Comparative Naval Architecture Analysis of Diesel Submarines

by

Kai Oscar Torkelson

M.S., Mechanical Engineering Virginia Tech, 1998
B.S., Mechanical Engineering Virginia Military Institute, 1991

Submitted to the Department of Ocean Engineering in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Naval Architecture and Marine Engineering

and

Master of Science in Ocean Systems Management

at the
Massachusetts Institute of Technology
June 2005

Signature of Author ....
Department of Naval Architecture and Marine Engineering
May 6, 2005

Certified by ....
David S. Herbein
Professor of Naval Architecture and Marine Engineering
Thesis Supervisor

Certified by ....
Henry S. Marcus
Professor of Ocean Engineering
Thesis Supervisor

Accepted by ....
Michael S. Triantafyllou
Chairman, Department Committee for Graduate Students
Professor of Ocean Engineering

Comparative Naval Architecture Analysis of Diesel Submarines

by

Kai O. Torkelson

Submitted to the Department of Ocean Engineering in Partial Fulfillment of the Requirements for the Degrees of Master of Science in Naval Architecture and Marine Engineering and Master of Science in Ocean Systems Management

Abstract

Many comparative naval architecture analyses of surface ships have been performed, but few published comparative analyses of submarines exist. Of the several design concept papers, reports and studies that have been written on submarines, no exclusively diesel submarine comparative naval architecture analyses have been published. One possible reason for few submarine studies may be the lack of complete and accurate information regarding the naval architecture of foreign diesel submarines. However, with some fundamental submarine design principles, drawings of inboard profiles and plan views, and key assumptions to develop empirical equations, a process can be developed by which to estimate the submarine naval architectural characteristics. A comparative naval architecture analysis creates an opportunity to identify new technologies, review the architectural characteristics best suited for submarine missions and to possibly build more effective submarines. An accurate observation is that submarines designed for different missions possess different capabilities. But are these unique capabilities due to differences in submarine naval architecture? Can mission, cost, or other factors affect the architecture? This study examines and compares the naval architecture of selected diesel submarines from data found in open literature. The goal is to determine weight group estimates and analyze whether these estimates provide a relevant comparison of diesel submarine naval architecture.

Thesis Supervisor: Professor David S. Herbein
Title: Professor of Naval Construction and Engineering

Thesis Supervisor: Professor Henry S. Marcus
Title: Professor of Ocean Engineering

Acknowledgements

"I can answer for but three things: a firm belief in the justice of our cause, close attention in the prosecution of it, and the strictest integrity." - George Washington

“Better to dare Mighty Things and fail, than to live in a gray twilight where there is neither victory nor defeat.” - Theodore Roosevelt

“Be an opener of doors for such as come after thee.” - Ralph Waldo Emerson

The work of a thesis brings together the efforts of so many people besides the author. I am therefore thankful to the many individuals from several organizations that provided invaluable background, technical assistance, and contributed time and support to this endeavor. I would like to acknowledge the contributions and advice from these people with sincere appreciation.

On the technical and writing side of the thesis, I recognize those that have had a direct contribution to the work. Rear Admiral Paul E. Sullivan, NAVSEA Deputy Commander for Integrated Warfare Systems (SEA-05), served as the thesis sponsor and provided the initial topic for the study, as well as making his staff available for data and reviews. My advisors, CAPT David S. Herbein and Professor Hank Marcus, were of great assistance in regular meetings to discuss the scope, direction and expected outcomes of the study. I also gratefully acknowledge the assistance of Electric Boat Corporation of General Dynamics in supplying photographs and drawings of many of the submarines studied. The willingly offered help of Mr. Carl Fast was especially appreciated.

On the support side, I recognize those that provided me with encouragement, prayers and growth. My family and friends are too numerous to list here, so I will mention a few representative of the rest. I give the most thanks to my mom, who’s had the added responsibility of filling in for my dad’s support since his death, but she has always been there to give this support. The many friends I have come to know through St Paul Lutheran Church, the Lutheran Episcopal Ministry at MIT, the brothers of SSJE, the monastery in Harvard Square, Big Brothers of Mass Bay, the cabin ‘up north’, and the opportunities in the area and elsewhere they provided, were all supportive in my time away from the books. To the many athletes who helped add competition to workouts including running, swimming, cycling and hiking, I thank you for pushing me to relieve stress through my favorite sports.

Last but not least of all, I want to pay tribute to the American taxpayers for ultimately providing the funding, and to the US Navy, the Submarine and the Engineering Duty Officer communities, where I was able to achieve the breadth of experience necessary to perform a study of this kind. I also owe a debt of gratitude to MIT for providing the very favorable environment most conducive to this endeavor. I hope that this study will contribute to the Navy’s pursuit of advanced submarine designs and assessment of foreign submarine capabilities.

I dedicate this work to my parents: Leif O. Torkelson, M.D. and Betty K. Torkelson

Table of Contents

List of Figures

List of Tables

1 Introduction

Several design concept papers, books and studies have been written on submarines but no exclusively diesel submarine comparative naval architecture analyses have been published. A comparative naval architecture analysis creates an opportunity to identify new technologies, review the architectural characteristics best suited for submarine missions and to possibly build more effective submarines. This study focuses on diesel submarine naval architecture from the end of the nineteenth century to present day. Over that time period, several significant technologies have vastly improved the capability of submarines. From the first combination of gasoline engines and energy-storing batteries in the *USS Holland*, to the development of the true diesel submarines of the first half of the twentieth century, to the advent of nuclear propulsion and its adaptation to the submarine in the 1950s, and recently to Air Independent Propulsion (AIP) systems, submarines have advanced to highly complex, systems-intense machines.

The urgency of submarine development, as with other military systems, was driven by the World Wars and Cold War, demanding improvements in acoustics, weaponry, safety, automation and submerged endurance. In the years leading up to and during World War II, over 1000 undersea boats and diesel submarines were built by Germany alone (1). During periods of WWII, Germany was producing over 35 diesel submarines per month. In fact, the total number of world submarines constructed during WWII, not including Japan, was well over 2500 (2). Although the focus was on rapid development and construction during WWI and WWII, submarine designs improved, especially in weapons and communications systems. With the advent of the Cold War and the need for longer submerged endurance, the focus shifted to nuclear submarines, causing an explosion in submarine production over the next 30 years. From 1955 to 1989 the Soviet Union and United States alone built over 350 nuclear submarines (3). From a high Cold War world count of 400 nuclear submarines in 1989, there are only approximately 160 today, as nuclear submarine production has experienced a significant slowdown worldwide (3). Building of nuclear submarines is limited to the United States, Russia, England, France, India and China. In the US, the production rate of nuclear submarines is only projected to be one per year over the next ten years.

While the nuclear submarine production rate has decreased recently, diesel submarine production rate today is growing. There are about 400 diesel submarines in the world today. Builders of diesel submarines include Sweden, Germany, Spain, Netherlands, France, Italy, Russia, China, Japan, and Australia. The world diesel submarine production rate is predicted to reach eight per year between 2004 and 2023 (4), which would increase the world diesel submarine count above 500 in the next twenty years. Additionally these predicted diesels possess advanced technology as evidenced by the spread of diesel electric with AIP systems. With such systems, diesel submarines may be suitable for more than coastal defense type missions and operate in more blue-water type scenarios.

Diesel submarine architecture seems quite similar at first glance from country to country and mission to mission. The basic submarine shape includes ellipsoidal or parabolic end caps, is either a hull of revolution or contains a parallel midbody in the center, and has various appendages attached along the body. Generally, diesel submarine designs tend to be of the single hull version, with a singular pressure hull over most of the midbody length and outer hulls at the ends used to create the ballast tanks and provide a hydrodynamic fairing for any other gear attached to the outside of the pressure hull. But, are there differences in the naval architecture of diesel submarines? Can distinct differences be noted, even when comparing two similar ships? Capability differences exist, such as propulsion, acoustic performance, and weapons systems. Do these capability differences affect the naval architect's approach to submarine design? What new construction techniques have been used worldwide? What shipyards have been most effective/efficient in submarine design and construction? How have submarine construction methods changed due to new shipyard methods or technology?

This study attempts to answer the questions posed above. The information researched and gathered was all collected from open literature and therefore is not technical source data from countries or manufacturers. Due to this open literature approach, much of the work was done by estimating volumes from drawings, pictures, similar submarine data bases, and from previous work in references (5), (6) and (10). One distinct difference from previous submarine comparative studies, as will be seen in chapter 3, is that standard Expanded Ship Work Breakdown Structure (ESWBS) weight groups are determined for each submarine included in the study and will be used throughout this report. These weight groups are defined as follows:

Group 100	Hull Structure
Group 200	Propulsion Machinery
Group 300	Electric Plant
Group 400	Command and Surveillance
Group 500	Auxiliaries
Group 600	Outfit and Furnishings
Group 700	Weapons Systems

Furthermore, a method is proposed to calculate these weight groups for any submarine, based on drawings, historical design databases and equations included in the appendices.

1.1 Purpose of the Study

The purpose of this study is twofold. First, it attempts to determine if diesel submarine architecture varies from country to country. Do factors such as mission, cost, or tradition affect submarine naval architecture? An in depth comparison is performed of six diesel submarine designs from four different countries to measure and compare any differences that may exist in their naval architecture. The outcome of these comparisons will also provide some tools to current and future submarine designers, possibly to better assess the attributes of a particular design.

Secondly, and perhaps more importantly for the author, a significant benefit in taking on such a study is to gain a better understanding of submarine design and construction. In order to determine if the submarine naval architecture differs from class to class and/or country to country, one must be familiar with the submarine design process and terminology. This understanding of submarine design will also provide possible advantages or spawn novel concepts by future designers.

1.2 Problem

Submarine design is a complex engineering systems process. To start with a blank sheet of paper and produce volumes and weights required for submarine design is a monumental task. Similarly, to determine the basic weight groups that make up a completed submarine is no easy task. Design in general begins with definition of requirements and progresses to performance characteristics, to concept studies, to feasibility studies, and finally to achieving the final level of detail for structure, arrangement, hydrodynamics, systems and hydrostatics (5). The goal of the designer is to accurately estimate weight groups, so that a satisfactory weight/buoyancy balance is attained. This study shares the goal of estimating submarine weight groups but differs from initial design by starting with the finished product and working "backwards" to accurately estimate the naval architectural characteristics that the submarine designer used to create the initial design.

1.3 Background

Previous work was completed in this particular area by John K. Stenard, *Comparative Naval Architecture of Modern Foreign Submarines*, in May 1988 (10). That study included a comparative design review of conventional and nuclear-powered fast attack submarines. Stenard's significant contribution was the initial parameterization of diesel submarine data and the development of equations to determine volume estimates for various submarines. As mentioned this study differs from the previous work by actually calculating the standard weight groups of diesel submarines, based both on hand-measured values from published drawings and relationships developed with the assistance of several references as described in subsequent chapters.

1.4 General Approach/Methodology

An open literature search was accomplished to find sufficient characteristics on a selected number of submarines to provide a useful comparison. Submarine weight groups were determined using measured volumes, developed equations, reference equations from previous work, known submarine databases, and estimates to "reverse engineer" the design characteristics of the submarine being studied. The weight group and naval architectural results of the selected submarines were then compared and analyzed.

1.5 Criteria for Success

Two areas to measure success: 1) Is the reverse engineering method valid? Does it produce accurate results?

2) Does the data produced allow for a relevant comparison of naval architecture of the various platforms?

2 Submarine Design Process

2.1 Design History

Before proceeding to the analysis of comparative naval architecture, this chapter is devoted to explaining the submarine concept design process. H.A. Jackson, R. Burcher and L. Rydill, E.S. Arentzen and P. Mandel have written very comprehensive and technical descriptions about submarine design history and methods. Rather than attempt to cover submarine design to an equivalent level of detail, this chapter focuses on some key aspects of the design process, that, once understood, will assist in the reverse engineering methodology of the study found in subsequent chapters.

History is rich with attempts to design and build successful submarines; several such designs were David Bushnell's *Turtle* in 1775, Robert Fulton's *Nautilus* in 1800 and John Holland's *Holland VI* in 1899. The *Holland VI*, built and tested in 1899 by the US Navy, foreshadowed several significant design features like low length/diameter ratio, axisymmetric circular form, single screw propeller and a small superstructure. These features have proven effective in achieving near optimum configuration of a submarine (5). In all of these early trials, the designers returned to the drawing boards many times to modify and improve their designs, a practice still present today in the iterative methods to develop a reasonable design that meets the design requirements.

2.2 Submarine Design

The most accurate one word description of submarine design is "iterative". Starting with a definition of requirements, the designer creates a concept "cartoon" (a broad-brush description of a possible design), proposes a set of estimates, works through many calculations by computer or by hand in feasibility studies, and derives an answer which often does not match the initial concept cartoon (6). The designer must then go back with new, more-accurate assumptions, and rework the calculations. The new answer should be close but may require further iterations. The process described can be summarized by the design spiral, often used in US Navy ship designs, shown in Appendix A.

Due to the complexities of submarine design, a database of volume and weight characteristics of previous designs is often used to obtain initial estimates. These estimates are applied to the designer's initial submarine "cartoon". Using math models to parameterize the design, feasibility studies are then performed to check the results against the owner's requirements and mission areas. Next the process is iterated until the design balances, i.e. where the buoyancy created by volume supports the weight of the submarine, and meets the owner's requirements. Finally the selected feasibility study is developed to sufficient detail for production drawings to be produced (5). Along with the design spiral, a flow chart shown in Appendix B is used to visually illustrate a conventional diesel (SS) submarine design process.

2.3 Design Weight to Space Relationship

H.A. Jackson stated in a submarine design paper, "The volume of the hull of the submarine is fixed by the weight of the submarine. If more volume is mandatory, it can only be provided by making the submarine larger, but this will increase the amount of lead to be carried and reduce the speed if the same power is provided. If the power is increased in order to meet the speed requirements, the submarine will grow even larger. The skill and experience of the designer is put to a crucial test in making a satisfactory design." (6) This statement is representative of the interrelated character of submarine design where changes to one parameter cause others to be adjusted and attempting to hold fixed any group of parameters is most difficult.

But there are fixed external limits to the size of the submarine. For instance, submarines have practical limits regarding diameter. Even when on the surface, as much as 90 percent of the submarine hull could be below the water surface. When considering a submarine diameter of 30 feet, the maximum draft could be 27 feet, significantly more than most surface ships. Although this draft would not present a problem in the open ocean, the submarine draft may be too deep for many ports and harbors, as well as impact coastal operations. Therefore the designer is limited to some practical limit of diameter, depending on the port of operation and the desired submarine missions. This maximum hull diameter in turn limits internal volume of the submarine.

Because of the limits on maximum diameter, the resulting limited hull volume of a submarine, and the required strength of the hull to withstand submergence pressures at deep depths, a significant amount of the designer's time and effort is devoted to the weight and space relationship. Unlike surface ship designs, in which the total enclosed volume is greater than the displacement, submarine designs start as "volume limited". This terminology of volume limited is common in ship design and simply means that the designer must creatively assess how to fit all of the structural and payload requirements into the volume of the hull. Design books may also use the term "space driven". For now, consider the hull volume as the limiting feature of design but as will be pointed out later, this limitation may change over the course of the design process.

Hull volume determines several significant properties of a vessel. The volume of the hull submerged compared to the total hull volume determines a vessel's reserve buoyancy (RB), which is the amount of excess buoyancy available in the event of an emergency or casualty which allows the sea to enter a portion of the submerged volume. A surface vessel has an RB due to the freeboard of the main hull and any superstructure which is watertight. The total volume of the vessel is larger than the volume underwater, i.e., the volume of water displaced. A submarine that is completely submerged does not have a freeboard and therefore does not have excess RB. The ratio of displaced volume to total volume can be used to develop some characteristic properties of ships shown in the following ratio (5):

$$\text{Ratio of the volume of displacement to the total volume} = \frac{1}{1+RB} \tag{1}$$

Because the buoyancy of volume displaced must equal the weight of the vessel by Archimedes' law,

$$\frac{1}{1+RB} = \text{Specific gravity of the vessel relative to sea water,} \tag{2}$$

which provides a measure of the overall density of the vessel. Table 1 shows typical values of specific gravity for surface ships and submarines.

Table 1: Specific Gravity Typical Values

Ship	**Specific Gravity,** $\frac{1}{1+RB}$	**Percentage of total volume above waterline**
Frigate	0.3	70
Aircraft Carrier	0.2	80
Bulk Carriers/Tankers	0.8	20
Surfaced Submarine	0.9	10
Submerged Submarine	1.0	0

From Table 1, the submerged submarine is therefore the densest of all marine vehicles. Another useful comparison is the weight to space relationship for typical diesel submarines, shown in Table 2 developed from reference (5).

Table 2: Weight/Space Relationship of Typical Diesel Submarines

Component	Weight Percentage	Space Percentage	Density Relative to Seawater (unity)
Payload	9	28	< 1
Structure	43	*	>> 1
Main and Auxiliary Machinery	35	56	< 1
Accommodation and Outfit	4	11	< 1
Stores	1	5	< 1
Permanent Ballast	8	*	> 1

* Structure and ballast take up relatively very little space

Table 2 may be used as a guide to densities by considering for each item the ratio of its weight percentage to its space percentage as shown in the far right column. If this result is unity, the item would be as dense as seawater, while the lower the ratio, the less dense the item (5). As can be seen in Table 2, the high overall submarine density is not due to payload or cargo but rather due to structure and the fact that in most cases the submarine needs to have a heavy pressure hull structure to enable it to achieve owner-specified depth requirements.

As a result of the high density of submarine structures, the design may evolve into one limited by weight rather than volume. The reason for transition from volume to weight limited is because once the volume is set, according to the space required to enclose all of the requirements, this volume must be able to support the weight of the submarine. In other words, Archimedes' principle of buoyancy matching weight must be met. If excess weight is present, buoyancy must be increased by expanding the volume, which in turn, causes weight to increase. As can be imagined, this process of increasing weight and expanding volume may soon exceed the size restrictions of the design. Unlike a surface ship, where a higher than estimated weight only results in a deeper draft, the lack of RB in a submarine requires the designer to increase size, as mentioned above, or reduce the amount of permanent ballast, which could result in a reduction of hydrostatic stability (5). In addition, the potential volume expansion has the effect of creating an upheaval in internal compartment arrangements and an impact on many other aspects of design including structure, maneuvering and control, and propulsion. Thus the criticality in submarine design of achieving accurate weight assessment cannot be overstated.

2.4 Weight Estimates and Weight Groups

As seen in the section above, weight assessment is a tedious but critical portion of submarine design. Without the use of weight data tables from previous designs, the work involved in weight assessment would increase significantly. The goal of the weight estimating process is developing design values for the weight groups of the submarine.

Parametric relations have been developed from previous submarine designs and are very useful in developing the initial weight group values. These initial values can be adjusted for the new requirements in refining the weight groups to a specific design. Once the revised weight estimate is complete and the ship balances, i.e., the buoyancy supports the weight and the ship balances longitudinally and transversely, the rest of the design process (per Appendix B flowchart) can proceed.

2.5 Design Summary

This chapter has given a brief introduction to submarine design and will be referred to in subsequent chapters as the dissection of submarine designs is carried out. The overall submarine concept design is a complex systems engineering process which utilizes many design tools to solve. Recall the starting point involved weight tables from previous designs, parametric relations to calculate new values, and a concept "cartoon". There are many requirements that may affect the volume and arrangement of the designer's concept submarine. Some of these requirements are speed, crew size, endurance (both submerged and surfaced), number of torpedo tubes, number of weapon stowage positions, cost constraints, diving depth, special features such as lockout trunks or special warfare interfaces, and acoustic performance or quieting. Additionally, the owner may place special emphasis on one specific design factor, such as the acoustic performance over the other requirements.

The product of the concept design should provide initial weights, initial volumes, initial hull shape, and a balanced ship. The concept design will then be analyzed under feasibility studies, model testing and finally be refined to give sufficient detail for production drawings (5).

3 Development of Procedure

3.1 Approach

The MathCAD computerized submarine synthesis tool entitled "MIT Math Model" was used initially to gain understanding of the submarine design process (11). This math model was developed at MIT, based on the submarine design process described in chapter 2 and draws heavily on notes from CAPT Harry Jackson's MIT Professional Summer Course "Submarine Design Trends" (9). The use of computerized mathematical software with adequate mathematical solving capability allows the designer to proceed quickly and efficiently through the complex design process.

For the study of existing submarines, the MIT math model was modified, incorporating several of the parametric equations from reference (9), to determine standard weight groups starting from open literature submarine drawings. As stated in section 1.2, the method used in this comparative naval architecture analysis of existing submarines starts at the opposite end of the design spiral from that of traditional submarine design. In other words, traditional submarine design begins with design requirements and ends with a finished submarine; this study starts with the finished submarine, measures the major areas and volumes, estimates the standard weight groups and draws conclusions from those naval architectural characteristics.

3.2 Procedure Description

The evaluation procedure consists of working backwards through submarine concept design and reverse engineering diesel submarine weight groups and naval architecture from the open literature, available drawings, and photographs. The author's goal was to develop a procedure to determine submarine characteristics that allow reasonable estimates to be made of submarine weight groups from the open literature information. Two approaches were utilized in order to draw accuracy comparisons from the set of results: 1) Dimensions were obtained from inboard profile and plan drawings that were then used to calculate volumes based on geometric equations; and, 2) Parametric equations were developed from historical designs and other references which were then used to calculate volumes and weight groups.

3.2.1 Submarines Selected for Analysis

This study compares diesel to diesel submarines, all of axisymmetric shape and single pressure hull design. A brief description is given below for each submarine studied, with a full description including pictures and drawings in Appendix D.

SS 580 USS Barbel

Surface Displacement:	2146 Ltons
Submerged Displacement:	2639 Ltons
Length:	67 m
Diameter:	8.8 m
Complement:	77 (8 officers)

Electrical Generator Capacity:	1700 KW
Propulsion Motor Power:	4800 SHP
Maximum Surfaced Speed:	14 Kts
Maximum Submerged Speed:	18 Kts
Diving Depth:	213 m

Overall Endurance Range:	14,000 Nm
Deployment Endurance:	90 Days
Torpedo Tubes:	6
Torpedo Capacity:	18
Builder:	Portsmouth Naval Shipyard
Year:	1959
Other:	Decommissioned 1989

AGSS 569 USS Albacore

Surface Displacement:	1692 Ltons
Submerged Displacement:	1908 Ltons
Length:	63 m
Diameter:	8.4 m
Complement:	52 (5 officers)
Electrical Generator Capacity:	1634 KW
Propulsion Motor Power:	7500 SHP
Maximum Surfaced Speed:	25 Kts
Maximum Submerged Speed:	33 Kts
Diving Depth:	183 m
Overall Endurance Range:	10,000 Nm
Deployment Endurance:	50 Days
Torpedo Tubes:	0
Torpedo Capacity:	0
Builder:	Portsmouth Naval Shipyard
Year:	1953
Other:	Experimental submarine; Decommissioned 1972

Type 209/1200

Surface Displacement:	1100 Ltons
Submerged Displacement:	1285 Ltons
Length:	56 m
Diameter:	6.2 m
Complement:	33 (6 officers)
Electrical Generator Capacity:	2800 KW
Propulsion Motor Power:	4600 SHP
Maximum Surfaced Speed:	11 Kts
Maximum Submerged Speed:	22 Kts
Diving Depth:	250 m
Overall Endurance Range:	7,500 Nm
Deployment Endurance:	50 Days
Torpedo Tubes:	8
Torpedo Capacity:	14
Builder:	Howaldtswerke-Deutsche Werft GmbH (HDW)
Year:	1993
Number of ships:	9 (one built at HDW, remaining in South Korea)
Other:	Possible AIP Backfit

Collins 471

Surface Displacement:	3050 Ltons
Submerged Displacement:	3350 Ltons
Length:	78 m
Diameter:	7.8 m
Complement:	42 (6 officers)
Electrical Generator Capacity:	4420 KW
Propulsion Motor Power:	7344 SHP
Maximum Surfaced Speed:	10 Kts
Maximum Submerged Speed:	20 Kts
Diving Depth:	300 m
Overall Endurance Range:	11,500 Nm
Deployment Endurance:	70 Days
Torpedo Tubes:	6
Torpedo Capacity:	22
Builder:	Australian Submarine Corp, Adelaide
Year:	1996
Number of ships:	6
Other:	Kockums' Design

Type 212A

Surface Displacement:	1450 Ltons
Submerged Displacement:	1830 Ltons
Length:	56 m
Diameter:	7 m
Complement:	27 (8 officers)
Electrical Generator Capacity:	3120 KW
Propulsion Motor Power:	3875 SHP
Maximum Surfaced Speed:	12 Kts
Maximum Submerged Speed:	20 Kts
Diving Depth:	350 m
Overall Endurance Range:	8,000 Nm
Deployment Endurance:	60 Days
Torpedo Tubes:	6
Torpedo Capacity:	12
Builder:	Howaldtswerke-Deutsche Werft GmbH (HDW)
Year:	2004
Number of ships:	4
Other:	Siemens PEM 306 KW Fuel Cell

IZAR S80/ P650

Surface Displacement:	1744 Ltons
Submerged Displacement:	1922 Ltons
Length:	67 m
Diameter:	6.6 m
Complement:	40 (8 officers)
Electrical Generator Capacity:	2805 KW
Propulsion Motor Power:	4694 SHP
Maximum Surfaced Speed:	12 Kts
Maximum Submerged Speed:	20 Kts
Diving Depth:	350 m
Overall Endurance Range:	7,500 Nm
Deployment Endurance:	70 Days
Torpedo Tubes:	6
Torpedo Capacity:	18
Builder:	IZAR, Cartegena Spain
Year:	2007
Number of ships:	4 (plus 4 as an option)
Other:	MESMA AIP 600kW Fuel Cell

3.2.2 Math Model Development

Characteristics

Several data files were created in Excel to provide the necessary submarine characteristics to MathCAD. An open literature search was performed to gather sufficient data on selected submarines to input into the Excel files. Submarine characteristics such as normal surfaced condition (NSC), submerged displacement (Δ_{sub}), length overall (LOA) and diameter (D) were read into MathCAD using an Excel read file function of MathCAD. Then each characteristic was assigned a descriptive variable name within the math model, such as NSC(i) where the 'i' identifies the specific submarine. These variables were then used in a simple iteration loop within MathCAD to calculate the results described below for each submarine. The MathCAD model file is included in Appendix C.

Volume Calculations

Inherent relationships exist between the volume and the weight of an ocean vessel. Archimedes showed that in order for a body to be neutrally buoyant, the weight of the volume of water displaced must equal the weight of the body. A goal of the submarine designer is to design the submarine to be neutrally buoyant when submerged. Therefore, by measuring volumes of a submarine, the weight of the vessel and that of the individual weight groups can be calculated. The procedure of volume measurements and subsequent weight estimation is the basis from which the final weight groups are derived. But first, the volumes of each major weight division are needed.

As stated, the study was limited to information available in open literature drawings, published submarine characteristics, and photographs. This limitation ensured the report would remain unclassified and provided some useful parametric equations which may be used in future diesel submarine analyses. The goal of the literature search was to obtain detailed inboard profile and internal deck plan view drawings. However, locating detailed scaled drawings in the open literature was not always possible, so a range of published drawings was used (as shown in Appendix D). Information sources ranged from historical records maintained in the MIT Naval Construction and Engineering library to internet websites to foreign shipbuilding company presentations on submarine designs. Scales of drawings were not available. Basic characteristics such as LOA and D are available in a variety of resources, and from these published dimensions along with the drawing measurements, a scale was determined from which to calculate the full size dimensions.

Areas of the major submarine spaces were then calculated and entered into MathCAD, where deck height, a hull curvature factor and passageway factor were applied to calculate the space volume. The hull curvature and passageway factors were obtained from parametric diesel electric submarine data of reference (11). All diesel submarines included for analysis contained only two compartments: 1) Engineroom (ER); and, 2) Operations (OPS). The overall method for calculating volume is summarized in the following steps:

- Measure the deck area for the following spaces
    - Command, Control, Communications, and Intelligence Functions
    - Propulsion Machinery and Battery Spaces
    - Motor Generators and Electrical Switchboards
    - Auxiliary Machinery Spaces
    - Berthing and Messing Spaces
    - Storerooms
    - Offices, Lockers, Laundry and Activity Spaces

- Armament/Weapons Spaces
- Tanks

- Multiply deck area by deck height
- Apply factors for hull curvature and passageway from reference (9)

The following calculation provides an example of the basic procedure for a major space.

$A_{wep}(0) = 77.331\_m^2$

$H_{Dwep}(0) = 3.934\_m$

$f_{Curve} \equiv 1.12$

$f_{Pway} \equiv 1.08$

$V_{wep}(i) := H_{Dwep}(i) \cdot f_{Pway} \cdot f_{Curve} \cdot A_{wep}(i)$

$V_{wep}(0) = 367.973\_m^3$

Some compartments and spaces were not clearly shown in open-literature drawings. For example, variable ballast tank measurements were not included in the drawings used. Where accurate measurements, or even estimated measurements, could not be obtained, parametric equations relying on historical databases and those developed by Jackson in reference (9) were used. Several of the parametric equations base the volume calculation on percentages of total pressure hull (PH) volume, which required an accurate estimate of the pressure hull volume (V_{PH}). This volume was calculated using offsets of a body of revolution, as presented in Submarine Concept Design (7). These calculations are shown in the MathCAD model printout of Appendix C. The method used to determine each major compartment area and volume is described in the next section.

3.2.2.1 Major Compartment and Space Calculations

Engineroom

Propulsion machinery, motor generators, aft battery (except *Barbel* and *Albacore*), and electrical switchboard areas were summed to obtain total ER area, which was then used as in the example above to calculate ER volume. Although most diesel submarines have both forward and aft batteries, the location of these batteries may not be divided between the forward (OPS) and aft (ER) compartments. In older diesel submarines such as *Barbel* and *Albacore*, both forward and aft batteries are contained in the OPS compartment. More recent foreign diesel submarines locate the aft battery in the ER and the forward battery in the OPS compartment. Therefore the ER volume equations differ for older US and foreign modern diesel submarines.

OPS Compartment

OPS Compartment area was calculated by adding the deck areas for Command and Control, Auxiliaries, Berthing and Messing, Storerooms, Forward Battery (and aft battery for *Barbel* and *Albacore*), Weapons and Other Spaces (offices, lounges, etc.). This area was converted to a volume as in the example above and designated as OPS volume *measured* (V_{opsm}). Then from the V_{PH} calculation, equations (3) and (4) from reference (9) were used to find auxiliary tank and variable load volumes, which were then added to the V_{opsm} above to yield the total V_{ops}, as in equation (5).

$$V_{aux}(i) = 0.041 \cdot V_{PH}(i) + .529m^3 \cdot N_T(i) \tag{3}$$

$$N_T(i) = \text{Complement}$$

$$V_{VB}(i) = 0.064\, V_{PH}(i) \tag{4}$$

$$V_{ops}(i) = V_{opsm}(i) + V_{aux}(i) + V_{VB}(i) \tag{5}$$

Outboard Volume and Sonar Array

All items outboard of the pressure hull but within the outer shell, such as air flasks, access trunks and fuel tank structure that displace water are considered outboard volume (V_{ob}). Due to the difficulty of measuring such items, generally absent from open literature drawings, their volume is estimated as a percentage of pressure hull volume, based on reference (9). Where major items such as bow sonar arrays are shown and have measurable dimensions, their volume is calculated. For all submarines studied, the bow sonar array was cylindrical, so calculating sonar array volume (V_{sa}) was accomplished using the equation for a cylinder.

Sonar Dome Water

The water in the space around the sonar array would typically be given in new designs and may be easily estimated for sonar *spheres* based on historical data. To estimate the *cylindrical* sonar array space water volume, measurements were taken of the submarines studied and a factor of multiplication was determined for the array space volume. The general conclusion was that sonar space water for a cylindrical array was significantly less than for a spherical array and in fact some sonar spaces may actually be free flood areas. To be consistent, the submarines in the study were assumed to contain a certain volume of dome water (V_d) surrounding the sonar array which was not counted as free flood.

Everbuoyant Volume

The everbuoyant volume (V_{eb}) is comprised of the pressure hull, the outboard items and sonar systems. Summing the volumes and multiplying by sea water density provides the everbuoyant displacement (Δ_{eb}).

$$V_{eb} = V_{PH} + V_{ob} + V_{sa} + V_d \qquad (6)$$

$$\Delta_{ebr} = V_{eb} \cdot \rho_{SW} \tag{7}$$

In a balanced ship, Δ_{eb} is equal to NSC. These two values are compared as a check of model validation and can be viewed in Appendix C.

Main Ballast Tank (MBT) Volume

The difference in Δ_{sub} and NSC is equal to the MBT displacement. Multiplying by the factor 35 ft^3/lton yields the MBT volume. Another method used in submarine design to estimate MBT volume is to multiply the NSC by the reserve buoyancy (RB), which is specified in the owner's requirements. Because the RB was not available in the open literature, MBT volume was calculated from the given NSC and Δ_{sub}.

Submerged Volume

Submerged displacement (Δ_{sub}) is a given characteristic in open literature sources. Assuming the source to be accurate allows a validity check of the calculations and measurements used to this point by using the fact that Δ_{sub} is equal to the sum of Δ_{eb} and MBT displacement.

$$\Delta_{sub} = \Delta_{eb} + MBT \tag{8}$$

Free Flood (ff)

As the name implies, free flood volume encompasses all those areas that are open to the ingress and egress of water within the outer shell of a submarine. Areas such as the sail, superstructure, "mud tank" (area surrounding the shaft exit from the hull), appendages, and torpedo tube shutter doors, among a few others, make up the free flood volume. A value of four to seven percent of the envelope volume for single hull submarines is given to calculate free flood volume in reference (9). Seven percent was used for this study because it produced the minimum error when cross checks were done.

Envelope Displacement

The entire volume enclosed by the outer shell of the submarine is called the envelope. Therefore, envelope displacement is the sum of submerged and free flood displacement. Using the estimate from above that free flood is seven percent of Δ_{env}, the following relationships can be expressed:

$$\Delta_{env} = \Delta_{sub} + \Delta_{ff} \tag{9}$$

$$\Delta_{ff} = 0.07 * \Delta_{env} \tag{10}$$

$$\text{Therefore, } \Delta_{env} = \Delta_{sub} + 0.07 * \Delta_{env} \tag{11}$$

$$\text{and } \Delta_{env} = \Delta_{sub}/0.93 \tag{12}$$

Envelope displacement is the final displacement value not including the sail and appendages such as rudder and control planes. Estimating volumes of such appendages is tedious and their contribution to the overall displacement is generally quite small. During initial design, these values may or may not be included, as long as the convention is consistent throughout the hull design (9). Therefore, appendage volumes were not included in this study. After obtaining required volumes and displacements, the next step is calculating the submarine weight groups.

3.2.2.2 Area and Volume Calculation Error Checks

For comparison purposes, parametric equations from reference (9) were used to calculate certain areas, as would be done in initial design. These areas were then compared to the measured areas for a check of parametric equations. For individual spaces, the majority of parametric area and volume equation results did not match the measured areas and volumes with any consistent level of error.

However the difference between whole-boat volumes of parametric results and the calculated volumes based on measured whole-boat dimensions were all within twenty percent. This difference in the individual volumes but not the overall sum indicates a possible difference in designations of certain spaces, inconsistencies in area measurements from inaccurate drawings or a combination of these. Rather than attempt to revise the detailed measurements or modify the parametric equations, the results were left as calculated, accepting a threshold error of twenty percent with a goal of ten percent comparison errors. Section V of the math model in Appendix C contains a summary of calculation error checks.

3.2.3 Weight Group Calculations

Weight Definitions

Standard weight groups were presented in section 1. The standard weight groups summed together account for a weight condition called A-1:

Group 100	Hull Structure
Group 200	Propulsion Machinery
Group 300	Electric Plant
Group 400	Command and Surveillance
Group 500	Auxiliaries
Group 600	Outfit and Furnishings
Group 700	Weapons Systems
Total	Condition A-1

Table 3 provides a summary of the weight breakdown of submarines and what each group is dependent upon.

Table 3: Submarine Weight Breakdown and Estimating

Group Number	Name	Function of
1	Hull Structure	NSC
2	Propulsion Machinery	SHP & Battery Volume
3	Electric Plant	KW
4	Command and Surveillance	NSC
5	Auxiliaries	NSC
6	Outfit and Furnishings	NSC
7	Weapons Systems	V_{wep}
A-1	Σ (1-7)	Weight Groups
Lead	Ballast	A-1
A	Σ (A-1 + Lead)	
VL	Variable Load	NSC
NSC	Σ (A + VL)	
MBT	Main Ballast Tanks	
Δ_{sub}	Σ (MBT + NSC)	
FF	Free Flood	
Δ_{env}	Σ (Δ_{sub} + FF)	

Adding the lead ballast to condition A-1 results in condition A (also known as the standard displacement of the Washington Treaty) (6). To condition A is added the variable load (VL), which is the combination of all the weights that can change from day to day plus the variable ballast required for the submarine to remain in equilibrium, and this sum of condition A and VL is the NSC.

In order to submerge, weight must be added to the submarine, which is done by filling large MBTs external to the pressure hull with water from sea. The result of NSC and MBT weight as shown in section 3.2.2 above is the submerged displacement (Δ_{sub}). Then adding the FF to Δ_{sub} yields the Δ_{env}, as shown in Table 3.

Weight Estimation

As stated, the overall goal of this study is to compare the naval architecture of selected submarines. The weight groups can be considered the basic building blocks of submarine architecture. Therefore developing accurate estimates of weight groups is the primary goal of the math model. Of course the most accurate method would be to add the known individual weights of all material and equipment (i.e., frames, steel plates, cabinets, etc.) that made up each group. However, even in initial concept design, the material and equipment weights must be estimated and such weights are definitely not listed in the open literature of diesel submarines. A much more detailed time consuming search could be performed, gathering information from vendors, shipping companies and experts in the submarine design field, but the lack of complete and accurate weight information in open literature sources would still require making some estimates. Model validation with acceptable error levels is explained in section 3.4.

This study includes a hybrid method of estimating weights. The first step is taking measurements of areas and computing volumes of the major compartment groups. Then these volumes are used in parametric equations developed from a combination of references (6) and (9) along with historical databases. The actual weight group breakdown was known for at least one submarine included in the study, the USS *Barbel*. Using the known values for *Barbel*, the parametric relationships were checked for validity and in some cases parametric equations from reference (6) for nuclear submarines were adjusted for use with diesel submarines.

Parametric Weight Estimates

Group 1 Hull Structure

Reference (6) contains a parametric relationship based on NSC and hull material. Whereas many of the reference (6) relationships are based on nuclear submarine databases, group 1 (GR 1) weight is less dependent on type of propulsion system and more dependent on diving depth, NSC and hull material. Using Figure 1 from reference (6), a factor of GR 1 to NSC weight is determined and equation (13) is used to estimate GR 1 weight.

$$W_{1est} = W_{1frac} \cdot NSC \tag{13}$$

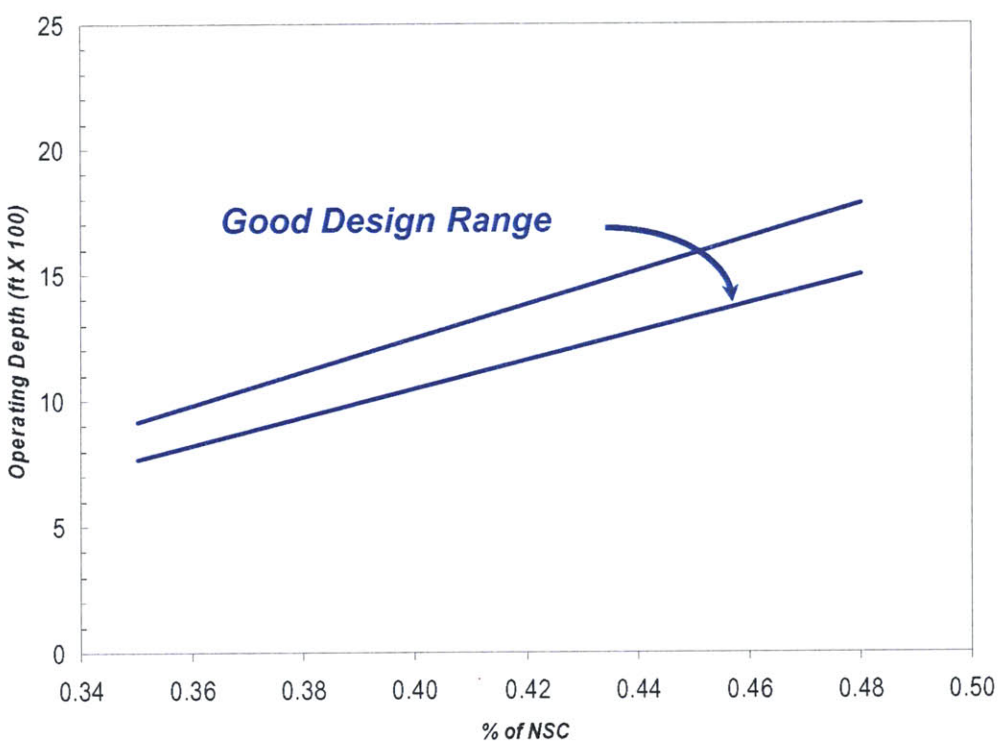


Figure 1: Group 1 Weight vs. Operating Depth

Group 2 Propulsion Machinery and Group 3 Electric Plant

As shown in Table 3, Weight Groups 2 and 3 are functions of SHP and KW, respectively. In a diesel submarine, both weight groups 2 and 3 are also functions of battery volume. However, to avoid double counting the battery volume, it was only included in the GR 2 parametric relationship. Although both *Barbel* and *Albacore* designs are over 50 years old, the study assumes that power densities have not changed significantly because diesel engines and lead acid batteries are still in use. If future submarines use new types of engines or new batteries, a different parametric equation would have to be developed.

To determine GR 2 alone, a parametric equation was developed from the known propulsion weights of *Barbel* and *Albacore*. Battery volumes were measured from drawings and equation (14) was developed:

$$W_{2est} = 1.759\frac{lton}{m^3}\cdot V_{Bat} + 0.005\frac{lton}{hp}\cdot SHP \qquad (14)$$

$$V_{Bat} = Battery\_Volume$$

To determine GR 3, equation (15), a factor was again determined from *Barbel* known weight groups and electric plant generating capacity in KW.

$$W_{3est} = K3\cdot KW_i \qquad (15)$$

$$K3 = 0.0126\frac{lton}{kW}$$

$$KW_i = KW\_installed$$

Group 4 Command and Surveillance

The estimation of GR 4 weight is complicated; technology of the equipment that makes up the group is rapidly changing and the magnitude of the group strongly depends on the submarine's mission (9). Mission components that make up the group weight include navigation, sonar, fire control and radar systems. To initially calculate this weight group, the volume of command and control (including all navigation, sonar, fire control and radar areas) was converted to displacement in Ltons and then compared to NSC. Results are shown below in Table 4.

Table 4: Group 4 Weight (from measured volume) as Percentage of NSC

	SS 580	AGSS 569	209	471	212A	P 650
GR 4 as W_{cc}/NSC	6.3%	8.2%	6.2%	6.8%	8.7%	9.2%
GR 4 Weight (Ltons)	134.7	138.8	67.8	207.0	125.9	161.0

The percentages of GR 4 to NSC and the GR 4 weights in Table 4 are higher than expected. The GR 4 weight from Table 4 is greater than 30 percent higher than the published GR 4 weight for *Barbel* of 48.8 Ltons. This error may be due to inaccurate drawings or counting all of the arrangeable volume in addition to that taken up by equipment. In order to obtain GR 4 weights more consistent with expected GR 4 weights, the general formula for GR 4 weight estimate from reference (9) of 4.2 percent of NSC, equation (16) was used for all submarines studied.

$$W_{4est} = NSC \cdot 0.042 \qquad (16)$$

Group 5 Auxiliaries and Group 6 Outfit and Furnishings

Similar to GR 4, the weights of groups 5 and 6 are proportional to the total weight of the submarine (9). As noted with the initial attempt to calculate GR 4 weight from volume measurements, GR 5 and 6 weights calculated from volume measurements were unexpectedly high. Therefore another method had to be used. In new submarine designs, a database of historical percentages for GR 5 and 6 is used to obtain the approximate percentage of NSC. Because a database of recent diesel submarines was not available, a database of US diesel submarines was used. Table 5 contains GR 5 and 6 weights as a percentage of NSC for four

US diesel submarines. The average percentages are used in equations (17) and (18) as an initial estimate of GR 5 and 6 weights for the submarines studied.

$$W_{5est} = W_{5frac} \cdot NSC \tag{17}$$

$$W_{6est} = W_{6frac} \cdot NSC \tag{18}$$

Table 5: Group 5 & 6 Weight Summary as Percentage of NSC

	Submarine				
Group	A	B	C	D	AVG
5	5.66%	8.72%	9.12%	7.20%	7.67%
6	3.52%	2.99%	3.21%	4.13%	3.46%

Group 7 Weapons Systems

Weapons systems weight depends on the volume of the weapons spaces, the number of torpedo tubes and handling systems. The following parametric equation (19) was modified from reference (10):

$$W_{7est} = \frac{0.0021\text{ton}}{\text{ft}^3} \cdot V_{wep} + TT \cdot 6 \tag{19}$$

TT = Torpedo_tubes

Lead and Variable Load (VL)

Lead is used as permanent ballast in diesel submarines. For a diesel of axisymmetric form and single hull configuration, eight percent of standard displacement (condition A) is generally allocated to permanent ballast (5). Therefore lead ballast will make up 8.7 percent of condition A-1 as shown below.

A-1 + Pb = A (20)

Pb = 0.08*A

A = 12.5*Pb (21)

Substituting (21) into (20) yields: Pb = 0.087*A-1

VL includes fluid and gas stowage (auxiliary loads), storerooms, personnel, weapons and variable ballast (9). It can be calculated as a percentage of NSC. To determine the fraction for this study, the percentages of NSC were calculated for auxiliary loads and variable ballast volumes. Storerooms, personnel and weapons were included in these percentages and not identified individually. For all submarines studied, average percentages of NSC for auxiliary loads and variable ballast were five and six percent, respectively. Therefore, adding these averages yielded eleven percent of NSC for VL estimates.

$W_{VLfrac} = 0.11$

$$W_{VL}(i) = W_{VLfrac} \cdot NSC(i) \qquad (22)$$

Finally, knowing the weight group, lead and VL estimates allows the NSC and Δ_{sub} to be calculated and compared to published values of NSC and Δ_{sub}. The analysis process is described in the next sections.

3.3 Overall Analysis Process

From the six selected submarines presented in section 3.2.1, the published dimensions are shown again in Table 6 below.

Table 6: Published Dimensions of Selected Submarines

Class		Barbel SS580	Albacore AGSS 569	Type 209 / 1200	Collins' 471	Type 212A	IZAR S80/P650
Displacement Ltons	**Surf**	2145.7	1692	1100	3050	1450	1744
	Subm	2639.2	1908	1285	3350	1830	1922
LOA m		66.8	62.6	56	77.8	56	67
Diameter m		8.8	8.4	6.2	7.8	7	6.6

Manual measurements were taken from the open literature drawings. Then using these dimensions along with published properties such as surfaced and submerged displacement, the calculations in section 3.2 above were completed. The MathCAD model results were output to tables where the results could be easily compared. The calculated characteristics and comparisons will be discussed in chapter 4.

3.4 Validation of Model Outputs

Two methods were used to validate the results of the method used to derive naval architecture characteristics in this study. First, if the actual weight group values are known for a particular submarine, the calculated weight groups can be compared directly to the known values. The actual weight groups are known for the *Barbel* and the *Albacore*, so their model weight group estimates and published weight group values are compared directly to obtain a measure of accuracy.

For cases where the actual weight groups are not known, a measure of accuracy can still be performed by comparing the model results of NSC and Δ_{sub} with the published values of NSC and Δ_{sub}. Additionally, model results of A-1 and envelope displacement can be compared with derived values of A-1 and envelope displacement. The envelope displacement accuracy check is shown below. Equation (23) relies only on LOA, D, and a shape factor K1, which is described following the equation.

$$\Delta_{env} = \frac{\pi \cdot D^3}{140} \cdot \frac{lton}{ft^3} \cdot \left(\frac{LOA}{D} - K1 \right) \qquad (23)$$

η_f = Entrance_factor $\qquad$ C_{pf} = forward_prismatic_coefficient

η_a = Run_factor $\qquad$ C_{pa} = after_prismatic_coefficient

$$K1 = 6 - 2.4C_{pf} - 3.6C_{pa} \quad (24)$$

$K1 = shape\_coefficient$

C_{pf} and C_{pa} are calculated from the hull offsets, determined by the published LOA, D and measured length forward and aft. Therefore the only unknowns in equation (23) are the shape factors of the ends, η_f and η_a, the entrance and the run, respectively. A fairly accurate estimate may be made of η_f and η_a from Figure 18 in Appendix E (9). The envelope displacement from equation (23) is then compared to that calculated in section 3.2 from area measurements.

The cross checking of model output as a measure of accuracy is shown in Table 7. The goal was to obtain differences within ten percent, with a threshold of fifteen percent. Refined measurements could be made to further reduce the error but the accuracies attained are considered sufficient for the comparative study to follow.

Table 7: Model Results Measure of Accuracy

		SUBMARINES					
Parameter		**SS 580**	**AGSS 59**	**209**	**471**	**212A**	**P 650**
A-1	Model	1664	1403	896	2351	1198	1316
Parametric A-1	Derived	1757	1385	901	2497	1187	1428
	Error	**-6%**	**1%**	**0%**	**-6%**	**1%**	**-8%**
Surfaced Displ	**Published**	2146	1692	1100	3050	1450	1744
Surfaced Displ	Model	1961	1686	1084	3145	1457	1570
	Error	**9%**	**0%**	**1%**	**-3%**	**0%**	**10%**
Submerged Displ	**Published**	2639	1908	1285	3350	1830	1922
Submerged Displ	Model	2461	1868	1394	3409	1731	1916
	Error	**7%**	**2%**	**-9%**	**-2%**	**5%**	**0%**
Env Displ (assumed 7% FF)	Derived	2838	2052	1382	3602	1968	2067
Env Displ (parametric eqn)	Model	2778	2248	1375	3154	1699	1861
	Error	**2%**	**-10%**	**0%**	**12%**	**14%**	**10%**

4 Comparative Naval Architecture

Data results are first compared on the basis of individual weight groups. Then the effects of differences in naval architecture are analyzed for factors of mission and cost in section 4.3.

4.1 Data Presentation

From the calculations of chapter 3, the math model output is presented in Table 8.

Table 8: Math Model Submarine Characteristics Output

Weight Breakdown	SUBMARINES					
(Ltons unless noted)	SS 580	AGSS 569	209	471	212A	P 650
GR 1	826.1	651.4	423.5	1174.3	558.3	671.4
GR 2	426.0	471.5	212.5	600.7	328.1	279.2
GR 3	21.4	20.6	35.3	55.7	39.3	35.3
GR 4	90.1	71.1	46.2	128.1	60.9	73.2
GR 5	164.6	129.8	84.4	244.0	111.2	133.8
GR 6	74.2	58.5	38.1	91.5	50.2	60.3
GR 7	62.0	0.0	56.3	56.8	50.4	63.0
A-1	1664.4	1402.9	896.2	2351.1	1198.3	1316.4
Parametric A-1	1756.8	1385.4	900.6	2497.2	1187.2	1427.9
Var Load	236.0	186.1	121.0	335.5	159.5	191.8
RB (%)	25%	13%	15%	10%	28%	10%
Surfaced Displ	**1960.8**	**1685.7**	**1084.1**	**3145.4**	**1456.6**	**1569.7**
MBT Displ	499.9	182.5	310.2	264.0	274.7	346.7
MBT Vol (m^3)	489.1	214.1	183.4	297.3	376.6	176.4
Vol PH (m^3)	1742.4	1457.4	1059.7	2477.5	1179.5	1518.1
V_{eb} (m^3)	1962.1	1646.9	1205.5	3098.9	1348.0	1732.6
Submerged Displ	**2460.7**	**1868.2**	**1394.3**	**3409.4**	**1731.3**	**1916.4**
Free Flood	185.2	140.6	104.9	256.6	130.3	144.2
Env Displ	2645.9	2008.8	1499.2	3666.0	1861.6	2060.7
Env Displ (parametric eqn)	2777.9	2247.7	1375.2	3153.8	1698.6	1860.9

The output in Table 8 is difficult to compare without normalizing or relating each individual weight as a percentage of an overall weight. Therefore a closer examination is made of the weight groups as a percentage of A-1. Table 9 and Figure 2 show the results for the submarines studied.

Table 9: Weight Groups as Percentage of A-1

	SUBMARINES					
Weight Breakdown	SS 580	AGSS 569	209	471	212A	P 650
GR 1	49.6%	46.4%	47.3%	49.9%	46.6%	51.0%
GR 2	25.6%	33.6%	23.7%	25.6%	27.4%	21.2%
GR 3	1.3%	1.5%	3.9%	2.4%	3.3%	2.7%
GR 4	5.4%	5.1%	5.2%	5.4%	5.1%	5.6%
GR 5	9.9%	9.3%	9.4%	10.4%	9.3%	10.2%
GR 6	4.5%	4.2%	4.2%	3.9%	4.2%	4.6%
GR 7	3.7%	0.0%	6.3%	2.4%	4.2%	4.8%
A-1	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

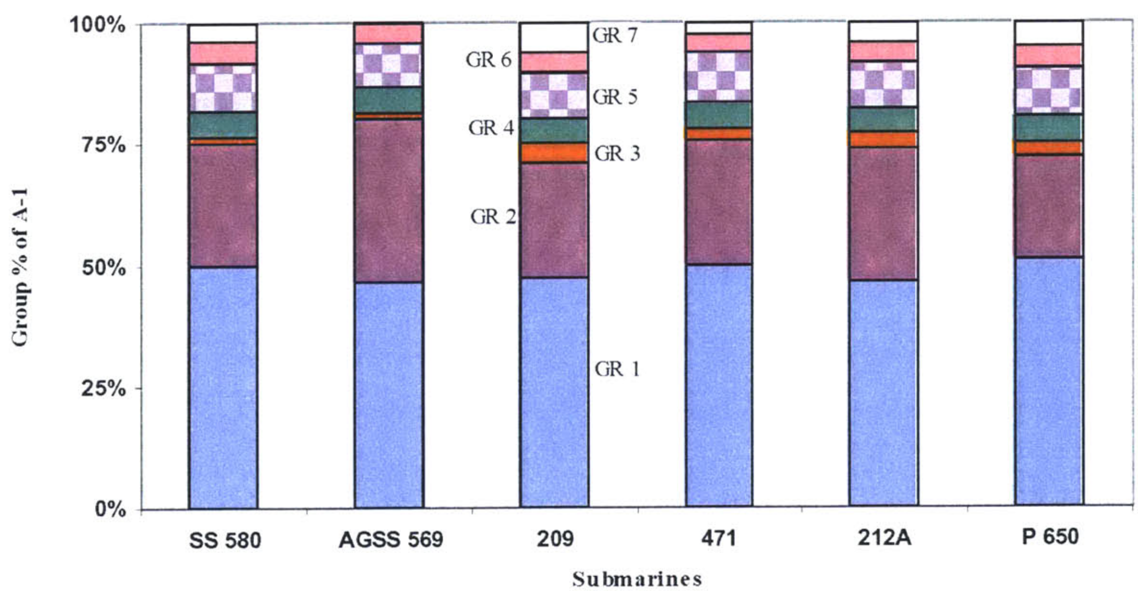


Figure 2: Weight Summary as Percentage of A-1

The mean and standard deviation of the weight group percentages is shown in Table 10.

Table 10: Weight Groups/A-1 Variation

Weight Breakdown	Mean	St Dev
GR 1	48.5%	2.0%
GR 2	26.2%	4.2%
GR 3	2.5%	1.0%
GR 4	5.3%	0.2%
GR 5	9.7%	0.5%
GR 6	4.3%	0.2%
GR 7	3.6%	2.2%

GR 2, and 7 have standard deviations greater than two percent. All group percentage variations over the submarines studied are dependent on the accuracy of the model-output A-1. Recall from Table 7 in section 3.4 that errors in A-1 varied from one to six percent. However, there is an added explanation for GR 2 and 7 standard deviations of 4.2 and 2.2 percent, respectively. AGSS 569 had a relatively large percentage (33.6 percent) devoted to GR 2 because it was an experimental ship built for speed. Additionally, AGSS 569 was built without armament and therefore has a GR 7 percentage of zero. Table 11 shows the mean and standard deviation without the AGSS 569 outlier values.

Table 11: Weight Groups/A-1 Variation Without AGSS 569

Weight Breakdown	Mean	St Dev
GR 1	48.9%	1.9%
GR 2	24.7%	2.3%
GR 3	2.7%	1.0%
GR 4	5.3%	0.2%
GR 5	9.8%	0.5%
GR 6	4.3%	0.3%
GR 7	4.3%	1.4%

Another observation of the small deviations in weight group percentages is that all the weight groups are calculated from the same model, using the same parametric relationships.

However, the parametric relationships were developed with the aid of measured areas converted to volumes of compartments and therefore do not degrade the accuracy of the results. As further proof of this point, compare the weight group percentages of NSC with published design norms for diesel submarine design from reference (5), shown below in Figure 3. The published values are shown in the center of the figure.

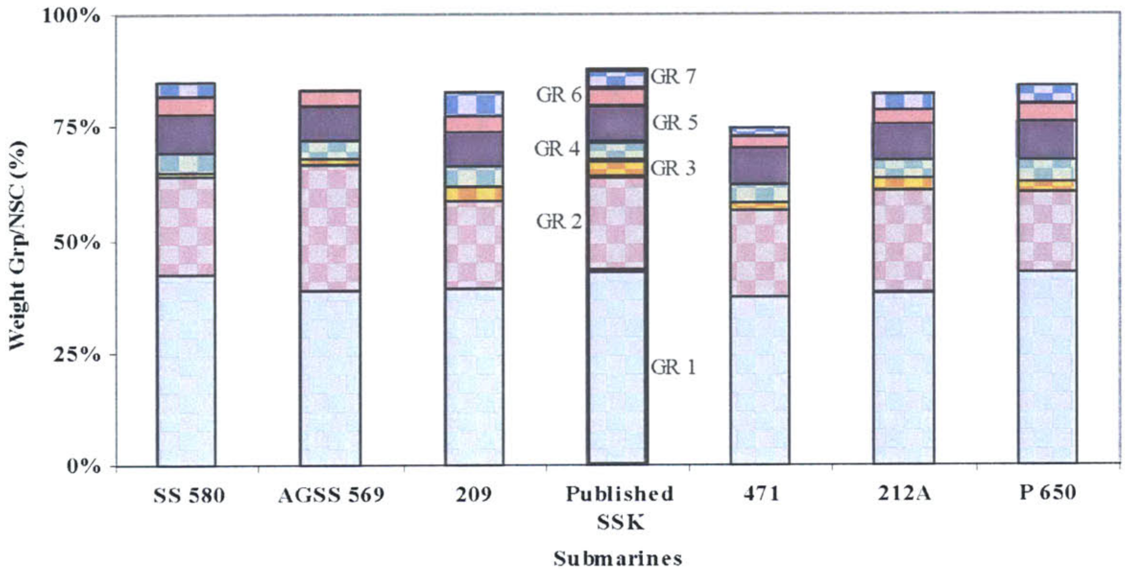


Figure 3: Weight Group Percentages of NSC Compared to Published SSK (5)

4.2 Analysis of Results

4.2.1 Historical Trends

As the submarines spanned a large number of years, an historical perspective can be examined in weight group 3, electrical systems. SS 580 and AGSS 569 both have GR 3 percentages below 1.5% while later submarines reach nearly 4%. This growth in GR 3 can be attributed to the increased number of electrical components onboard, requiring a greater generator kW capacity. Possible explanations in this growth include: 1) equipment functions once performed with hydraulics or air systems are now performed with electrical-driven motors or actuators; 2) computer-based system increase in fire control, radar, radio, navigation and sonar.

Going beyond the standard weight group comparison, GR 6 weight (outfit and furnishing) can be analyzed from the perspective of space per man. GR 6 percentages have a mean of 4.3 percent and standard deviation of 0.2 percent over the selected submarines. The interesting aspect of GR 6 constancy is that the overall number of crewmembers has decreased on diesel submarines. Using the equivalent volume from the GR 6 weight output and the complement, space per man (m^3) was calculated and plotted for the corresponding year of commissioning in Figure 4.

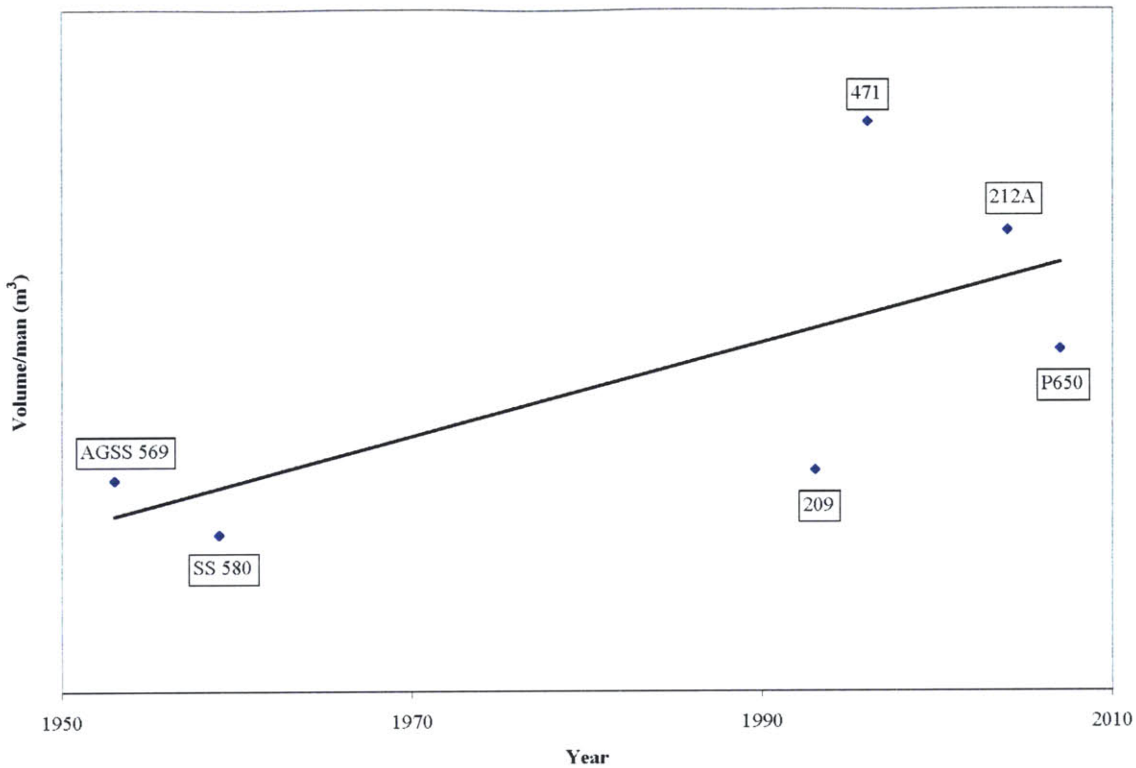


Figure 4: Group 6 Trend Shown as Space per Man

There are at least two possible explanations for this result: 1) the living accommodations per man have steadily increased from 1950 to present day; 2) furnishings such as lounge and recreation areas have increased on board, so the space is not only allocated to people but to furniture as well. Additional data would be necessary to determine the actual use of the increased volume per man.

4.2.2 Mission Effects

Mission effects on naval architecture are evident in the GR 2 and GR 7 results of AGSS 569 explained in section 4.1 above. The AGSS 569 was designed as an experimental platform, with a hull of revolution or "teardrop" shape, smaller appendages and no weapons systems, all of which clearly affect the respective weight groups.

Additionally, an apparent distinction in individual comparisons is seen in GR 7 results of the remaining submarines. The Type 209 weight percentage of 6.3 percent, greater than any other submarine, is due to the increased number of torpedo tubes in the 209. A possible consequence is a reduction of RB of 15 percent in the Type 209, compared to its most similar hull class, the Type 212A which has a RB of 28 percent. The hull dimensions of the two hulls are similar but more volume was taken up by mission-related functions in the Type 209, leaving less volume for MBTs and therefore smaller RB.

This relatively large RB for Type 212A is unexpected. Most US submarines have RB values between ten and twelve percent, so a value twice that stands out. Possible reasons and future recommendations will be discussed in chapter 5.

4.2.3 Construction Effects

The leading submarine manufacturer is Thyssen Nordseewerke (HDW/TNSW), the newly-formed combination of long-time manufacturers Howaldtswerke-Deutsche Werft GmbH (HDW) of Kiel and Emden, Germany and Kockums of Karlskrona, Sweden. France operates Direction Construction National (DCN) and competes with TNSW for competing submarine contracts. Spain has recently started building submarines at Cartegena under the manufacturer IZAR, in collaboration with DCN. Other European countries building diesel submarines include Greece, Turkey and Italy, all under license of HDW/TNSW. In Asia, Japan continues to steadily produce diesel submarines and China is improving its submarine-building programs (14). But the submarines typically built by Japan and China are for their sole use.

The information found on submarine construction methods indicated a history of modular construction techniques, similar to the recent nuclear submarine *USS Virginia* construction. A look at history shows this construction method to have been extensively used by Germany in WWII, where the U-boat construction was parceled out to many assembly groups, each completing parts and subassemblies, termed modules. These modules were brought together in decreasing numbers of subassemblies and finally into one shipyard for final assembly (5). Prior to computer aided drafting (CAD) submarine designs would sometimes be tested for fit up using full scale mock ups. More recent diesel designs have used fifth-scale models rather than full mock ups, and CAD programs have significantly assisted arrangements (5).

What are nations looking for in submarine capabilities? With the exception of nations building nuclear submarines, nations seeking to obtain submarines are looking for inexpensive but effective diesel submarines possessing advanced design without the need for extended range (14). Specifications for bids include:

- Turbo exhaust gas blowers for diesels
- High level of automation/computerization for minimum crew size
- Either a fuel cell AIP component or a closed cycle, external combustion AIP engine such as the Kockums Stirling.
- Hull construction of high carbon yield steel with non-magnetic, low field signature.
- Variable-speed motors and high efficiency alternators.

Diesel submarines should be suited for detection of hostile submarine intrusion into home waters, bottom mapping of shore regions, detection of mines, detection of electronic emissions and ability to carry unmanned submerged vehicles. Overall nations are looking for minimum cost and stealth as priorities for their diesel submarine acquisitions (14).

4.2.4 Cost Effects

Cost information is difficult to find in open literature. Countries that sell diesel submarines do not list published prices of their submarines for the general public. The only accurate data obtained was that of the Type 212A selling for just over $500 M in 2004 (14).

An important distinction must be made between price and cost. The price of a submarine is the amount a shipbuilder is willing to offer to build the vessel to specification. Price depends on the number of boats planned to be built, how quickly they are required, the level of competition, the resources, expertise of the shipbuilder, and the facilities. Thus the price of a submarine can vary drastically, even with the same design requirements (5).

The cost, however, is the total of the individual costs of the contents. Cost is an inherent property of a submarine usually determined early in the design stages. Cost estimating has traditionally been based on weight group breakdown, and a cost per ton was normally determined to find the overall cost of the submarine. But more recently, submarine designers and builders have moved toward functional costing or relating cost directly to the functional performance parameters of the design (5). However, the accuracy of functional costing is difficult to predict because it is almost impossible to obtain a single valued function to cost relationship.

With one major leading European manufacturer, TNSW/HDW, competition for prices may be difficult. Other builders are starting interesting programs, one of which was covered in this study, Spain's P 650 built by IZAR. From the analysis, P 650 appears to be a very capable platform and may compete well with the German designs of HDW. But the first

P 650 will not be commissioned until 2007, so competition with HDW will have to be compared at that time. Therefore, cost effects on naval architecture are largely qualitative due to the limited amount of data available. One conclusion that doesn't require quantitative data is that it is not feasible to put performance above all cost considerations and in most designs, the designer must carefully account for the mix between performance, cost and resources (5).

4.3 Discussion of Results

Reviewing again the results of Table 11 above, the lack of significant difference in standard deviation is not surprising when considering that the basics of ship design have remained the same. The basic law of Archimedes still applies, regardless of advances in technology, mission differences, cost factors or construction techniques. This result may have been shown for submarines of the same country before but never explicitly shown for submarines of different countries. Comparative studies of surface ships have found similar conclusions. For example, Kehoe and Graham note that although the process of design for US and foreign surface ships varied, the average values of characteristics did not vary significantly (13).

Submarine design is typically volume-limited, with a pressure hull structure as the limiting factor. Although technology and construction techniques have changed over the years of submarine design, the conclusion is that the changes have not been significant enough to alter the traditional submarine design process. Another possible reason for the similarity in results is what was mentioned in chapter 1, that initial design starts with previous submarine databases. Estimates are made early in the design from those databases that carry throughout the final product, resulting in similar weight divisions. This result will be discussed in further detail in chapter 5.

5 Conclusions

5.1 Summary of Work

In conclusion, this study has presented a method to obtain volumes and weight groups of diesel submarines given dimensions normally found in open literature. Furthermore the weight group percentages were found to not vary significantly from one design to the next. The similarity in weight groups may be attributed to using historical databases and borrowing from previous designs to develop the initial estimates for a new design. As Jackson notes, "Weight and volume estimating depends on the accumulation of data from a great many sources in a systematic manner…It is the crux of the concept design phase as weights and unit volumes must be intelligent guesses while everything else is subject to rigorous mathematical analysis" (7). These intelligent guesses come from databases of previous designs and therefore are similar in proportion.

Mission factors do have an effect on weight groups, if the mission factor is of a "large scale". Those factors found to be large enough in this study were the presence or absence of one type of mission, such as the lack of armament or the emphasis on speed in the mission.

Cost does seem to have an implied effect of leveling the field of possible designs due to constraints on size, cost and arrangements of submarine designs, but no quantitative data was found for this conclusion. The fact that countries seek the least expensive, most capable submarines gives qualitative reasoning to this statement.

No new or unusual solutions or concepts to make ships smaller, less expensive, or more effective have been revealed by this analysis of diesel submarines. Diesel submarine hull characteristics have grown beyond the ideal of *Holland* and therefore have become less hydrodynamically efficient than the hull of revolution design. It is difficult to reduce size constraints once they have grown and been incorporated into new ships. Designers must resist the tendency of volume growth trend but the reversal of such a trend is contrary to the perception that a more effective platform must meet more capability based requirements.

5.2 Future Work and Recommendations

In performing this study, the following areas were identified that would expand the scope of the comparative naval architecture analysis.

5.2.1 Survey Size

Six submarines were selected and two of those were mainly included for the development of parametric equations. The two older US submarines provided a historical perspective but additional modern submarines would give a more comprehensive comparison of modern technologies. As diesel submarine numbers increase, more data may be available and therefore should ease the task of gathering that data. Additionally, more submarine data will enable refinement of the parametric equations used in the math model.

5.2.2 Math Model

The math model can be improved to output additional characteristics and therefore add to the comparisons available. Volumes and weight groups were the only naval architectural characteristics calculated. If more complete and accurate drawings are obtained, additional weights could be calculated of frames, plates and bulkheads for instance, which could yield more accurate estimates of structural weight. Additionally, more accurate measurements of internal areas could be obtained to calculate more accurate volumes and to develop more precise parametric equations for cases where drawings were not available.

5.2.3 Reserve Buoyancy

An interesting result is the relatively large RB of Type 212A. The RB was calculated in the math model by dividing the MBT volume by the everbuoyant volume.

RB = MBT Vol / V_{eb}

From Table 8 the math model output for RB was 28 percent. If RB is calculated from published values, the result is 26 percent as shown below.

Know that in a balanced ship, V_{eb} = NSC

And $V_{bt} = \Delta_{sub} - NSC$

Published values:

NSC_{212} = 1450 Lton

Δ_{sub212} = 1830 Lton

Therefore $RB_{212} = V_{bt} / NSC_{212} = (1830 - 1450) / 1450$

RB_{212} = 26 %

This result is over twice that of design-lane values of 10 to 12.5 percent, even when considering smaller submarine hulls will have larger RB values. The possible causes were not researched further in this report but rather left to future work.

5.2.4 Advanced Technology

This study's focus was on the comparison of submarine weight groups but more detailed comparisons may be made of advanced technology in propulsion systems (AIP), acoustics, new battery technology and weapon systems. Research of propulsion and weapons capabilities would provide a more thorough comparative analysis of the submarines studied.

5.3 Closing

This study covered in detail the submarine design procedure, foreign diesel submarine designs, and methods of comparative naval architecture. A math model was developed to estimate volumes and weight groups from open literature diesel submarine drawings. The overall conclusion is that submarine design has not changed significantly, with regard to the major components of naval architecture, the weight groups. Submarine designers must continuously make engineering estimates and rely on previous designs for volume and weight predictions, then adjust these to meet operational or owner requirements.

References

1. Lienau, Peter. "The Working Environment for German Submarine Design During WWII." December 2 1999 <http://www.navweaps.com/index_tech/tech-050.htm>

2. The Simon and Schuster encyclopedia of World War II / edited by Thomas Parrish; chief consultant editor, S.L.A. Marshall. – New York: Simon and Schuster, 1978. <http://www.angelfire.com/ct/ww2europe/stats.html>

3. "Nuclear Powered Ships." *World Nuclear Association.* October 2004. <http://www.world.nuclear.org/info/inf34.htm>

4. "Bulletin 22." *Submarine Research Center, AMI International.* November 2003. <http://www.submarineresearch.com/bulletins.html>

5. Burcher, Roy, and Louis Rydill. *Concepts in Submarine Design.* Cambridge: Cambridge UP, 1994.

6. Jackson, Harry A., P.E., CAPT USN (Ret). "Fundamentals of Submarine Concept Design." SNAME Transactions, Vol. 100, pp 419-448, October 1992.

7. Jackson, Harry A., P.E., CAPT USN (Ret). "Submarine Concept Design." ASNE, October 5 1988.

8. Arentzen E.S., Capt, USN, and Philip Mandel. "Naval Architectural Aspects of Submarine Design." SNAME, November 17-18, 1960.

9. Jackson, Harry A., P.E., CAPT USN (Ret). MIT Professional Summer Course "Submarine Design Trends", 1992.

10. Stenard, John K., LT, USN. *Comparative Naval Architecture of Modern Foreign Submarines.* Massachusetts Institute of Technology. May 1988.

11. Cann, Glenn, et al., eds. Introduction to Submarine Design. 1995 IAP Submarine Design Course notes. Dept of Ocean Engineering, Massachusetts Institute of Technology, 13 December 1994.

12. Jane's Information Group Limited. *Jane's Fighting Ships 2002-2003, One Hundred Fifth edition.* Commodore Stephen Saunders RN, editor. Coulsdon Surrey, UK, 2002.

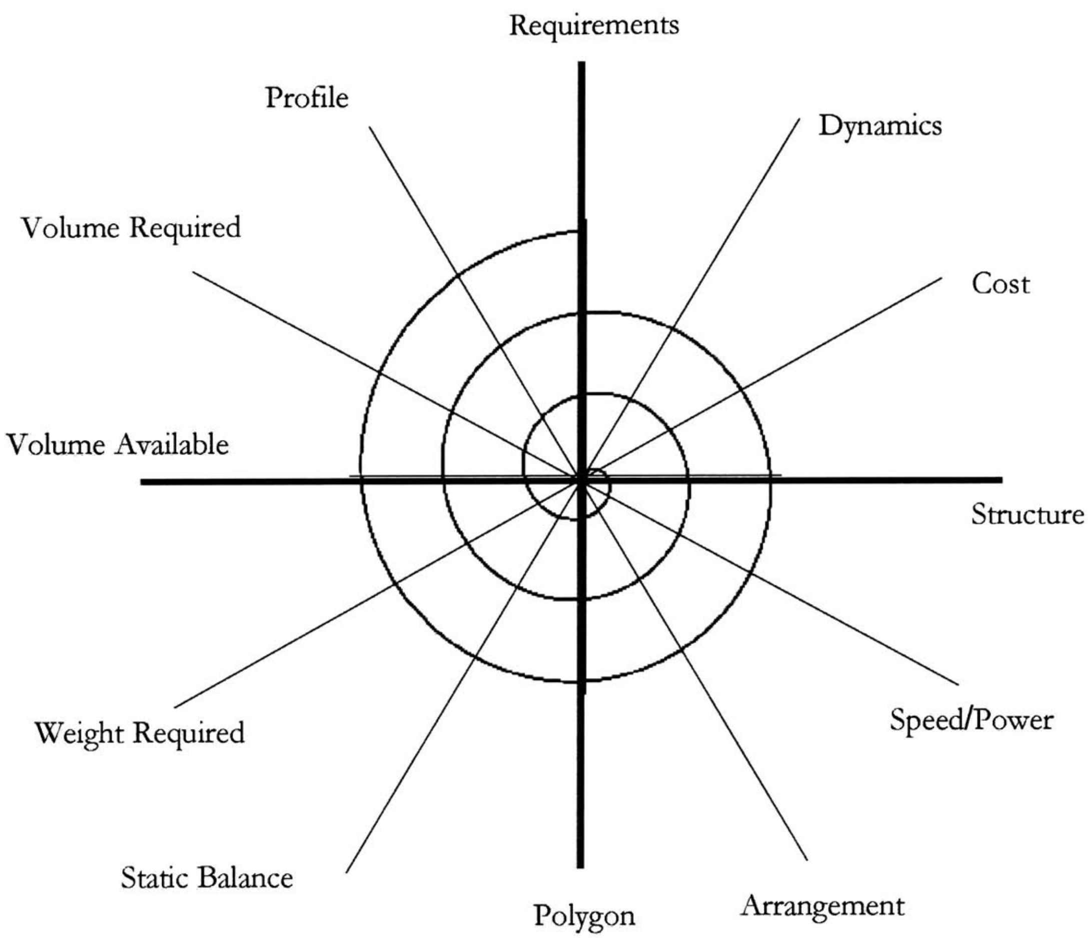
13. Kehoe, James W., Jr, CAPT USN, and Clark Graham, CDR USN, Kenneth Brower, and Herbert A. Meier. "Comparative Naval Architecture Analysis of NATO and Soviet Frigates." Naval Engineers Journal, October 1980.

14. "Bulletin 25." *Submarine Research Center, AMI International.* January 2004. <http://www.submarineresearch.com/bulletins.html>

Appendices

Appendix A: Design Spiral

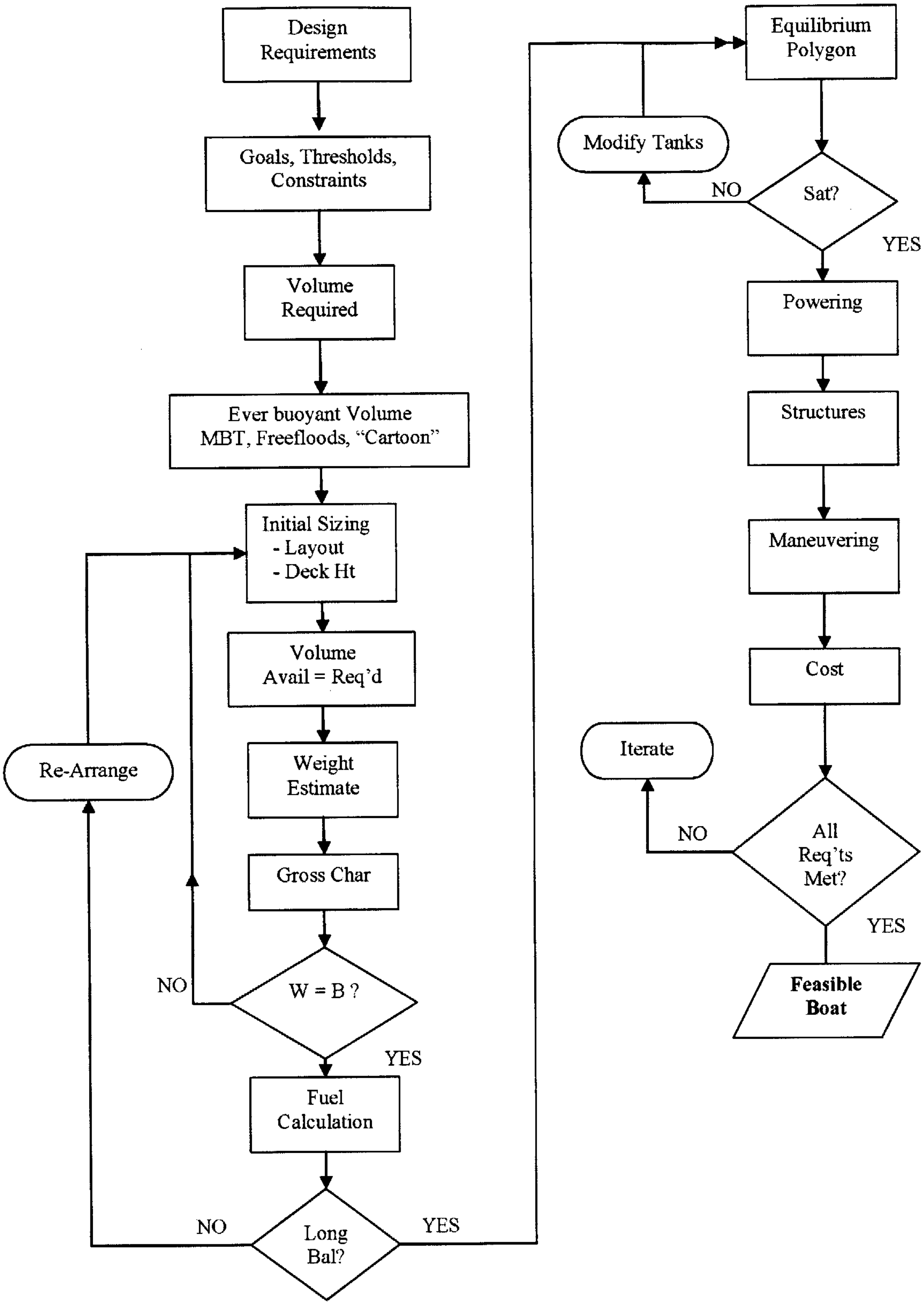
Submarine Design Spiral



Professional Summer Program at
Massachusetts Institute of Technology, 2004

Appendix B: SS Design Flowchart

SS DESIGN GUIDE FLOWCHART



Appendix C: Math Model

Diesel Submarine Comparative Naval Architecture Analysis Math Model
Developed from the MIT Math Model
Kai O. Torkelson, LCDR, USN, 6 May 2005

i. CONSTANTS

$\rho_{SW} \equiv 1020\frac{kg}{m^3}$ $f_{Curve} \equiv 1.12$ $lton := 1016.05kg$ $NM := 1852m$ $knt := \frac{1NM}{1 \cdot hr}$ $kW := 1.34102hp$

f_{Curve} = factor_for_hull_curvature   fcurve obtained from 1994 SS design section of Introduction to Submarine Design

Input excel file containing dimensions of submarines 0 through i:

The input excel file, Mathcad_input.xls, draws from a variety of input excel files which provide all necessary submarine data that is used throughout this model to calculate the the desired output characteristics. Each input is read from the input matrix individually and assigned a range variable, such as NSC(i) or LOA(i), for the i-number of submarines included as candidates.

I. CHARACTERISTICS

$i := 0..5$

Surfaced Displacement $NSC(i) := I_{0,i} \cdot lton$ Normal Surfaced Condition = Surfaced Displacement

Submerged Displacement $\Delta_{sub}(i) := I_{1,i} \cdot lton$

Length Overall $LOA(i) := I_{2,i} \cdot m$

Diameter $D(i) := I_{3,i} \cdot m$

Complement $N_{crew\_officer}(i) := I_{4,i}$

$N_{crew\_other}(i) := I_{5,i}$

$N_T(i) := \left(N_{crew\_officer}(i) + N_{crew\_other}(i)\right)$

Speed max surfaced $V_{surfaced}(i) := I_{6,i} \cdot knt$

Speed max submerged $V_{submerged}(i) := I_{7,i} \cdot knt$

Number of Torpedo Tubes: $TT(i) := I_{8,i}$

Patrol endurance, days $E(i) := I_{9,i}$

Diving Depth (m):	$D_D(i) := I_{10,i} m$
Passageway Factor:	$f_{Pway} \equiv 1.08$ 1.08 as used in 1994 Intro to Sub Design for SS (diesel subs)
Deck Height Measured:	$H_{Deck}(i) := I_{11,i} m$
SHP Installed:	$SHP(i) := I_{12,i} hp$
Electric Plant Power Installed:	$KW_i(i) := I_{13,i} \cdot kW$

II. VOLUME CALCULATIONS

This section calculates compartment and space volumes within the submarine, based on input data from plan and inboard profile drawings. The Variables indicate the type of volume and the subscript indicates the location.

A. Engineroom Volume:

Using submarine profile drawings/pictures, measure the area for the Engine Room (ER):

ER Area: $A_{ER}(i) := I_{14,i} m^2$

Aft Battery Area: $A_{AB}(i) := I_{29,i} m^2$ $\quad H_{Batt}(i) := I_{31,i} m$

ER Volume: $V_{ER}(i) := f_{Curve} \cdot f_{Pway} \cdot \left(A_{ER}(i) \cdot H_{Deck}(i)\right)$ $\quad V_{AB}(i) := A_{AB}(i) \cdot H_{Batt}(i)$

B. OPS Compartment Volume

OPS Compartment will be calculated by a deck area analysis for Auxiliaries, Berthing & Messing, Storerooms, and Other Spaces. For comparison purposes, parametric equations have been used to calculate certain areas, as would be done in initial design. These areas can then be compared to the measured area for a check of parametric equations. The subscript m indicates measured areas for various spaces.

1. Command & Control: $A_{cc}(i) := I_{15,i} m^2$ $\quad V_{cc}(i) := f_{Pway} \cdot f_{Curve} \cdot H_{Deck}(i) \cdot A_{cc}(i)$

2. Berth & Mess: $A_{bm}(i) := 22.4 ft^2 \cdot N_T(i)$

Measured Berth & Mess: $A_{bmm}(i) := I_{16,i} m^2$

3. Storerooms: $A_{sr}(i) := 8.3 \cdot ft^2 \cdot E(i)$

Measured Storerooms: $A_{srm}(i) := I_{17,i} m^2$

4. Other Spaces (offices, etc) $A_{os}(i) := \left(100 ft^2 + .7 \cdot ft^2 \cdot N_T(i)\right)$

Measured Other Spaces (offices, etc) $A_{osm}(i) := I_{18,i} m^2$

5. Forward Battery: $A_{FB}(i) := I_{30,i} m^2$

$V_{FB}(i) := A_{FB}(i) \cdot H_{Batt}(i)$

6. Weapons Handling: $A_{wep}(i) := I_{19,i} m^2$ $\quad H_{Dwep}(i) := I_{20,i} m$ $\quad V_{wep}(i) := H_{Dwep}(i) \cdot f_{Pway} \cdot f_{Curve} \cdot A_{wep}(i)$

7. Parametric-Calculated Ops Volume: (Barbel and Albacore aft batteries are included in ops compartment)

$$A_{Pops}(i) := f_{Pway} \cdot f_{Curve} \cdot \left(A_{cc}(i) + A_{bm}(i) + A_{sr}(i) + A_{os}(i) + A_{wep}(i) + A_{FB}(i)\right)$$

$$A_{Pops}(i) := \begin{cases} \left(A_{Pops}(i) + f_{Pway} \cdot f_{Curve} \cdot A_{AB}(i)\right) & \text{if } i < 3 \\ A_{Pops}(i) & \text{if } 3 \le i \end{cases}$$

$$V_{Pops}(i) := f_{Pway} \cdot f_{Curve} \cdot \left[H_{Deck}(i) \cdot \left(A_{cc}(i) + A_{bm}(i) + A_{sr}(i) + A_{os}(i) + A_{wep}(i)\right) + H_{Batt}(i) A_{FB}(i)\right]$$

$$V_{Pops}(i) := \begin{cases} \left(V_{Pops}(i) + f_{Pway} \cdot f_{Curve} \cdot H_{Batt}(i) \cdot A_{AB}(i)\right) & \text{if } i < 3 \\ V_{Pops}(i) & \text{if } 3 \le i \end{cases}$$

8. Measured Ops Volume:(Barbel and Albacore aft batteries are included in ops compartment)

$$A_{opsm}(i) := f_{Pway} \cdot f_{Curve} \cdot \left(A_{cc}(i) + A_{bmm}(i) + A_{srm}(i) + A_{osm}(i) + A_{wep}(i)\right)$$

$$A_{opsm}(i) := \begin{cases} \left(A_{opsm}(i) + f_{Pway} \cdot f_{Curve} \cdot A_{AB}(i)\right) & \text{if } i < 3 \\ A_{opsm}(i) & \text{if } 3 \le i \end{cases}$$

$$V_{opsm}(i) := f_{Pway} \cdot f_{Curve} \cdot \left[H_{Deck}(i) \cdot \left(A_{cc}(i) + A_{bmm}(i) + A_{srm}(i) + A_{osm}(i) + A_{wep}(i)\right) + H_{Batt}(i) \cdot A_{FB}(i)\right]$$

$$V_{opsm}(i) := \begin{cases} \left(V_{opsm}(i) + f_{Pway} \cdot f_{Curve} \cdot H_{Batt}(i) \cdot A_{AB}(i)\right) & \text{if } i < 3 \\ V_{opsm}(i) & \text{if } 3 \le i \end{cases}$$

C. Auxiliary andPressure Hull Volume:

1. Using the pressure hull measured values of L, D, and length of parallel mid-body and forward & aft shape factors.

Note: These factors are for the pressure hull only, not the overall hull shape

Entrance: $\eta_{fph}(i) := I_{34,i}$

Run: $\eta_{aph}(i) := I_{35,i}$ $\quad L_{fph}(i) := I_{37,i} m$

$L_{ph}(i) := I_{36,i} m$ $\quad L_{aph}(i) := I_{38,i} m$

$L_{pmbph}(i) := L_{ph}(i) - L_{fph}(i) - L_{aph}(i)$

$D_{ph}(i) := I_{46,i} m$

check:

$$one(i) := \frac{L_{fph}(i)}{L_{ph}(i)} + \frac{L_{aph}(i)}{L_{ph}(i)} + \frac{L_{pmbph}(i)}{L_{ph}(i)}$$

2. Entrance & Parallel Mid-Body:

$$yf1_{ph}(x1,i) := \left[1 - \left(\frac{L_{fph}(i) - x1}{L_{fph}(i)}\right)^{\eta_{fph}(i)}\right]^{\frac{1}{\eta_{fph}(i)}} \cdot \frac{D_{ph}(i)}{2}$$

3. Run:

$$ya_{ph}(x1,i) := \left[1 - \left[\frac{x1 - \left(L_{fph}(i) + L_{pmbph}(i)\right)}{L_{aph}(i)}\right]^{\eta_{aph}(i)}\right] \cdot \frac{D_{ph}(i)}{2}$$

4. Total Pressure Hull:

$$offt_{ph}(x1,i) := \begin{cases} yf1_{ph}(x1,i) & \text{if } x1 < L_{fph}(i) \\ \frac{D_{ph}(i)}{2} & \text{if } L_{fph}(i) \le x1 \le L_{fph}(i) + L_{pmbph}(i) \\ ya_{ph}(x1,i) & \text{if } x1 > L_{fph}(i) + L_{pmbph}(i) \end{cases}$$

5. Pressure Hull Volume

$$V_{PH}(i) := \int_{0 \cdot ft}^{L_{ph}(i)} offt_{ph}(x1,i)^2 \cdot \pi \, dx1 \qquad V_{PH} = \blacksquare$$

$$\Delta_{ph}(i) := \frac{V_{PH}(i)}{35 \cdot 0.02831685 \frac{m^3}{lton}}$$

From PH volume, calculate auxiliary and variable ballast volumes:

$$V_{aux}(V_{PH}, i) := 0.041 \cdot V_{PH}(i) + .529 m^3 \cdot N_T(i)$$

V_{aux} equation from Harry Jackson's notes. This includes auxiliary machinery, tanks, etc.

$$V_{VB}(V_{PH}, i) := 0.064 V_{PH}(i)$$

V_{VB} equation from Harry Jackson's notes. Volume of variable ballast tanks.

$$V_{aux}(i) := V_{aux}(V_{PH}, i)$$

$$V_{VB}(i) := V_{VB}(V_{PH}, i)$$

D. Total Ops Compartment:

$$V_{ops}(i) := V_{opsm}(i) + V_{aux}(i) + V_{VB}(i)$$

$$V_{phm}(i) := V_{ops}(i) + V_{ER}(i) \qquad \Delta_{phm}(i) := V_{phm}(i) \cdot \rho_{SW}$$

$$Err_{vph}(i) := \frac{V_{PH}(i) - V_{phm}(i)}{V_{PH}(i)}$$

If $Err_{vph} < 0$, then calculated volume is smaller than that derived from drawing measurements.
If $Err_{vph} > 0$, then that derived from drawing measurements is larger than calculated volume.
IF ERROR > +/- 10% ADJUST YOUR HULL CHARACTERISTICS - LOOK CLOSELY AT MEASURED VOLUMES.

E. Outboard Volume:

$$V_{ob}(i) := .12 \cdot V_{PH}(i)$$

0.12 obtained from Intro to Sub Design (SS) 1994

F. Sonar Arrays *Assumes a cylindrical bow sonar array*

Measure radius and height of bow sonar array: $r_{sa}(i) := I_{32,i}\,m$ $h_{sa}(i) := I_{33,i}\,m$ $V_{sa}(i) := \pi \cdot r_{sa}(i)^2 \cdot h_{sa}(i)$

G. Sonar Dome Water:

$$V_d(i) := V_{sa}(i) \cdot 5$$

H. Everbuoyant Volume: The everbouyant volume is used later to compare with NSC weight.

$$V_{eb}(i) := V_{PH}(i) + V_{ob}(i) + V_{sa}(i) + V_d(i)$$

$$\Delta_{ebr}(i) := V_{eb}(i) \cdot \rho_{SW}$$

I. Main Ballast Tank Volume: Determinant of reserve buoyancy

$$V_{bt}(i) := \left(\Delta_{sub}(i) - NSC(i)\right) \cdot \left(35 \cdot \frac{ft^3}{lton}\right)$$

$$RB(i) := \frac{V_{bt}(i)}{V_{eb}(i)}$$

J. Submerged Volume:

$$V_s(i) := V_{eb}(i) + V_{bt}(i)$$

$$\Delta_s(i) := V_s(i) \cdot \rho_{SW}$$

K. Envelope Volume

$p(i) := I_{39,i}$ Enter submerged free flood fraction of envelope displacement. check: $K_1(i) := I_{42,i}$

Envelope volume eqn from HJ notes in Submarine Concept Design

$$V_{env}(i) := \frac{V_s(i)}{1 - p(i)}$$

$$\Delta_{envc}(i) := \frac{\pi \cdot D(i)^3}{140} \cdot \frac{lton}{ft^3} \cdot \left(\frac{LOA(i)}{D(i)} - K_1(i)\right)$$

$$\Delta_{env}(i) := V_{env}(i) \cdot \rho_{SW}$$

L. Free Flood Volume:

$$V_{ff}(i) := p(i) \cdot V_{env}(i)$$

$$\Delta_{ff}(i) := V_{ff}(i) \cdot \rho_{SW}$$

III. ENVELOPE VOLUME BY PARAMETRIC EQNS

A. Hull Characteristics:

Using the volume requirements calculated in Section II and measured values of (Figures 2-1, 3-1/2/3, 5-2/3) - L, D, and length of parallel mid-body and forward & aft shape factors.

Entrance: $\eta_f(i) := I_{40,i}$

Run: $\eta_a(i) := I_{41,i}$

Calculate L/D: $LOD(i) := \frac{LOA(i)}{D(i)}$

$LOD = \text{function} \quad L = \text{function}$

Measured values and calculations:

$L(i) := LOA(i)$

$L_f(i) := 2.4 \cdot D(i)$ $\qquad$ $\text{fwd\_end\_frac}(i) := \frac{L_f(i)}{D(i)}$

$L_a(i) := 3.6 \cdot D(i)$ $\qquad$ $\text{aft\_end\_frac}(i) := \frac{L_a(i)}{D(i)}$

$L_{pmb}(i) := (LOD(i) - 6) \cdot D(i)$

check:

$$one_h(i) := \frac{L_f(i)}{LOA(i)} + \frac{L_a(i)}{LOA(i)} + \frac{L_{pmb}(i)}{LOA(i)}$$

B. Volume Calculations for total ship:

1. Entrance & Parallel Mid-Body:

$$yf1(x1,i) := \left[1 - \left(\frac{L_f(i) - x1}{L_f(i)}\right)^{\eta_f(i)}\right]^{\frac{1}{\eta_f(i)}} \cdot \frac{D(i)}{2}$$

2. Run: $\qquad L_a = \text{function}$

$$ya(x1,i) := \left[1 - \left[\frac{x1 - (L_f(i) + L_{pmb}(i))}{L_a(i)}\right]^{\eta_a(i)}\right] \cdot \frac{D(i)}{2}$$

3. Total Ship:

$$offt(x1,i) := \begin{cases} yf1(x1,i) & \text{if } x1 < L_f(i) \\ \frac{D(i)}{2} & \text{if } L_f(i) \le x1 \le L_f(i) + L_{pmb}(i) \\ ya(x1,i) & \text{if } x1 > L_f(i) + L_{pmb}(i) \end{cases}$$

4. Total Ship Volume

$$V_{tot}(i) := \int_{0 \cdot ft}^{L(i)} offt(x1,i)^2 \cdot \pi \, dx1 \qquad V_{tot} = \text{function}$$

Compare to envelope volume from above:

$$Err_{env}(i) := \frac{V_{tot}(i) - V_{env}(i)}{V_{tot}(i)}$$

If $Err_{env} < 0$, then calculated volume is smaller than that derived from drawing measurements.
If $Err_{env} > 0$, then that derived from drawing measurements is larger than calculated volume.
IF ERROR > +/- 10% ADJUST YOUR HULL CHARACTERISTICS - LOOK CLOSELY AT MEASURED VOLUMES.

5. Total Prismatic Coefficient

$$C_p(i) := \frac{V_{tot}(i)}{\pi \cdot \left(\frac{D(i)}{2}\right)^2 \cdot L(i)}$$

C_p = function

6. Forward Prismatic and Wetted Surface Area Coefficients:

$$C_{pf}(i) := \frac{\int_{0 \cdot ft}^{2.4 \cdot D(i)} offt(x1,i)^2 \cdot \pi \, dx1}{\pi \cdot \frac{D(i)^3}{4} \cdot 2.4}$$

C_{pf} = function

$$C_{wsf}(i) := \frac{\int_{0 \cdot ft}^{2.4 \cdot D(i)} 2 \cdot offt(x1,i) \cdot \pi \, dx1}{\pi \cdot D(i)^2 \cdot 2.4}$$

C_{wsf} = function

7. After Prismatic and Wetted Surface Area Coefficients:

$$C_{pa}(i) := \frac{\int_{(L(i)-3.6 \cdot D(i))}^{L(i)} offt(x1,i)^2 \cdot \pi \, dx1}{\pi \cdot \frac{D(i)^3}{4} \cdot 3.6}$$

$$C_{wsa}(i) := \frac{\int_{(L(i)-3.6 \cdot D(i))}^{L(i)} 2 \cdot offt(x1,i) \cdot \pi \, dx1}{\pi \cdot D(i)^2 \cdot 3.6}$$

C_{wsa} = function

8. Wetted Surface Area, Envelope Displacement & misc. Coefficients:

$K1(i) := 6 - 2.4 C_{pf}(i) - 3.6 C_{pa}(i)$ $K2(i) := 6 - 2.4 C_{wsf}(i) - 3.6 C_{wsa}(i)$ $WS(i) := \left[\pi \cdot D(i)^2 \cdot (LOD(i) - K2(i))\right]$

K1 = function K2 = function

$$WS_{tot}(i) := \int_{0 \cdot ft}^{L(i)} 2 \cdot \pi \cdot offt(x1,i) \, dx1$$

WS = function WS_{tot} = function

Eqn (12-24) from Gilmer and Johnson $C_s(i) := 1.03 C_p(i)^{\frac{2}{3}}$ Hull wetted surface coefficient calculation from Gilmer and Johnson

$$\Delta_{envd}(i) := \frac{\pi \cdot D(i)^3}{140} \cdot \frac{lton}{ft^3} \cdot \left(\frac{LOA(i)}{D(i)} - K1(i)\right)$$

9. Envelope Volume Balance.

Note: The outboard volumes external to the main envelope of the submarine are not included in the hull sizing.

Δ_{envc} = function Δ_{envd} = function

$$Err_{\Delta env}(i) := \frac{\Delta_{envd}(i) - \Delta_{envc}(i)}{\Delta_{envd}(i)}$$

Check of calculated displacement and that derived from K1 estimate +/- 1%:

If $Err_v < 0$, then calculated displacement is smaller than that derived from K1 estimate.
If $Err_v > 0$, then that derived from K1 estimate is larger than calculated displacement.
IF ERROR > +/- 10% ADJUST YOUR HULL CHARACTERISTICS - LOOK CLOSELY AT K1 ESTIMATE IN envc.

IV. INTERNAL LAYOUT

Based on your data and inboard profile drawings , input the longitudinal location of the following bulkheads measured from fore to aft. The general methodology is to work from fore and aft towards amidships. Starting forward and working aft....

A. Dome:

Sonar Dome Bulkhead location: $Dome_{aft}(i) := I_{21,i} m$

B. Fwd MBT aft Bulkhead:

FWD MBT aft Bulkhead (FWD OPS) location: $FMBT_{aft}(i) := I_{22,i} m$

NOW, starting aft and working forward, still using the profile drawing as the basis input the following locations...

C. Forward bulkhead of the mud tank:

Mud Tank Bulkhead location: $MUD_{fwd}(i) := I_{23,i} m$

$L(i) - MUD_{fwd}(i)$

D. Forward Bulkhead of AMBT (ER aft Bulkhead):

AFT ER (AMBT fwd) Bulkhead location: $ER_{aft}(i) := I_{24,i} m$ $\quad R_{ER}(i) := offt(ER_{aft}(i), i)$

Aft MBT length: $MUD_{fwd}(i) - ER_{aft}(i)$ $\quad PH_{aft}(i) := ER_{aft}(i) + R_{ER}(i)$ $\quad PH_{aft} = \text{function}$

E. Forward Bulkhead of ER:

FWD ER Bulkhead location: $ER_{fwd}(i) := I_{25,i} m$

ER Stack length actual: $ER_{length}(i) := ER_{aft}(i) + R_{ER}(i) - ER_{fwd}(i)$ $\quad ER_{length} = \text{function}$

F. Fwd OPS Bulkhead

FWD MBT aft Bulkhead (FWD OPS) location: $OPS_{fwd}(i) := I_{26,i} m$

OPS fwd bulkhead location:

$$R_{OPSc}(i) := offt(OPS_{fwd}(i))$$

$$R_{OPS}(i) := offt(OPS_{fwd}(i), i)$$

$$PH_{fwd}(i) := OPS_{fwd}(i) - R_{OPS}(i)$$

$$PH_{fwd} = \text{function}$$

OPS Stack length actual: $OPS_{length}(i) := ER_{fwd}(i) - OPS_{fwd}(i) + R_{OPS}(i)$ $\quad OPS_{length} = \text{function}$

V. Summary of Error Checks

A. Overall measured PH vs. calculated PH volume

$$Err_{vph}(i) := \frac{V_{PH}(i) - V_{phm}(i)}{V_{PH}(i)}$$

$Err_{vph}(i) =$

3.22
-19.88
16.224
18.717
-4.444
13.066

%

If $Err_{vph} < 0$, then calculated volume is smaller than that derived from drawing measurements.
If $Err_{vph} > 0$, then that derived from drawing measurements is larger than calculated volume.
IF ERROR > +/- 10% ADJUST YOUR HULL CHARACTERISTICS - LOOK CLOSELY AT MEASURED VOLUMES.

B. Overall total ship measured vs. total ship calculated volume

$$Err_{env}(i) := \frac{V_{tot}(i) - V_{env}(i)}{V_{tot}(i)}$$

$Err_{env}(i) =$

4.265
10.172
-9.575
-16.833
-10.156
-11.297

%

If $Err_{env} < 0$, then calculated volume is smaller than that derived from drawing measurements.
If $Err_{env} > 0$, then that derived from drawing measurements is larger than calculated volume.
IF ERROR > +/- 10% ADJUST YOUR HULL CHARACTERISTICS - LOOK CLOSELY AT MEASURED VOLUMES.

C. Overall parametric-derived envelope vs. measured envelope displacement

$$Err_{\Delta env}(i) := \frac{\Delta_{envd}(i) - \Delta_{envc}(i)}{\Delta_{envd}(i)}$$

$Err_{\Delta env}(i) =$

0.394
-3.12
-0.014
0.142
-0.016
0.202

%

If $Err_{v} < 0$, then calculated displacement is smaller than that derived from K1 estimate.
If $Err_{v} > 0$, then that derived from K1 estimate is larger than calculated displacement.
IF ERROR > +/- 10% ADJUST YOUR HULL CHARACTERISTICS - LOOK CLOSELY AT K1 ESTIMATE IN envc.

VI. WEIGHT ESTIMATION

A. Initial A-1 Weight Estimation:

Input the Group1 fraction of NSC (Fig 1): $W_{1frac} := .385$ $\quad W_{1est}(i) := W_{1frac} \cdot NSC(i)$

Calculate the Group 2 weight from parametric equation:

Total battery volume: $V_{Bat}(i) := V_{FB}(i) + V_{AB}(i)$

$$W_{2est}(i) := 1.759\frac{lton}{m^3} \cdot V_{Bat}(i) + 0.005\frac{lton}{hp} \cdot SHP(i)$$

Input the Group 3 K3 (developed from SS580): $K3 := 0.0126\frac{lton}{kW}$ $\quad W_{3est}(i) := K3 \cdot KW_i(i)$

Input the Group 4 percentage of NSC: $W_{4frac}(i) := I_{43,i}$ $\quad W_{4est}(i) := NSC(i) \cdot W_{4frac}(i)$

Input the Group 5 fraction of NSC: $W_{5frac}(i) := I_{44,i}$ $\quad W_{5est}(i) := W_{5frac}(i) \cdot NSC(i)$

Input the Group 6 fraction of NSC: $W_{6frac}(i) := I_{45,i}$ $\quad W_{6est}(i) := W_{6frac}(i) \cdot NSC(i)$

Calculate Group 7 Weight (Use modified Stenard parametric equation):

$$W_{7est}(i) := \frac{0.0021ton}{ft^3} \cdot V_{wep}(i) + 6lton \cdot TT(i)$$

Sum the weight estimates to get A-1:

$$A1(i) := W_{1est}(i) + W_{2est}(i) + W_{3est}(i) + W_{4est}(i) + W_{5est}(i) + W_{6est}(i) + W_{7est}(i)$$

Input the lead fraction of A-1: $W_{PBfrac} := .087$ $\quad W_{PB}(i) := W_{PBfrac} \cdot A1(i)$

Input the Variable Load % of NSC: $W_{VLfrac} := .11$ $\quad W_{VL}(i) := W_{VLfrac} \cdot NSC(i)$

A-1 fraction of NSC: $A1_{frac} := \frac{1 - W_{VLfrac}}{1 + W_{PBfrac}}$ $\quad A1_{frac} = 0.819$ $\quad A1_c(i) := NSC(i) \cdot A1_{frac}$

Write in terms of Surfaced Displacement to solve for NSC displacement in terms of weight:

$W_{5est2}(i) := A1_c(i) \cdot W_{5frac}(i)$

$W_{6est2}(i) := A1_c(i) \cdot W_{6frac}(i)$

$$\Delta_{surfest}(i) := \frac{(1 + W_{PBfrac}) \cdot \left(W_{1est}(i) + W_{2est}(i) + W_{3est}(i) + \frac{V_d(i)}{35 \cdot \frac{ft^3}{lton}} + W_{7est}(i) \right)}{\left[(1 - W_{VLfrac}) - (1 + W_{PBfrac}) \cdot \left[\left(\frac{W_{4frac}(i)}{A1_{frac}} + W_{5frac}(i) + W_{6frac}(i) \right) \cdot A1_{frac} \right] \right]}$$

VII. OUTPUT

$$\text{Volumes} := \begin{pmatrix} V_{ER}(0) & V_{ER}(1) & V_{ER}(2) & V_{ER}(3) & V_{ER}(4) & V_{ER}(5) \\ V_{opsm}(0) & V_{opsm}(1) & V_{opsm}(2) & V_{opsm}(3) & V_{opsm}(4) & V_{opsm}(5) \\ V_{aux}(0) & V_{aux}(1) & V_{aux}(2) & V_{aux}(3) & V_{aux}(4) & V_{aux}(5) \\ V_{VB}(0) & V_{VB}(1) & V_{VB}(2) & V_{VB}(3) & V_{VB}(4) & V_{VB}(5) \\ V_{PH}(0) & V_{PH}(1) & V_{PH}(2) & V_{PH}(3) & V_{PH}(4) & V_{PH}(5) \\ V_{s}(0) & V_{s}(1) & V_{s}(2) & V_{s}(3) & V_{s}(4) & V_{s}(5) \\ V_{env}(0) & V_{env}(1) & V_{env}(2) & V_{env}(3) & V_{env}(4) & V_{env}(5) \\ V_{ff}(0) & V_{ff}(1) & V_{ff}(2) & V_{ff}(3) & V_{ff}(4) & V_{ff}(5) \\ V_{ob}(0) & V_{ob}(1) & V_{ob}(2) & V_{ob}(3) & V_{ob}(4) & V_{ob}(5) \\ V_{sa}(0) & V_{sa}(1) & V_{sa}(2) & V_{sa}(3) & V_{sa}(4) & V_{sa}(5) \\ V_{eb}(0) & V_{eb}(1) & V_{eb}(2) & V_{eb}(3) & V_{eb}(4) & V_{eb}(5) \\ V_{bt}(0) & V_{bt}(1) & V_{bt}(2) & V_{bt}(3) & V_{bt}(4) & V_{bt}(5) \\ V_{tot}(0) & V_{tot}(1) & V_{tot}(2) & V_{tot}(3) & V_{tot}(4) & V_{tot}(5) \\ V_{FB}(0) & V_{FB}(1) & V_{FB}(2) & V_{FB}(3) & V_{FB}(4) & V_{FB}(5) \\ V_{AB}(0) & V_{AB}(1) & V_{AB}(2) & V_{AB}(3) & V_{AB}(4) & V_{AB}(5) \\ V_{cc}(0) & V_{cc}(1) & V_{cc}(2) & V_{cc}(3) & V_{cc}(4) & V_{cc}(5) \end{pmatrix}$$

$$\text{Areas} := \begin{pmatrix} A_{sr}(0) & A_{sr}(1) & A_{sr}(2) & A_{sr}(3) & A_{sr}(4) & A_{sr}(5) \\ A_{os}(0) & A_{os}(1) & A_{os}(2) & A_{os}(3) & A_{os}(4) & A_{os}(5) \\ A_{opsm}(0) & A_{opsm}(1) & A_{opsm}(2) & A_{opsm}(3) & A_{opsm}(4) & A_{opsm}(5) \\ WS_{tot}(0) & WS_{tot}(1) & WS_{tot}(2) & WS_{tot}(3) & WS_{tot}(4) & WS_{tot}(5) \end{pmatrix}$$

$$\text{Lengths} := \begin{pmatrix} L_{f}(0) & L_{f}(1) & L_{f}(2) & L_{f}(3) & L_{f}(4) & L_{f}(5) \\ L_{a}(0) & L_{a}(1) & L_{a}(2) & L_{a}(3) & L_{a}(4) & L_{a}(5) \\ L_{pmb}(0) & L_{pmb}(1) & L_{pmb}(2) & L_{pmb}(3) & L_{pmb}(4) & L_{pmb}(5) \\ ER_{length}(0) & ER_{length}(1) & ER_{length}(2) & ER_{length}(3) & ER_{length}(4) & ER_{length}(5) \\ OPS_{length}(0) & OPS_{length}(1) & OPS_{length}(2) & OPS_{length}(3) & OPS_{length}(4) & OPS_{length}(5) \end{pmatrix}$$

$$\text{Weights} := \begin{pmatrix} W_{1est}(0) & W_{1est}(1) & W_{1est}(2) & W_{1est}(3) & W_{1est}(4) & W_{1est}(5) \\ W_{2est}(0) & W_{2est}(1) & W_{2est}(2) & W_{2est}(3) & W_{2est}(4) & W_{2est}(5) \\ W_{3est}(0) & W_{3est}(1) & W_{3est}(2) & W_{3est}(3) & W_{3est}(4) & W_{3est}(5) \\ W_{4est}(0) & W_{4est}(1) & W_{4est}(2) & W_{4est}(3) & W_{4est}(4) & W_{4est}(5) \\ W_{5est}(0) & W_{5est}(1) & W_{5est}(2) & W_{5est}(3) & W_{5est}(4) & W_{5est}(5) \\ W_{6est}(0) & W_{6est}(1) & W_{6est}(2) & W_{6est}(3) & W_{6est}(4) & W_{6est}(5) \\ W_{7est}(0) & W_{7est}(1) & W_{7est}(2) & W_{7est}(3) & W_{7est}(4) & W_{7est}(5) \\ A1_c(0) & A1_c(1) & A1_c(2) & A1_c(3) & A1_c(4) & A1_c(5) \\ \Delta_{surfest}(0) & \Delta_{surfest}(1) & \Delta_{surfest}(2) & \Delta_{surfest}(3) & \Delta_{surfest}(4) & \Delta_{surfest}(5) \\ \Delta_s(0) & \Delta_s(1) & \Delta_s(2) & \Delta_s(3) & \Delta_s(4) & \Delta_s(5) \\ \Delta_{ff}(0) & \Delta_{ff}(1) & \Delta_{ff}(2) & \Delta_{ff}(3) & \Delta_{ff}(4) & \Delta_{ff}(5) \\ \Delta_{env}(0) & \Delta_{env}(1) & \Delta_{env}(2) & \Delta_{env}(3) & \Delta_{env}(4) & \Delta_{env}(5) \\ \Delta_{envd}(0) & \Delta_{envd}(1) & \Delta_{envd}(2) & \Delta_{envd}(3) & \Delta_{envd}(4) & \Delta_{envd}(5) \\ W_{VL}(0) & W_{VL}(1) & W_{VL}(2) & W_{VL}(3) & W_{VL}(4) & W_{VL}(5) \end{pmatrix}$$

$$\text{Hull\_Form} := \begin{pmatrix} LOD(0) & LOD(1) & LOD(2) & LOD(3) & LOD(4) & LOD(5) \\ C_p(0) & C_p(1) & C_p(2) & C_p(3) & C_p(4) & C_p(5) \\ C_s(0) & C_s(1) & C_s(2) & C_s(3) & C_s(4) & C_s(5) \end{pmatrix}$$

$$\text{Error\_checks} := \begin{pmatrix} Err_{vph}(0) & Err_{vph}(1) & Err_{vph}(2) & Err_{vph}(3) & Err_{vph}(4) & Err_{vph}(5) \\ Err_{env}(0) & Err_{env}(1) & Err_{env}(2) & Err_{env}(3) & Err_{env}(4) & Err_{env}(5) \\ Err_{\Delta env}(0) & Err_{\Delta env}(1) & Err_{\Delta env}(2) & Err_{\Delta env}(3) & Err_{\Delta env}(4) & Err_{\Delta env}(5) \end{pmatrix}$$

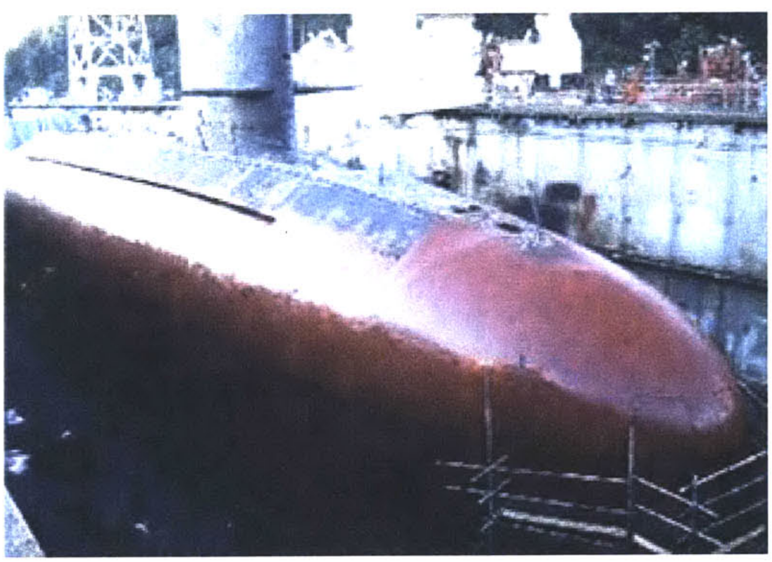
END

Appendix D: Submarine Profile and Plan Drawings

SS 580 USS Barbel

Surface Displacement:	2146 Ltons
Submerged Displacement:	2639 Ltons
Length:	67 m
Diameter:	8.8 m
Complement:	77 (8 officers)
Electrical Generator Capacity:	1700 KW
Propulsion Motor Power:	4800 SHP
Maximum Surfaced Speed:	14 Kts
Maximum Submerged Speed:	18 Kts
Diving Depth:	213 m
Overall Endurance Range:	14,000 Nm
Deployment Endurance:	90 Days
Torpedo Tubes:	6
Torpedo Capacity:	18
Builder:	Portsmouth Naval Shipyard
Year:	1959
Other:	Decommissioned 1989

* Plan and Profile dimensions obtained from Submarine SS 580 Booklet of General Plans, BUSHIPS NO. SS 580-845-1702763, Naval Shipyard Portsmouth, NH

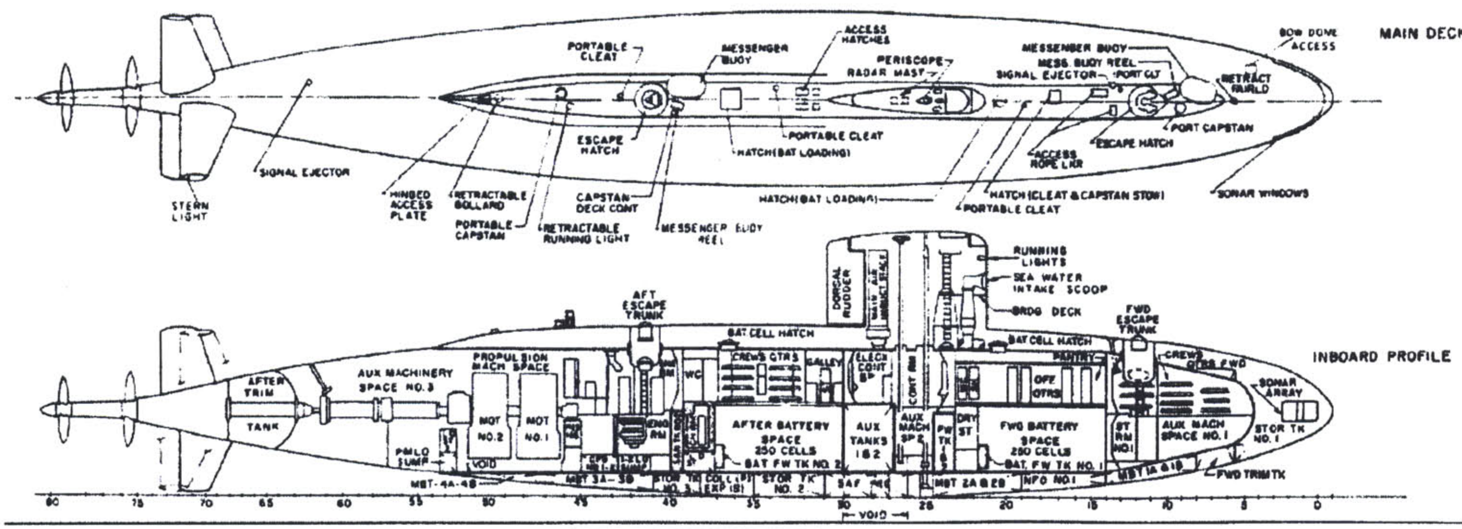


AGSS 569 USS Albacore

Surface Displacement:	1692 Ltons
Submerged Displacement:	1908 Ltons
Length:	63 m
Diameter:	8.4 m
Complement:	52 (5 officers)
Electrical Generator Capacity:	1634 KW
Propulsion Motor Power:	7500 SHP
Maximum Surfaced Speed:	25 Kts
Maximum Submerged Speed:	33 Kts
Diving Depth:	183 m
Overall Endurance Range:	10,000 Nm
Deployment Endurance:	50 Days
Torpedo Tubes:	0
Torpedo Capacity:	0
Builder:	Portsmouth Naval Shipyard
Year:	1953
Other:	Experimental submarine; Decommissioned 1972 Low L/D ratio of 7.5:1 Counter-rotating propellers "X" Shaped Stern
Batteries:	Lead-Acid produced 7500 SHP Silver-Zinc produced 15,000 SHP

* Scaled plan view dimensions obtained from SS 580

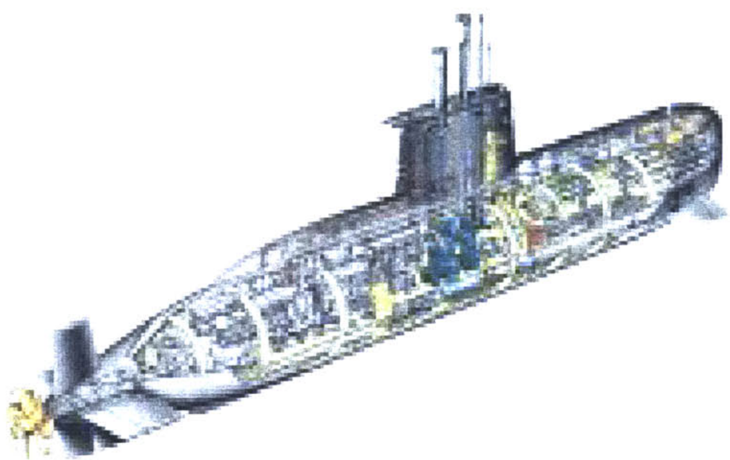
USS ALBACORE (AGSS 569)



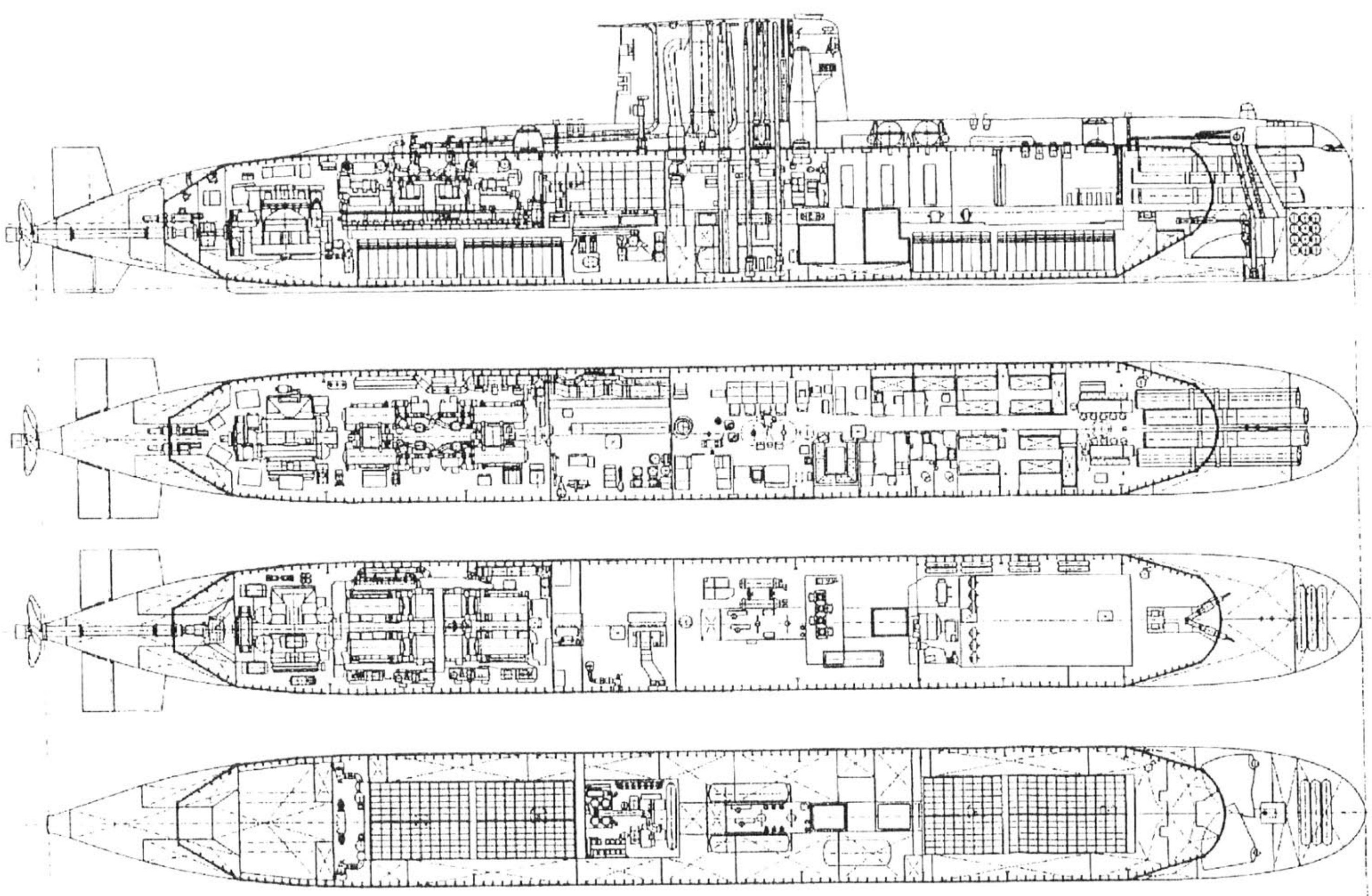
Profile View

Type 209/1200

Surface Displacement:	1100 Ltons
Submerged Displacement:	1285 Ltons
Length:	56 m
Diameter:	6.2 m
Complement:	33 (6 officers)
Electrical Generator Capacity:	2800 KW
Propulsion Motor Power:	4600 SHP
Maximum Surfaced Speed:	11 Kts
Maximum Submerged Speed:	22 Kts
Diving Depth:	250 m
Overall Endurance Range:	7,500 Nm
Deployment Endurance:	50 Days
Torpedo Tubes:	8
Torpedo Capacity:	14
Builder:	Howaldtswerke-Deutsche Werft GmbH (HDW)
Year:	1993
Number of ships:	9 (one built at HDW, remaining in South Korea)
Other:	Possible AIP Backfit



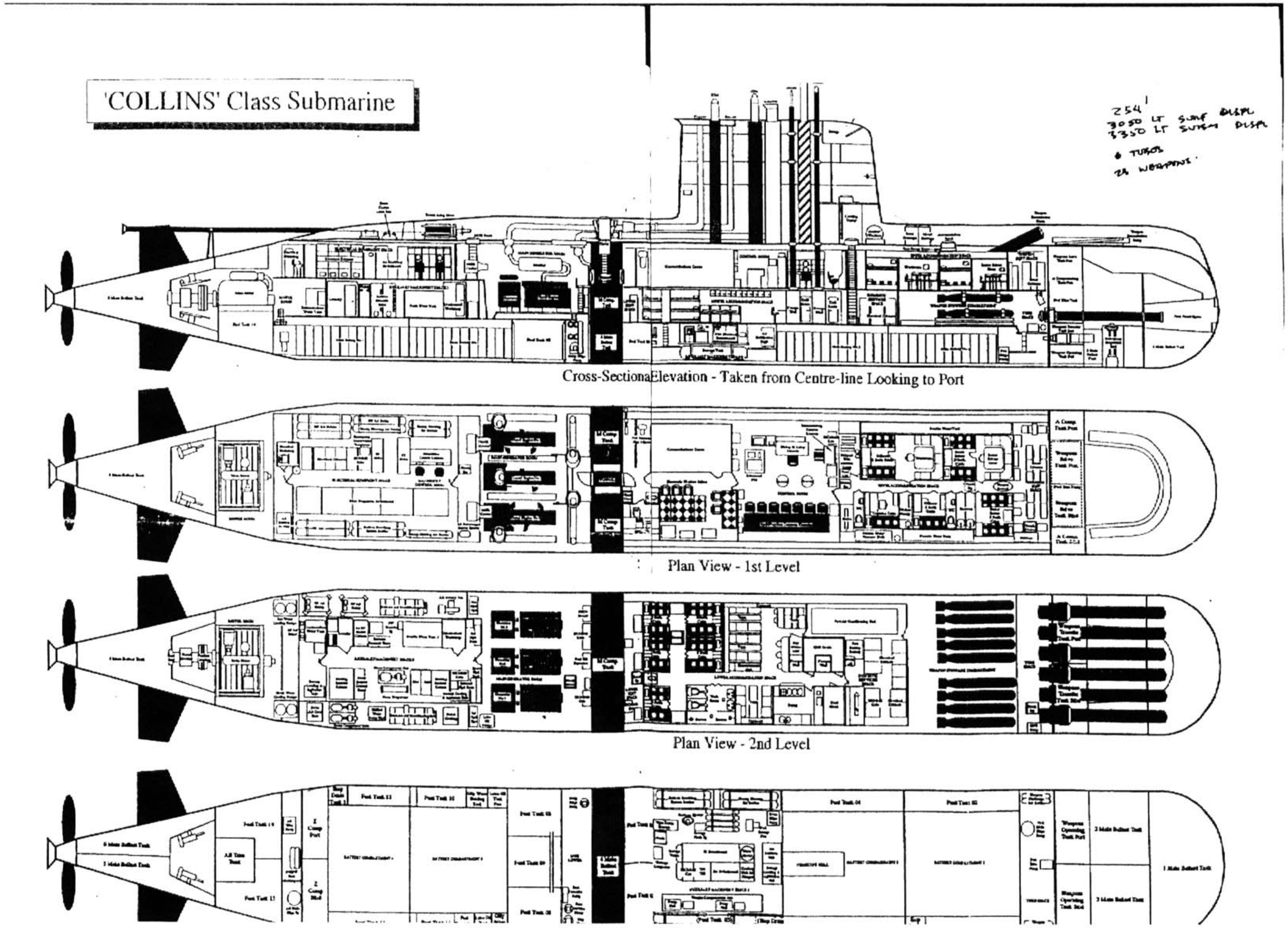
Type 209/1200



Profile and Plan Views

Collins 471

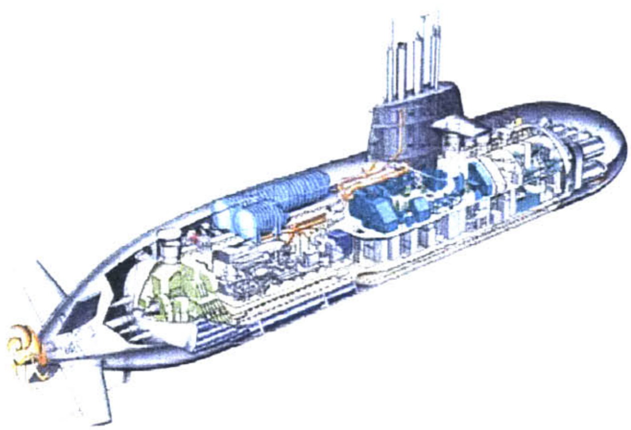
Surface Displacement:	3050 Ltons
Submerged Displacement:	3350 Ltons
Length:	78 m
Diameter:	7.8 m
Complement:	42 (6 officers)
Electrical Generator Capacity:	4420 KW
Propulsion Motor Power:	7344 SHP
Maximum Surfaced Speed:	10 Kts
Maximum Submerged Speed:	20 Kts
Diving Depth:	300 m
Overall Endurance Range:	11,500 Nm
Deployment Endurance:	60 Days
Torpedo Tubes:	6
Torpedo Capacity:	22
Builder:	Australian Submarine Corp, Adelaide
Year:	1996
Number of ships:	6
Other:	Kockums' Design



Profile and Plan Views

Type 212A

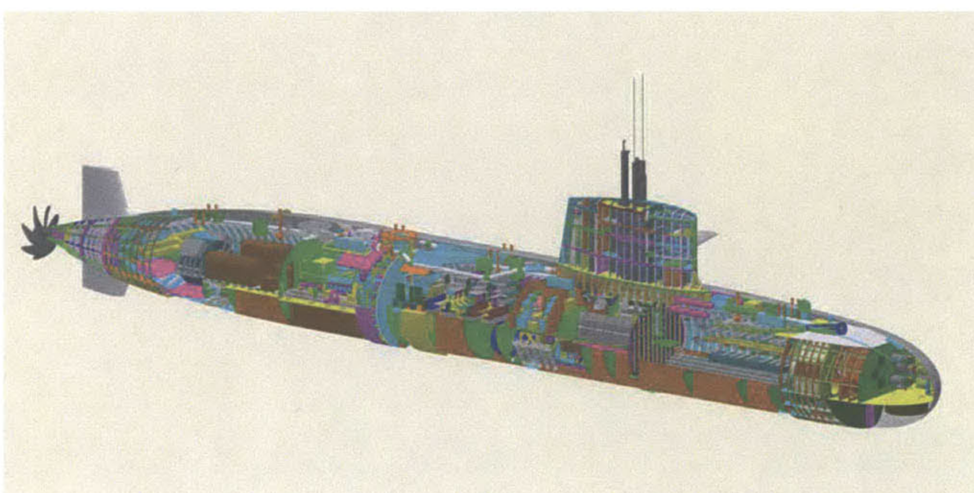
Surface Displacement:	1450 Ltons
Submerged Displacement:	1830 Ltons
Length:	56 m
Diameter:	7 m
Complement:	27 (8 officers)
Electrical Generator Capacity:	3120 KW
Propulsion Motor Power:	3875 SHP
Maximum Surfaced Speed:	12 Kts
Maximum Submerged Speed:	20 Kts
Diving Depth:	350 m
Overall Endurance Range:	8,000 Nm
Deployment Endurance:	60 Days
Torpedo Tubes:	6
Torpedo Capacity:	12
Builder:	Howaldtswerke-Deutsche Werft GmbH (HDW)
Year:	2004
Number of ships:	4
Other:	Siemens PEM (Proton Exchange Membrane) 306 KW Fuel Cell



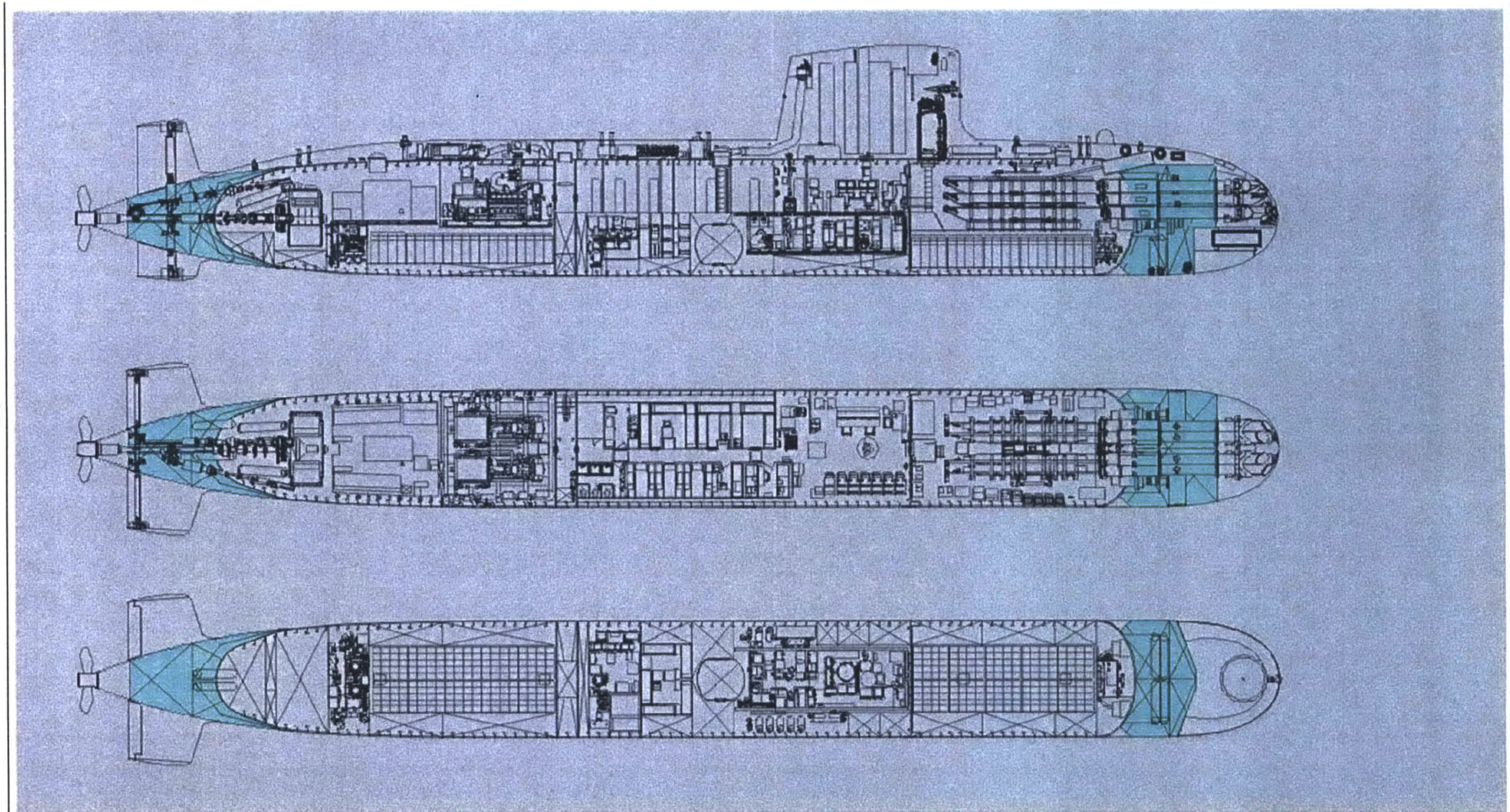
* Scaled plan view dimensions obtained from Type 209/1200

IZAR S80/ P650

Surface Displacement:	1744 Ltons
Submerged Displacement:	1922 Ltons
Length:	67 m (AIP Add-on Section, 9 m)
Diameter:	6.6 m
Complement:	40 (8 officers)
Electrical Generator Capacity:	2805 KW
Propulsion Motor Power:	4694 SHP
Maximum Surfaced Speed:	12 Kts
Maximum Submerged Speed:	20 Kts
Diving Depth:	350 m
Overall Endurance Range:	7,500 Nm
Deployment Endurance:	50 Days
Torpedo Tubes:	6
Torpedo Capacity:	18
Builder:	IZAR, Cartegena Spain
Year:	2007
Number of ships:	4 (plus 4 as an option)
Other:	MESMA (Module Energie Sans-Marin Autonome) AIP 600kW Fuel Cell
Indiscretion Rate:	17% @ 8 knots; 6.5% @ 4 knots SOA
Diving Endurance:	400 nm @ 4 knots (1,500 nm with AIP)
Masts:	Hoisting mechanism for 7 masts; only penetrating mast is the attack periscope
Batteries:	Two Groups of 200 Battery Cells



P 650



Profile and Plan Views

Appendix E: Submarine Shape Factors

Figure 18 from Reference (9)

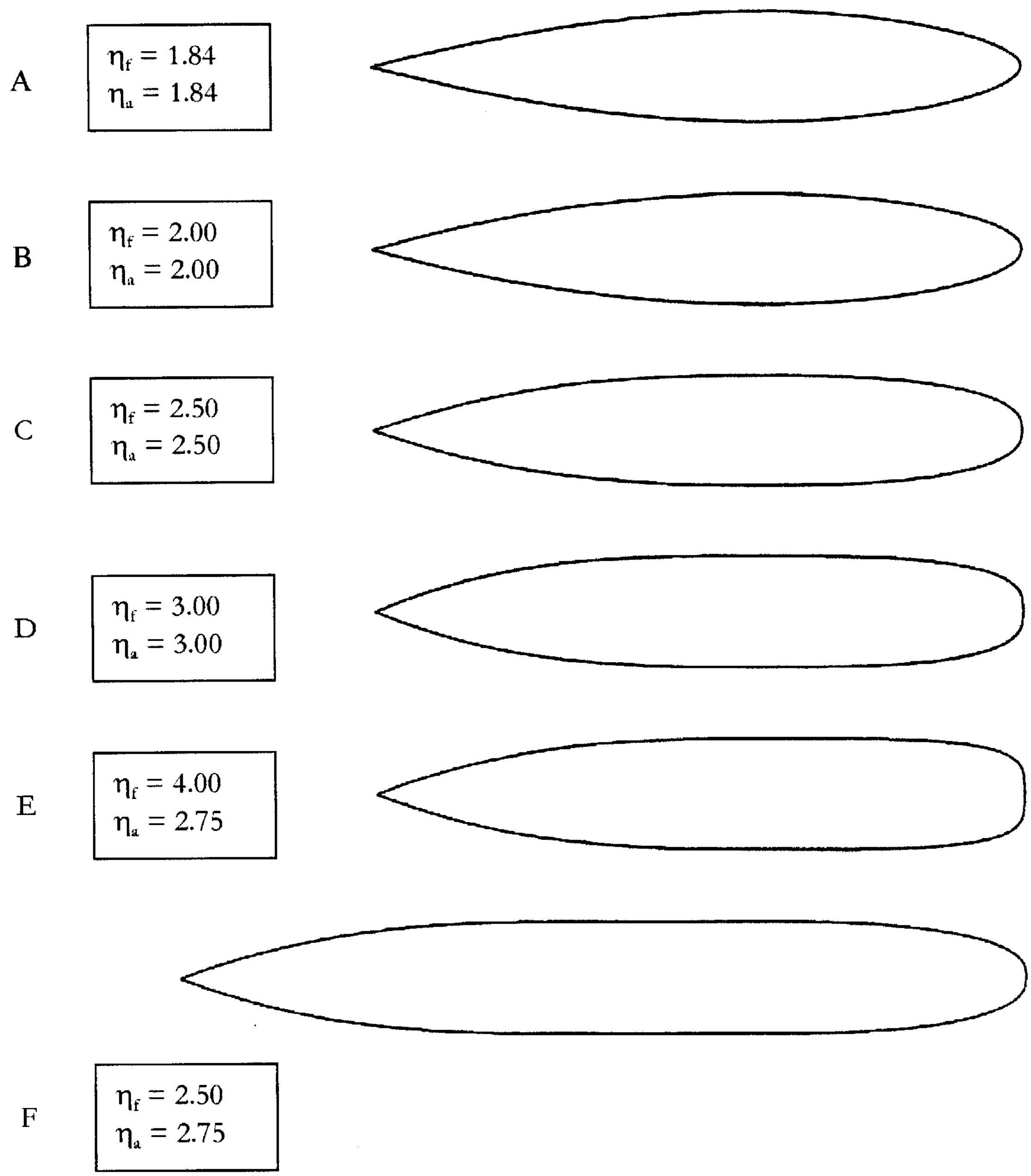


Figure 18 contains profiles of submarines developed from equations in reference (9). Hull A is near the optimum in the series 58 model basin tests (9).