(2)	8	15
Urinals	(3)	(3)	(3)
Water closets	10	12	20
Showers	10	20	50

NOTES:
(1) At least one electric hand dryer shall be provided in each community sanitary space.
(2) One lavatory unit with built-in washbasin, toilet case, mirror, light, and receptacle shall be provided in each stateroom.
(3) No specified requirement. Constraints of individual ship design shall control this feature.

Table 18: Habitability Standards for Sanitary Spaces in Submarines (Reference l)

Table 19 shows the mess capacities of the PISR messing facilities

Messing Facility Capacity		
Facility	**Seats**	**Required Capacity**
Crew's Mess	62	45.15
Wardroom	13	10.5

Table 19: PISR Messing Capacities

Table 20 provides the requirements for mess seating per the Habitability Design Criteria Manual.

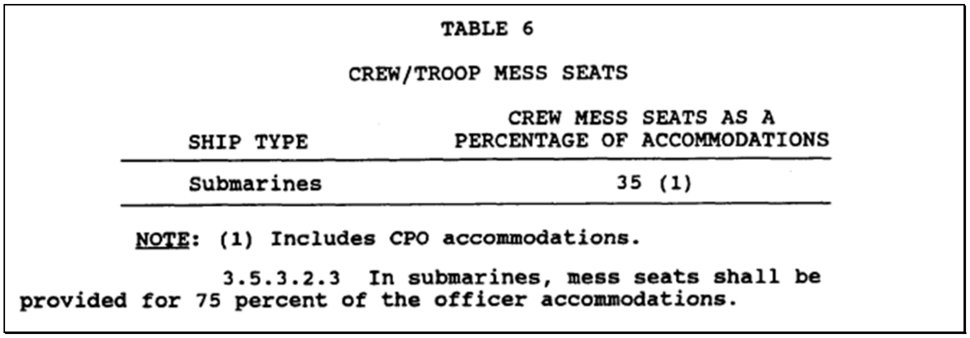


TABLE 6

CREW/TROOP MESS SEATS

SHIP TYPE	CREW MESS SEATS AS A PERCENTAGE OF ACCOMMODATIONS
Submarines	35 (1)

NOTE: (1) Includes CPO accommodations.

3.5.3.2.3 In submarines, mess seats shall be provided for 75 percent of the officer accommodations.

Table 20: Habitability Standard Messing Requirements for Submarines (Reference 1)

In generously exceeding the requirements for berthing, messing, and sanitary facilities, PISR improves the underway living conditions for the crew and embarked personnel to alleviate much of the hardship of high-endurance operations of up to 4 months.

4.1.9 Structural Design

Submarine pressure hulls fail by one or a combination of the following failure modes:

- Elastic General Instability
- Shell Lobar Buckling
- Shell Yield
- Frame Yielding
- Frame Instability

Photographs of Elastic General Instability, Shell Lobar Buckling and Shell Yield are shown below:

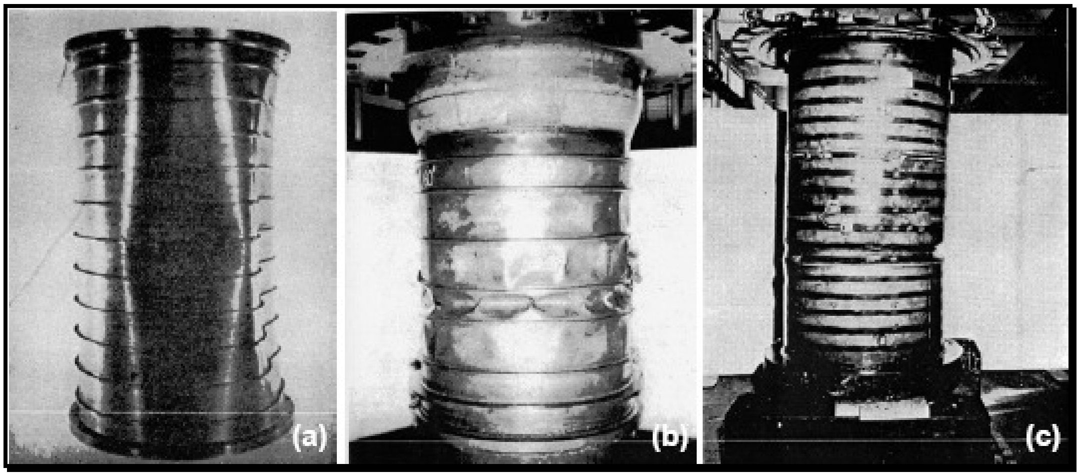


Figure 48: a) Elastic General Instability b) Shell Lobar Buckling c) Shell Yield (Reference 3)

Elastic general instability is characterized by deformation along a large portion of the longitudinal axis of the pressure vessel. Shell lobar buckling is characterized by a pleated wave deformation pattern between shell stiffeners around the pressure vessel circumference. Shell yield is characterized by a single pleat deformation between shell stiffeners around the circumference. Frame yielding is characterized by permanent deformation of the frame stiffeners while the frame maintains its relative orientation to the shell. Frame instability is sometimes referred to as frame tripping and is characterized by a change in the relative orientation of the frame to the pressure vessel shell.

In designing a pressure hull, all failure modes must be prevented. Due to the differences in certainty with which the failure modes can be predicted, each failure mode has a different factor of safety. Nominal factors of safety for each of the failure modes are:

- Elastic General Instability – 3.75
- Shell Lobar Buckling – 2.25
- Shell Yield – 1.50
- Frame Yielding – 1.50
- Frame Instability – 1.80

In designing the pressure hull, two different tools were experimented with. One was a MATLAB script developed by LCDR Joshua LaPenna (Reference 2) and the other was Paramarine. Both of the programs allow the designer to minimize the weight of the structure for a given material and design depth while preventing hull failure with a prescribed factor of safety.

Since the submarine parametric study was performed using the Paramarine software and because both tools gave similar results, Paramarine was used for the pressure hull structural design. Pressure hull frame structure is a significant impediment to the internal arrangements of the submarine. In order to limit the amount of arrange able volume lost to pressure hull frames, it was decided to limit the scantling depth to 18 inches. Figure 49 shows a preliminary study which was performed during design iteration to examine the impact of hull steel and design depth choice on pressure hull weight. Pressure hull diameter and length were 35ft and 270ft respectively for this study. Figure 49 shows that significant weight increases occurs if an HY80 steel is used for a design depth of 1,600ft over HY80 steel for a design depth of 1,200ft. Figure 49 also shows that a hull made of HY100 steel with a design depth of 1,600ft weighs more than a hull made of HY80 designed for 1200ft. In order to limit the weight of the pressure hull for a maximum scantling depth of 18in, a design depth of 1,200ft using HY80 steel was selected.

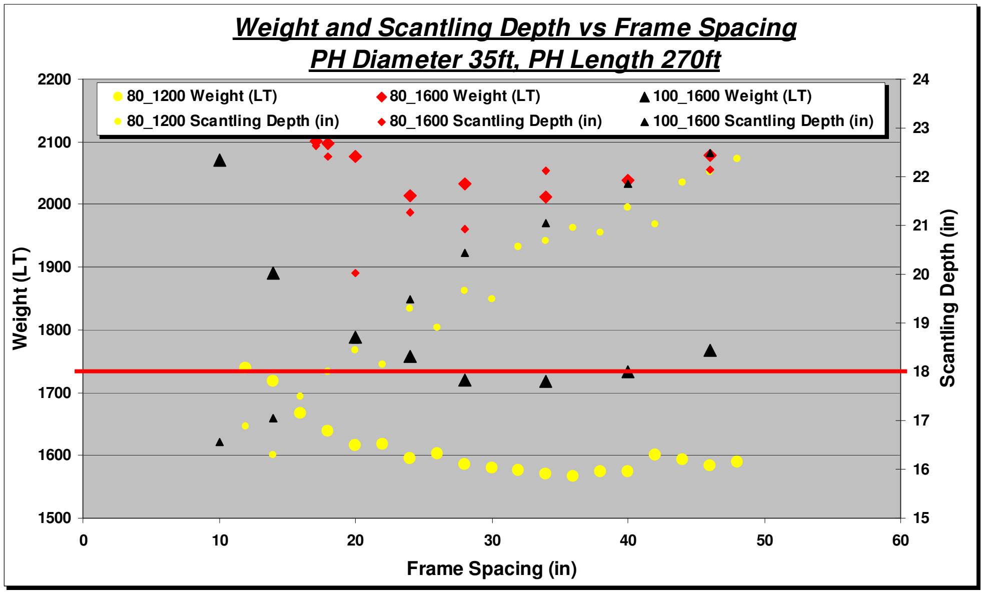


Figure 49: Pressure Hull Scantling Study

As additional design spiral iterations were completed it became necessary to add volume to the pressure hull. This was accomplished by increasing the pressure hull length from 270ft to 328ft which meant that another pressure hull design with a new weight estimate was necessary. Figure 50 shows the results of the second pressure hull study which was performed using a pressure hull diameter of 35ft, pressure hull length of 328ft, design depth of 1,200ft and HY80 steel.

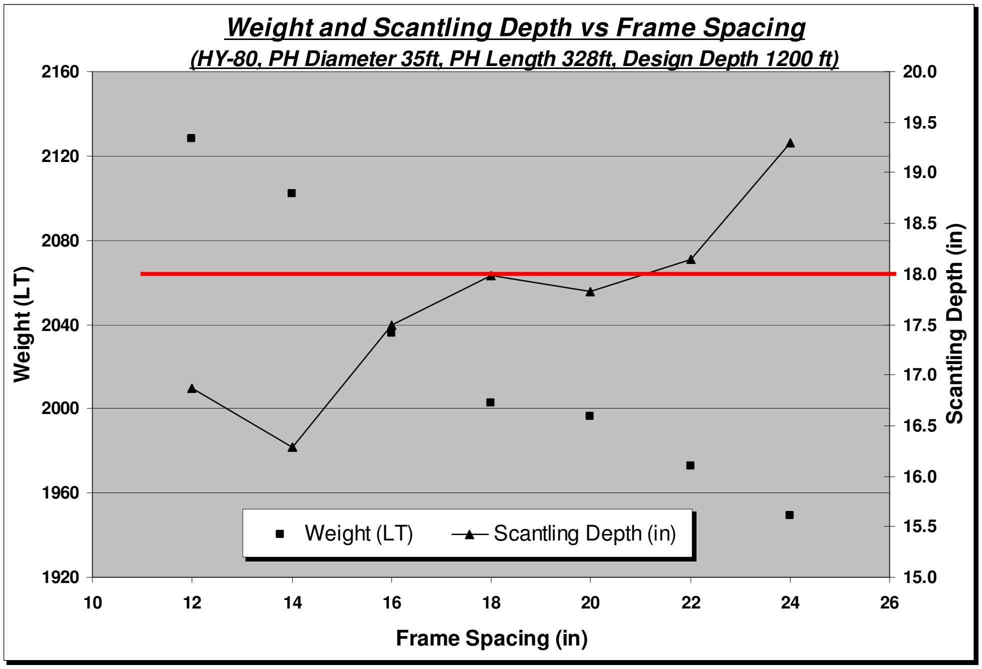


Figure 50: HY-80 Pressure Hull Scantling Study

Based on the pressure hull scantling studies shown above, a 20in frame spacing using HY80 was selected. The complete scantling dimensions are shown in Table 21 for all the data points shown in Figure 50. The column highlighted in yellow shows the scantling dimensions that were used in the design.

Material: HY80, Depth: 1200 ft, Pressure Hull Length: 328ft								
Paramarine	**Frame Spacing (in)**	**12**	**14**	**16**	**18**	**20**	**22**	**24**
	Dome Thickness (in)	2.32	2.32	2.32	2.32	2.32	2.32	2.32
	Shell Thickness (in)	1.51	1.70	1.72	1.74	1.87	1.80	1.84
	Web Height (in)	13.76	12.91	14.03	14.45	14.12	14.46	15.53
	Web Thickness (in)	0.71	0.62	0.69	0.71	0.68	0.69	0.77
	Flange Width (in)	8.29	9.09	8.45	8.71	8.87	10.18	9.36
	Flange Thickness (in)	1.60	1.68	1.74	1.79	1.83	1.88	1.92
	Weight (LT)	2128.19	2102.07	2035.68	2002.95	1996.59	1972.66	1949.04
	Scantling Depth (in)	16.88	16.29	17.49	17.99	17.82	18.14	19.29

Table 21: Scantling Dimensions

4.1.10 Weights

Table 22 identifies the weight progression of the concept design for each completion of the design spiral. This table shows that the submerged displacement is well below the maximum allowable displacement of 15,000 LT. The PISR design can specifically account for most of the weight in weight groups 100, 200, 300 and 700. The weight listed for weight groups 400, 500 and 600 comes from parametric equations contained in Ref. 4 and 5.

			Round 3			
Weight Group	**Round 1 Weight (LT)**	**Round 2 Weight (LT)**	**Round Weight (LT)**	**Fraction of A-1**	**Fraction of NSC**	**Fraction of Sub. Disp.**
100	3,660	3,000	3,365	0.46	0.37	0.32
200	1,188	1,668	1,729	0.24	0.19	0.16
300	480					
400	164	194	224	0.03	0.02	0.02
500	533	631	653	0.09	0.07	0.06
600	233	379	400	0.05	0.04	0.04
700	399	442	907	0.12	0.10	0.09
A-1	6,657	6,314	7,278	1.00	0.81	0.68
Lead	865	857	911	0.13	0.10	0.09
A-1+Lead	7,522	7,171	8,189	1.13	0.91	0.77
VL	654	585	789	0.11	0.09	0.07
NSC	8,176	7,756	8,978		1.00	0.84
Main Ballast	1,584	1,183	1,659		0.18	0.16
Sub. Disp.	9,760	8,939	10,637			

Table 22: Weight Summary

In order to arrive at useful group 700 weight estimates, a rough scaling of the weights associated with large diameter tubes currently in use was performed. The weights were broken into four categories as shown in Table 23:

Weight Item	Scaled By
Payload Related	Tube Volume
Tube Structure	Tube Sheet Area
Hatch	Tube Cross Section
Tube Services	Number of Tubes

Table 23: Weight Scaling for PISR Payload Tubes

Using this approach, the total group 700 weight estimates for the tubes were obtained. The yellow highlighted row in Table 24 shows this estimate.

Number of Tubes	Weight (LT)	OB Volume (LT)
16	523.58	288.31
18	589.03	324.35
20	654.48	360.39
22	719.93	396.43
24	785.38	432.47
26	850.82	468.51
28	916.27	504.54
30	981.72	540.58
32	1047.17	576.62
34	1112.62	612.66
36	1178.06	648.70

Table 24: Payload Tube Weight Estimation

Figure 51 plots the data from Table 23 for selection comparison

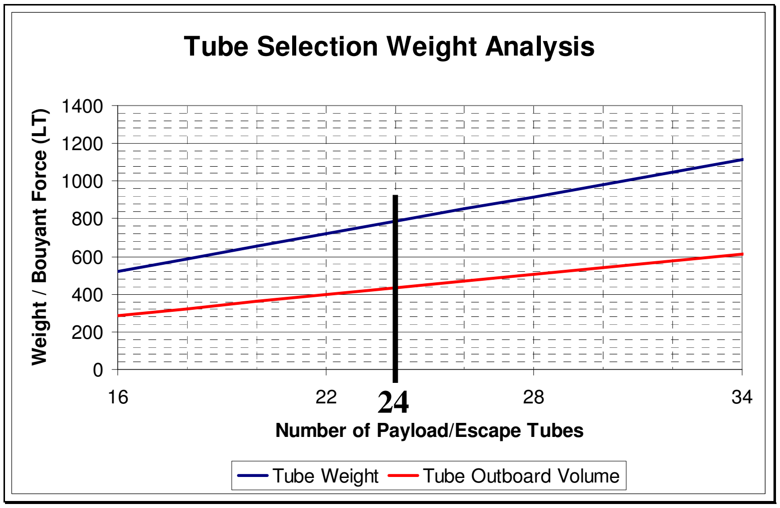


Figure 51: Payload Tube Number Selection Analysis

A total of 24 tubes (8 escape, 16 payload) were selected since 16 payload tubes were deemed to be the minimum to take adequate advantage of the double hull architecture while still permitting full crew escape via the 8 capsules.

One of the areas of uncertainty in weight estimation for this design is the weight of the non-pressure hull structure. The parametric equations do not apply to this structure because this structure is not present in the submarines which were used to develop the parametric relationships. In order to be able to design a reasonable non-pressure hull structure, the loads carried by this structure would have to be calculated or estimated. It was assumed that the loads carried by this structure would only be hydrodynamic loads and that the pressure hull would carry all of the hydrostatic loads. Design tools for calculation or estimation of this type of hydrodynamic loading on the non-pressure hull structure were unavailable. Therefore, it was assumed that the non-pressure hull structure would be similar to that of a surface ship and that the weight of this structure could be estimated from a study of surface ship group 100 weights. This study shows that 1,200LT is a reasonable estimate for the non-pressure hull structure. A graph of the results of this study is shown below.

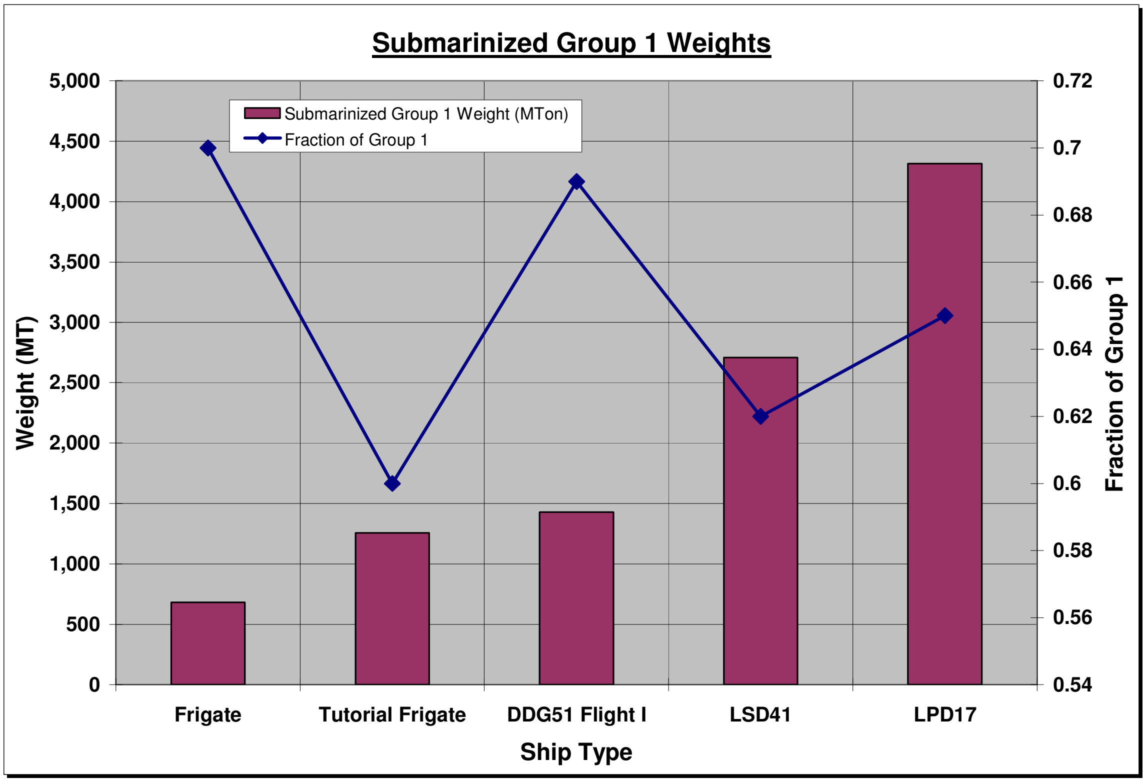


Figure 52: Submarinized Group 1 Weights

In "submarinizing" the group 1 weights, non-submarine related weight items were removed from the surface ship group 1 weights. The largest of the items removed was the deckhouse. This method for weight estimation of the non-pressure hull structure of PISR probably provides an excessively conservative weight estimation since group 1 on a surface ship provides both hydrostatic and hydrodynamic support and on PISR this structure is expected to carry only hydrodynamic loads. The design of the non-pressure hull structure is an area for further study.

4.2 Performance Analysis

4.2.1 Mission Effectiveness

In every mission area, this submarine meets or exceeds mission requirements. The primary mission of the submarine is satisfied in every way by the features incorporated in the PISR concept study. In the secondary mission area, the mission requirements are exceeded. Through the use of cruise missiles PISR is capable of performing a land attack mission which was not called for by the mission requirements. In the tertiary mission area PISR meets mission requirements. Ability to host SOF is provided through extra berthing and an enlarged mess decks area. Mine warfare is accommodated through use of the 4 main torpedo tubes and some of the torpedo tube stowage locations.

Parameter	Threshold	Goal	Concept Result
Maximum Submerged Speed	25 kts	35 kts	29.25 kts
Endurance, Time on Station	90 days	120 days	120 days (+15 days Transit)
Max Draft	36’	29’	30.7’
Max Beam	50’	< 50’	50’
Max Pressure Hull Beam	43’ 4”	< 43’ 4”	35’
Payload Weight Fraction (Submerged Disp)	4%	8%	9.47%
Payload Volume Fraction (Envelope Volume)	2%	4%	3.17%
Cost	2x “Average SSN” Lead-ship Cost	“Average SSN” Lead-ship Cost	1.10x ‘Average SSN’ Lead Ship Acquisition Cost
Risk	Moderate Risk (as determined by engineering judgment)		Moderate Risk

Table 25: PISR Concept Design Performance

Weapon	Required Quantity	Installed Quantity
Mk-54 Lightweight Torpedo	24	26
Common Very Lightweight Torpedo	12	20
Tomahawk Land Attack Missile	12 (Vertical)	Up to 64 (Vertical)
AIM-9X	12	Up to 48

Table 26: PISR Concept Weapon Summary

4.2.2 Strength

Assessment of the submarine hull’s strength can be done in several ways. One way is to compare actual stresses in the hull to stress criteria. Another way is to compare actual factors of safety against accepted factors of safety. The second method incorporates the first and is the method used to analyze the hull strength of the PISR submarine. Note that the discussion of hull strength in this paper only relates to the pressure hull. Non pressure hull structure was not analyzed for strength because the loads on the non-pressure hull structure require more sophisticated analysis tools that are beyond the scope of completing a concept design. The method used to estimate the weight of the non-pressure hull structure is discussed in section 4.1.10 above.

Paramarine uses the following failure modes and factors of safety in its pressure hull structure optimization routine:

Paramarine		**Conventional**	
Failure Mode	**Value**	**Value**	**Failure Mode**
Dome Collapse	2		
Elastic Interframe Collapse	1.5	2.25	Shell Lobar Buckling
Elastic Longitudinal Yield	1.6	2.5	Shell Yield
Elastic Overall Collapse	1.8	3.75	Elastic General Instability
Elastoplastic Overall Collapse	1.3	1.5	Frame Yielding
Stiffener Tripping	2	1.8	Frame Instability

Table 27: Factor of Safety Comparison

In spite of the difference in the values for the safety factors for the various failure modes, similar results were achieved when using software other than Paramarine to perform pressure hull structure optimization. LaPenna provides some insight in Reference 2 into the differences between Paramarine hull structure optimization and his code which uses the conventional safety factors.

As modeled in Paramarine for a pressure hull diameter of 35ft and pressure hull length of 328ft with no internal structural bulkheads, the actual safety factors for the pressure hull are:

Actual	
Failure Mode	**Value**
Dome Collapse	2
Elastic Interframe Collapse	2.2
Elastic Longitudinal Yield	1.96
Elastic Overall Collapse	1.84
Elastoplastic Overall Collapse	1.45
Stiffener Tripping	6.15

Table 28: Actual Safety Factors from Paramarine

Table 28 above shows that the pressure hull is capable of withstanding a depth of 1,200ft.

4.2.3 Stability, Trim and Surfaced Draft

After developing detailed (3-digit SWBS) weight estimates for the fixed loads on the ship (see Appendix D), the submarine was balanced using the moment and weight changes expected under a variety of loading conditions. Figure 53 shows the resulting equilibrium polygon from these analyses. The blue points represent the range of loading conditions anticipated during the operation of the ship. Since all points lie well within the green outline of the polygon, the variable ballast system is sufficiently sized to counteract these weight additions/subtractions/movements to restore the ship to a satisfactory trim condition. For the 4 lower load conditions, analysis of the affect of launching all 64 missiles (TLAMs were assumed for this analysis) and then draining the tubes dry again was performed. This load change is shown by the dashed red line. Operational flexibility to be able to continue to operate with any 4 of these tubes flooded once the missiles were away was also desired. These loading conditions are shown with the dashed blue lines. The dark lines that extend down and to the left are a result of flooding the UUV access tube in the sail. With the exception of the Artic point, all points and lines lie well within the polygon. As currently sized, the variable ballast system cannot accommodate the weight change associated with flooding the UUV access tube while in the Artic condition. However, there is sufficient lead available for removal and volume for variable ballast tank expansion that this condition could be accomodated within the polygon. This problem would be resolved on subsequent iterations.

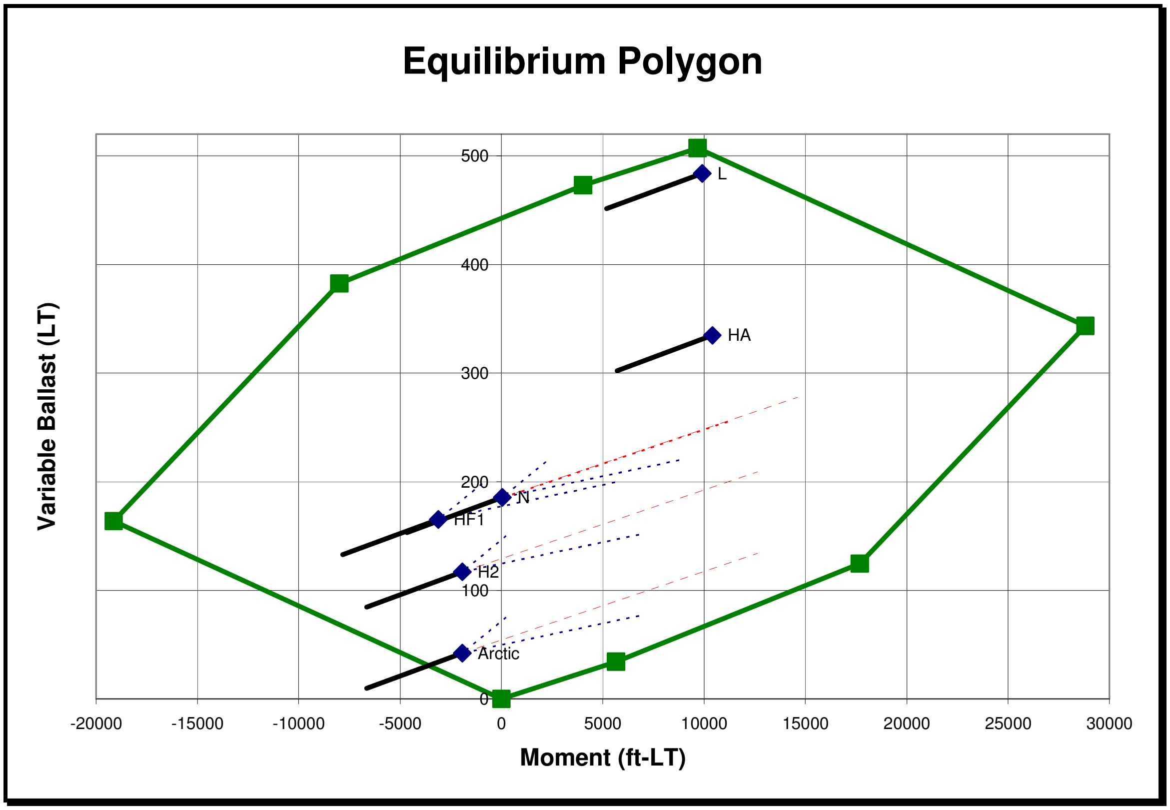


Figure 53: PISR Trim Polygon

The PISR concept was also analyzed for surfaced draft and trim. This was done by iterating the draft and trim, finding the centroid and moment of area characteristics of the water plane and then solving for a new draft and trim. Figure 54 shows the water plane for the PISR in the Normal Surfaced Condition.

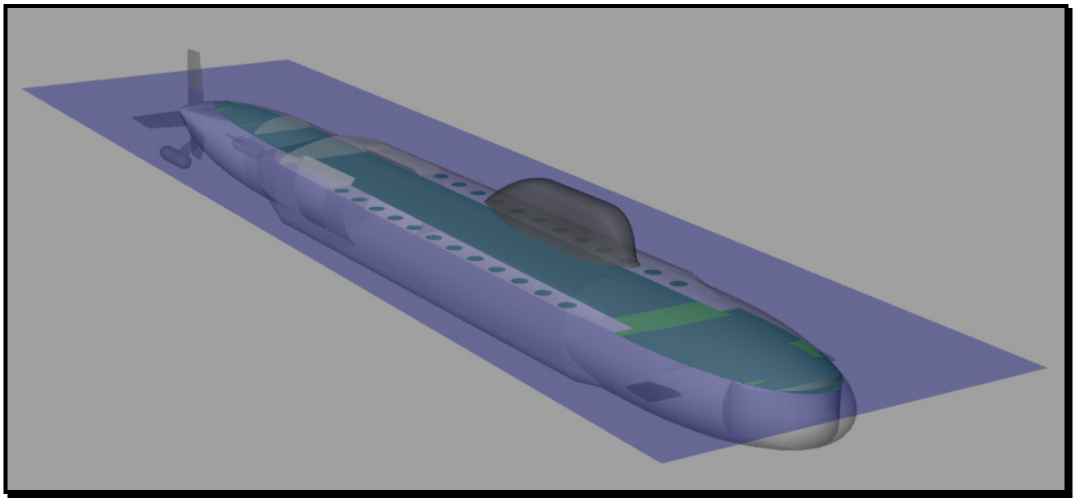
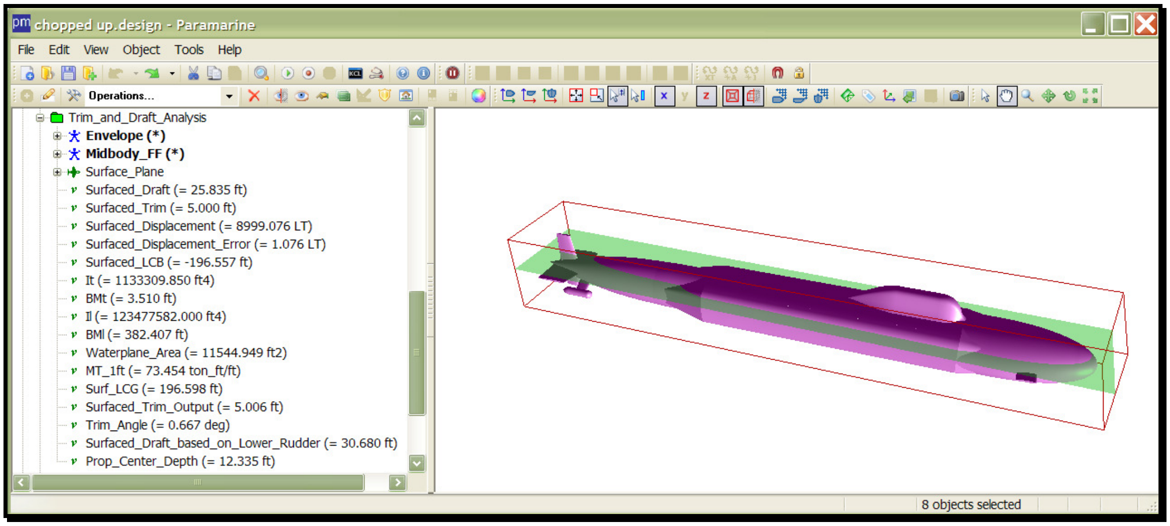


Figure 54: Water plane for Trim and Draft Analysis

Figure 55 shows the final iteration as incorporated in the PISR Paramarine Model.



```
Trim_and_Draft_Analysis
  Envelope (*)
  Midbody_FF (*)
  Surface_Plane
  Surfaced_Draft (= 25.835 ft)
  Surfaced_Trim (= 5.000 ft)
  Surfaced_Displacement (= 8999.076 LT)
  Surfaced_Displacement_Error (= 1.076 LT)
  Surfaced_LCB (= -196.557 ft)
  It (= 1133309.850 ft4)
  BMt (= 3.510 ft)
  Il (= 123477582.000 ft4)
  BMl (= 382.407 ft)
  Waterplane_Area (= 11544.949 ft2)
  MT_1ft (= 73.454 ton_ft/ft)
  Surf_LCG (= 196.598 ft)
  Surfaced_Trim_Output (= 5.006 ft)
  Trim_Angle (= 0.667 deg)
  Surfaced_Draft_based_on_Lower_Rudder (= 30.680 ft)
  Prop_Center_Depth (= 12.335 ft)
```

Figure 55: Trim and Draft Analysis Using Paramarine

With an input draft of 25.835 ft and trim of 5 ft (by the stern), an output trim of 5.006 ft and a maximum surfaced draft of 30.68 ft (at the trailing tip of the lower rudder) is obtained.

4.2.4 Powering/Resistance (i.e., speed and endurance range)

Initial powering and resistance estimates were performed using the MIT Submarine Concept MathCAD Model. Three trials were attempted: trial 1 used a body of revolution hull form of the same max cross-sectional area of the PISR, PISR's 428 ft length overall, and the wetted surface area of the hull as modeled in Paramarine; trial 2 used a body of revolution hull form with PISR's LOA and a diameter of 37 ft, the max molded depth of the PISR; and trial 3 used a body of revolution hull form with PISR's LOA but a diameter of 50 ft, the max beam of the PISR SSN.

MathCAD Model Speed Analysis

	Diameter	Wetted Surface Area	SHP	PC	V_{max} Surf	V_{max} Sub
Trial 1	44.72 ft*	51780.980 ft^{2**}	48,000 hp	0.81	20.1 kts	26.9 kts
Trail 2	37 ft	45528.43 ft^{2}	48,000 hp	0.81	21.4 kts	30.0 kts
Trail 3	50 ft	61524.905 ft^{2}	48,000 hp	0.81	20.0 kts	24.6 kts

*- Effective Diameter (Based on Max Sectional Area)

**- Based on Hull as Modeled in Paramarine

Table 29: MIT MathCAD Model Speed Analysis

This analysis showed that the PISR IPS would at least deliver the threshold speed of 25kts. A more detailed analysis was then performed using Paramarine's powering analysis tools. Figure 56, below, displays the resistance coefficient lookups that Paramarine uses to develop the effective submerged power. Based on the concept geometry, a Cr + Ca of 0.00097 was employed in the powering estimate.

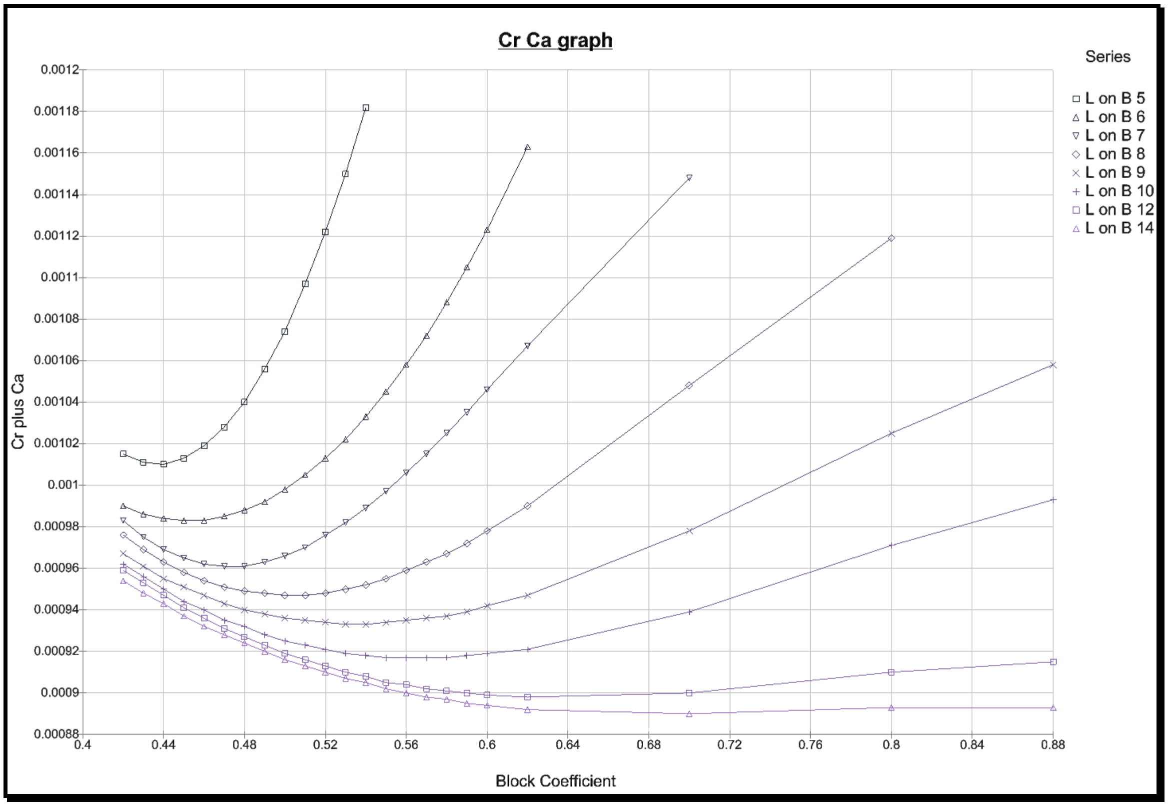


Figure 56: Cr + Ca Resistance Coefficients in Paramarine Analysis

Using the propeller design in section 4.2.6, the powering curves in Figure 57 and Figure 58 were produced.

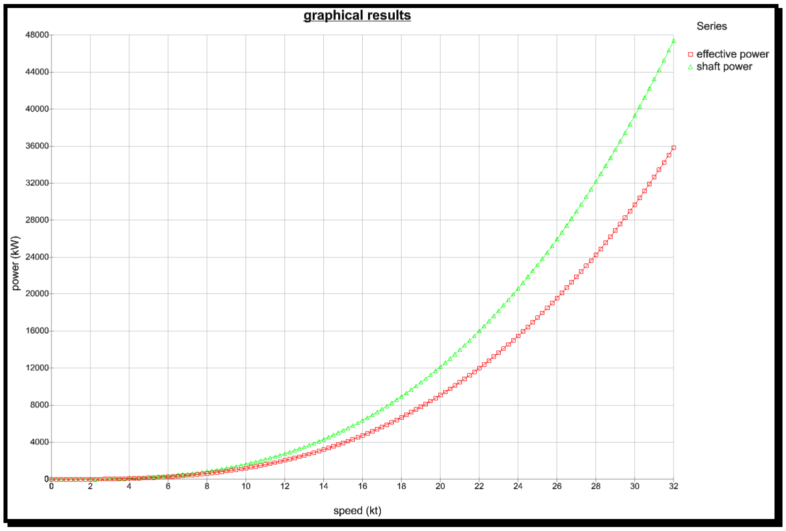


Figure 57: Submerged Powering Requirements

Figure 57 indicates that a submerged speed of 29.25 kts is achievable. The surfaced analysis in Figure 58, however, is not convincing.

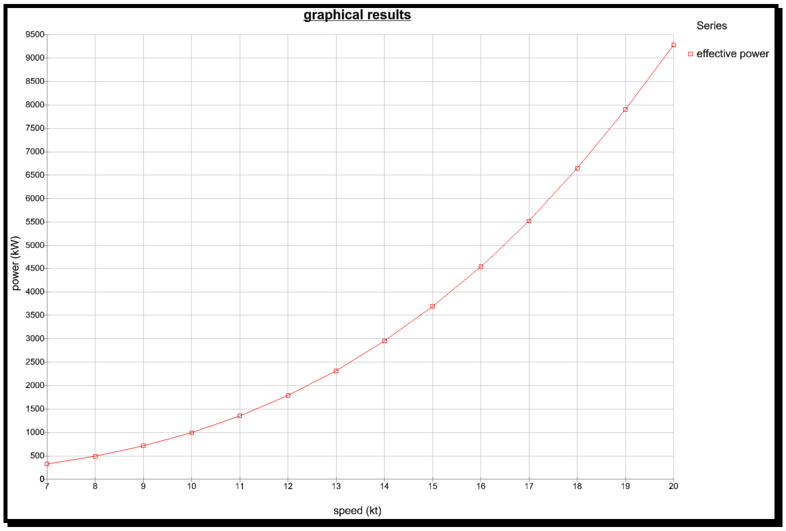


Figure 58: Surface Powering Requirements

It seems that the Paramarine surfaced speed analysis is unable to account for the significant wave making observed with submarines on the surface. Therefore, the Paramarine surfaced powering results are unrealistic.

4.2.5 Maneuverability and Control Surfaces

Considerable effort was made to create control surfaces that made the PISR dynamically stable and adequately maneuverable. The resulting control surfaces produced a G_V of 0.566 and a G_H of 0.292 which meet design requirements as set out in Ref. 4.

4.2.5.1 Control Design

Using a non-dimensional analysis of previously deployed submarine designs, initial estimates for the required sizes for the control surfaces were developed. These estimates are the center column in Table 30 while the final concept design control surfaces are at right.

Control Surface Sizing							
Non-Dimensionalized		Dimensionalized			As Modeled Based on Paramarine Dynamic		
A_{BP}	0.012	A_{BP}	229.70	ft^2	A_{BP}	221.47	ft^2
A_{R}	0.035	A_{R}	669.96	ft^2	A_{R}	500.56	ft^2
$A_{\text{SP (total)}}$	0.040	$A_{\text{SP (total)}}$	765.67	ft^2	$A_{\text{SP (total)}}$	1009.48	ft^2
$A_{\text{SP (movable)}}$	0.020	$A_{\text{SP (movable)}}$	382.83	ft^2	$A_{\text{SP (movable)}}$	336.71	ft^2
A_{Dihedral}	0.016	A_{Dihedral}	306.27	ft^2	A_{Dihedral}	358.17	ft^2

Table 30: Control Surface Sizing

4.2.5.2 Circle Maneuvers

Table 31 summarizes four submerged maneuvering cases analyzed in Paramarine, plots from which are shown in Figure 59, Figure 60, Figure 61, and Figure 62.

Turning Maneuverability Results				
Speed (kts)	Rudder (°)	Advance (yd)	Transfer (yd)	Tactical Diameter (yd)
15	12	597.8	450.3	904.5
15	25	393.9	273.2	560.7
20	3	1428.3	1159.8	2319.4
20	15	512.6	316.8	739.1

Table 31: Circle Maneuver Results

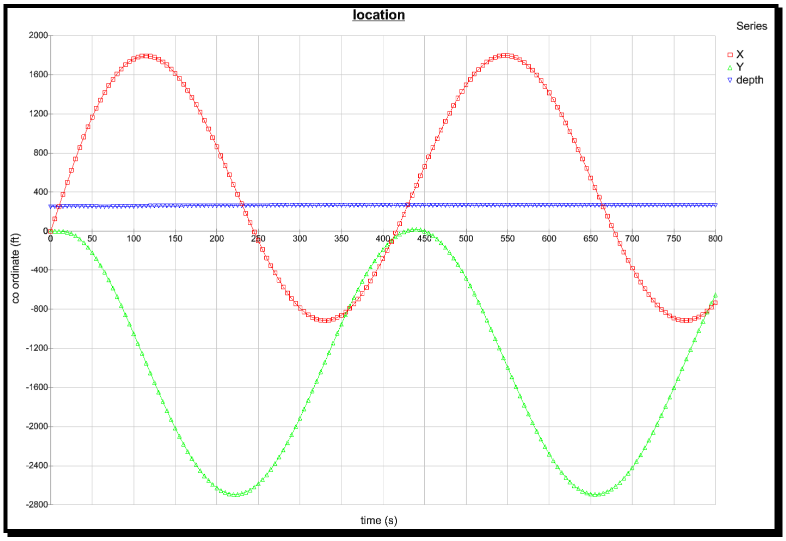


Figure 59: 15-kt Circle Maneuver with 12° Rudder

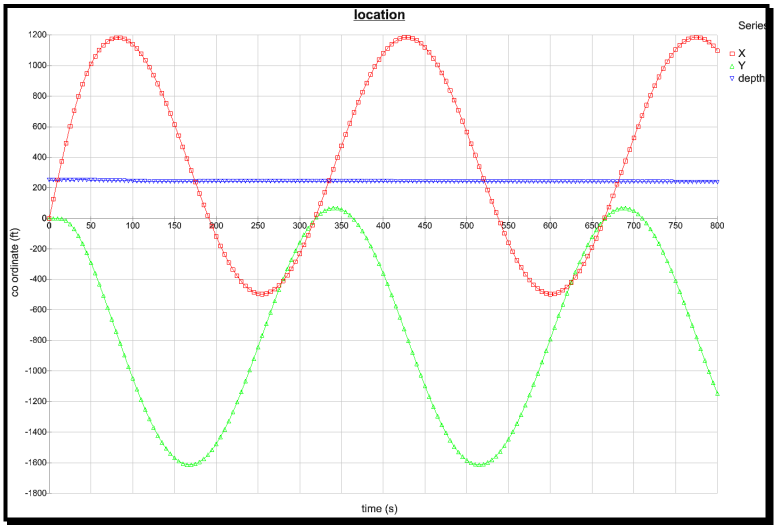


Figure 60: 15-kt Circle Maneuver with 25° Rudder

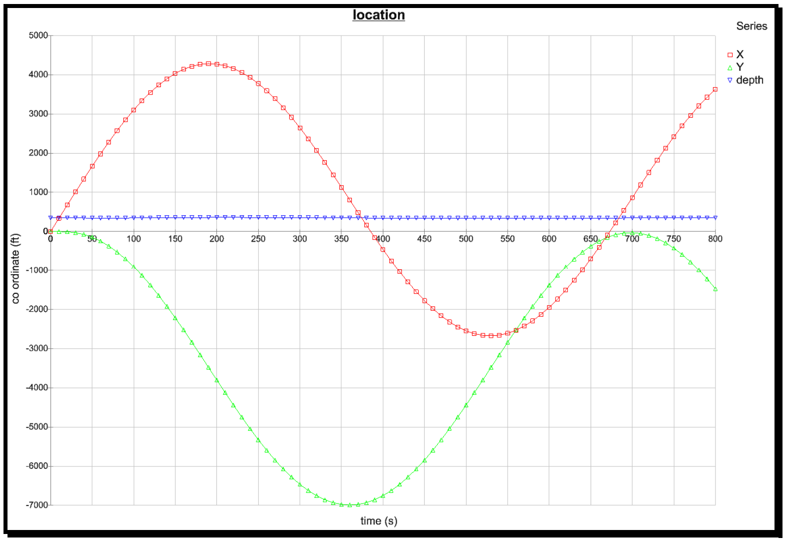


Figure 61: 20-kt Circle Maneuver with 3° Rudder

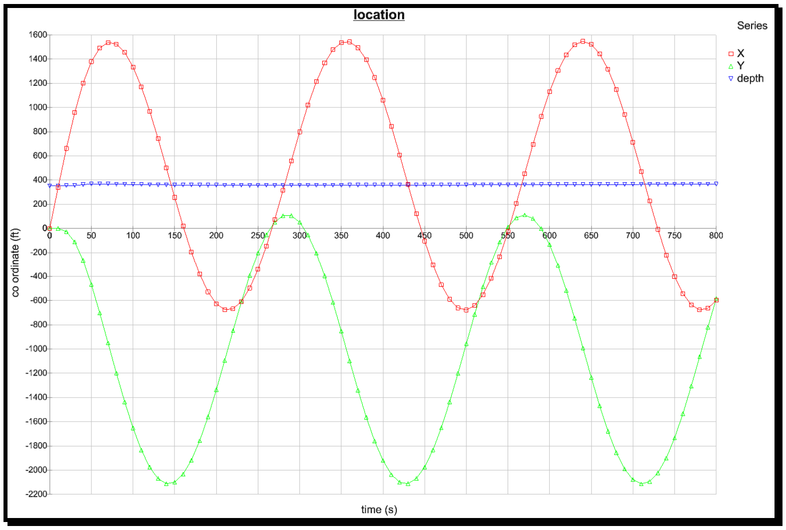


Figure 62: 20-kt Circle Maneuver with 15° Rudder

4.2.5.3 Depth Change Maneuver

Continuing the maneuvering analysis in Paramarine, a depth change maneuver at 10 kts from 200’ to 920’ was analyzed. As shown in Figure 63 and Figure 64, the PISR can complete this maneuver in approximately 180 seconds after reaching and maintaining a ~30° down angle on the ship.

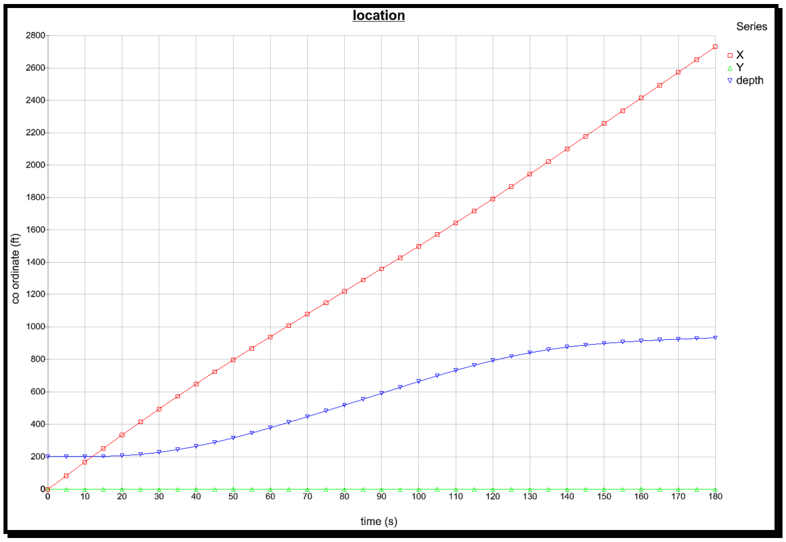


Figure 63: 720-ft Depth Change Maneuver (Position)

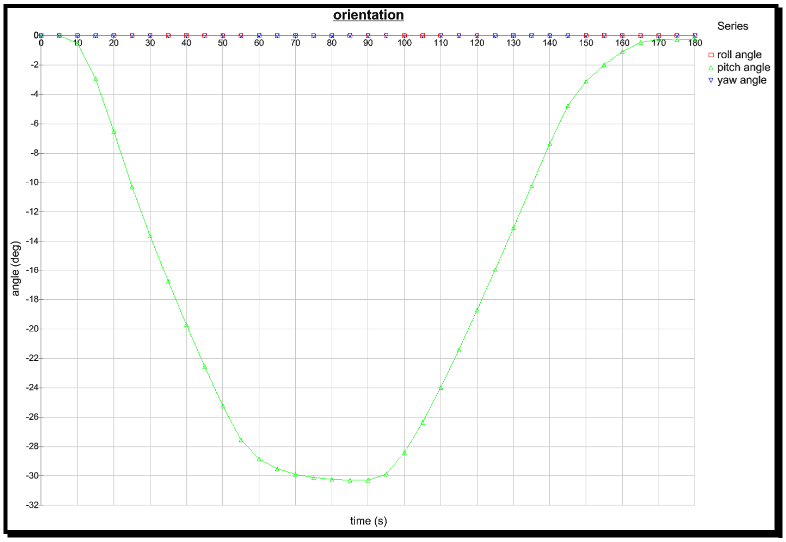


Figure 64: 720-ft Depth Change Maneuver (Orientation)

4.2.5.4 Fishtail Maneuver

The impact of a fishtail maneuver on the ship was found to be that a significant up angle was achieved without any additional action of the control surfaces. The location and orientation results of these analyses are shown in Figure 65 and Figure 66, respectively.

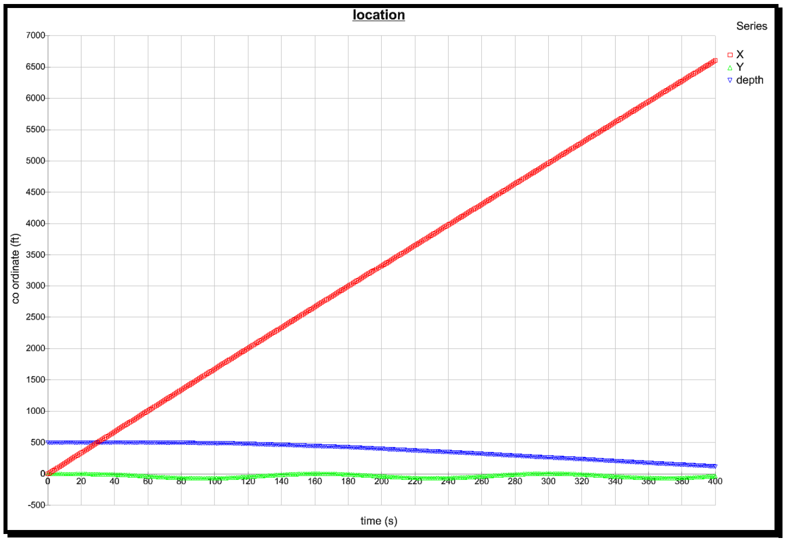


Figure 65: 14-kt Fishtail with 5° Rudder (Location)

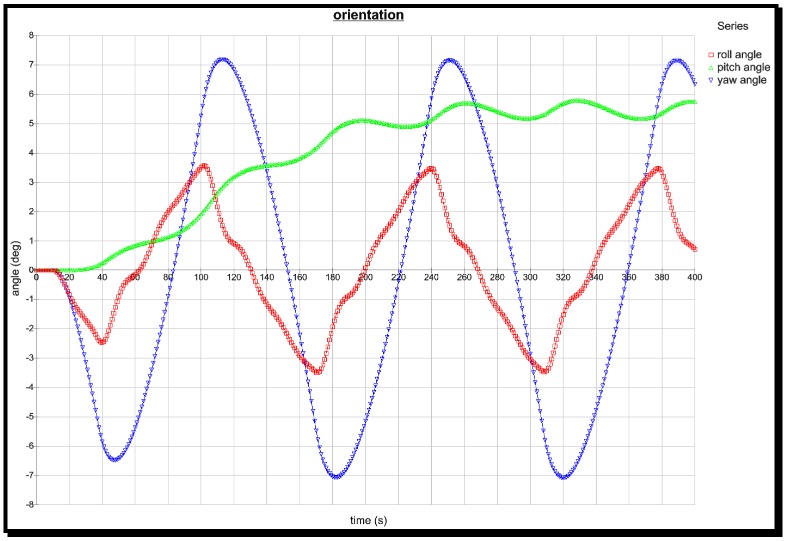


Figure 66: 14-kt Fishtail with 5° Rudder (Orientation)

4.2.5.5 Jam Rise and Emergency Deep

An analysis for a 14kt, 10° jam rise casualty on the stern planes was performed. The result of quickly backing down and counteraction by the bow planes results in an upward depth excursion of ~150 ft. The results of this Jam casualty study are shown in Figure 67 and Figure 68.

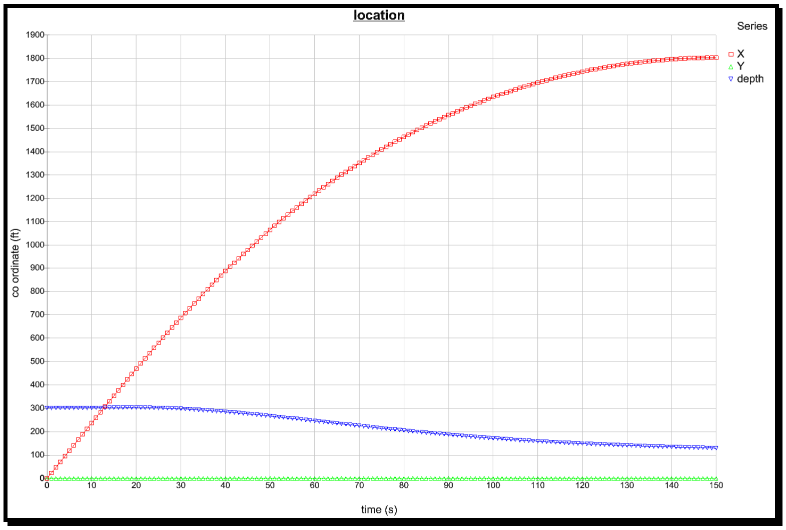


Figure 67: 14-kt 10° Stern plane Jam Rise Casualty (Location)

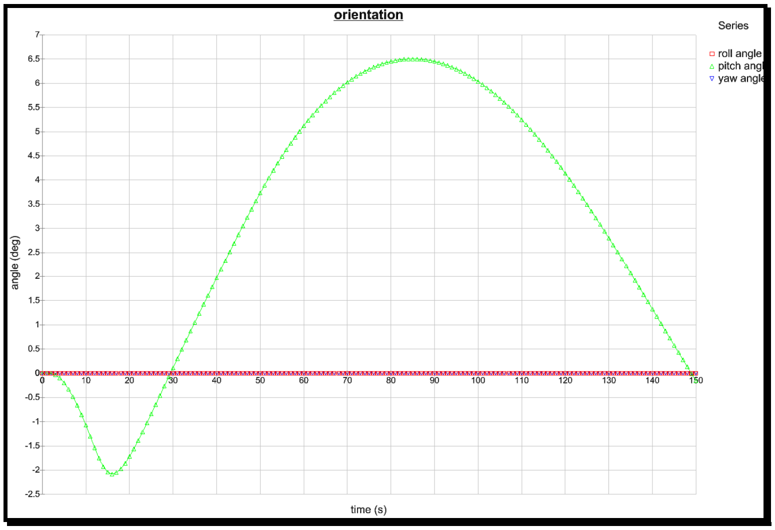


Figure 68:14-kt 10° Stern plane Jam Rise Casualty (Orientation)

A critical maneuvering requirement for the ship is the ability to quickly reach a safe operating depth after sighting a close aboard contact while at periscope depth (PD). As a particularly challenging scenario, the ship was travelling at 2 kts and no alteration to the weight of the ship (no flooding of auxiliaries to achieve negative buoyancy) was made. The result is shown in Figure 69. PISR takes approximately 70 seconds to reach a safe depth during an emergency deep. Additional analysis is warranted to examine the impact of flooding depth control to see how much this figure might be improved.

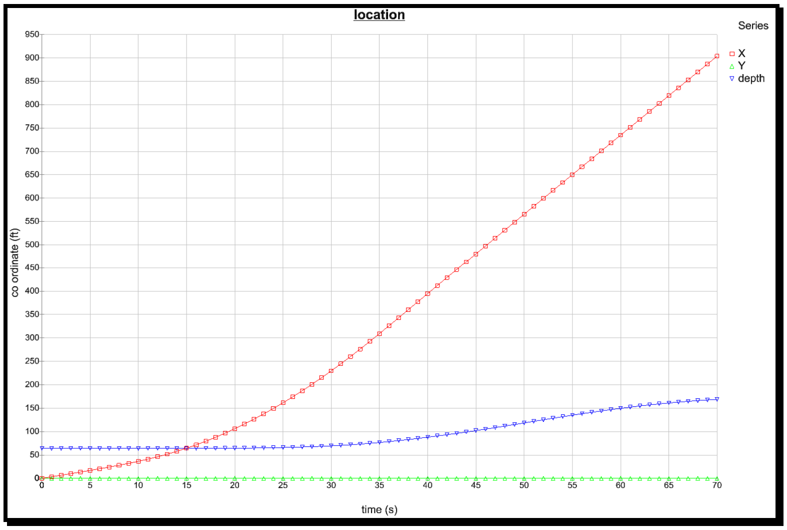


Figure 69: Emergency Deep Maneuver from PD at 2 kts (Location)

4.2.5.6 Submerged Operating Envelope and Plane Limits

Paramarine was used to determine an appropriate safe operating envelope for the PISR. As this ship is designed to have retractable bow planes, there are two categories of control surface casualties: those at low speed where the bow planes are out and may be used to aid in the recovery of the ship from the casualty, and those at high speed where bow planes are rigged in and the severity of the casualty at speed would require limitations in the plane angles permitted. It was determined that an acceptable transition speed is 15 kts, above which a dive/rise limiter is used and the bow planes are rigged in. Figure 70 shows the resulting low speed SOE. Effectively, PISR can recover from nearly any control surface casualty at low speed and so the SOE is almost unencumbered.

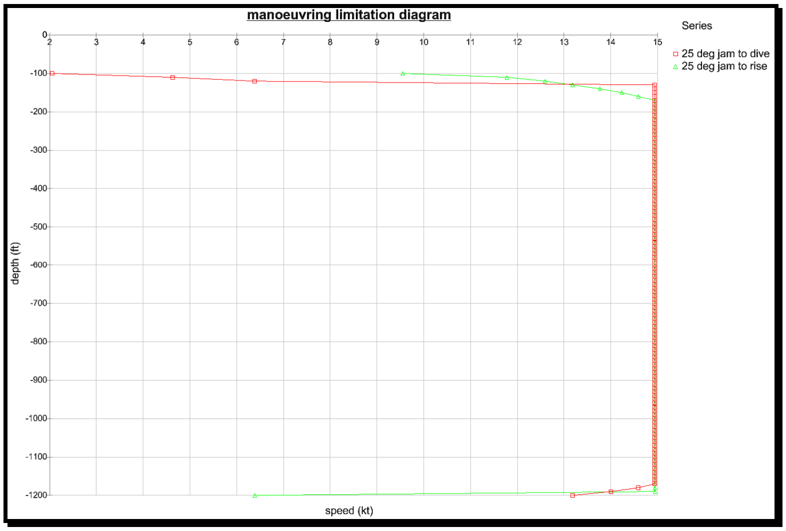


Figure 70: Low Speed Submerged Operating Envelope

Figure 71 shows the high speed SOE. Without the use of the bow planes, the ship is significantly more limited in the depth and speed combinations that are safe to operate in. Through successive iterations, it was determined that a 5° dive and 7° rise limiter were required at high speed to be able to operate the ship at all speeds.

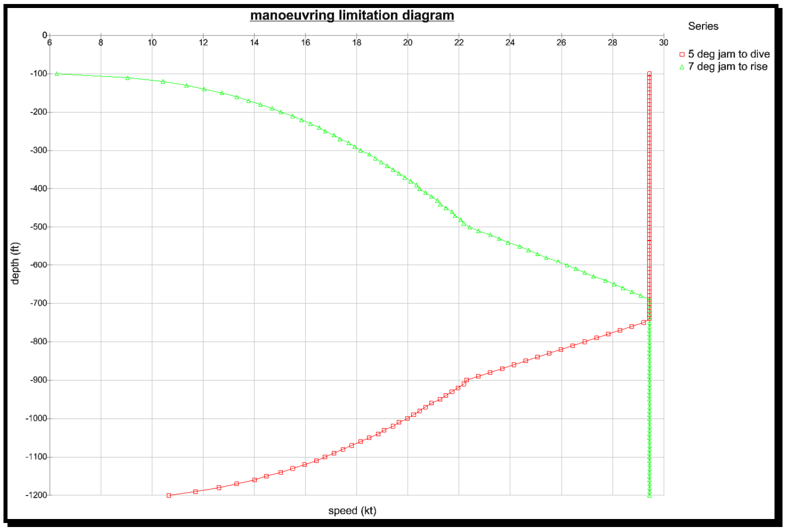


Figure 71: High Speed Submerged Operating Envelope

4.2.6 Propeller Design

The propeller design process for PISR started by selecting the number of blades for the propeller. The propeller design and analysis tool used to design the propeller was OpenProp. Six blades were selected for this propeller because of the desire to minimize the possibility of cavitation. By increasing the number of blades for a given amount of thrust, the likelihood of cavitation is reduced because each blade is more lightly loaded. A blade that is more lightly loaded has a higher pressure on the suction side which means that cavitation is less likely. 18 knots was selected as the design speed instead of the predicted maximum speed because the submarine will likely spend most of it life operating at speeds below its maximum speed. Optimizing a propeller's performance for high speed operations means that the propeller is inefficient a lower speeds. Designing the propeller in consideration of the expected operational profile will reduce the energy required from the reactor core and ease the reactor core design.

In order to estimate the required propeller thrust it was assumed that the maximum shaft horsepower would be required to achieve a maximum desired speed of 28kts and a propulsive coefficient (PC) of 0.81. Using these assumptions and the relationship, $SHPxPC = Force\ x\ Speed$, it was determined that the required thrust to achieve a speed of 28kts is 1,991,000 N.

Assuming a cubic relationship between power and speed it was determined that the required thrust to achieve a speed of 18 kts is 820,000N. The combination of 18kts, 820,000N and 6 blades was used as input for Figure 72. Typically, the results of a study similar to the one shown in section 4.2.4 would be used to determine required thrust; however, in order to generate the figures of 4.2.4, propeller performance characteristics were required. Therefore, the necessary propeller performance was approximated using the method just described and then entered into Paramarine.

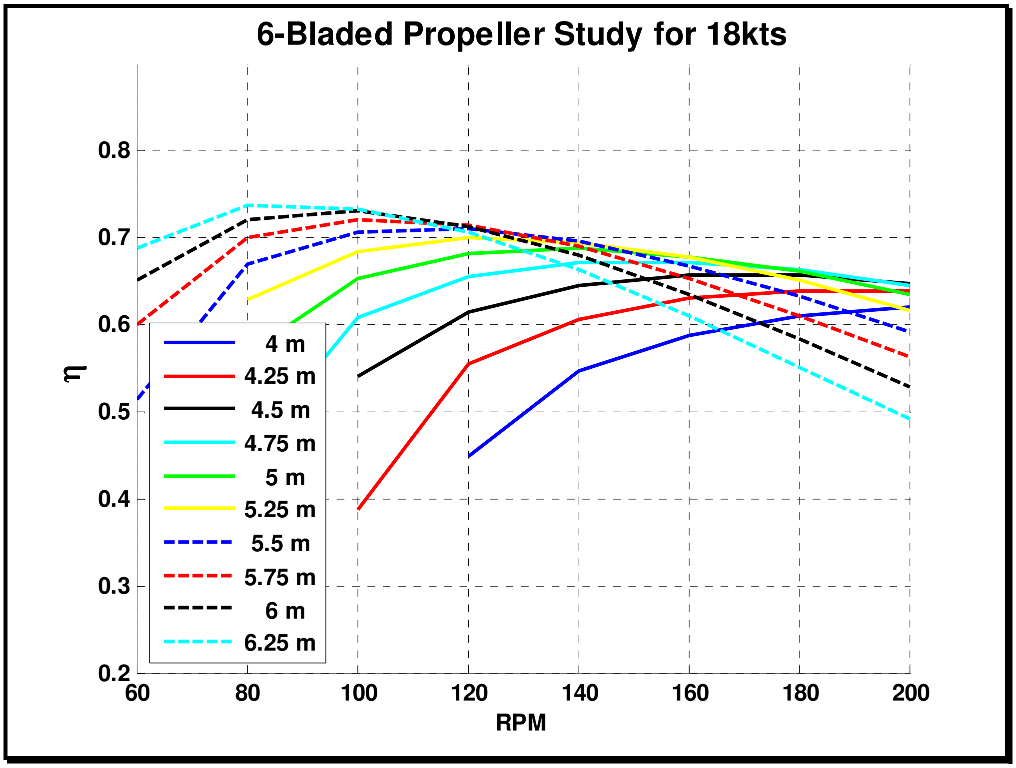


Figure 72: Propeller Efficiency Study

Figure 72 above shows that maximum propeller efficiency occurs from 80-100RPM. Figure 72 also shows that increasing propeller diameter increases the maximum possible efficiency of the propeller. An operational rotation rate of 90RPM and a diameter of 6m was selected. The rotation rate was chosen to maximize efficiency; the diameter choice was restricted to the maximum possible diameter allowable to keep the propeller submerged while on the surface.

Using Figure 72 the propeller design was further constrained to a 6 bladed propeller, 6m in diameter, operating in a free stream flow speed of 18kts producing 820,000N of thrust at 90RPM. These parameters represent the design point for the propeller and were entered into OpenProp to generate optimum blade geometries to achieve the desired performance. The propeller geometry is shown in Figure 73.

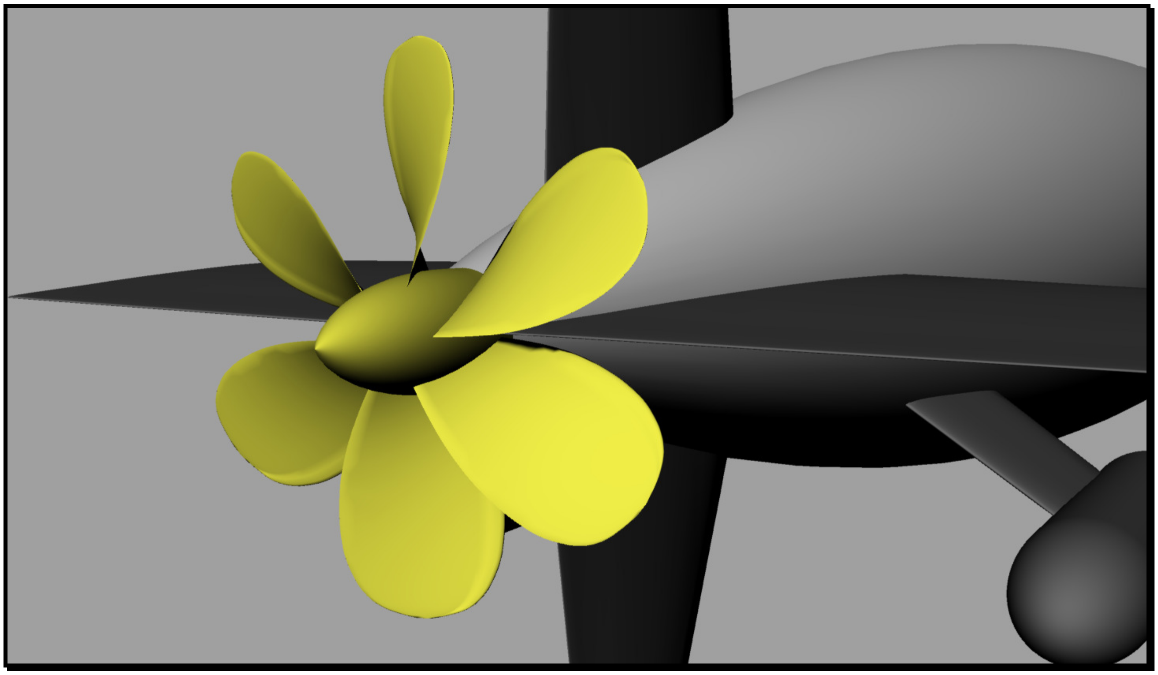


Figure 73: Propeller Design

Performance curves for the propeller design are shown in Figure 74:

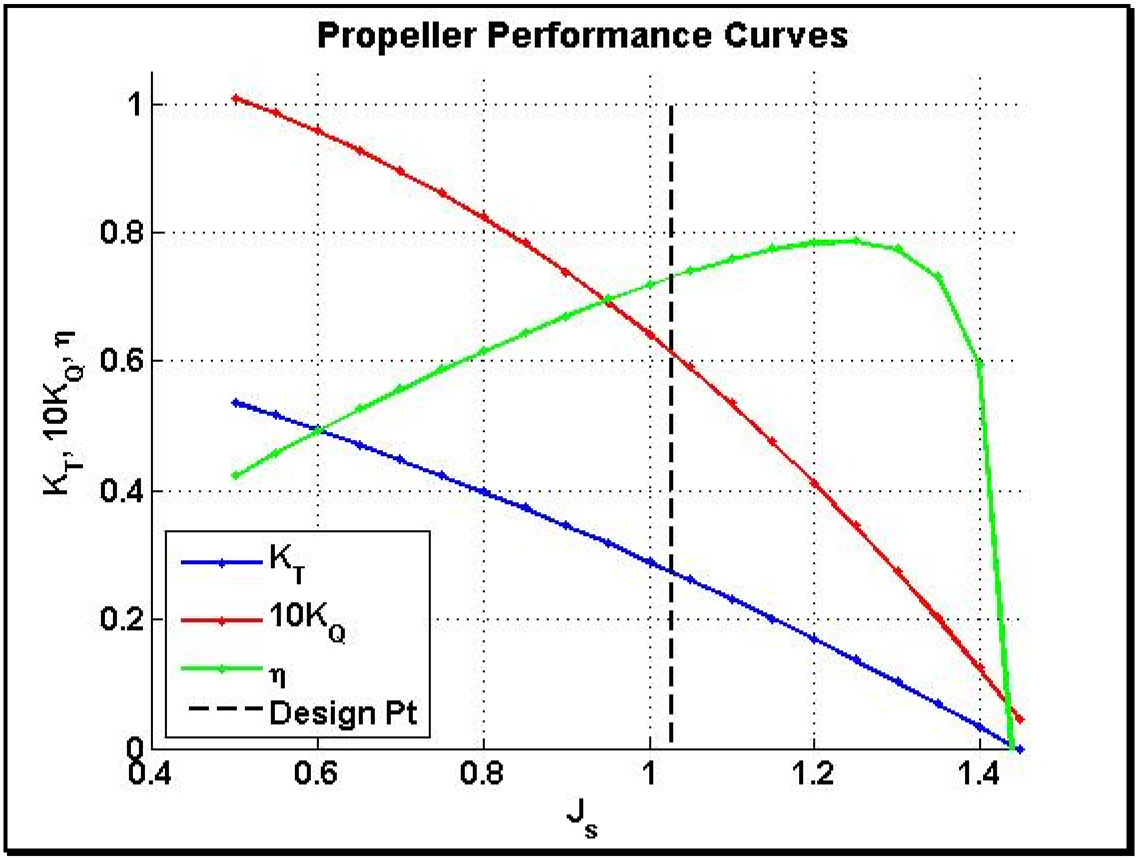


Figure 74: Propeller Performance

4.2.7 Submarine Escape

One of the key architectural aspects of this concept design is the ability of the entire crew to escape the ship should it become stranded. This is accomplished through the use of escape capsules in 8 of the 24 payload and escape tubes. The vital access to the escape capsules requires that the RC tunnel be designed to test depth (but not crush depth) and both ends of it be hatched so it can be accessed from the Turbine Room or Operations Compartment regardless of the extent of the damage to the other compartment. The escape capsules and access tunnels are shown in Figure 75 and Figure 76 below (Capsules and Motor Room LET in orange, RC tunnel in purple, access tunnels in light green). Four of the capsules are accessed from the Operations Compartment, two are accessed from the Turbine Room and two may be accessed from either compartment using the hardened RC tunnel.

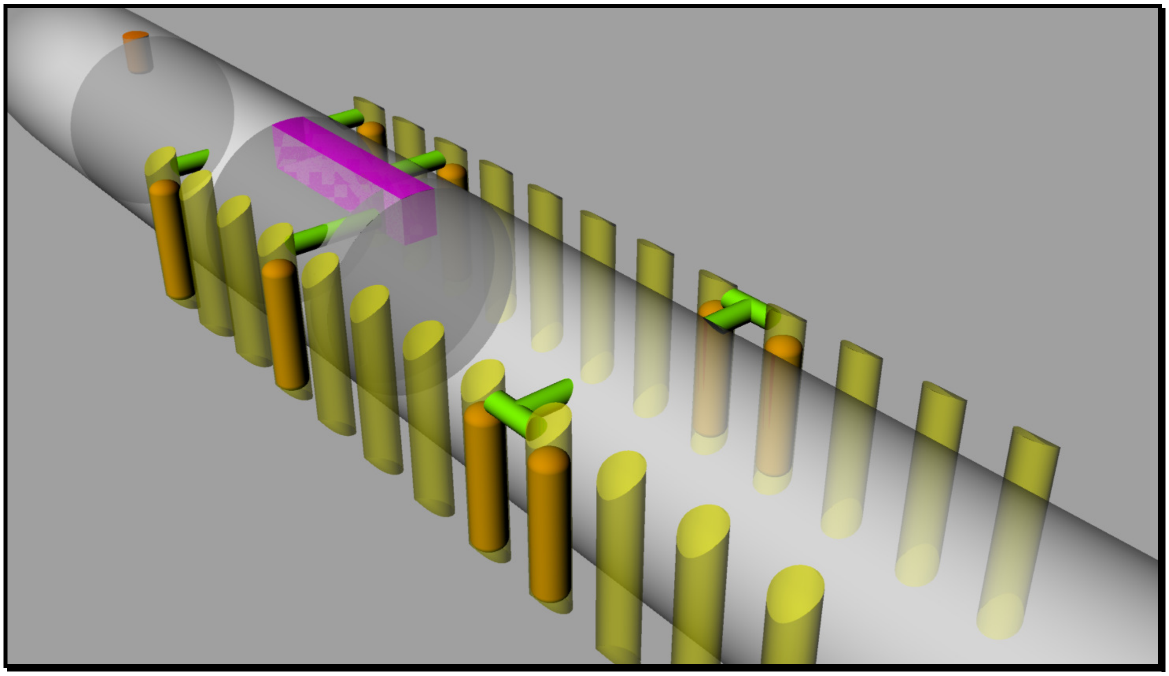


Figure 75: PISR Escape Systems Configuration (Perspective, Bow Right)

As the motor room does not have direct access to the escape capsules, a logistics escape trunk is provided. This capability is likely to be used during a flooding casualty in the Engine Room where the ship successfully made it to (or near) the surface but the flooding could only be arrested through the pressurization of the Turbine Room. In this case, the mid ER bulkhead is expected to hold and access to the Turbine Room escape capsules is cut off.

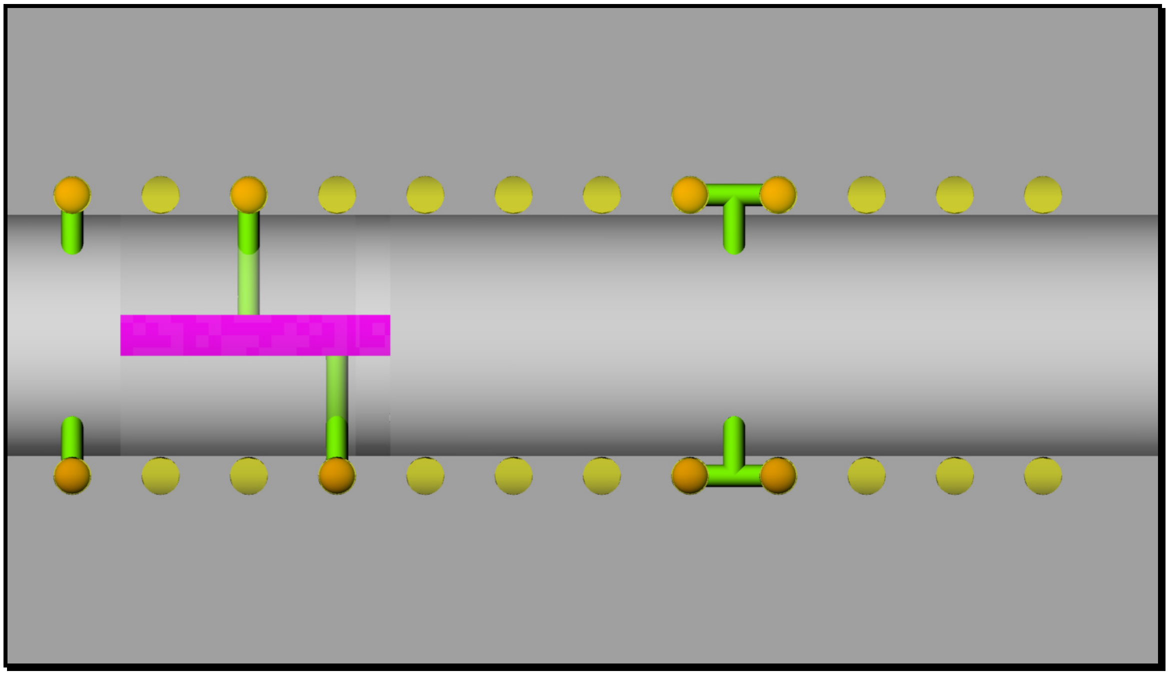


Figure 76: PISR Escape Capsule Configuration (Plan View, Bow Right)

4.3 Design Refinements

Refinement of this design was made by completing pressure hull structural optimization and analysis using the Paramarine software. Refining the pressure hull design was foundational to establishing a more concrete estimate of the group 100 weight. Further refinement was made by completing a maneuvering study which allowed the sail to be placed in a position to achieve longitudinal stability in the horizontal plane. The maneuvering study also allowed the stern planes to be sized for dynamic stability in the vertical direction. Other design refinements included completing a powering and resistance study which led to the ability to perform a propeller design and included it as part of the overall design.

4.4 Cost

In calculating costs for this project it was desirable to use a simple cost model and report expected costs against a normalized value. A simple model to calculate costs is a weight based cost model. This type of cost model does not capture the subtleties of cost estimating and makes the estimation of total lifecycle costs difficult since this type of cost model does not contain factors related to operation and maintenance but does provide a reasonable estimate of submarine acquisition costs.

The normalized cost value was obtained by using rough, single digit weight group weights for several submarine classes and then averaging these numbers to obtain weight estimates for an "average" submarine. These average numbers were entered into a weight based cost model and the resulting cost was used to normalize the costs of PISR which is what is presented in Figure 77. Note that the average cost number is what was used to determine compliance with the requirement that the submarine cost not exceed twice that of an “Average SSN” submarine. Using the weight based cost model the cost of “Average SSN” was $2.5 billion (FY05).

4.4.1 Producibility and Acquisition Cost

Table 32 below shows the complete acquisition cost breakdown by weight group. The assumptions made in creating Table 32 are shown in Table 33.

Cost Model Input	
Service Life (Ls)	30
Number of Ships (Ns)	20
Desired Fiscal Yr (Yfy)	2012
Initial Operability (Yioc)	2016
Base Year (Yb)	2005
Inflation Rate (R)	3.5
Annual Production Rate (Rp)	2
Man Hour Rate ($/hr)	50
Overhead Rate	1.5
Profit (%)	11

Table 32: Cost Model Input

PISR											
Weight Group	LT	Labor Factor (Hr/LT)	Labor Cost ($M)	Material Factor ($K/LT)	Material Cost ($M)	Integration Costs ($M)	Assembly Costs ($M)	Direct Costs ($M)	Indirect Costs ($M)	Profit ($M)	Total ($M)
100	3365	486	81.77	8.51	36.45	14.87	62.55	195.63	293.45	53.80	542.89
200	1382	560	38.70	55.61	97.78	10.26	48.93	195.66	293.49	53.81	542.96
300	347	1838	31.89	99.36	43.87	6.98	31.51	114.25	171.38	31.42	317.04
400	224	3066	34.34	78.23	22.29	6.52	27.95	91.10	136.66	25.05	252.81
500	653	1278	41.73	107.60	89.39	10.42	48.91	190.45	285.68	52.37	528.50
600	400	1470	29.40	125.60	63.92	7.38	34.69	135.38	203.08	37.23	375.69
700	907	810	36.73	8.25	9.52	6.41	26.46	79.12	118.67	21.76	219.55
Total			**294.55**		**363.22**	**62.84**	**280.99**	**1001.60**	**1502.40**	**275.44**	**2779.44**

Table 33: Acquisition Costs by Weight Group

In determining the total acquisition costs for a 20 ship class, three different learning curves were considered: at 95%, at 90% and at 80%. Each of these curves is shown in Figure 77 below. In calculating the total acquisition cost for the class, a pessimistic view of cost reduction via a learning curve was taken and the 95% learning curve was used. This is considered a worst case scenario and cost reduction would likely be dramatically improved over the period of construction if funds were specifically set aside to study and implement cost reduction measures. Using these assumptions, the acquisition cost of the lead PISR is expected to be $2.78 billion (FY05) and the total acquisition cost for a 20 submarine class is estimated to be $47 billion (FY05).

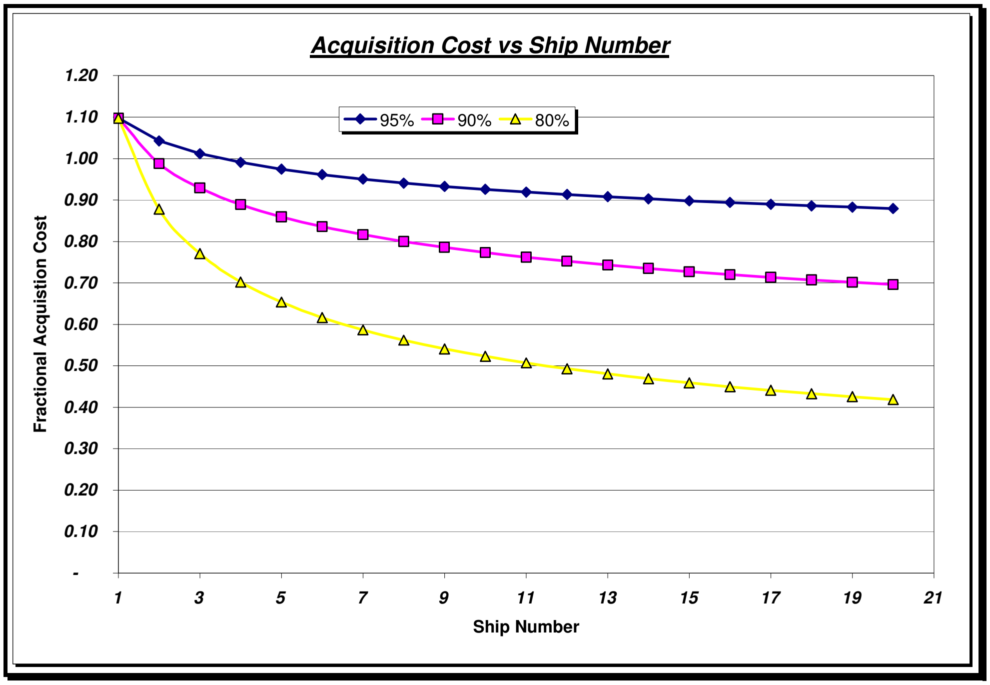


Figure 77: Acquisition Costs by Ship Number

It is expected that this submarine will be constructed using state of the art modular construction and assembly methods to reduce costs. The internal components and layout do not improve or restrict the ability to use modular construction techniques. However, there are several features of this ship that may alter the construction cost paradigm:

1. Torpedo room location and layout
2. Extent of the non-pressure hull structure in the parallel mid body of the submarine
3. Conformal water backed bow array
4. Canister style vertical launch system (VLS)
5. UUV interface

Internal weapons for PISR are expected to be loaded through the launch tubes. The torpedo room is located on the top deck and sufficiently far enough forward to allow weapons to be loaded through the launch tubes. This torpedo room location means that less shipboard auxiliary equipment will be required to load weapons into the ship since a shipping line will not have to be aligned. Because the shipbuilder does not have to construct and test a long shipping line, there should be a cost savings. All of the torpedo room costs will be with weapon handling and not weapon shipping.

Extensive non-pressure hull structure will increase the cost of this submarine over a submarine which uses a traditional hull layout. The non-pressure hull structure has varying curvature; this changing curvature will likely mean that the fixtures and assembly techniques used for hull construction will have to be re-evaluated. Funds for specialized fixtures will have to be set aside for shipyard capitalization as part of the PISR construction program. It is expected that the cost savings of the torpedo room construction will be more than offset by the increased costs associated with non-pressure hull construction.

Traditional air-backed spherical bow arrays are costly to build and maintain. PISR uses a very large conformal water backed bow array that will be easier to construct and maintain than the traditional bow arrays. The bow array used for this submarine will provide improved performance and cost reduction.

All of the vertically launched weapons on this submarine are located on the beams between the pressure hull and non-pressure hull in canisters. Each canister holds 4 weapons which can be individually launched. Grouping the vertically launched weapons in canisters reduces the number of support systems required to launch weapons. For instance, the fraction of watertight hatches to the number of weapons in VLS is significantly reduced compared to a VLS which houses the weapons in individual launch tubes.

One of the ways that this submarine accomplishes its primary mission of persistent intelligence, surveillance and reconnaissance is through the use of off hull sensors, specifically UUVs. UUVs present a unique challenge in the design of the ship due to the requirement to be able to deploy and retrieve them effectively and provide the capability to perform maintenance on them while underway. This submarine stores UUVs in two locations at the aft end of the non-pressure and provides dry access through a horizontal tube located in the sail. Deployment and retrieval of UUVs will require specialized equipment to aid in deployment and retrieval and to secure the UUVs in their storage location. This additional equipment will come at an increased cost, particularly for the first few ships of the class.

4.4.2 Operations and Support Cost

Quantification of the operations and support cost associated with the various features of this submarine is difficult. The features which are expected to change the operations and support cost from current submarines are:

1. Extent of non-pressure hull
2. UUV interface
3. Canister style VLS
4. Conformal bow array
5. Torpedo shipping

In general, the more complex the system, the more complex to maintain. For this reason, it is expected that the operation and support cost will increase due to the extensive non-pressure hull structure and UUV interface. Non-pressure hull structure will increase the operation and support cost due to the extensive preservation work that will be required throughout the life of the ship. UUV interfaces will increase operation and support cost because the mechanisms that are required for UUV retrieval are typically difficult to maintain.

Canister style VLS will reduce operations and support cost because there are fewer support systems to maintain. A conformal bow array will reduce operation and support cost because there are few watertight penetrations with this system. Locating the torpedo room high in the ship such that the launch tubes can be used for weapon shipping reduces the operation and support cost because two launch tubes could be used simultaneously to load weapons which will reduce the amount of time to load weapons therefore the amount of the time that pier side weapons services are required.

4.5 Technical Feasibility and Risk Assessment

There are several areas of this submarine's design that are not implemented in today's US Navy submarine fleet. These areas are listed below in order of decreasing risk and increasing technical feasibility.

1. UUVs external to the submarine
2. Routine access to the UUVs
3. Surface to air missiles
4. UAVs launched from the sail
5. Non pressure hull structure
6. Electric propulsion

4.5.1 UUVs

The primary mission of this submarine is to be a persistent intelligence, surveillance and reconnaissance platform. One of the primary ways that this mission will be accomplished is by making maximum use of UUVs. However, the extent and method of UUV utilization in PISR has not been done before. The combination of primary mission importance and lack of experience with this technology makes the area of incorporating UUVs into the design the highest risk and least technically feasible. If the UUV system on this submarine does not function reliably, the primary mission of this submarine is compromised. Several parts of the UUV system make the implementation challenging.

1. Fairing Doors
2. Retrieval/Deployment Mechanism

Incorporation of UUVs in to the submarine requires a stowage location and dry access tube. Both of these locations will require large fairing doors to be manufactured. The ability to construct and maintain these large doors with tight fairness tolerances will be severely tested. The UUVs will likely also require a retrieval/deployment mechanism if the UUV cannot navigate to its stowage location on its own. The mechanism would probably be an "arm" that can reach out from the stowage location and release or attach itself to the UUV. This type of mechanism will be difficult to design, construct, operate and maintain both from an electrical and mechanical standpoint.

4.5.2 Surface to Air Missiles

Surface to air missiles are incorporated into this submarine as part of the on station persistence of this submarine. The US Navy submarine force has extensive experience in launching missiles while submerged and the small surface to air missiles should not present a significant challenge to launch while submerged. However, targeting the missile may be more difficult. The optimum targeting method would be to give the missile general target bearing, distance and elevation and have the missile seeker head locate the target after launch. If the missile requires that the submarine continuously illuminate the target, the enemy's ability to locate PISR will be increased in the event that a missile launch is necessary.

4.5.3 UAVs

The sail of PISR incorporates tubes that house and launch UAVs. The technical feasibility of providing UAV capability is less than that for UUVs and is deemed less risky due to the impact on overall ship performance if this capability is not reliable. PISR could still perform most of its primary mission without this capability. The principle problems with incorporating UAVs are providing space for sufficient wing span and in the desire to launch them while submerged.

4.5.4 Non-Pressure Hull Structure

PISR incorporates a significant amount of non-pressure hull structure that is not a body of revolution shape and contains compound curvature. While shapes of this type are routine in surface ship construction, they are an anomaly in submarine construction. It is anticipated that this structure will have to be made with tighter tolerances for a submarine than for a surface ship for hydro acoustic reasons. Non-pressure hull structure for this submarine will require unique fixturing to manufacture. This feature of the submarine is relatively low risk with relatively high technical feasibility and is only mentioned because it is not typically done in US Navy submarines.

4.5.5 Electric Propulsion

In order to reduce the risk and increase the technical feasibility of using electric propulsion, a motor that has already been designed and tested was selected. Experience and lessons learned in the DDG-1000 program with electric propulsion are expected to translate into the detailed design and construction of PISR. Electric propulsion is deemed to be completely feasible and the only risk is the effect on the total ship signature.

4.6 Research & Development Needs

There are several unique features of this submarine that will require further study prior to implementation; two of these are: UUV deployment and retrieval and the hydrodynamics of the sail. UUV deployment and retrieval requires further study because the UUVs are being deployed and retrieved horizontally near the stern of the submarine in a flow region that is expected to be very unsteady. It is anticipated that the submarine will have to hover in order to deploy and retrieve UUVs and that a retrieval mechanism of some type will have to be used in order to guide the UUV into its stowage location in the UUV bay. Further study is needed to determine if UUV deployment or retrieval can be done while the submarine is underway. Additional study is needed to determine if a retrieval mechanism is actually necessary and if it is, how it should be configured to interface with various UUV shapes and sizes.

The sail shape used in the PISR design is unique and its flow characteristics are unknown. Additionally, the sail houses a large diameter tube near its trailing edge to be able retrieve a UUV into a dry location. The flow characteristics of this unique sail need to be studied to determine the overall sail drag, flow noise from the sail and the effect of the sail wake on propulsor performance. In order for the sail to accommodate a large diameter tube, a method to access the tube needs to be examined. The PISR design uses two large doors which meet at the trailing edge of the sail and hinge outward. This door configuration needs to be examined in detail in order to ensure that sufficient access to the large diameter tube is provided and that no flow related problems are created by the presence of the doors.

A third area for further investigation is the method used to size the stern planes. The Paramarine software seems to be over sizing the stern planes. This judgment is made merely on the appearance of the planes. A separate tool or method for stern plane sizing is necessary to validate the Paramarine results. Further research is needed in this area.

4.7 Operational Considerations

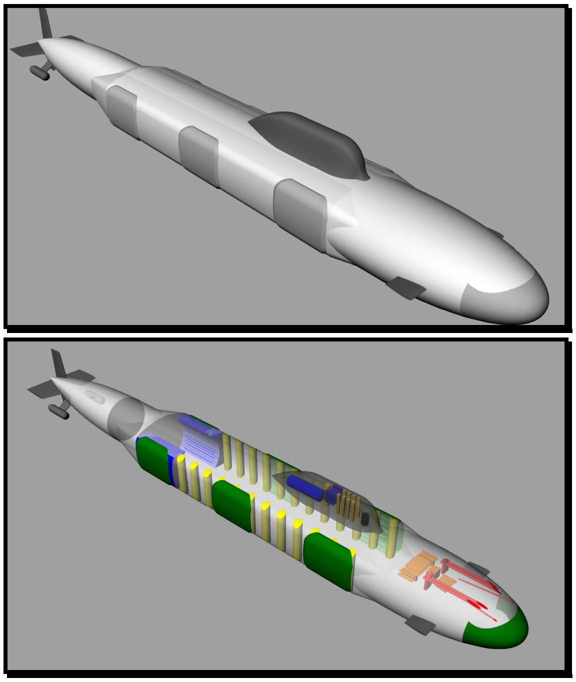
The combination of nuclear power, large habitability spaces and numerous large diameter payload tubes leads to a submarine which provides maximum operational flexibility while requiring little to no sustainment while on station. The payload tubes are capable of four different types of payload: cruise missiles, surface to air missiles, UUVs, and (potentially) heavyweight torpedoes. The ability to mix and match payloads throughout the payload tubes means that the weapon load out can be tailored to the expected mission assignments.

Large habitability spaces means that the crew will be able to endure longer times on station with minimal crew fatigue and without requiring additional stores replenishment. The requirement to host SOF meant that additional racks had to be provided. Since it is anticipated that SOF will only be aboard the submarine for short, infrequent periods, the racks can be used by the crew in the absence of SOF. This will ensure that no crew members will have to share a berth.

5.0 Conclusions and Recommendations

5.1 Summary of Final Concept Design

The PISR concept design meets or exceeds mission requirements in every area and can be constructed with the cost constraint. PISR provides the fleet with a persistent ISR platform that is capable of numerous other missions. A figure of key parameters for PISR is shown below:



PISR Key Characteristics	
Length Overall	428 ft
Max Beam	50 ft
Pressure Hull Length	328 ft
Pressure Hull Diameter	35 ft
Hullform Depth	37 ft
Design Depth	1,200 ft
Hull Material	HY-80
Shaft Horsepower	48,000 Hp
Payload	26 Mk-54 LWT
	20 CVLWT
	28 UAVs
	8-12 Large Diameter UUVs
16 Large Diameter VL Tubes	up to 64 TLAM or
	up to 64 Mk-48 HWT or
	up to 48 AIM-9X or
	16 Additional UUVs
Escape Capability	8 X 22-Person Escape Capsules
	Motor Room LET
Submerged Speed	29.25 kts
Surfaced Speed	>17 kts
Crew	145
Accomodations	166
Normal Surfaced Draft (Rudder Tip)	30.7 ft
Surfaced Trim	5.0 ft
Surfaced Displacement	8,978 LT
Submerged Displacement	10,637 LT
Envelope Displacement	14,314 LT
Reserve Buoyancy (% of Sub Disp)	15.3 %
Margin Lead	446 LT

Figure 78: PISR General Characteristics

5.2 Study Conclusions and Areas for Further Study

The primary conclusion of this concept design is that in order to place a significant number of weapons external to the hull on the beams of the ship, additional ever buoyant volume is required. This additional volume is required to support the weight of the payload tubes and hatches. In other words, the submarine design which incorporates large numbers of external weapons is weight limited. A second conclusion is that electric propulsion increases the flexibility of the arrangement of the engine room.

Additional areas for study on the PISR concept include:

1. Stern plane sizing
2. Hydrodynamic effect of unique sail shape
3. Incorporation of downward opening hatches on the payload tubes
4. Design of non-pressure hull structure

6.0 References

1. Department of the Navy, Shipboard Habitability Design Criteria Manual (T9640-AB-DDT-010/HAB), 1 December 1995.

2. LaPenna J.J., Surfacing Rescue Container Concept Design for Trident Submarines, MIT Master of Science Thesis, 2009

3. Principles of Naval Architecture, Society of Naval Architects and Marine Engineers, 1967.

4. Introduction to Submarine Design, Revision 4, MIT Class notes, 1997

5. Jackson H.A., Submarine Design Trends, MIT Professional Summer course notes, 1997

APPENDIX A: PISR STUDY GUIDE

Study Guide
for

PERSISTENT INTELLIGENCE, SURVEILLANCE AND RECONAISSANCE (ISR) SUBMARINE

Jon Gibbs, Jerod Ketcham

22 June 2009

PERSISTENT INTELLIGENCE, SURVEILLANCE AND RECONAISSANCE (ISR) SUBMARINE

INTRODUCTION

This document defines the process, studies, inputs and assumptions that will be used in developing a Concept Design for an Analysis of Alternatives (AoA) for the PISR, a submarine capable of performing an extended intelligence, surveillance and reconnaissance mission. Performance, inherent characteristics, capabilities as well as cost and technical risk areas of a baseline persistent ISR submarine will be identified through this process.

GENERAL APPROACH

The initial effort will concentrate on development of a well defined baseline set of weapons that will be consistent across all subsequent design variants. A baseline weapon set will be developed around the requirements in the Initial Capabilities Document (ICD) for the persistent ISR submarine. Using the baseline weapon set, several possible hull configurations and machinery configurations will be developed in order to perform a trade off study and select the optimum hull and machinery configuration to meet mission and cost requirements.

A requirement for machinery configuration is that the submarine have an Integrated Power System (IPS) and use electric motor propulsion. The IPS architecture is required to be common with surface ship variants of IPS in order to increase commonality and reduce total ship ownership costs to the U.S. Navy (USN). Groups from Naval Postgraduate School (NPS) will assist in providing details of weapons systems volume, weight and powering requirements. Surface ship project groups in the naval engineering program at the Massachusetts Institute of Technology (MIT) will define the general architecture of an IPS ship.

Other desirable goals of the persistent ISR submarine project are to:
1) Eliminate the diesel engine
2) Eliminate a standard torpedo room that is inboard to the pressure hull
3) Maximize the use of external weapons

OVERVIEW

The Navy has numerous submarines capable of performing many different missions including ISR. However, persistent ISR is not performed as well as desired. The goal of this study is investigate a submarine which can perform a persistent ISR mission well and examine what, if any, other submarine missions must be eliminated or reduced in order to provide a persistent ISR capability to today’s submarine force.

Additional mission areas that this submarine will perform are:

1. Anti Submarine Warfare (ASW)
2. Anti Surface Warfare (AsuW)
3. Limited Special Operations Forces (SOF)
4. Limited MIW

ASSUMPTIONS

As described in the ICD, the persistent ISR submarine would serve as a submerged persistent ISR platform with the capability of additional missions as mentioned in the Overview section above. Specifically it will:

- Displace less than 15k LT submerged
- Stay on station for 90 days at a time
- Store and retrieve UUVs
- Be manned to a level commensurate with current submarines
- Be capable of hosting (not employing) SOF
- Accommodate multiple manned/unmanned surface and underwater vehicles; launch and recovery
- Have an Extremely Large Reconfigurable wet/dry space (e.g. payload bay) – greater than or equal to D5 tube
- Possess quiet launch capability
- Shoot the following weapons: CVLWT, Mk-54, Tomahawk
- Deploy from CONUS or Hawaii

STUDY PRODUCTS TO BE DEVELOPED

The project's efforts will be documented in a final report that includes the following products:

- Study Guide (this document)
- Initial Capabilities Document
- Electric Load Analysis
- Cost estimate.
- Ship Characteristics Summary Placemat
- Weight estimate
- Manning Analysis and Allocation document

APPROACH

Process

The process to be used in the development of a feasible submarine concept capable of performing a persistent ISR mission is to first establish a baseline set of weapons and sensors that can accomplish the desired missions and then investigate the advantages and disadvantages of installing those weapons in various hull configurations. Each initial variant will possess sufficient detail to support a rough order of magnitude (ROM) acquisition cost estimate. Initial variants will be rated using a matrix and a one of the variants will be selected for further development and refinement. Exceptional efforts will not be made to reduce the crew size, however, the number of crew members will be commensurate with a submarine of the size of the final variant selected. After selection of a final variant for development and refinement, two technical areas of submarine design or construction will be selected for in depth engineering investigation and analysis.

Reviews

In addition to the regularly scheduled briefings to the Design Review Board (DRB), the following reviews and briefings will be held according to the schedule below:

Week of:	Participants:	Topic:
Aug 3	Sponsor	Completion of Concept Exploration
Sep 7	Peers	Peer Review
Sep 21	Sponsor	Completion of Cost-Effectiveness Analysis and Preferred Concept Selection
Jan 18	Peers	Peer Review
Apr 19	Peers	Peer Review
Apr 29	Sponsor	Final Presentation at Ship Design & Technology Symposium

Tools

The following design and analysis tools will be utilized in the performance of the persistent ISR submarine project:

- Spreadsheets for the production of graphs and reports - Microsoft Excel will be used
- Spreadsheets for weight estimation - Microsoft Excel will be used
- CAD for sketches and drawing – Rhino will be used
- Parametric models for concept selection – MIT Math Model and Paramarine will be used
- Hydrodynamic models for powering and resistance – Paramarine and HydroMax will be used
- Structure models for evaluating structural efficiency – Paramarine will be used

Schedule

The study will be a year long submarine concept design project which will be complete on 29APR10.

Study Participation

The study team is composed of representatives from the following organizations:

- MIT 2N Students
- MIT 2N Instructors
- NAVSEA (05U)
- NSWC-CD
- NUWC-NP

SUB-SYSTEM DEVELOPMENT METHODOLOGIES

Computer aided design tools will be used to track variations between variants to permit quantification of differences between submarine variants for use in final variant selection.

Hull Structures - SWBS 100

The structure for this submarine will be very similar to previous classes of submarines with the exception of the non-pressure hull (NPH) structure. It is anticipated the NPH will be used extensively to accommodate the numerous weapons and sensors that will be employed on this submarine.

Propulsion Plant - SWBS 200

The propulsion plant will be integrated with the electric plant into an IPS engine room.

Electric Plant - SWBS 300

The electric plant will be integrated with the propulsion plant on this submarine and form part of the IPS engine room. Elimination of the diesel engine and possibly the battery is a goal of this project.

Command & Control - SWBS 400

C4I systems will likely require augmentation over those used in current USN submarines in order to be able to process the data from the additional and larger sensors that will be installed on this ship.

Auxiliary Systems - SWBS 500

Auxiliary systems will be identical to those on USN submarines with the exception of those necessary to replace the functionality provided by the diesel generator and battery.

Outfit & Furnishings - SWBS 600

Habitability standards for the ships operational crew will be identical to those of current USN submarines.

Armament - SWBS 700

Armament will be installed almost exclusively in the NPH structure. Specific weapon types and number will match the desired mission of the submarine.

TECHNICAL ASSESSMENT

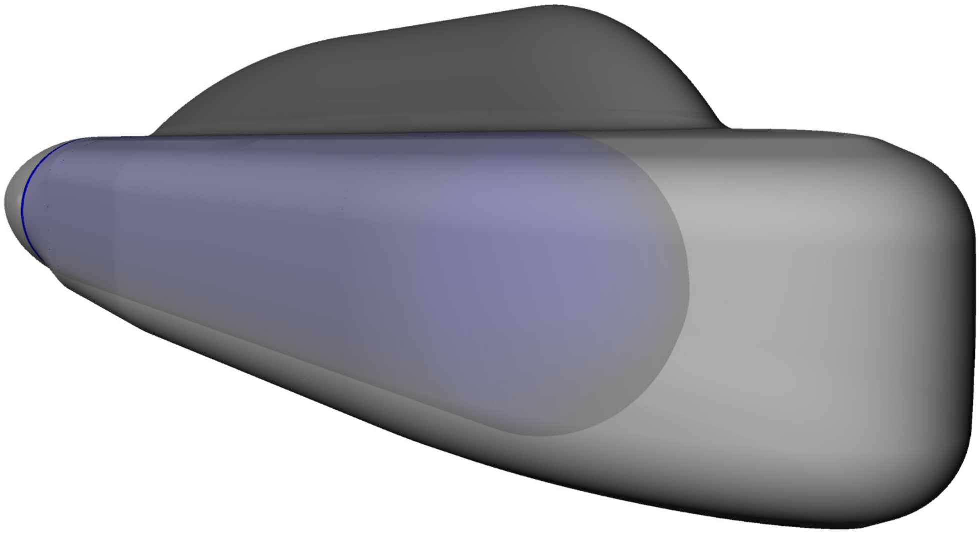
The MIT student team will evaluate the following areas to assure technical feasibility, characterize performance and support cost estimating. In some cases, the evaluations will be qualitative.

- Mission systems performance
- Weight
- Stability
- Area/volume
- Equilibrium Polygon
- Manning
- Electric Loads
- Ship Systems
- Range

Cost Estimation

A cost estimate for the ship will be produced using the MIT 2N, Weight Based Cost Model.

APPENIDX B: INITIAL CAPABILITIES DOCUMENT



INITIAL CAPABILITIES DOCUMENT
FOR
PISR SUBMARINE

Potential ACAT: I

Validation Authority: JROC

Approval Authority: JROC

Milestone Decision Authority: PEO SUBS

Designation: JROC Interest

Prepared for Design Review Board

25 June, 2009

1. Concept of Operations Summary

The PISR Submarine will deploy from current submarine bases in CONUS, Hawaii, or Guam, transit to a mission area, and remain on station for up to 90-120 days of continuous operations. Specifically designed to the ISR mission, she will carry sophisticated sensors and off board vehicles (AUVs/UUVs), to include an extremely large, reconfigurable payload bay. With a flexible payload capability, PISR will support full spectrum dominance of the battle space from surveillance and early-warning through to hostile prosecution ASW, AAW, and ASuW threats.

The enabling capabilities required to achieve the desired operational outcomes include:

a) Extremely high on-station endurance (including AAW self defense) and operational availability
b) High surge to theater capability (from domestic basing)
c) Sophisticated and upgradable sensor suite
d) Large, reconfigurable payload capacity with payload-flexible ship-sea interfaces
e) Precision maneuvering and station keeping (e.g. periscope depth, hovering in support of UUVs)
f) State of the art signature reduction
g) Habitability (specifically: the removal of hot racking on station)

2. Joint Functional Area

The PISR Submarine will provide critical intelligence preparation of the battle space (IPB) capabilities, greatly surpassing those of current fleet assets. Specifically, through the extensive use of off board sensors and vehicles, she will dramatically improve the operational commander's situational awareness. With enhanced endurance and operational availability, PISR will provide increased sensor time on-station before returning to port or resupply.

Development of future sensor platforms and systems in the near term presents many exciting possibilities for the ISR mission. Manned submarine-based systems, however, have significant advantages over other (remote) systems in endurance, flexibility, survivability, and stealth. These factors are critical to the ISR mission and will drive toward nuclear powered submarines.

3. Required Capability

- Displace less than 15k LT submerged
- Stay on station for 90 days at a time
- Store and retrieve UUVs
- Be manned to a level commensurate with current submarines
- Be capable of hosting (not employing) SOF
- Accommodate multiple manned/unmanned surface and underwater vehicles; launch and recovery
- Have an Extremely Large Reconfigurable wet/dry space (e.g. payload bay) – greater than or equal to D5 tube
- Possess quiet launch capability
- Shoot the following weapons: CVLWT, Mk-54, Tomahawk
- Deploy from CONUS or Hawaii

4. Capability Gaps

While modern fleet submarines perform ISR missions routinely, additional modularity and accessibility is required in integrate off board platforms and sensors into the ISR mission. Current submarine assets lack the infrastructure and interfaces to support such integration. While operational endurance of fleet submarines approaches that of PISR, significant degradation of crew performance and morale is experienced on significantly extended operations. PISR will enhance crew habitability and stores capability over current designs to support extended mission time. Additionally, PISR will be less susceptible to Maritime Patrol Aircraft (MPA) through an organic AAW capacity. This will increase the platform's survivability and ability to stay on station despite harassment from the enemy.

5. Threat and Operational Environment

The PISR Submarine will operate both in littoral and deep ocean environments. While she will be capable of ASW and ASUW mission areas, she is expected to rely primarily on stealth for survivability. Armed with Mk-54 torpedoes and CVLWT, PISR will be able to engage surface and submarine targets under deliberate prosecutions, as well as maintain adequate self-defense capability. Additionally, PISR will be designed with AAW capability to further enhance staying power in air-threat environments, such as operations in the littorals.

6. <u>Functional Solution Analysis Summary</u>
    a) Doctrine, Organization, Training, Materiel, Leader Development, Personnel and Facilities (DOTMLPF) Analysis: ISR missions may be performed by non-submarine assets, but are more susceptible to enemy detection and are less able to operate in hostile threat environments than submarine assets.

    b) Ideas for material approaches
        (1) Conversion and upgrading of existing fleet submarines: This alternative would likely prove extremely costly when considering the service life already expended on the platform and the limited number of conversion changes possible. Back fitting of sensors and off-hull platform interfaces would not represent the type of specialization of the PISR capability requirements.
        (2) Modified-Repeat build of *Virginia Class* submarine: While some flexibility is lost over a clean-sheet design, substantial cost savings may be realized through reduced design costs and built-in commonality with existing fleet assets. It is unlikely, however, that even with extensive design changes a modified *Virginia* cannot present the greatly enhanced capabilities described above for the ISR mission.
        (3) Perform a clean sheet design for a new PISR submarine: This material solution offers the greatest flexibility in producing a solution tailored to the capability requirements but carries with it the greatest potential cost and technical risk, especially considering all of the new technologies and architectures expected to become part of the PISR design.

7. Final Recommendations

Going forward, the PISR Submarine project should examine the feasibility of a clean-sheet design of a submarine platform. This will most effectively provide the fleet with the enhanced ISR mission capabilities identified in this document.

APPENIDX C: PISR Placemat

Naval Construction
and Engineering
(Course 2N)

PISR SSN Design Characteristics

2.705 2009-2010
LCDR Jerod Ketcham
LT Jonathan Gibbs
Updated: 30 MAR 2010

DIMENSIONS

Length, Overall:	428 ft	130.45 m
Max Beam:	50 ft	15.24 m
Hullform Depth:	37 ft	11.28 m
Pressure Hull Length:	328 ft	99.97 m
Pressure Hull Beam:	35 ft	10.67 m
Normal Surfaced Draft:	30.7 ft	9.36 m
Surfaced Trim:	5.0 ft	1.52 m

PERFORMANCE

Submerged Speed:	29+ knots
Surfaced Speed:	>17 knots
Service Life:	33 Years

ACCOMMODATIONS

Off	CPO	Flex	OEP	Tot	Margin
14	13	24	114	165	20

Habitability: per OPNAV INST 9640.1A
- 62-Seat Mess Deck
- 13-Seat Wardroom
- Crew's Study and Lounge
- 3 Enlisted Heads

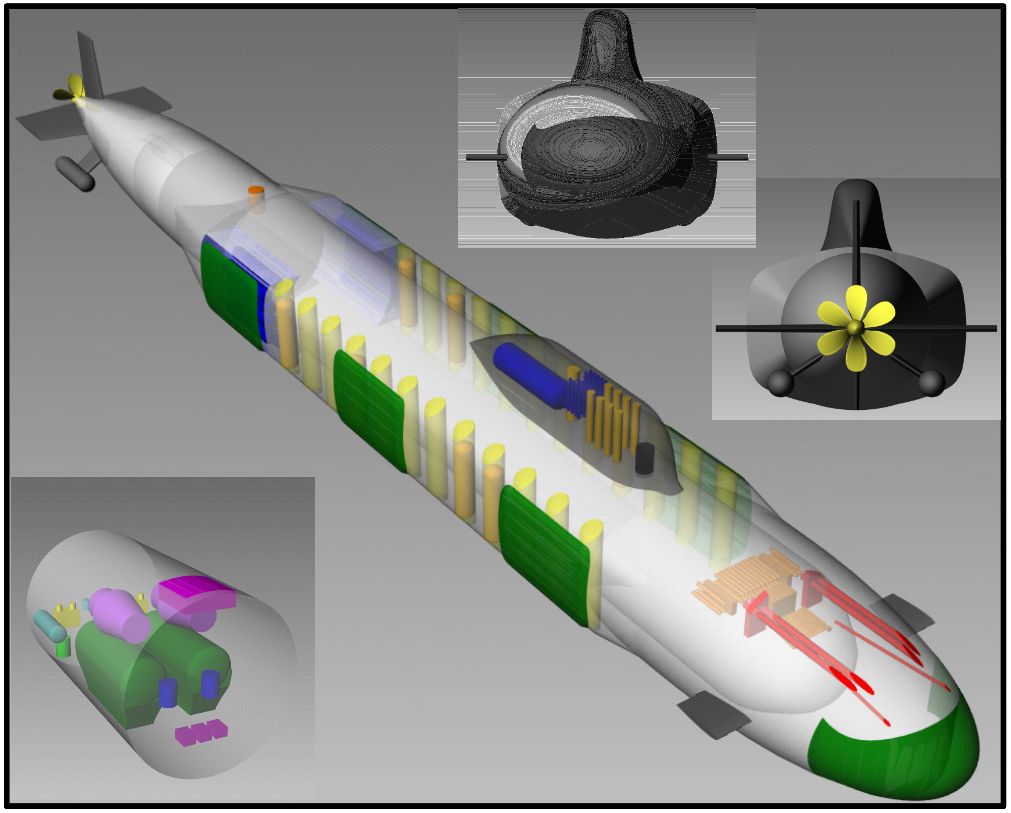
MACHINERY SYSTEMS

Nuclear Reactors:	1
Steam Turbines:	2
25 MW Turbine Generators:	2
36.5 MW / 48,000 hp Permanent Magnet Motor:	1
1 MW Emergency Diesel Generator:	1

IPS Architecture with
1000 VDC Service Busses
and Main Storage Battery

AUXILLIARY SYSTEMS

2 1000-ton AC Units
3 Hydraulic Plants
2 Trim Pumps
2 R/O Units (12,000 gpd)



PRIMARY COMBAT SYSTEMS

Bow Array: 786 ft^2 / 73.0 m^2; 32 ft / 9.75 m Beam
Thin Line Towed Array
Fat Line Towed Array
Wide Aperture Array 5,754 ft^2 / 534.6 m^2; 77.3 ft / 23.6 m Spacing (Center to Center)
12 4-ft Diameter UUVs (or 8 6-ft Diameter UUVs)
28 10-in Diameter x 7.8 ft long UAVs

SECONDARY COMBAT SYSTEMS

26 Mk-54 Light Weight Torpedoes
20 Common Very Ligtht Weight Torpedoes
16 65"-Diameter x 22.5' Long Payload Tubes
- Up to 64 TLAM
- Up to 48 AIM-9X Subsurface-to-Air Mis.
- Up to 20 Mk-48 ADCAP (Drop Out)

WEIGHTS

(By SWBS Group)

100	3,365 LT	3,419 MT
200 & 300	1,729 LT	1,757 MT
400	224 LT	228 MT
500	653 LT	663 MT
600	400 LT	406 MT
700	907 LT	922 MT
A-1	7,278 LT	7,395 MT
Lead	911 LT	926 MT
A-1 + Lead	8,189 LT	8,320 MT
VL	789 LT	802 MT
NSC	8,978 LT	9,122 MT
MBT	1,659 LT	1,686 MT
Sub Disp	10,637 LT	10,808 MT
FF	3,689 LT	3,748 MT
Env Disp	14,326 LT	14,556 MT

Service Life Allowance Margin Lead	446 LT / 453 MT (6.1% of A-1)

STABILITY

Submerged BG	1 ft / 0.30 m

SURVIVABILITY AND HULL

Design Depth:	1,200 ft
Material	HY-80
Reserve Buoyancy	15.3% of Sub Disp
Escape	8 22-Person Escape Capsules; Motor Room LET

PROVISIONS in days

Ship	135 days
Repair Parts	135 days

WEIGHT BASED COST ESTIMATE

$2.78 B (yr-2005)

Table 34: PISR Concept Design Summary Placemat

APPENIDX D: Weight and Volume Analyses

PISR Weight Report

		WT (LT)	LCG (ft from FP)	VCG (ft from HCP)
100	HULL SHELL	1350	180.00	1.19
101	HULL FRAMING	690	180.00	0.59
103	PLATFORMS	164	160.00	-2.62
111	SUPERSTRUCTURE	24	129.00	23.76
112	PROPULSION FOUNDATIONS	301	280.00	-6.50
113	AUX AND OTHER EQPT FOUNDATIONS	151	170.00	-9.50
114	BULKHEADS	192	205.00	0.00
115	TRUNKS AND ENCLOSURES	305	205.00	14.00
119	STRUCTURAL CASTINGS AND FORGINGS	23	265.00	-12.00
121	BALLAST AND BOUYANCY UNITS	12	170.00	-15.00
123	DOORS HATCHES NON BALLAST	22	195.00	13.00
127	SONAR DOME	12	13.00	0.00
128	MASTS-RADIO, RADAR, SUB ID	8	140.00	23.08
150	WELDING	42	205.00	0.47
152	STEEL TOLERANCES	69	205.00	0.47
		WT (LT)	LCG (from FP)	VCG (from HCP)
200	STORAGE BATTERY	60	140.00	-13.00
201	PROPULSION UNITS / MOTOR DRIVES	203	310.00	-4.00
202	MAIN CONDENSORS AND AIR EJECTORS	83	245.00	-3.00
203	MAIN SHAFTING, BEARINGS AND PROPELLER	65	330.00	0.00
206	PROPULSION CONTROL EQUIPMENT	3	315.00	11.00
207	MAIN STEAM SYSTEM	19	250.00	-7.00
208	FEED AND CONDENSATE SYSTEM	40	250.00	-9.00
209	SEAWATER AND FRESHWATER COOLING ER	83	260.00	-6.00
211	PROPULSION L.O./PURIF FILL AND TRANSFER	26	305.00	-8.00
212	STEAM GENERATING	110	210.00	3.00
213	REACTOR	120	209.00	-5.00
214	REACTOR COOLANT SYSTEM	90	209.00	2.00
215	REACTOR PLANT MECHANICAL SYSTEMS	60	215.00	0.00
216	REACTOR PLANT AUX SYSTEMS	23	220.00	0.00
217	REACTOR I & C	25	235.00	7.00
218	PRIMARY SHIELD	90	209.00	-3.00
219	SECONDARY SHIELD	201	215.00	1.00
250	PROPULSION REPAIR PARTS	16	250.00	2.00
251	PROPULSION OPER FLUIDS	65	240.00	-2.00
		WT (LT)	LCG (from FP)	VCG (from HCP)
300	SSTG / TGLO / SSMG / EDG	190	265.00	4.00
301	POWER DIST SWBDS	51	305.00	-2.00
302	POWER DIST SYSTEM	90	200.00	-3.00
303	LIGHTING	10	215.00	0.00
350	ELECTRIC PLANT REPAIR PARTS	3	255.00	-3.00
351	ELECTRIC GEN FLUIDS	3	265.00	-5.00
		WT (LT)	LCG (from FP)	VCG (from HCP)
400	NAVIGATION LIGHTS/WHISTLE/I.C.	7	135.00	0.46
401	INTERIOR COMMUNICATIONS	14	135.00	0.46
404	ELEX COUNTERMEASURE SYSTEM	2	135.00	0.46
407	TORPEDO FIRE CONTROL SYSTEM	9	135.00	0.46
408	RADAR SYSTEM	1	135.00	0.46
409	RADIO SYSTEMS AND TEST EQPT	5	135.00	0.46
410	ELECTRONIC NAVIGATION SYS	0	135.00	0.46
412	SONAR SYSTEM	56	135.00	0.46
413	ELEC TACTICAL DATA SYS	4	135.00	0.46
450	C&C REPAIR PARTS	14	135.00	0.46
451	C&C OPERATING FLUIDS	112	135.00	0.46
		WT (LT)	LCG (from FP)	VCG (from HCP)
501	VENTILATION & ATMOSPHERE CONTROL	62	200.00	1.19
502	AIR CONDITIONING/ CHILL WATER SYSTEM	64	200.00	1.19
503	REFRIGERATION PLANT/SPACES	5	200.00	1.19
505	PLUMBING	3	200.00	1.19
507	FIRE EXTINGUISHING	1	200.00	1.19
508	MAIN & AUX DRAIN/SANITARY SYSTEM	53	200.00	1.19
509	POTABLE WATER SYSTEM	2	200.00	1.19
511	FUEL/DIESEL OIL FILL & XFER	1	200.00	1.19
513	SHIPS SERVICE AIR SYSTEMS	138	200.00	1.19
514	STEAM AND ER GRAVITY DRAINS/GLAND SEAL	24	200.00	1.19
515	BUOYANCY CONTROL SYSTEM	4	200.00	1.19
516	SS HYD/EXT HYD/SHAFT SEAL/EAFW	117	200.00	1.19
517	DISTILLING PLANT	13	200.00	1.19
518	STEERING AND DIVING HYDRAULICS	32	200.00	1.19
519	RUDDER	34	200.00	1.19
520	ANCHOR, CHAIN, DECK MCHRY	10	200.00	1.19
522	RETRACTABLE PLANE OPERATING GEAR	2	200.00	1.19
527	DIVING PLANES & STAB FINS	44	200.00	1.19
550	AUX SYS REPAIR PARTS	7	200.00	1.19
551	AUX SYS OPER FLUIDS/AIR IN BANKS	37	200.00	1.19
		WT (LT)	LCG (from FP)	VCG (from HCP)
600	HULL FITTINGS*	18	190.00	0.46
603	LADDERS AND GRATING*	4	190.00	0.46
604	NON-STRUCTURAL BLKHDS*	76	190.00	0.46
605	PAINTING PLAQUES & LABEL PLATES*	39	190.00	0.46
606	DECK COVERING*	7	190.00	0.46
607	HULL INSULATION*	125	190.00	0.46
608	STOREROOMS / LOCKERS*	65	190.00	0.46
609	EQUIP FOR UTIL SPACES*	2	190.00	0.46
610	EQUIP FOR WORKSHOPS*	6	190.00	0.46
611	EQUIP FOR GALLEY/SCULLERY/PANTRY*	12	190.00	0.46
612	FURNISHINGS FOR LIVING SPACES*	19	190.00	0.46
613	FURNISHINGS FOR OFFICES ELECT AND RDR*	5	190.00	0.46
614	FURNISHINGS MEDICAL SPACES*	3	190.00	0.46
650	OUTFIT AND FURNISHINGS REPAIR PARTS*	19	190.00	0.46
		WT (LT)	LCG (from FP)	VCG (from HCP)
700	GUN MOUNTS AND LAUNCH SYSTEMS*	749	155.00	2.50
701	AMMUNITION HANDLING SYSTEM*	55	60.00	8.00
702	AMMUNITION STOWAGE*	20	60.00	8.00
750	AMMUNITION REPAIR PARTS*	8	163.40	2.50
751	AMMUNITION OPERATING FLUIDS*	75	163.40	2.50

* Based on SSN-637 Class Weight Breakdown

Table 35: PISR Weight Report (3 Digit SWBS)

Ballast Tank Sizing									
			Design	Final BT (Total)			Final BT Weight (Excluding EB Volumes, 2% Slack)		
	V_{BT}	V_{OB}	V_{Total}	V_{Total}	LCG (ft from FP)	VCG (ft from HCL)	WBT (LT)	LCG (ft from FP)	VCG (ft from HCL)
MBT 1	11676.65 ft^3	1355.40 ft^3	13032.05 ft^3	13270.47 ft^3	20.40	0.00	325.43	19.68	-0.13
MBT 2	11676.65 ft^3	1809.54 ft^3	13486.18 ft^3	14836.01 ft^3	35.61	0.00	325.43	35.89	-0.30
MBT 3	11676.65 ft^3	2561.62 ft^3	14238.27 ft^3	13119.89 ft^3	55.42	0.00	325.43	55.29	-0.31
MBT 4	11676.65 ft^3	1255.67 ft^3	12932.31 ft^3	12069.65 ft^3	359.68	0.00	325.43	359.17	-0.33
MBT 5	11676.65 ft^3	1725.67 ft^3	13402.31 ft^3	14867.43 ft^3	385.88	0.00	325.43	386.97	0.26
				68163.45 ft^3	171.40	0.00	1627.14	171.40	-0.16

Table 36: Ballast Tank Volumes

Outboard Volume Analysis			
Sail	**Volume**	**LCB**	**VCB**
Mast Enclosures	471.06 ft^3	117.39	24.81
UUV Tube	1133.92 ft^3	145.55	22.10
Bridge Trunk	104.56 ft^3	101.40	21.03
AAV Tubes	118.62 ft^3	124.10	27.40
Sonar Dome	**Volume**	**LCB**	**VCB**
	2877.10 ft^3	8.93	0.00
MBTs	**Volume**	**LCB**	**VCB**
Anchor	200.00 ft^3	380.00	-12.00
TAHS	105.00 ft^3	375.00	6.00
EMBT Air Banks / Piping	4152.08 ft^3	165.24	0.00
HP Service Air Banks / Piping	2076.04 ft^3	57.00	0.00
Oxygen Banks	452.52 ft^3	109.10	0.00
MBT Vents/Oper	75.00 ft^3	167.20	15.63
Torpedo Tubes	173.11 ft^3	36.07	12.99
Bow Plane Cavities	219.15 ft^3	43.82	0.00
SPM	250.00 ft^3	380.00	-8.00
LP Blow Piping	300.00 ft^3	166.90	15.57
HP Blow Piping	300.00 ft^3	166.90	15.57
Shafting	125.00 ft^3	391.30	0.00
Aft Control Surface Handling	300.00 ft^3	385.62	0.00
PMB	**Volume**	**LCB**	**VCB**
Escape Capsule Access Tunnels	363.91 ft^3	172.21	11.44
Payload and Escape Tubes	12931.24 ft^3	165.51	0.00
Total	26728.31 ft^3	143.35	2.07

Table 37: Outboard Volume Analysis

Free Flood Volumes			
Free Flood Item	Volume	LCG (ft aft of FP)	VCG (ft Above PH Midplane)
MSW	40.00 ft^3	275.00	-10.00
DEASW	10.00 ft^3	180.00	-10.00
Mud Tank	906.73 ft^3	415.19	0.00
Sail	8794.38 ft^3	124.88	25.01
PMB	101604.27 ft^3	172.86	0.00
Bat Cave	16528.33 ft^3	260.50	0.00
Misc Sea Chests	10.00 ft^3	240.00	-15.00
MBT Bottoms	32.5427 ft^3	171.40	-17.00
	127926.26 ft^3	182.64	1.71

Table 38: Free Flood Volume Analysis