Applying Set Based Methodology in Submarine Concept Design

by

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B.S. Mechanical Engineering, Virginia Military Institute, 2001

Submitted to the Department of Mechanical Engineering and the Engineering Systems Division
in Partial Fulfillment of the Requirements for the Degrees of

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ABSTRACT

Early stage ship design decisions continue to be a challenge for naval architects and engineers. The complex interactions between the different elements of the ship and the broad spectrum of disciplines required in ship design make it difficult to fully realize the effects and limitations early decisions place on design flexibility.

Naval ship design has primarily focused on using point based design methods that do not necessarily produce the most cost effective, innovative, and high quality designs. Recognizing these shortcomings, U.S Navy design is exploring the use of Set Based Design (SBD) principles and methodology in designing the fleet for the 21st century. Existing research has shown the merits of SBD in other industries; however, research on the use of SBD in naval design does not exist.

The thesis explores how to execute SBD in light of the recent restructuring of the U.S. Navy acquisition process calling for the use of SBD in pre-preliminary design. This is undertaken using the knowledge gained from exploration of the Ship-to-Shore Connector (SSC) program, the first use of SBD in a new start acquisition program.

The thesis concludes by applying the derived information to an early stage submarine concept design. This effort focused on how to develop submarine design parameters and exploration of how to create and reduce integrated concepts.

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BIOGRAPHICAL NOTE AND ACKNOWLEDGEMENTS

Matthew Frye is a Lieutenant in the U.S. Navy. He received his B.E. from Virginia Military Institute in Mechanical Engineering in 2001. Commissioned as an Ensign in the U.S. Navy from Officer Candidate School, he is qualified in submarines and served three years aboard the USS CHEYENNE (SSN 773). He transferred into the Engineering Duty Community where he will design, maintain, and acquire submarines for the U.S. Navy.

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1.0 Introduction

Submarine design is one of many engineering design activities that involve complex relationships ranging from satisfying customer design requirements to detailed design drawings created for manufacturing. With the dearth of information available in textbooks and across the internet, one can readily find information on submarine design and engineering practices. Much of this information follows from historical design methods such as point based approaches and building block methods. This paper seeks to add to the body of existing work by exploring a methodology, Set-Based Design (SBD), and its application in the concept exploration phase of submarine design. Much of the work will center on U.S. naval design and all information contained within is obtained from open sources.

1.1 What is Set Based Design?

SBD has become a recognized design methodology (based on the study of Toyota Motor Corporation described in Chapter 2) and as summarized by Bernstein, "While set- based concurrent engineering [set based design] consists of a wide variety of design techniques, the basic notions can be stated in two principles: 1) engineers should consider a large number of design alternatives, i.e., sets of designs, which are gradually narrowed to a final design, and 2) in a multidisciplinary environment, engineering specialists should independently review a design from their own perspectives, generate sets of possible solutions, and then look for regions of overlap between those sets to develop an integrated final solution." [1]

1.2 Motivation for Research

Failures in ship programs have been traced to a host of factors including failures in the design process, unrealistic expectations, changing requirements, etc. The traditional design process has succumbed to these issues because historical methods are not inherently capable of managing the complexity of large-scale product design. Success has been achieved in the past; however, it often came at the hands of individual efforts to push through the existing design environment and process hurdles. In design environments where many of the critical skills and experience of the U.S. naval design community have been lost, the transition to younger designers prevents the reliance on personnel experience and capabilities. The ability to capture created knowledge that can be imparted later in the design or potentially many years later would alleviate such issues.

This transition is happening at a time when the already complex nature of ship design is seemingly becoming more complex. This can be owed to component and equipment advances and high technology refresh rates. Employing innovation in new designs requires understanding the potential tradeoffs and interface management. Thus, there is a need to explore multiple options and provide a sound framework to compare integrated concepts.

These are only a couple of the concerns in the future naval design environment. One not previously discussed, but potentially the most important is the budget. Naval design operates within the confines of the Department of Defense (DOD) acquisition process. Acquisition is an incredibly regulated activity and although reform in that area is beyond the scope of this thesis, the manner in which a design is approached has direct connections in creating a better system. In an era where limited budgets, emerging technology, and evolving mission capabilities complicate the design space, solutions to these issues come in many forms.

Naval design has experienced an evolution of design methods and practices. The use of Integrated Product Teams (IPT) is one such example. Keane et. al. discuss the critical need to extend this effort beyond detailed design phase to produce a collaborative product development environment with the hopes of providing a solution to some of the Navy's critical cost and future design issues.[3] In the current design environment, new methods for design communication, integration, and information transfer are needed.

SBD represents one such method; however, the ability to transition into an environment where a new methodology can be implemented requires a large amount of work such as:

- Determining what platforms SBD can be implemented on? [Where]
- When can SBD be used? [When]
- How is SBD executed? [How]
- What is the real (versus hypothetical) value in SBD? [Validation]

The list above is only a few of the many concerns and questions surrounding SBD implementation. Research in this area seeks to answer existing questions which will undoubtedly uncover new ones.

1.3 Objective and Outline of Thesis

The goal of this thesis was to explore how to execute SBD recognizing the recent restructuring of the DOD acquisition process calling for its use in pre-preliminary design. This is then applied to an early stage submarine concept design in order to:

1) Provide a framework for trade space exploration.
2) Determine best method and practices for screening of design factors.
3) Develop a method for design parameter integration that can be used to selectively reduce the number of integrated concepts.

This task was undertaken through looking at SBD applications in a naval design environment. Although this research contains discussions of other design methodologies, the goal of the research was not to expound upon the virtues of SBD. Rather, this work aims to focus on the execution side (how, when, and if's) of SBD. Any discussion that includes commentary in regards to the advantages of SBD is intended to provide context for the methodology.

Chapter 2 discusses where SBD fits in within the naval acquisition process, potential value it brings to the table, and what one could expect from its use. This section concludes with a general discussion of how to apply SBD.

The thesis continues by looking at the Ship-to-Shore Connector (SSC) program, the first use of SBD in a new start acquisition program, and is contained in Chapter 3. The knowledge gained from exploration of the program and the lessons learned from the SSC program provide guidance on how to execute SBD, how SBD interacts and fits in with the plethora of naval design guidance documents, and what hurdles and issues that arose throughout that design effort. Commentary is included on the success and failures the program achieved using SBD.

Chapter 4 follows by taking the information garnered from the SSC program and developing a framework that can be used for naval applications. This framework identifies general steps for concept exploration with details provided on methods for executing these steps.

Chapter 5 looks at applying elements from the developed framework to the submarine concept exploration process. In particular, this section identifies how the "sets" are defined (elements, attributes, and ranges), the process by which these sets are narrowed, and how to develop integrated concepts. Additionally, how to use SBD principles to facilitate requirement development and traceability is included.

The thesis concludes by looking at methods to facilitate the transition to SBD by looking at the early stage design processes of the OHIO Class replacement program. Advanced concepts in SBD are noted and areas for future work identified.

2.0 Design Process Background

Prior to exploring a shift to a new design paradigm, one must first look at the evolution of naval design practices which has historically been characterized by a spiral design approach. SBD is then introduced and its role in the ship design process is discussed. This sets the stage for discussion of the use of SBD in the SSC program.

2.1 Evolution of Ship Design Methods and Practices

The traditional approach to developing ship designs utilized a process dubbed the "design spiral" as published by J. Evans in 1959. This model recognizes the complex nature of ship design and approaches the design process from the view of conducting iterative passes from one element to the next: weight, volume, structure, stability, resistance, powering, trim, etc. By systematically addressing each element in sequence and doing so in increasing detail in each pass around the spiral, a single balanced design which satisfies all constraints can be reached. This approach to design is synonymous with the term point based design since each pass through the spiral attempts to resolve conflicts between elements and develop a design that meets requirements. The result is a base design that is feasible but not typically a global optimum. Another disadvantage is that the number of iterations around the spiral is generally limited by the available time and budget with the design often considered complete when the design period has reached the end of its scheduled time.

The highly iterative nature of point based approaches has evolved over time. One such evolution is concurrent engineering (CE). In CE, a point based design approach is still implemented but the integration of development teams allows engineers to analyze design facets in parallel and helps in design communication. [1] These cross functional teams, or IPTs, allow for faster feedback and flows of information. IPTs, discussed below, were utilized heavily by in the VIRGINIA (VA) class submarine design process. Communication is further enhanced through collocation. Collocation shortens the design processes and mitigates the errors due to limited intra-team communication caused by distance. The increased complexity of designs in many industries has driven the CE push; however, it does not change the fundamental point design process. [1]

The development of the VA class submarine used a multidisciplinary team-based concurrent engineering approach. Integrated Product and Process Development (IPPD) teams brought the combined experience of the shipbuilders, vendors, designers, engineers, and ship operators to bear on the ship design.[4] IPPD is a concurrent approach to developing all the life cycle processes necessary to design, build, operate, and maintain the craft at the same time the craft is being developed. Thus, IPPD is a multi-disciplinary integration and teamwork approach based on the use of IPTs involving the life cycle process stakeholders in the design of the craft. IPTs are project specific groups consisting of designated personnel from stakeholder organizations whose participation ranges from a full-time commitment to ad-hoc representation to address specific issues. Specifically for the VA class submarine project, the IPT structure facilitated decision-making and product development. The IPT approach took advantage of all members' expertise. The early involvement of production personnel on these teams ensured a match between the design and the shipbuilder's construction processes and facilities, allowed a smoother transition from design to production, and reduced the number of engineering change orders typically required during lead ship construction.

The IPPD approach has been augmented with an additional methodology, Design-Build-Test (DBT) which is a repetitive iterative approach based on designing concepts, testing concepts, and improving concepts based on testing. DBT facilitated the integration process.

2.2 Defining Set Based Design Principles

What is known about the principles as well as execution of SBD is derived in large part to the significant body of research involving the Toyota Motor Corporation; a car manufacturer that created a strategy coined "set based development" and has become one of the car industry leaders. [5] Traditional product development wisdom dictates the early selection of a single design in order to freeze interfaces between product subsystems so that team members can work effectively in parallel. This would seem to result in more productive product development effort. This makes sense considering that uncertainty in product development projects creates significant challenges for managers who strive to increase product quality, while reducing development time and costs. Toyota has however capitalized on its ability to converge to a final preferred concept in a manner which does not restrict the trade space early on and actually uses delayed decision making and "sets" with variable ranges to explore the trade space. Once information becomes available to the designers at stages further along the design path, decisions are then made on what alternatives to eliminate. Remaining concepts continue in development until additional information and studies are performed. These principles are not only applied to the design itself but also to the engineering requirements. Thus, Toyota develops a variety of concepts which would meet a range of requirements. [5] The main features of this design process are summarized as follows:

- Broad sets of design parameters are defined to allow concurrent design to begin.
- These sets are kept open longer and explored in greater detail than typical to more fully define tradeoff information.
- As the sets narrow, the level of detail (or design fidelity) increases.
- The sets are gradually narrowed until a more globally optimum solution is revealed and refined.

This was characterized by Alan Ward as set-based design. It differs from point-based design where critical interfaces are defined by precise specifications early in the design so that subsystem development can proceed. Often these interfaces must be defined, and thus constrained, long before the needed tradeoff information is available, inevitably resulting in a sub-optimal overall design.

2.3 Defining the Value of SBD

There is no arguing the success that Toyota has experienced; however, clearly linking this success to the use of a SBD mentality requires looking deeper into the Toyota design process. This begins by studying the balance between manufacturing and design processes. At first, they seem to be counter intuitive. This has been written and discussed by multiple sources and is dubbed the first Toyota paradox and is associated with Toyota in its Lean Manufacturing System and just-in time inventory. The paradox comes in the form that during the 1980's, Toyota did not follow traditional manufacturing approaches. Traditional manufacturing practice holds that economy of scale is the best path to better products at lower cost: one minimizes price by maximizing machine speed and capacity while neglecting the impact of space, transportation, and inventory; however, Toyota operated with little to no inventory and manufactured vehicles at a lower cost with better quality.

A second paradox, described by Ward et. al., lies at the foundation of the SBD concept and demonstrates how even though Toyota severely delays critical design decisions when compared to other auto manufacturers, their time to market is shorter than the competition. [6] Delaying decisions has the initial undesirable consequence of carrying along design alternatives that will be trimmed later on directly resulting in greater cost and man-hours up front. Delaying decisions, however, allows the design team to make decisions when more knowledge has been acquired. This provides designers and engineers greater influence on the design space as it is defined in greater detail and ideas on cost are more clearly understood.

This highlights the first major area where SBD has impact: Cost. A major problem in U.S. naval design practices (if not in many product development organizations) is that early in the design process, cost estimates on the final product are made and a budget is created that attempts to match the initial cost. This happens even though the major portions of the total ship cost are not incurred until much later in the design process. SBD strives to reduce the Committed Costs to more closely follow the Incurred Costs. The work of Bernstein illustrates this mismatch.

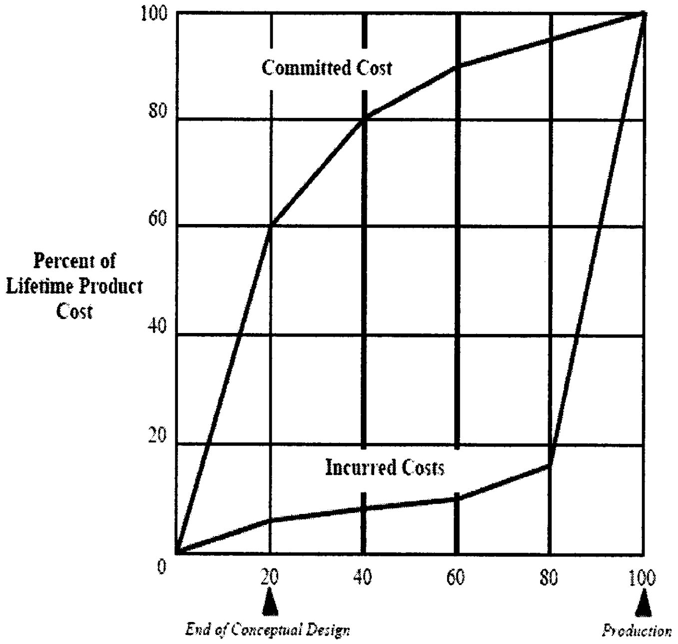

Figure 1: Designed in Costs [1]

Late in the design cycle, the ability to affect cost is significantly decreased and often times, the ability to pull money from one source and reallocate is not possible.

This follows with the next major area where SBD has impact: Knowledge. In any design, knowledge increases over time. The ability to leverage this fact and take full advantage is not something traditional design practices have been able to accomplish. Early design decisions are made by the engineers and managers even though the customer is not sure what they want and the details of the design are not well defined, developed, or understood. Consequently, the decisions made during these stages are done so with incorrect and incomplete data. As the design evolves over time the engineers, managers and customer better understand, due to analysis and experience, the product and the requirements that are driving the product design.

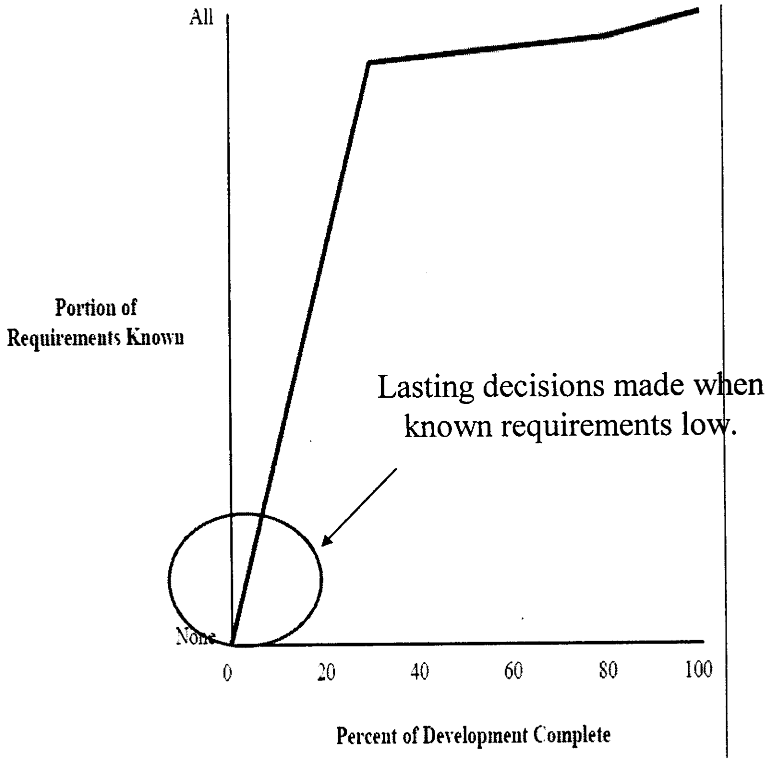

Figure 2: Evolution of Design Knowledge [1]

One area remains where SBD has impact: Stakeholder Influence. As touched on before, the initial stages of the design process are where stakeholders can have the greatest impact. At this stage, the design and its requirements can be considered a blank canvas and thus any decision made has a direct impact on the final product performance and cost. As the design proceeds, the ability to impact the design diminishes because the design becomes more locked in and any major change, cost prohibitive. This ultimately results in the following figure which illustrates the desire to delay cost commitment and increase stakeholder influence late in the design while recognizing the knowledge/requirement relationship.

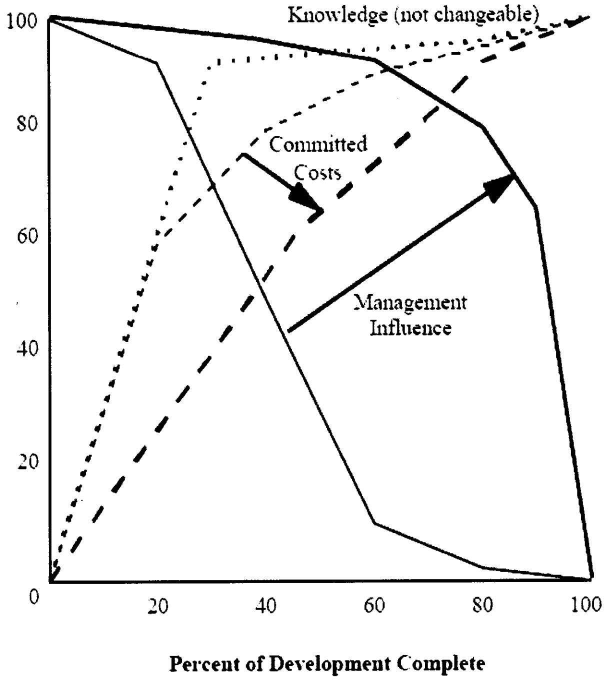

Figure 3: Areas of SBD Impact [1]

As stated earlier, the goal underpinning the use of SBD is the delay of critical decisions to the latest point possible. By delaying decisions, one can improve the design by delaying the commitment of cost until later in the design process and until such time that information is much better. By delaying the cost commitment one also increases the time in which stakeholders can influence a design.

Much of the research done on Toyota has demonstrated how they were able to achieve a competitive advantage using SBD. As noted earlier, the parallel development that exists in this type of environment requires additional resources which will incur greater up front cost. The danger here lies in the fact that if these cost were to be so large as to dominate the creation of value in the project, overall project success, particularly that tied to SBD principles, would be in jeopardy. Without understanding the underlying mechanisms at work, applying set-based development is fraught with risk. [7] Ford, et. al warns that a better understanding of the underlying causal relationships within this approach is needed for organizations to take maximum advantage while minimizing risk.

2.4 Where does Set Based Design fit in?

Although many organizations would like to emulate the success of Toyota, completely copying the model set forth by the company would not work in a number of industries namely U.S naval design. The nature of the car industry combined with the culture of the company makes it implementation in that form ideal.

In a naval design application, matching a design methodology with that required to make ship design a process that is innovative, affordable, flexible, etc., requires matching the available inputs and outputs of steps throughout the process to the method that is used. These steps are defined in the DOD acquisition process which was implemented in its modified form in 2008 by the Secretary of the Navy. [8/9] The goal of the modification from its preceding form was to involve the appropriate stakeholders in the acquisition decisions at an earlier stage. As shown in Figure 1, the "2 Pass – 6 Gate" process, involvement begins with the Initial Capabilities Document (ICD) and continues through system development and demonstration.

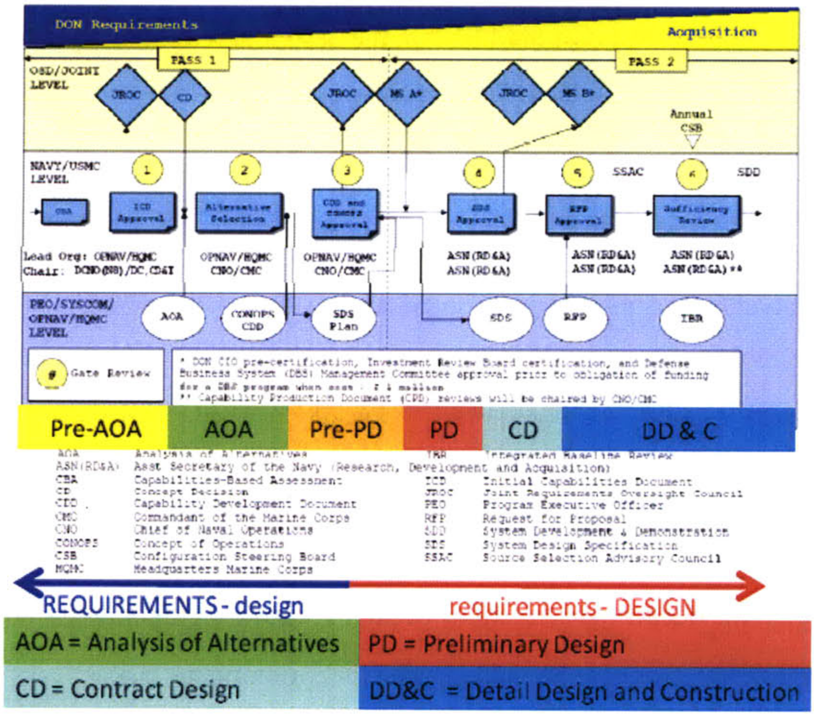

Figure 4: Navy Acquisition 2 Pass, 6 Gate Acquisition Process and Stages of Design

Figure 4 maps the traditional ship design stages onto the new process. Of particular note is the Pre-Preliminary Design (PPD) phase between the completion of the Analysis of Alternatives (AOA) and Preliminary Design (PD). SBD is anticipated to provide the greatest benefit during this phase as the general inputs and outputs in its use fit both the AOA and PD.

In the past, the outcome of an independently conducted AOA was a preferred alternative, or at most two or three alternatives, that would proceed into a PD. This has not been the case in the last few years as the AOAs for LHA(R), MPFF, and CG(X) did not produce a preferred alternative that the Navy proceeded to produce. For LHA(R) and MPFF, the final acquisition alternative implemented was not part of the recommended solution set coming out of the AOA.[10/11] For CG(X), the final acquisition alternative had not been selected a year after the originally scheduled completion of the AOA and final program cancellation only recently occurred.[12] The AOAs essentially only managed to identify a range of possible solutions for a range of desired capabilities which as shown later works within the context of SBD but not in the realm of point based preliminary design. It was thus left to the Navy to further refine the requirements and solutions before the commencement of PD. This led to the new "2 Pass – 6 Gate" process which recognizes the need for PPD between Gates 2 and 3.

2.5 Leveraging Set Based Design in the Acquisition Process

PPD provides the opportunity to perform trade-offs among individual system performance, total ship performance, requirements, the Concept of Operation (CONOPS) and cost. [13] Having recognized the inputs from the AOA may or may not provide a solid context or guidance for PD, PPD provides an opportunity to use SBD methodology where the plethora of activities performed by the wide range of geographically dispersed organizations presents a challenge for standard design doctrine.

By the completion of PPD, performing SBD in parallel with the development of a Capabilities Development Document (CDD)[1] allows for an earlier and more informed exploration of feasible requirements as specified in the CDD. This essentially leads to delaying decisions until requirements are better understood and helps the designers understand the impact of the requirements. This eventually leads to a fixed set of requirements that are derived with a total ship impact in mind. The ship design then proceeds at a level of detail where a quality cost estimate can be performed.

This varies significantly from past, traditional design efforts where at the start of PD, the requirements for the ship are largely fixed and large changes are generally avoided. This is the case despite information or studies coming to light that may cast doubt on the applicability of early design decisions. SBD practice offers considerable flexibility as changes or decisions made later in the design process provide system refinement and narrow the trade space ultimately resulting in a design that converges.

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[1] A CDD provides operational performance attributes, including supportability, for acquisition personnel in the military. It includes Key Performance Parameters (KPPs) and other parameters that guide the development, demonstration, and testing of the current increment. It also outlines the overall strategy for developing full capability.

3.0 Exploring the use of SBD on development of the SSC

The SSC program is the first ship/craft acquisition program to use SBD. Based on the scarcity of information available that discusses actual SBD implementation, exploration of its use in this program provides a framework in which to implement SBD in naval design. Some aspects of its implementation are sensitive in nature; however, discussion of those areas is not necessary for the purpose of understanding the SSC programs implementation of SBD. Much of the information contained in this section is contained from Reference 2 obtained from the SSC program office.

As compared to the Toyota method for applying SBD contained in Chapter 2, the SSC programs use of SBD was not part of the full concept/design/manufacturing life cycle. It was conducted in accordance with the PPD phase as noted in Chapter 2.

3.1 What is the SSC program?

The Ship-to-Shore Connector (SSC), as taken from its industry day announcement, is an Air Cushion Vehicle (ACV) that represents the future Navy craft for transporting vehicles, cargo, and personnel from ship-to-shore and/or seabase-to-shore. It is the planned replacement for the current Landing Craft, Air Cushion (LCAC), shown in Figure 5, as these craft reach the end of their service life.

Figure 5: US Navy LCAC
(photo courtesy of blog.richardslowry.com/.../01/NAVY_LCAC_lg.jpg)

SSC goals include providing high speed, over the horizon, heavy lift capability to transport personnel, equipment, and material for the United States Marine Corps' Marine Expeditionary Brigade (MEB). Like the LCAC, the SSC must have the ability to operate in the well decks of U.S. Navy amphibious ships, operate in planned amphibious and Maritime Prepositioning Force (MPF) ships, operate over beaches, ice, mud, and marsh areas, operate in inland regions, ascend varying beach gradients, and transport a cargo greater than 60 short tons.

Currently, the LCAC Service Life Extension Program (SLEP) started in 2002 is bridging the gap until the SSC is brought into the fleet. [14] For reference, the LCAC SLEP has a design payload of 70 short tons and maintains the available deck area of the LCAC. The SSC is intended to provide increased performance in the following areas: ability to operate in higher sea state conditions; increased payload, range, and speed; reduced crew; reduced maintenance and operational costs; and increased reliability and maintainability. The LCAC is scheduled for replacement by the SSC starting in the year 2019.

3.2 SBD Vocabulary

Terms key to an understanding of SBD are included below:

- Design Factor: A design factor (or design parameter and heretofore referred to as a factor) is an independent variable; it is something the designer can choose or influence to impact the design. In the SBD effort, all factors were initially assumed to impact the SSC design at the Craft level.
- Design Trade Space: The design trade space is defined by elements made up of candidate design factors.
- Element: An element describes a partitioned area of the trade space.
- Design Options: Factors are decomposed into design options (heretofore referred to as an option) that can either be a discrete or continuous range.
- Dominated Option (Combinations): A dominated option is one which has been determined to be inferior in all attributes to another. Those options left after the dominated options have been discarded are called non-dominated. This can also apply to combination of options within an element or across elements.

3.3 SBD role in the SSC Preliminary Design

The SSC program began in the fall of 2007. In light of the change to the new acquisition process and recent issues in translating the results from the AOA into PD, NAVSEA desired to implement a SBD effort in the PPD of the SSC program. The SBD effort operated within the SSC organizational structure utilizing IPTs. The design team was led by experienced naval architects and marine engineers from a number of organizations (NAVSEA, Warfare Centers, Academia, Contractors).

The organizational breakdown for the SSC program is located in Figure 6.

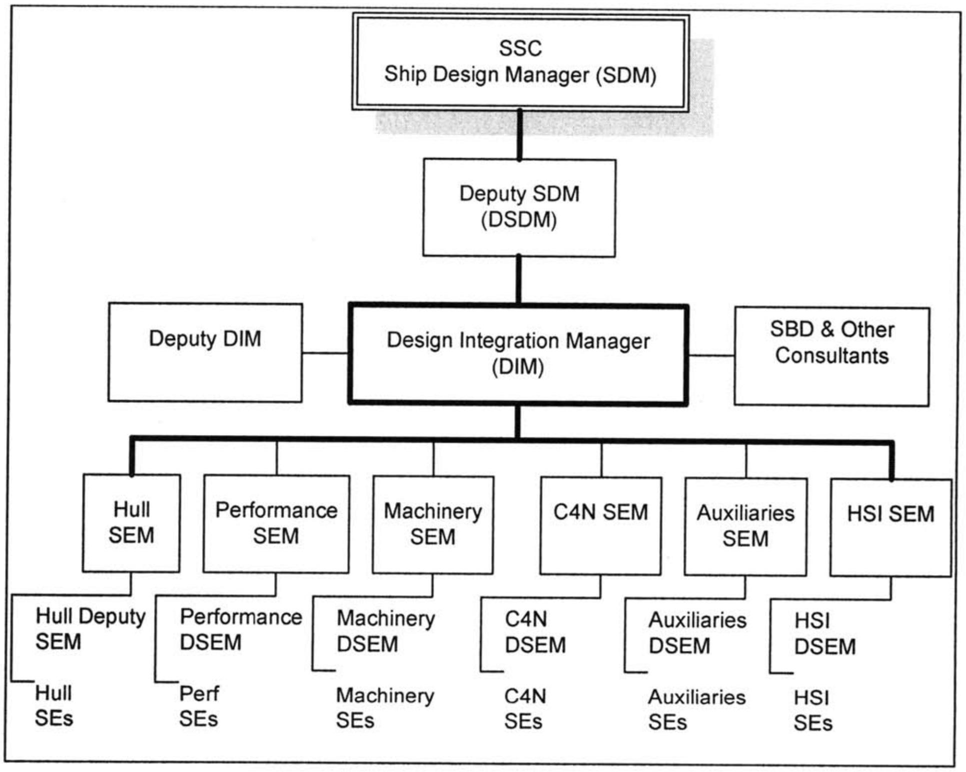

Figure 6: Design Integration IPT for SSC's SBD Effort

- Ship Design Manager (SDM): The lead system engineer on the project, this individual represents the design team in all matters with outside organizations.
- Design Integration Manager (DIM): This individual is responsible for facilitating communication, decision making, and integration among all the elements.
- System Engineering Manager (SEM): These individuals represent the system expert in the specific element field.

The effort began with the application of the Decision Oriented Systems Engineering (DOSE)[2] method in order to design a SSC executable SBD process. DOSE was intended to help deal with the complicating and potentially conflicting demands, the guidance of the Navy System Engineering (SE) Guide and the Ship Design Manager's (SDM) Manual, directives to apply the Set Based Design methodology in conjunction with regression analysis techniques, and directives to support requirements traceability using Dynamic Object Oriented Requirements System (DOORS). The DOSE analyses resulted in an executable process compliant with the Navy SE guide. Although multiple views of the process exist, the following figure provides a summary of the activities at a level of detail required for process understanding.

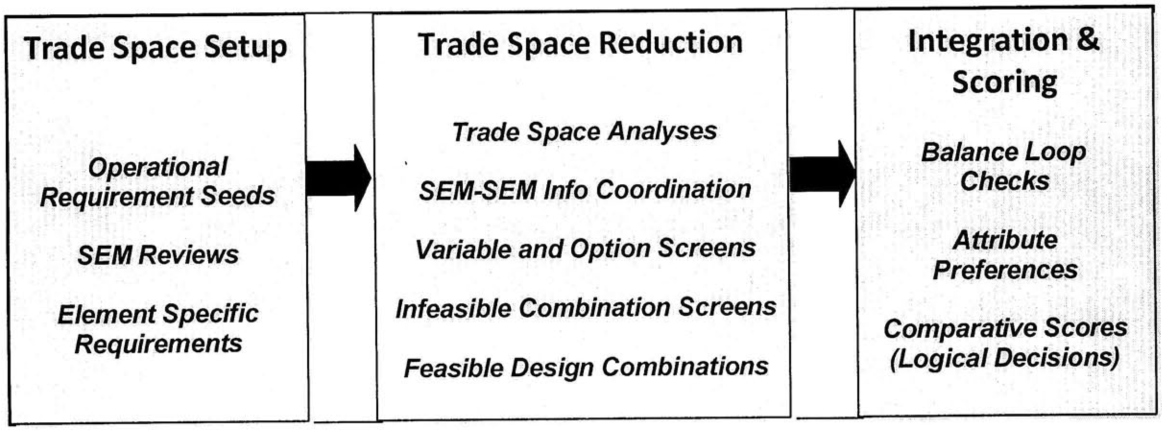

Figure 7: SBD Process for the SSC

With a process defined to apply SBD principles to the SSC Program, the next step was to describe the trade space so that the SBD process could be implemented. This involved translating the design issues into a formal trade space description. The method used to describe the trade space was a characterization scheme that provided for apportionment of factors, options, and operational constraints among the elements, or subsystems. As an example consider the platform attribute speed. As an SSC platform attribute, speed is a function of skirt resistance, thrust, etc. Similarly, skirt resistance is a function of skirt materials and skirt material properties, including properties descriptive of the behavior of platform-specific skirt designs in specific sea states and coastal terrains. Expanding this example to include all platform level capabilities, a field of attributes, attribute ranges,

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[2] DOSE is a Systems Engineering method that can facilitate process design needs.

options, and component alternatives were developed that, taken together, spanned all derived element attributes and completely described the trade space to be explored.

The trade spaces were then analyzed at the element level. The SSC elements include Hull, Performance (Skirt), Machinery, Command, Control, Communications, Computers & Navigation (C4N), Auxiliaries, and Human Systems Integration (HSI). The selection of elements was not a product of the SBD effort, but rather this was the breakdown the project had initially intended to use. An example of the trade space summary for the auxiliary element is contained below in Table 1.

Auxiliaries Trade Space	
Candidate Key Design Parameters	**Specific Options, Variable Ranges of Study**
Fire Suppression Options	Self Contained Water Mist, Pump Package Water Mist, Aerosol, CO2
HVAC System Options	Traditional Vapor Compression Cycle, CO2, Bleed-Air
Ventilation Enclosure Options	Cushion Air, Dedicated Fan, Inductive Ventilation
Fuel Tank Corrosion Control Options	Fuel Bladders, Internal Paint Systems, Tank Plating
Couplings Options	Gamma Couplings vs Conventional Couplings
Filtration Options	TBD Number of Specific Types of Fuel Filters vs TBD Contaminant Removal Filtration Methods
Fuel Pump Options	60 Hz Pumps vs DC Pumps vs 400 Hz Pumps
Fuel Quality Maintenance Options	TBD Number of COTS Sensor Types
Fuel Tank Arrangement Options	4 vs 5 Tanks (includes a center tank)
Trim & Center of Gravity Maintenance Options	Automated Trim and Ballast System vs Manual Trim Control
Fuel Heating System Options	Electric Fuel Tank Heaters, Waste Heat Exchanger, or Combination
Tank Insulation Options	with or w/o Tank Insulation
Control Actuator Options	DC Electric, 400 Hz, 60 Hz, vs Hydraulic Actuators,
Actuator Distribution Options	Distributed, Stand Alone, Combination

Hydraulic Piping	Flex Hoses vs Rigid Tubing
Actuator Drive Options	Belt-Driven vs Gear-Driven,
Scavenging Pumps	Electric vs Hydraulic
Oil Cooler Fans	Hydraulic vs Electric

Table 1: Auxiliary Trade Space Summary

Each of the remaining four elements contained factors and options like those in Table 1. The Trade Space Summary for all elements can be found in Reference 2. Table 2 details the number of factors and options for each element.

ELEMENT	FACTORS	OPTIONS
Hull	25	70+ (discrete) / 4 (ranges)
Performance	6	12
Machinery	22	80+ (discrete) / 3 (ranges)
C4N	25	Non listed
Auxiliaries	18	40+ (discrete) / 2 (ranges)
HSI	19	40+ (Discrete)

Table 2: Initial Element/Factor/Option Summary for SSC

Once the trade spaces were established, analysis efforts focused on the application of SBD principles to reduce the trade spaces. However, each reduction required substantiation and for this, each SEM conducted trade studies to develop and comparatively evaluate subsystem alternatives within the element trade space. SEMs also developed evaluation criteria to support the comparative evaluation of the subsystem alternatives. SSC measures were defined in an evolutionary manner[3] to assist in the comparative evaluation of integrated concepts.

The SEMs conducted element-specific analyses to screen the trade spaces of infeasible or dominated options and develop a set of non-dominated attribute ranges, leaving the still

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[3] Evolutionary refers to the manner in which the metrics used for ultimate concept scoring were derived in part using the factor and option attributes. Thus, if a factor was screened and its attributes no longer relevant at the whole craft level, that measure would be removed.

feasible regions of the trade space on the table. The Design Integration Team (DIT, made up personnel ranging from the SDM through the DIM) facilitated the trade space reduction efforts with constant and proactive oversight. Involvement of the Technical Warrant Holders (TWHs)[4] was fundamental to the SSC implementation of SBD. They were involved from the start, from the initial setup of the element trade spaces to the concurrence of SBD results.

The reduction effort culminated in reduced trade space summaries like that shown in Table 3. Starting from 18 factors and 40+ options, the Auxiliary trade space was reduced to 3 factors and 11 options.

Auxiliaries Trade Space	
Candidate Key Design Parameters	**Specific Options, Variable Ranges of Study**
Fire Suppression Options	Self Contained Water Mist, Pump Package Water Mist, Aerosol, CO2
Fuel Pump Options	60 Hz Pumps vs DC Pumps vs 400 Hz Pumps
Control Actuator Options	DC Electric, 400 Hz, 60 Hz, vs Hydraulic Actuators,

Table 3: Reduced Auxiliary Trade Space Summary

The number of possible combinations for the Auxiliary trade space was 48. Although still quite large, this was a significant reduction from the initial thousands of combinations for this element alone. This table also does not show possible dominated combinations (inter/intra element) that would provide further reduction. Similar reduction efforts were conducted on all the elements with a summary of the results contained in Table 4.

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[4] Technical Warrant Holders are individuals holding Technical Authority (TA) for a given technical area. The TWH is accountable for establishing, maintaining, and interpreting technical standards, tools, and processes including certification requirements for the design and life cycle engineering of Navy ships and systems. Upon identifying the appropriate TWHs for the SSC effort, the SEMs kept the appropriate TWHs briefed on events and progress in the SBD effort, soliciting their inputs as warranted.

ELEMENT	FACTORS	OPTIONS
Hull	Material 1: 6 Material 2: 7 Hybrid	16 (Discrete) 16 (Discrete) 6
Performance	1	2 (Discrete)
Machinery	9	26 (Discrete) / 1 (Range)
C4N	0	0
Auxiliaries	3	11 (Discrete)
HSI	6	17 (Discrete)

Table 4: Reduced Element/Factors/Options Summary for SSC

Efforts for further reduction continued until allotted project time required the DIT to move to developing integrated (craft level) concepts for comparative evaluation. These were constructed based on combinations of non-dominated candidate systems solutions that were developed by looking across the elements and then subjected to a balancing loop to ensure that the design candidates passed a first order test for platform viability. The number of concepts that entered the balance loop numbered just over 10,000. Figure 8 shows a diagram of the balance loop process used by the SSC.

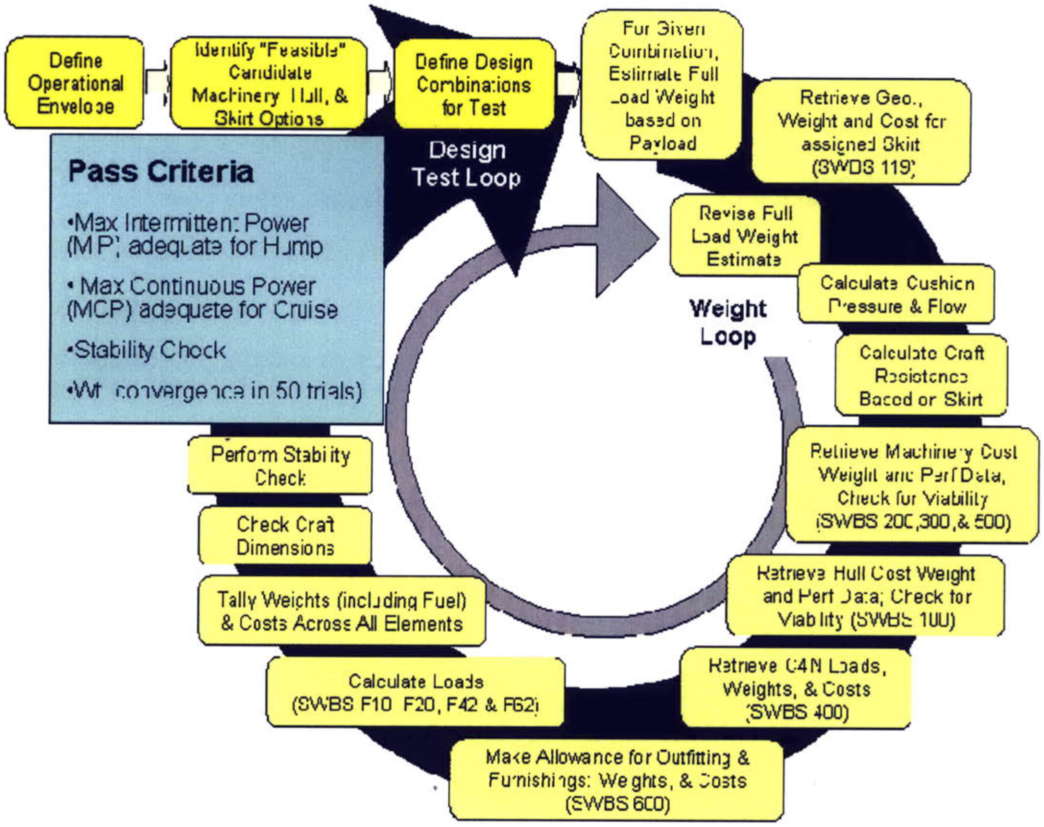


Figure 8: Diagram of the SSC Balance Loop Process

The deep yellow blocks, the first three blocks in Figure 8, describe the initialization steps in the Balance Loop. A few craft level operational envelope parameters are established such as assumed payloads and required cruise speed, ambient temperature, and wave height. In addition, parameters describing the sets of non-dominated options remaining for each of the elements are defined so that the total possible combinations remaining may be exhaustively tested in the Balance Loop.

Candidate designs that made it through the balancing loop were comparatively evaluated using a multi-attribute utility model: (1) defined by the craft-level measures resulting from the metric development effort that took place throughout the PPD work; and (2) developed specifically for this purpose using commercially available software. Finally, an SSC Baseline Design was selected for further analysis in PD.

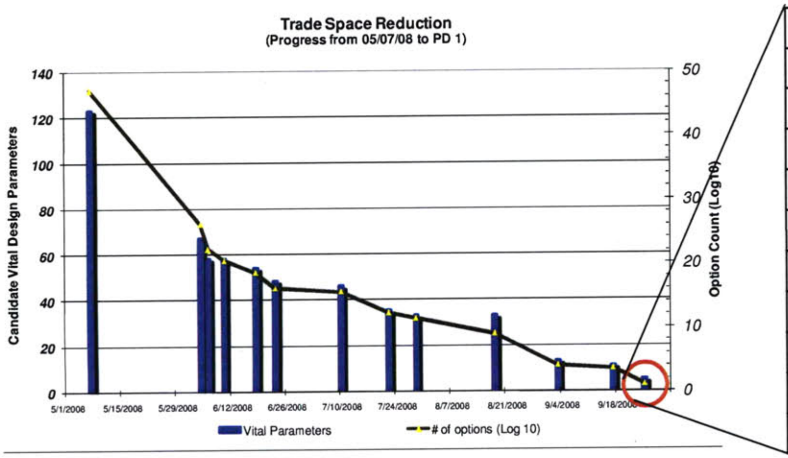
3.4 SBD Hurdles

Being the first instance of the use of SBD in the naval ship design community, significant engineering hurdles were faced by the SSC Program. Combining the organizational structure of naval design with that optimal for SBD was not completely possible due to the timing of instituting SBD in the project. The design was also constrained on selection of options in some elements. Considering SBD design is about enhancing design flexibility through design space exploration and delayed design making, the extent to which these decisions limit the work was unclear.

Cultural hurdles were also faced as in general, engineers are very solution oriented, trying to get to solutions as efficiently as possible. Given a problem, they are excellent at detailed designed solutions; however, a SBD approach shifts away from this line of thinking. The focus turns from deriving a specific solution to looking at a host of design variables and options that could accomplish the required task. It becomes paramount to substantiate why an option will not work rather than why it might work, especially early on. This lies at the core of how SBD design practice achieves greater design flexibility.

3.5 Design Process Results

The design effort in the SSC project began with greater than 115 design parameters with an almost uncountable number of option combinations. This was reduced to a design space of 11 key factors (design parameters) and slightly less than 3400 design combinations (those remaining after the balance loop) that were comparatively scored at the craft level. From these design combinations, a preferred concept was selected with backup options for key components in the identified 11 key parameters. These key parameters along with the trade space reduction summary are contained in Figure 9.



Design Parameter
Hull Material
Hull Depth
Transverse Bulkhead Spacing
# of Longitudinal Bulkheads
Skirt Type
Machinery Architecture
Propulsor Duct Diameter
Electrical System Architecture
Electrical Service Frequency
EPLA Electric Load

Figure 9: Trade Space Reduction Summary along with key Design Parameters

The design effort revealed a lot in regards to requirements and decision traceability. In particular, the evolution of requirements throughout the process needed to be accommodated by the evolutionary reduction of the trade space to adequately capture and reflect changes. Since each element began with a list of initial (draft) requirements, the changes made had to be balanced with the reduction of options and the learning that occurred (in regards to various options) that leads to design discovery. Simply stated, new requirements were discovered and included due to design factor exploration.

Traceability lies at the foundation of SBD as it provides for future design flexibility and allows for delayed decision making. It also allows tracking of which decisions are made by the SEMs and which need to be approved at a higher level of authority. This is important as with the large number of decision and design space reduction required, having to have all decisions approved by too high of an authority would have hindered any progress. Conversely, some decisions involve key design issues and as such, need extra visibility.

3.6 SBD success

Being the first use of SBD in U.S. Navy ship design, the program identified early in the effort four ways in which to measure the SBD success. These are presented in order of increasing impact to the initial design and are based on the thoroughness of the result.

- Did the SBD effort produce a truly unique solution? This was not achieved; however, the reason can be found in the constraints placed on the process. One particularly limiting constraint was precluding the use of any technology not already demonstrated in a similar operational environment. Thus, any combinations of chosen options would be unique in the sense that those chosen options may have never been combined before at the integrated level; however, on a component level, it contains mature technology and thus uniqueness was not necessarily achievable. Such constraints limit innovation at the sake of reducing risk.

- Did the SBD effort provide a thorough canvass of the design space, with a sound body of analysis substantiating the tradeoffs available? This was achieved and the only debatable issue is the thoroughness of the effort. Determination in this regard may only happen at a later time when requirements are changed.

- Did the SBD effort identify those design parameters of greatest impact to a good design and which options or ranges of these parameters are of greatest value to a good craft? As previously stated, the 11 most important design parameters were determined along with the ones of greatest.

- Did the SBD effort provide a staged progression towards a globally optimal design, with each stage resolving design details with successively greater fidelity? This was not achieved and further SBD work is required to understand how to achieve this outcome.

Overall, true judgment of the SBD effort will only come later on as the program progresses through the acquisition process where requirement changes experienced during subsequent phases allow the design team to leverage the body of data and analysis that remains.

The question then arises whether a point based design approach would have provided the same results. There is a chance that the same design could have been created; however, the question then reverses to what would happen to this design in the face of future requirement changes. Point based approaches are not geared to handle changes late in the design process. Doing so requires tradeoffs that may result in a design that is less than optimal. The ability to identify the most important design parameters would also be in question as the construction of the design space in a SBD application facilitates the evaluation of design parameters where the point based approach does not.

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4.0 Defining the SBD Framework

The SSC program provided an overview of their PPD effort that utilized SBD principles; however, this chapter seeks to define a general framework for SBD implementation that can be applied to the broader scope of naval design projects. This framework provides the basis for undertaking the submarine concept design presented in the next chapter.

4.1 Framework Summary

Although the use of SBD design was initiated in the SSC project as part of the PPD process, Figure 10 provides a generic model that illustrates the major steps in the SBD process.

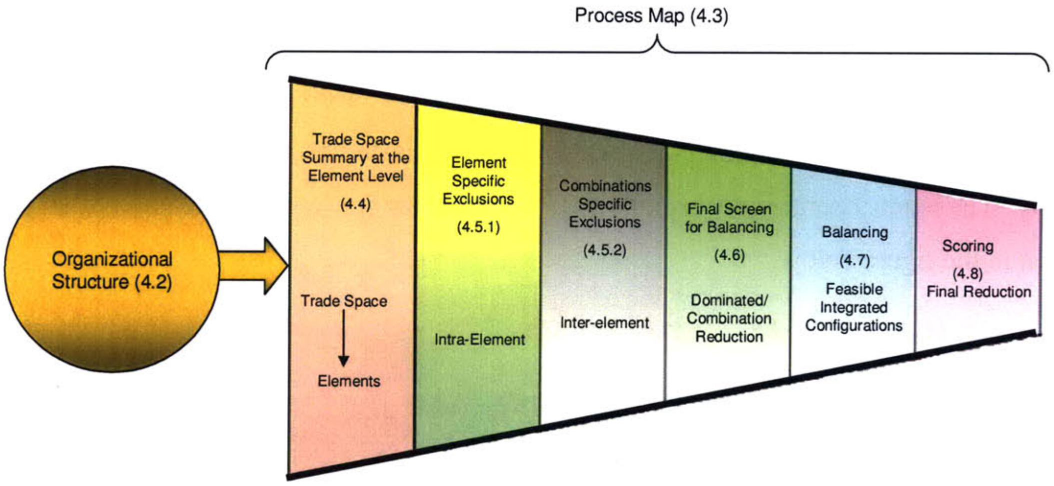

Figure 10: SBD Framework Model

The shape of the figure illustrates the narrowing of the design space until a preferred concept or family of concepts is selected. The remainder of this chapter discusses how this framework is implemented with examples provided from the SSC example highlighting how they accomplished certain aspects.

4.2 Organizational Structure

Prior to beginning exploration in the trade space, there is a certain amount of set up work required. As in any process, proper preparation and role definition is imperative for the proper functioning of the SBD effort and developing an organizational structure that operates in conjunction with the SBD effort is vital to ensuring success. At the same time, if early on in the acquisition process there is a clear understanding that SBD is to be used, a SBD decomposition that matches future organization breakdown can be more easily created.

Specifically, the IPPD approach used in the VA submarine class along with the successes achieved through its use provide a good idea of how future submarine development will proceed. In the event that SBD is to be used in concept exploration or PPD, the goal of team organization should be to match the structure that will be used for later design processes. Key elements of IPPD approach where an SBD effort can takes its organizational structure from include the Functional Area Teams and System Integrations Teams. The teams operate concurrently with the modular breakdown of the design as shown in the figure below.

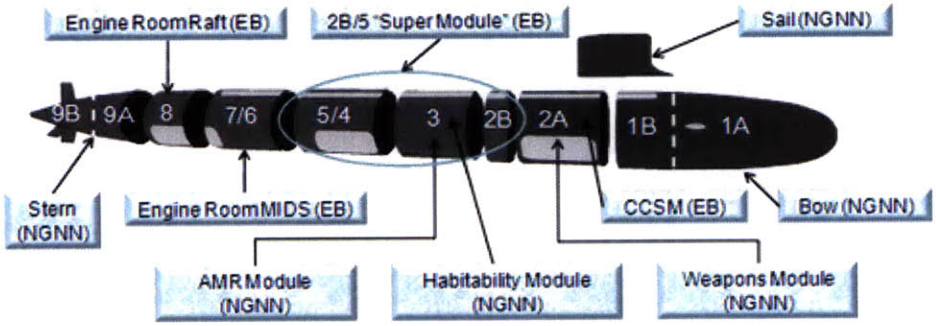

Figure 11: Virginia Class Design Modules
(image found at ussnewmexico.net)

In environments where the IPPD will not be employed, organizational breakdown should still follow that which will be used in design and construction.

4.3 Process Map

Once an organizational structure is defined and understood, the next major requirement is the development of an executable process. Development of such a process requires accommodating multiple document requirements and directives (e.g. Navy Systems Engineering Guide, Ship Design Manual). Process development requires defining and deriving the key decisions and determining the flow of information throughout the process. Once completed, the process can assist the program in detailed planning of the technical effort, resolve dependencies, and assist in modifying the process to meet all program requirements. This work should lead to a full process map that directs the entirety of design process.

The use of DOSE facilitated the SSC programs development of an executable program; however, any tool that allows the design team to develop a process that takes into account all required inputs, outputs, value flow, information flow, and stakeholders needs can be used. The process itself is used to communicate how the overall SBD effort moves from a collection of element/factors/options/variables to ship level concepts. Model based software is another tool that can be used to illustrate this flow. Appendix A contains the SSC program process map. The final process should guide the SBD effort from element creation to a final preferred concept.

4.4 Set Development

With an organizational structure in place and a process defined to apply SBD principles, the next step is to describe the trade space so that the SBD process can be implemented. An initial consensus compilation of operational requirements is developed to begin the set-based activity. This compilation goes beyond notional requirements and looks at the operational environment. This will result in a mix of hard and soft constraints, capabilities asked for by the customer or other stakeholders, and capabilities required of similar craft in similar operational environments.

Requirements in general are evolving as some will not change throughout the design effort, some will change with TWH input, and others will change based on stakeholder direction. Additionally, others will change based on the need to satisfy conflicting requirements. Lastly, new requirements will emerge as the design progresses and there is a better understanding of the details of the design. This evolution and maturation process drives changes to the requirements documents. Thus, the initial compilation used to initiate the set-based design is meant only to get the SBD effort started.

With the compiled set of operational requirements, a list of options, attributes, and attribute ranges necessary to characterize the ship at the platform level and satisfy requirements, is developed.

4.4.1 Element Definition and Variable/Range Selection

The initial exploration of the trade space yields results that serve as inputs into the chosen element breakdown. The development of factors is derived from the exploration of how the notional requirements (and operational requirements) can be met. Although some factors are naturally part of the design and do not necessarily map to a specific requirement, others will have direct ties. With a list of initial factors or elements defined, the effort then moves to selection of elements to represent a set of factors. The selection of elements should model the product architecture.

Chosen attributes and ranges serve only as points of the departure; each Element Manager (EM)[5] is free to relax any of the ranges based on their knowledge of the available design issues and available technologies. The ideal implementation requires any relaxation assumptions made by the EMs to be subject to review by someone, as defined in the organization structure and mapped by the design process, with oversight responsibility for the total design space.

This part of the process must ensure that the trade space summary reflect the EM's best judgments regarding the factors and options to be examined with a detailed plan for their study completed. Also, there must be a sound reason for the inclusion of each factor and option (e.g. the factor has not been eliminated as a potential vital factor at the craft level.)

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[5] An EM as defined here would be synonymous with the role of the SEM in the SSC project.

The factor or option in question should not be included if it does not impact the design enough to be considered within the SBD process. Also, where there is a tight schedule and no time for basic science inquiry, the technology needs to be understood. If the EM does not understand the factor well enough to measure it, or can not anticipate how it might impact their design, the factor does not warrant a place in the trade space.

4.5 Narrowing the Set Trade Space

The trade space reduction effort seeks to screen the trade spaces of infeasible or dominated options and develop a set of non-dominated attribute ranges. This leaves the still feasible regions of the trade space on the table. The trade space reduction efforts can be described as two sub-efforts: (1) Factor/Option Screening (4.5.1), and (2) Combination Screening (4.5.2). The Factor/Option Screening effort focuses on screening whole design parameters and options or option sets, while the Combination Screening effort focuses on screening specific combinations of options based on incompatibilities.

The trade space reduction effort requires constant oversight as the necessity to reduce initially large sets of data must be balanced by the need to not exclude reasonable, and potentially optimal, solutions. Frequent meetings by EM's can usher the process along and provide the necessary push for continued progress.

Of all activities involved in the SBD effort, trade space reduction is the most challenging and stressful. Considerable time and resources in this part should be allocated for full exploration of options and combinations. Proper documentation is paramount throughout the process as the studies conducted and decisions made create the data store where future design efforts and flexibility are derived.

4.5.1 Element Specific Exclusion

The ability to narrow the element trade space focuses on a factor (design parameter) / option (variable range) screening process where the reduction effort is tracked in trade space summaries. The following represent the screening rules used in the reduction effort:

1) A design factor is determined to have little impact at the ship-level in any of the key metrics likely to be used in assessing submarine value.
2) Differences among the discrete options within a given factor or response value performance differences over the variable range for a continuous factor is deemed insignificant at the craft level.
3) Certain options of a factor are identified as dominated solutions; i.e., an option is deemed inferior to another option in every attribute likely to be of interest in the craft level evaluation.

During the reduction process, when a single option remains in a factor, that factor becomes a given in the ship level design and is therefore formally removed from the trade space. Also, when the variable range across a factor is deemed insignificant, the factor is also removed from the trade space.

Element-specific DOE experiments, Pugh Matrices, and other analyses provide the methods by which the factor/option screening is conducted. For the SSC program, the initial reduction efforts were to use regression analysis, and more specifically, response surface methods; however, early trade space reviews revealed a preponderance of discrete variables. By the time the trade spaces were firmly established, less than 10% of the total design parameters selected for study had been identified as continuous variables.

Response Surface Methods (RSMs) are regression analysis techniques designed primarily for continuous variables[6]. Initial plans for the conduct of SBD for SSC assumed the design parameter space at issue could be well represented with response surfaces. As it became evident that discrete variables would play the dominant role in the SBD exercise, the original plans were modified to accommodate a hybrid approach, a mix of RSMs and brute force set reduction (described in Section 4.6).

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[6] RSM techniques have their advantages, but they do not easily handle attributes that are most tenuous early in the design effort, attributes like maintainability and reliability. Such attributes can be handled early in the design under informal SBD practices: by discussions among element experts. Such discussions may not resolve such issues, but such discussions will ensure that these issues will not be overlooked early if they shouldn't be.

Some of the SEMs applied RSMs at the element level, and the brute force approach was used everywhere else. When it quickly became apparent that the discrete variables would continue to dominate, the brute force approach became the dominant method and was used exclusively at the craft level.

4.5.2 Combination Specific Exclusion

As the trade space reduction effort reaches a point where further element reduction is not possible, work then begins on determining, infeasible and incompatible relationships for specific option combinations. This effort first takes place between elements as selection of factors and options within an element were chosen as to prevent any limitation of option as this level. Exploration of combinations between elements was termed negotiating relationships in the SSC project and specifically referred to an option selection in one element that influences options that would work in other elements. Not surprisingly, such analyses lead to a large number of relationships that require a full factorial characterization to identify each and every one that has varying level of impact; however, this is necessary as the reduction along these lines creates a transparent trade space.

4.6 Final Screen for Balancing

A very real concern at this point in the reduction effort is that the remaining number of factors and options result in an unmanageable trade space with the combination of integrated designs numbering in the millions. For a ship design where complexity is high, this might be an expected result; however, reducing the number of options at this point is vital in allowing the SBD effort to proceed and combine factors and options into whole ship concepts.

The following are four categories of methods, deemed integration closure options, looked at by the SSC program in this juncture of their reduction effort. These can be applied to the broader naval design approach.

1) **Brute Force Method.** The most basic of all the methods, it is tied to the fact that every excluded option, combination of options or design parameter is tied to a specific reason with no automated tools used to filter the trade space. Such an effort is labor intensive and begins by eliminating the non-vital factors, the dominated solutions, the incompatible combinations, and finally the infeasible, and being left with what was feasible.

2) **Design Synthesis Tool.** The next method relies on the use of a design synthesis tool that sampled the remaining combinations of options considered feasible and developed designs according to a set of design heuristics. A risk associated with this option is an inevitable lack of transparency into how the designs were formulated, and a similar lack of transparency into the penalties and rewards of various features of a given configuration. For submarine design, this is an area where SUBCODE[7] may provide benefit as this program is not a black box software tool. The user has the ability to look at what heuristics the program is pulling from and determine which specific options provide the greatest value.

3) **Factor Screening Using JMP.** The Brute Force Method and the Design Synthesis Model marked opposite ends of a continuum. This method falls in between and could complete the SBD effort with a factor screening effort assisted by the JMP (statistical software), using derived prediction coefficients to develop configurations with higher value based on the developed and approved response values. An anticipated advantage of this option is its transparency and reproducibility of outputs as it was used for screenings at the element level. However, the largely discrete nature of the trade space makes it a poor method for the final screenings at the whole ship level.

4) **Complex Negotiating Function Model.** An alternative to the Factor Screening this method uses negotiating functions in JMP to reduce remaining combinations to a

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[7] SUBCODE is Microsoft Excel based submarine synthesis program designed for use in early stage concept design. SUBCODE is intended to provide quick, accurate, and cost effective analysis of numerous submarine concepts at a level of detail appropriate for a quantitative down-select process prior to the use of traditional concept design methods.

manageable set of configurations for scoring and sensitivity analysis; however, it could be difficult to provide transparency into the potentially complex interactions resulting from the negotiating functions. Consequently, it could look like a black box synthesis model. Its advantage was that if the transparency issue could be successfully addressed it would be equivalent to the Brute Force Method taken to its logical conclusion. Again, the largely discrete nature of the trade space also makes this method a poor choice for the final screenings at the craft level.

The amount of time allocated to the reduction effort, available software, and the hurdles faced up until this point ultimately decide which option, or combination of options, can be used. Maintaining and documenting the design effort is imperative, and thus, any method chosen must be able to specifically report why an option was eliminated. Thus, the danger here lies in the fact that the team could eliminate desirable, potentially optimal, results based on the fact that the design is out of time and reduction had to be accomplished.

4.7 Creation and Reduction of Integrated Designs

The combination of factors and options available for selection may still be relatively high. At this point in the SBD effort, further reduction takes place on integrated (whole ship level) concepts which are developed for comparative evaluation. These designs as based on combinations of non-dominated candidate systems solutions that are developed by looking across the elements. These candidates are then subjected to a Balancing Process (Balance Loop in the SSC program) to ensure that the design candidates pass a first order test for platform viability.

This is required for two reasons. The first is that this further reduction can not take place at the inter/ intra-element level. Secondly, unfeasible concepts are easier to discriminate in an environment where they are tested against physics based criteria. For the SSC project, the balance loop screened combinations by performing an initial stability check, a test for adequate power to get over the hump, and a test for adequate power to maintain the required cruise speed. These are all vital, high-level attributes that must be met within that environment.

4.8 Concept Scoring

Throughout the design effort, exploration on attributes that define and map to the SBD effort should be ongoing. This is required to develop a complete list of measures for comparative evaluation. Although many measures such as cost and risk are easily identified as key attributes, a more methodical approach can ensure that attributes most important to all stakeholders are included.

The SSC developed their set of measures taking into account four stakeholder perspectives: acquirer (craft), operator, builder, and maintainer. At the same time, the SEM's in the SSC project had to ensure that the measures could be traced back to the design parameter and associated response variables. Maintaining the tie between the two facilitates requirement development and provides traceability.

Major challenges in developing measures include the need to ensure that metrics are:

- Non-overlapping: A measure must not be a combination of other measures or representable in that manner.
- Decomposable: The measures must be able to be quantified and mapped to specific elements.
- Complete: The complete set of measure must cover all attributes important for comparing options.
- Sufficient: Include no more attributes than is necessary to distinguish the options

For the SSC program, the initial set of attributes and measures are contained in Appendix B.

Taking the outputs from the balancing process whose outputs are integrated concepts, final selection is performed by comparative evaluation using the developed metrics. Based on the number of integrated concepts remaining, this process can utilize such methods as the Pugh Controlled Divergence where the number of options under consideration is manageable or multi-attribute utility models where the number of integrated concepts number in the thousands.

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5.0 Executing SBD in a Submarine Concept Design

Having provided a framework for the execution of SBD in naval design, this section explores the application of elements of the framework in a submarine concept design. Prior to undertaking this task, background is provided on submarine design in general with some specifics on the concept exploration phase of the VA class submarine. This application of the framework specifically focuses on elements of the process to include requirement development (and the evolution effort) set development and subsequent reduction efforts, creation and filtering of integrated concepts, and discussion of method to select final concepts. This is not intended to be an exhaustive effort but rather a look at how to generally execute SBD in this arena.

For the SBD application, the concept is focused on developing a conventional powered submarine.

5.1 Submarine Design Background

As stated by Schank in Sustaining U.S. Nuclear Submarine Design Capabilities, "The design of a nuclear submarine, or any naval ship, progresses through four basic phases, with each successive phase adding more detail to the evolving design products."[15] These phases are a generalization of the DOD acquisition process discussed earlier; however, by looking at the design process in these phases, it is easier to determine an area to apply SBD principles. The four phases are shown below in Figure 12.

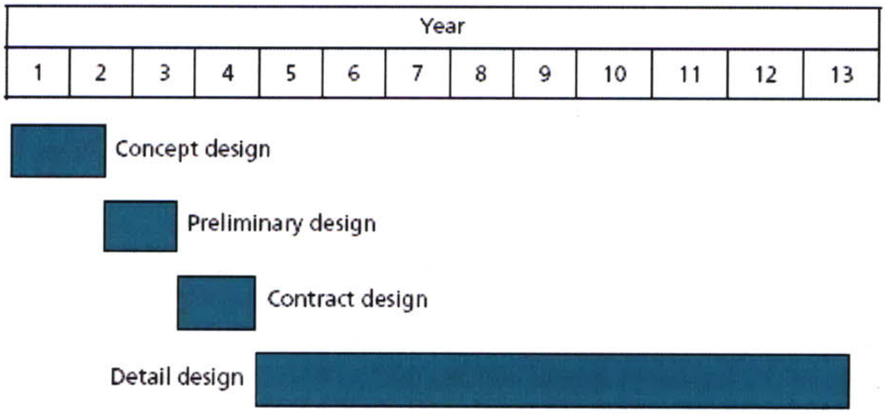

Figure 12: Submarine Design Phases

The development of a new class of submarine in the U.S. Navy begins almost a decade prior to the actual production processes begin as was the case for the development of the VA submarine class[8]. As a replacement for the Los Angeles class, concept studies began in 1988/1989 (production in 1998) conducted most notably by both Naval Sea Systems Command (NAVSEA), General Dynamics, Electric Boat and Northup Grumman, Newport News Shipbuilding. Over 15 studies were conducted over a three year period during the concept exploration phase. The subject of these point studies included (the studies were conducted in the order shown):

1. Six Torpedo Tube Large (~10000 long tons) Submarine
2. Half Size Submarine (60% of VA Class Submarine displacement)
3. Machinery Configuration: Mechanical Drive Options
4. Machinery Configuration: Electric Drive Options
5. Reconfigurablility Options (5 or 6 options)
6. Analyze the effects of larger diameter (40 feet)
7. Look at system trade space (bow planes, auxiliary systems, etc.) with the idea of flagging performance/ cost
8. Rafted design
9. Look at a family of ships (multiple submarine concept)
10. Look at a family of half sized ship (multiple submarine concept)
11. Sonar sphere and rafted decks
12. Cost reduction methods
13. Concept with a lot more technical risk
14. Cost reduction methods
15. Cost reduction methods

As concept exploration moved forward, convergence was natural but far from optimized. The number of or method that the trade studies were conducted was not decided on early in the exploration process. Thus, the concept phase is the chosen area where SBD was applied. Although this is not in accordance with the previously identified area where SBD could be used (namely PPD as shown in the SSC project), this is a good area for applying the developed framework while providing insight into the dynamics of SBD in the submarine arena.

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[8] The development process is defined as beginning when concept exploration phase begins. For the VA submarine class, the design phase began in 1992, followed by production in 1998, with the first ship delivered in 2003/04.

5.2 Design Setup: Requirements

Inputs into the defined framework come in the form of requirements: notional and operational. The following is a list of requirement issues that are present at the beginning of submarine concept exploration:

- Mission Areas: This includes the primary and secondary mission areas that the submarine is required to meet. Although a number of systems can be employed to provide the required capability, specifics are not normally given. If the platform is replacing an existing asset, there may be requirements to use existing architecture/equipment as the staged technology growth of the hardware is in a mature state.

  In a conventional submarine concept, designing a platform capable of multi-mission tasking may not be possible without limiting capability or increasing size, both of which might lead to unacceptable solutions; however, a combination of the two may provide the best answer. Determination of how various options can be accommodated (e.g. by functional area specialist) while looking of other design parameters is provided through application of SBD.

- On Station Endurance: Not necessarily a design driver in nuclear design, this plays a major role in conventional design. The mission and operating area of the submarine also places limits on this parameter, but are important in shaping the early design concept.

- Technology: Early design decisions may choose to explore advanced technologies that are not necessarily part of the submarine operating system itself. The ability to determine the readiness of the technology along with the interdependencies the equipment/component allows the designers to better capture how to account for this in the early trade space.

- Powering/Electrical Configuration: On the cusp of the transition to all electric concepts, there exists a relatively large trade space in this arena. The varying types of equipment as well as desires to realize cost reductions through commonality make this an area worth substantial study.

- Payload: Potentially the area of greatest uncertainty, the list of possible configurations and packages that a submarine can carry are major drivers of the size of the ship and heavily affect other aspects of the design. If the payload is something that is imparts new technology with significant risk, the design may want to limit risk in other design areas.

This list provides examples of requirement concerns in areas consistent with submarine design. Notably missing are performance based requirements such as speed and displacement. As the trade space is fully explored, these types of attributes become part of the scoring metric that assesses the value of various created concepts. Thus, it allows decision makers to more fully explore the trade space and is part of the requirement evolution process.

The intentional vagueness of requirements also allows designers to look at a wide range of potential systems, equipment, and components. Although provided here with a list of requirements areas, a reasonable entering assumption into the model is that there are no clearly defined requirements. Such a notion is not a stretch as early recognition of a need in ship acquisition does not correlate to any clearly defined needs that must be met. For early concept studies where the ship under study is a replacement of an existing platform, the requirements levied on the previous design can serve as a "starting point" and information deduced from exiting ship classes can provide guidance on where the design may proceed.

In a set based environment, the lack of clearly defined requirements does not hinder the design as SBD in general begins with a trade space that is open. The process leads to requirement development and understanding is where the requirement evolution process is performed. The delaying of decisions until requirements are better understood is supposed to use the SBD results to help understand the impact of the requirements.

5.3 Set Development

In line with submarine design (and more specifically conventional submarine design), sets were developed that included key elements of the conventional powered submarine design. These included Hull, Performance, Power & Propulsion, Auxiliary, and Payloads. These elements were not chosen based on the IPPD breakdown of the VA class submarine. They were instead based on collecting like factors together into functional groupings.

The set development can be aided by the use of computer software that can explore ranges and provide context to the initial values. For submarine design, a program such as the previously mentioned SUBCODE would fulfill this role. As a submarine synthesis program, SUBCODE can be applied in a Design of Experiment role. Thus, the program can help develop the initial candidate seed values and ranges. These are locations and regions in the design trade space that offered reasonable promise for feasible designs.

5.3.1 Element Definition and Variable/Range Selection

Table 5 provides an example of an element trade space with potential variable ranges provided as such. This is one out of the five aforementioned elements with the remainder contained in Appendix C. The placement of factors into specific elements is done with the intent of grouping factors that fall within the chosen element division. The element division suggested is notional and alternate division is possible; however, the affects of alternative factor mapping and element breakdown on the design space and subsequent reduction effort was not explored here but could impact the overall concept exploration. Looking at the Hull Trade Space, hull material naturally falls in line with the hull trade space; however, hull treatment does not necessarily fall into this element as it could be viewed more from its acoustic performance affects.

Hull Trade Space						
Trade Categories	**Candidate Key Design Parameters**	**Specific Options, Variable Ranges of Study**				**Discrete/ Continuous**
Hull	Material	SS	HY80	HY100	Composite	Discrete
	Type of Hull	Single BOR[9]	Double BOR	Single NBOR	Double NBOR	Discrete
	Structures - Bulkhead Spacing	Varies				Continuous
	Structures – Stiffener Spacing	Varies				Continuous
	Structures – Stiffener Sizing	Varies				Continuous
	Hull Treatments	% of Hull		Type		Discrete
Geometry	L/D	6		11		Continuous
	Diameter	25	32	40		Discrete
	PH Volume	Varies				Continuous
	Deck Rafting (% of decking)	Location		Type		Continuous
	# of Decks	2	3	4		Discrete
	Bow Shape Factor	1.5		4		Continuous
	Stern Shape Factor	1.5		4		Continuous
	Curvature Factor	Varies but generally between 1-1.37				Continuous
	Frame Factor	Varies but generally between 1-1.10				Continuous
Misc.	Superstructure	Length	Volume	Contents		Discrete

Table 5: Hull Element Trade Space

In conjunction with the trade space creation, each element manager (EM) would develop a trade study and analysis plan tailored to the specific element design issues. This plan would work in the bounds of the process diagram.

5.4 Narrowing the Set Trade Space

Of the two previously identified methods used for reduction (1) Factor/Option Screening, and (2) Combination Screening, the first option is explored below.

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[9] BOR: Body of Revolution defined as a circular cylinder. Conversely, NBOR is a Non-Body of Revolution which can take many forms.

5.4.1 Element Specific Exclusion

The Factor/Option Screening effort focuses on screening whole design parameters and options or option sets. To recap the screening rules contained in Section 4.5.1, a design factor is eliminated if it presents a dominated solution, is insignificant at the ship level (is not something that affects the combination screening), or is a variable that will have no impact on assessing the whole ship level.

Looking at Table 5 , the reduction effort may follow as such:

- Material: Conducted in the context of conventional submarine design, the use of a number of materials is not completely unfamiliar to the U.S. Navy; however, a trade study looking at construction cost, risk, and capability would narrow the factor options or lead to mapping the material needs to varying mission profiles.
- Type of Hull: The benefits associated with the non body-of-revolution (NBOR) and double hull designs do not outweigh the low risk nature of a single body of revolution design. For a low risk design, this would provide an example of dominated solutions.
- Structures: Many of the aspects associated with structural design involve the weight that the structure represents. This can be captured and manipulated by selection of a suitable diving depth. Eloquent designs may require structural considerations; however, for concept exploration, this factor is eliminated based on applicability.
- Hull Treatments: Although detailed analysis of hull treatment application is difficult to model and impacts the overall weight of the ship, this factor was not carried forward.
- L/D: Exploration of varying L/D ratios showed this to be a better variable at assessing and comparing whole ship concepts. As such, it was removed from the set.
- Diameter: This is a highly important factor with a significant impact on the whole ship concept. Exploration of the initial diameters proved that the discrete values chosen did not represent the desires of the concept. Alternative values were chosen.
- PH Volume: Much like L/D ratio, this value is defined by the selection of other components and was removed from the set.

- Deck Rafting (% of decking): For concept exploration, this has no impact on exploring whole ship level.
- # of Decks: Important on a more detailed design level.
- Shape Factor: Important on a more detailed design level.
- Curvature/Frame Factor: Based on structural and hull configurations. Removed from concept level study.
- Superstructure: Important on a more detailed design level.

This reduces the element to the factors and ranges shown in Table 6.

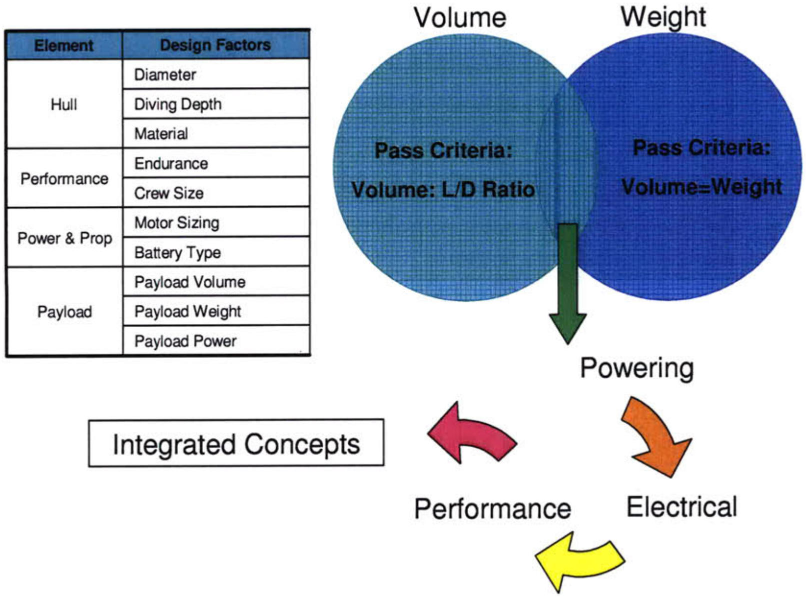
Trade Categories	**Candidate Key Design Parameters**	**Specific Options, Variable Ranges of Study**		
Hull	Material	SS	HY80	
Geometry	Diameter	25	27	29
Misc.	Diving Depth	175	250	

Table 6: Hull Element Reduction Effort

Likewise efforts were conducted on the Performance, Power & Propulsion, Auxiliary, and Payload elements. Of note, the element Auxiliaries had no unique factors carried along at the concept level. A fixed volume and weight (as a percentage of pressure hull volume) could be estimated for all auxiliary systems that scaled with pressure hull volume.

5.5 Developing Balanced Designs

Once the design space has been reduced, the effort then turned to creating integrated designs and subsequently screening these whole submarine designs. For a submarine concept, this took the form of a balance filter. The balance filter shown below performs a volume, weight, and powering/resistance balance. Operation of the balance filter is illustrated in Figure 13 and discussed in the following section.



Element	Design Factors
Hull	Diameter
	Diving Depth
	Material
Performance	Endurance
	Crew Size
Power & Prop	Motor Sizing
	Battery Type
Payload	Payload Volume
	Payload Weight
	Payload Power

Figure 13: Balance Filter

5.5.1 Balance Filter

Development of the balance loop can take many forms. For the submarine concept, the work here is based on parametric equations taken from Concepts in Submarine Design by Burcher and Rydill. For a submarine concept, this provides a good first pass look as nonfeasible combinations become readily apparent. Thus, the question then turned to what method or tool would be used to accomplish this task. Recognizing that the initial number of combinations numbers in the thousands, a method to quickly and accurately reduce the number of combinations was desired.

Looking at the outputs from the factor/option screening, all the factors were discrete values (or made discrete as discussed later) that could be combined to form integrated concepts. Submarine design often uses parametric equations used to perform initial sizing, powering, electrical load analysis, etc. They are often volume based estimates although this line of thinking is not the only method possible. Looking at the design from a weight perspective is also a viable approach.

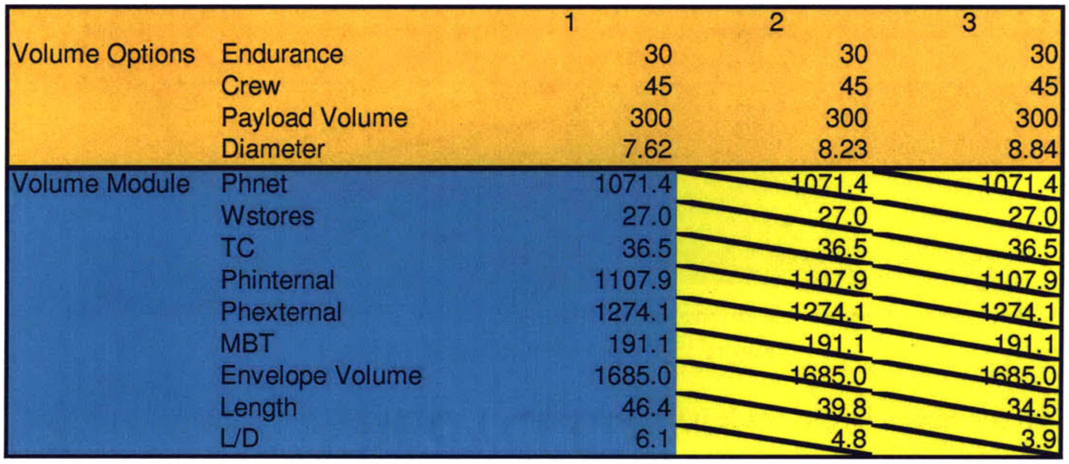
Having recognized the need for a balance filter and what it must accomplish, the inputs from the remaining factors and options were evaluated to ensure that there associated attribute could fit in the balance filter. For those factors that represent actual equipment instances, a volume, weight, and power associated with that factor was required. Factors and associated options are contained in Table 7.

Element	**Design Factors**	**# of options**	**Module**	**Options**			**Units**
Hull	Diameter	3	V	7.62	8.23	8.84	m
	Diving Depth	2	W	175	250		m
	Material	2	W	HY-80	SS		Density
Performance	Endurance	2	V	30	60		Days
	Crew Size	2	V	45	60		Number
Power & Prop	Motor Sizing	2	P	6	9		KW
	Battery Type	2	E	2	4		Power/Battery Cell
Payload	Payload Volume	3	V	300	500	700	m^3
	Payload Weight	2	W	150	300		tons
	Payload Power	2	E	150	200		Kw
Possible Combinations		2304					

Table 7: Design Factors and Options

The full list of parametric equations used in the balance filter is contained in Appendix D. The balance filter is broken into four major sections: Volumes, Weight, Powering, and Electrical. A fifth selection is included, Performance, which does not have independent factors associated with it but is necessary to calculate performance characteristics. As shown in Table 7, four of the factors map to the volume element, three to weight, one to powering, and two to electrical loading. The number of factors and options in Table 7 represents 2304 possible configurations. The objective of the filter is to reduce the number of integrated concepts. This is accomplished by subjecting sections of the filter to pass criteria. Combinations of factors that do not meet these criteria are rejected.

Starting with the volume module, the four design parameters have a total of 36 possible combinations. Figure 14 shows three out of the possible 36 combinations with all configuration and results shown in Appendix D.



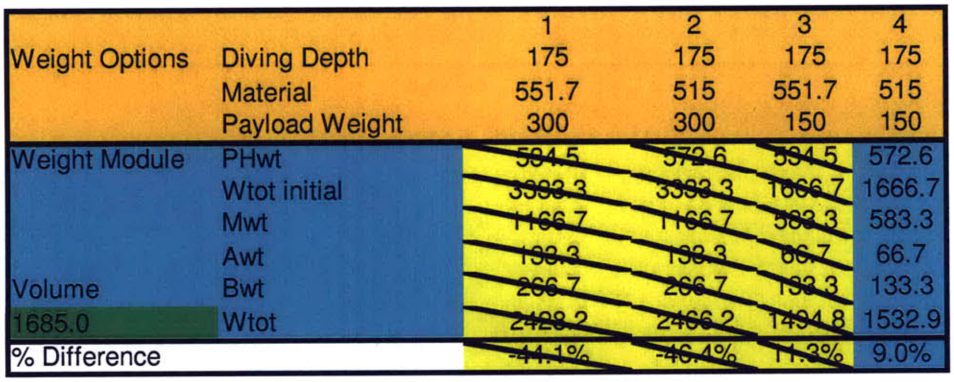
		1	2	3
Volume Options	Endurance	30	30	30
	Crew	45	45	45
	Payload Volume	300	300	300
	Diameter	7.62	8.23	8.84
Volume Module	Phnet	1071.4	~~1071.4~~	~~1071.4~~
	Wstores	27.0	~~27.0~~	~~27.0~~
	TC	36.5	~~36.5~~	~~36.5~~
	Phinternal	1107.9	~~1107.9~~	~~1107.9~~
	Phexternal	1274.1	~~1274.1~~	~~1274.1~~
	MBT	191.1	~~191.1~~	~~191.1~~
	Envelope Volume	1685.0	~~1685.0~~	~~1685.0~~
	Length	46.4	~~39.8~~	~~34.5~~
	L/D	6.1	~~4.8~~	~~3.9~~

Figure 14: Balance Filter Volume Module

Of the first three combinations, only option one is a viable option as the Length to Diameter ratio for the options 2 and 3 are outside the pass criteria. The pass criteria for this module was chosen as a L/D ratio between 6 and 11. This minimum value represents the optimal hydrodynamic shape (tear drop); however, as the L/D decreases further, flow separation and arrangeable area issues dominate. The maximum value is derived based on three factors. First, as the L/D increases, the design moves farther from optimal hydrodynamic performance. Secondly, a longer ship experiences greater effects such as suction forces when operating close to the surface, and lastly at moderate angles, the submarine risks broaching or going out of depth.

For the three combinations shown, only the diameter varies. Thus, the larger diameters in options 2 and 3 would require a shorter submarine and subsequently would not result in the optimal hydrodynamic performance or optimal use of volume. From the 36 combinations, 20 made it to the next level of the filter.

The balance filter next moved to the weight module. For each volume combination, there are three factors, Diving Depth, Material, and Payload Weight, with two possible options for each resulting in eight combinations. Figure 15 shows the results from the first four possible combinations.



		1	2	3	4
Weight Options	Diving Depth	175	175	175	175
	Material	551.7	515	551.7	515
	Payload Weight	300	300	150	150
Weight Module	PHwt	~~584.5~~	~~572.6~~	~~584.5~~	572.6
	Wtot initial	~~3333.3~~	~~3333.3~~	~~1666.7~~	1666.7
	Mwt	~~1166.7~~	~~1166.7~~	~~583.3~~	583.3
	Awt	~~133.3~~	~~133.3~~	~~66.7~~	66.7
Volume	Bwt	~~266.7~~	~~266.7~~	~~133.3~~	133.3
1685.0	Wtot	~~2428.2~~	~~2466.2~~	~~1494.8~~	1532.9
% Difference		~~-44.1%~~	~~-46.4%~~	~~11.3%~~	9.0%

Figure 15: Balance Filter Weight Module

The 20 combinations that made it through from the volume module combined with the eight combinations of the weight resulted in 160 total combinations. Reduction came in the form of a second pass criterion. Looking at Figure 15, the volume from the first module is contained on the left side of the figure and highlighted in green (1685 m^3). From the weight estimate, the maximum allowed percent difference between volume and weight is 10%. From the four combinations shown above, only option four meets the criterion.

The 10% was selected based on two factors. The first factor was the necessity to select a difference that was manageable in the context of creating a balanced ship without requiring significant tradeoffs up front. The second was to constrain the number of viable configurations. This value essentially acts as a margin for the weights although negative percentages were allowed to remain (weight was greater than volume displacement). Ultimately, balancing of a ship that only had at most 10% difference between volume and weight was deemed the maximum allowable.

An interesting facet of the balance worth exploring was the effect of varying the payload weight ranges on the number of passing concepts. The payload weight was varied from 100 tons to 700 tons with the number of passing concepts for percent differences up to 25% recorded. This revealed the payload weight for balanced designs to be a minimum of 150 tons and a maximum of 400 tons. Figure 16 shows results from the analysis. The results are tied to the fact that starting with payload volumes ranging from 300 to 700 m^3, the payload weight must represent a fraction of that volume but never anything greater than or equal to that actual volume. This makes sense as selection of a payload weight that is greater than its associated volume is representative of dense payload items such as ballistic missiles.

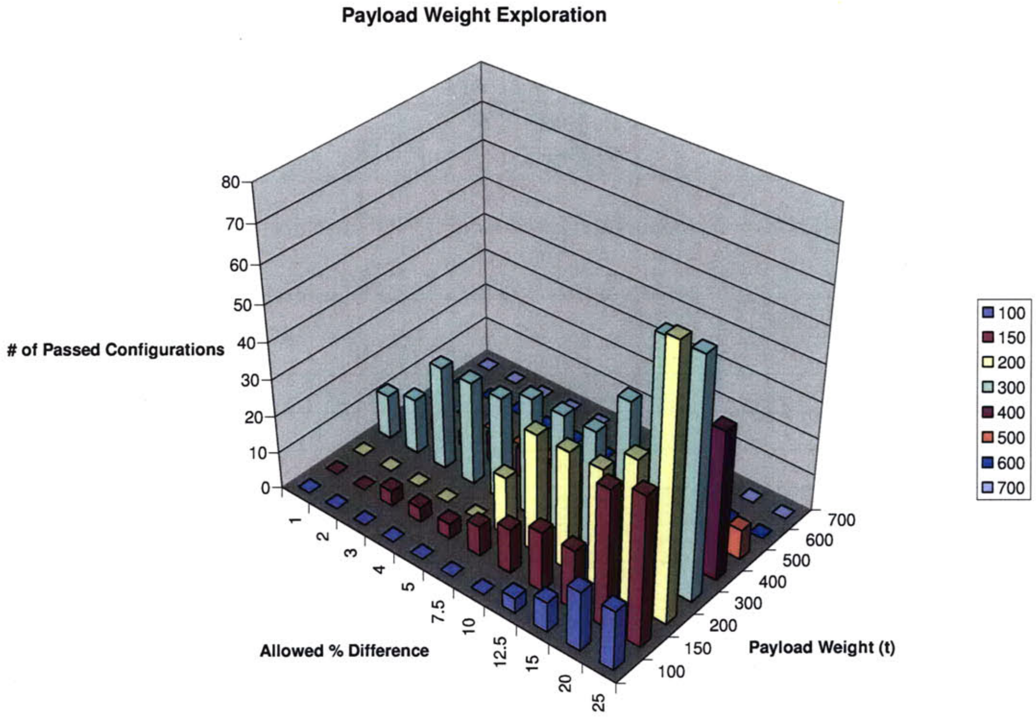


Figure 16: Payload Weight Exploration

From the weight module, the design space had been reduced to 44 designs. The remainder of the filter contained the powering, electrical, and performance module. No further pass criterion was levied on the configurations. One example output for the balance filter is shown below. Table 8 shows the summary of the inputs and Table 9 shows the result from one completed concept.

Volume Options	Endurance	30	Days
	Crew	45	
	Payload Volume	300	m^3
	Diameter	7.62	m
Weight Options	Diving Depth	175	m
	Material	515	MPa
	Payload Weight	150	Tons
Powering Options	Motor Size	6	MW
Electrical	Battery Power	2	kw/cell
	Payload Power	150	kw

Table 8: Example Integrated Concept Factor/Variable Summary

Volume Module			Powering Module		
Phnet	1071.4	m^3	EHP	4498.2	kw
Wstores	27.0		Umax	26.4	kts
TC	36.5	m^3	Psub	18.8	kw
Phinternal	1107.9	m^3	Psnort	268.5	kw
Phexternal	1274.1	m^3	Pmean	95.4	kw
MBT	191.1	m^3	Psurface	455.6	kw
Envelope Volume	1685.0	m^3	Elec. Module		
Length	46.4	m	Hotel Load	238.9	kw
L/D	6.1		# of Batteries	193	
Weight Module			Diesel Power	2762.1	kw
PHwt	572.6	t	Misc. Module		
Wtot initial	1666.7	t	Fuel Volume	57.3	m^3
Mwt	583.3	t	Psprint	2004.3	kw
Awt	66.7	t	Total Power	10587.1	kw
Bwt	133.3	t	Time at Sprint	0.13	hrs
Wtot	1532.9	t	Indiscretion Ratio	20.17%	
% Difference	9.03%		Surfaced Range	5368.0	Nm

Table 9: Integrated Concept Output Summary from Balance Filter

The combination of the 44 configurations coming out of the weight module with the number of factors and associated variables in the remaining modules results in 352 possible configurations with results from each comparable to that shown in Table 9. The balance filter successfully reduced the total possible initial configurations from 2304 to 352.

Of note, some of the factors had initially had continuous ranges (e.g. depth). The plan was to break the ranges into discrete values. Once all the integrated concepts were completed, a review of those integrated concepts that made it through revealed how the chosen discrete values performed. For depth, the results showed that 28 out of the 44 configurations coming out of the weight module (64%) used the shallower depth value with the remaining 16 using the deeper depth value. Thus, the selection of discrete values in this area was satisfactory.

5.6 Concept Scoring

Candidate designs that made it through the Balance Filter check would then be comparatively evaluated although this work was not undertaken in the thesis. This final step could use a number of techniques discussed in Section 4.8. The advantage of using the Multi-Attribute model is the development of attributes and measures for comparative evaluations that trace back to the initial trade space development and evolve along the entire process. Submarine level value will most likely include attributes of component risk, maintainability, payload fraction, displacement, speed, performance characteristics, and cost.

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6.0 Conclusion

The goal of the thesis was to develop a framework for SBD execution and apply this to selected elements in an early stage submarine concept. This was accomplished by first exploring how the SSC Program applied SBD principles and methodology during its PPD phase. The resulting work explored the methods used by the program to execute the SBD effort and directly led to the development of a generic framework for SBD execution. This framework covers organizational structure, requirement inputs, set creation and reduction, creating integrated designs, and final concept selection.

When applied to a submarine concept, the elemental breakdown provides a good context to explore individual factors and combination of factors within selected elements. The development of a balance filter shows promise in its ability combine factors and option that result in feasible concepts. Additional research is required to determine the amount of design flexibility the framework allows, to what extent design making can be delayed, and to what level knowledge is truly captured

6.1 The Future of Submarine Design

The U.S. Navy currently finds itself in the midst of the OHIO replacement program[10]. Beginning nearly two years ago, the program recognized that due to the long times between studies, very near two decades, many of those engineers and designers that worked on the Virginia class concept exploration process have moved on to other fields or are no longer available for referencing. Design exploration also kicked off with thought by some in the community that the replacement would carry the maximum number of tubes with maximum diameter and for that maximum capability, cost is not a major issue. This mentality has changed as the program is now looking at the full trade space and encouraging people to come to the table with innovative solutions. This, however, has still made the idea of specifying ranges for design parameters difficult. As stated by one senior naval architect familiar with the program, "If you are driving the

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[10] The OHIO replacement program is the name given to the program that will eventually develop the submarine to replace the OHIO Ballistic Missile Submarine Class. Although a final program name has not been settled up on, this paper will refer to the program as mentioned.

design, you would have to do that deliberately. Most of the designers are detailed design people built around the idea of certifying ships to go to sea and are used to working from specifications. Their mindsets are not revolved around options but rather solutions and detailed design. This mentality is derived from working for a customer, and counterpart at NAVSEA, who has similar mindset and will not accept a range of ideas and in some instances, think they already know what they want and the answer they seek is justification of the solution in an unexplored trade space." This, combined with a mindset that resists change that falls outside of their comfort area naturally leads to resistance to adopt new practices.

Although design options are discussed, the process is moving forward methodically. Senior leadership is comprised of broad thinking individuals who are willing to listen to alternatives and proper construction of the design space is required. The senior naval architect goes on to say that "An open trade space is a good thing and decisions can be made with properly formatted, relayed information." The need to identify performance factors associated with specific options has also been identified as decision makers require this information.

To obtain performance factors, the program has turned to SUBCODE to map the design space. Using point studies to calibrate SUBCODE, the program has completed over 5000 balanced ships and has utilized DOE to vary five performance variables. There remains a great deal of hesitancy to put point studies on the table that digress significantly from what concepts centered around an OHIO class submarine with larger diameter tubes. Thus, SUBCODE has been used to do a lot of the heavy lifting; however, the point studies so far are not conducted in a systematic approach to look at characteristics, develop options, and reduce the options in a manner to arrive at a chosen concept. The method is not point based, but it also does not go down the track of set based design.

Another problem with this approach is the lack of an ability to capture knowledge that drives design decisions. The same problems experienced by the shortfall of experience today will inevitably happen in the future when a replacement concept is being looked at for the next attack submarine beyond the VA Class. SUBCODE is the current method to store information as it allows the designer to map the thinking of previous designs and utilize that information. However, knowledge capture must go beyond that seen in the design tool and become part of the overall process. SBD may hold the answers of how to evolve the design process.

6.2 Suggestions for Implementation

Although the use of SBD has been suggested for the PPD process, use in such a manner should only be undertaken if this is the plan from the onset. Once a program is underway, restructuring of the elements of an organization in support of a SBD effort may not be possible. Plus, the use of SBD will most likely be the first instance of its use in whatever particular program it is used in and not setting up the environment for success from the onset may lead to failure of the effort.

Also, once concept exploration is complete, the execution of SBD later in the overall design process may lose some its value. Take the submarine design factor diameter. Selection of an actual value is done very early in the design process and thus, waiting until PPD would not allow this factor to be varied and multiple options explored. However, this factor is one of the most important design factor selections and exploring its affect on other elements, factors, and options would be beneficial.

6.3 Areas for Future Study

Additional work should look at conducting a SBD effort with focus on developing an executable process that can be implemented in an actual ship design project. In particular, the number of commercially available tools for surface ship design is significantly greater than those available for submarine design. Utilizing software such as Advanced Surface Ship Evaluation Tool (ASSET), a design environment where staged, varying requirements can simulate real world design efforts and provide a look at how SBD provides design flexibility.

Lastly, the discussion of SBD has focused on how to execute SBD; however, to fully facilitate the transition the U.S. Navy desires, additional research and understanding of how to implement change is required. It seems like the only time changes in a design environment is welcomed is when the previous method no longer works. SBD should be viewed as a methodology that works in conjunction with other design functions.

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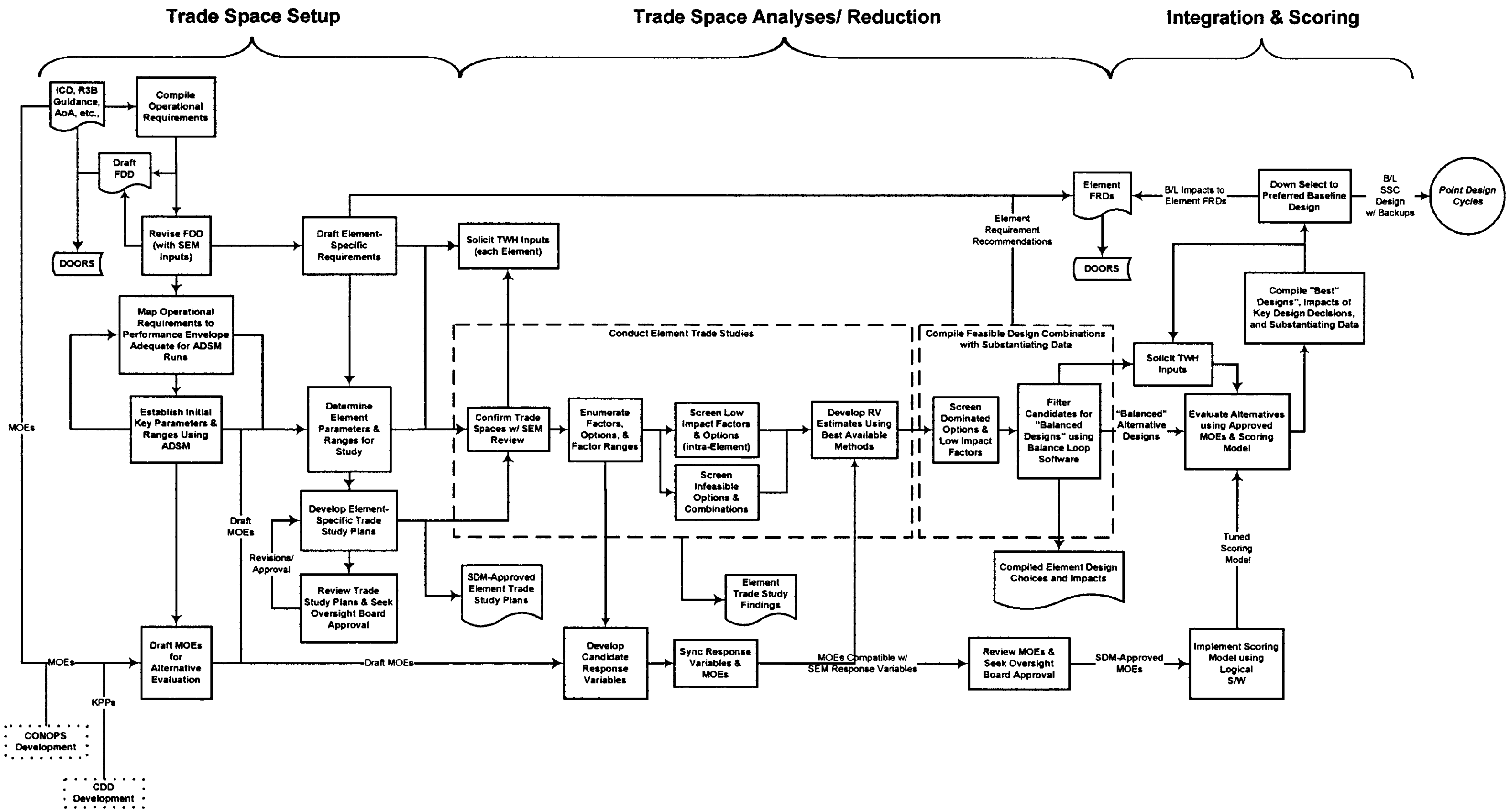
Appendix A: SSC Program Process Map



Process 1: Compile Operational Requirements. A consensus compilation of operational requirements was developed to kick off the set-based design activity. Limited to operational requirements drawn from the ICD, AoA, R3B Guidance Memo and DoD 5000, and referred to as the Draft Functional Design Document (FDD), the FDD needed to be just robust enough to establish (with the assistance of a program called the Air Cushion Design Synthesis Model (ADSM) or similar) a set of performance and weight parameter ranges adequate to kick off the set-based design activity. The FDD was an important marker in the requirements traceability story.

Process 2: Revise FDD with SEM and other inputs. The Draft FDD was subjected to SSC Team review. The revised FDD was used to kick off the Set-Based Design Process. (This version of the FDD was captured in DOORS®.)

Process 3: Draft Element Specific Requirements. Each SEM used the revised FDD and element knowledge, and solicited inputs from the TWHs to draft a first cut at element specific requirements which were called the element specific Functional Requirements Document (FRD). The FRD was intended to house candidate functional requirements necessary to characterize the element. The Element FRDs are an evolving set of assumptions and potential requirements to further define the element trade spaces and ultimately constrain element specific requirements. The FRD is a living document and maintains the SEM's current 'best' view of subsystem requirements. At the time of first review, it contained a mix of candidate requirement statements: (a) references to standards that may need to be accommodated at some point and (b) references to craft level requirements that could include inferred qualifications based on element specific knowledge. At a minimum, the FRD needed to contain known "must have" requirements.

Process 4: Map Operational Requirements to Craft Level Parameter Ranges. With the approved FDD in hand, a minimum set of SSC options, attributes, and attributes ranges necessary to characterize SSC at the platform level was developed. Performance data derived from the FDD was developed into data files adequate for platform level studies using the ADSM model. Objective levels for key performance parameters and weight targets bound the ADSM data on one end and threshold levels bound the ADSM data on the other end.

Process 5: Establish Initial Key Parameters & Ranges Using ADSM. Using the data from Process 4, the ADSM model was used to develop the performance and weight ranges to be used by the SEMs. The DIT conducted a set of ADSM runs engineered to focus on higher payoff configurations using Design-of-Experiment methods. Performance and weight allocations were made at the element level, seeding the initial element trade spaces.

Process 6: Determine Element Parameters & Ranges for Study. The results of Process 5 above were tempered with the Draft Element Requirements of Process 3. Then the SEMs relaxed the parameters, options and parameter ranges based on their knowledge and expectations for promising areas of study. It was the SEM's responsibility to translate the resulting relaxed performance and weight ranges into a set of corresponding options, subsystem and component sets, and associated attributes that defined their element's trade space. The DIT facilitated this effort, capturing the information in Trade Space Summaries spanning all of the elements.

Process 7: Develop Element Specific Trade Study Plans. Each SEM developed Element Specific Trade Study Plans consistent with the FRDs, plans which included using Design of Experiment methods where appropriate to simplify search of the defined trade space and focus on regions of significant promise. To develop these Trade Study Plans, each SEM relaxed the assigned performance and weight ranges for his element based on his/her knowledge of available components, technologies, materials, etc., that could offer benefit, if included. Each **Plan** was required to contain the following: (a) a definition of the element specific trade space, including how the element response surface equations will be characterized; (b) an element FRD (as an Appendix); and (c) a plan for executing the studies.

Process 8: Review Trade Study Plans and Seek Oversight Board Approval. The Element Specific Trade Study Plans were presented to the Oversight Board for approval. The Oversight Board included the SDM and Deputy SDM. Upon approval of the Trade Study Plans, the SEMs commenced their Trade Studies.

Process 9: Solicit TWH Inputs. This is the first of several noted instances/ opportunities for TWH input and influence during the Set-Based Design effort. The pace of the set-based design effort was furious and demanded multiple polling of the TWHs for concurrence. In addition, many TWHs had been identified for a given element. Therefore, it was virtually impossible to have each TWH polled and given time for response for each polling opportunity specified in the process diagram. However, it was the SEM's responsibility to make the information available to the TWHs (or send notice) as appropriate.

Process 10: Conduct Element Trade Studies. Consistent with the approved Element Specific Trade Study Plans, the trade studies commenced with an opportunity for inputs from the TWHs. Following a DIT-facilitated capture of the Trade Spaces information in the Trade Space Summaries with SEM Review, the DIT attempted to facilitate completion of the enumerated factors, options, & factor ranges and commence the trade space reduction effort. Low Impact Factors & Options (intra-Element) were screened, as well as Infeasible Options & Combinations. As the rate of reduction leveled off, it became important to nail down which Response Variables would be necessary and figure out how they would be measured.

Process 11: Draft Measures for Alternative Evaluation. The evolution of measures started early in the SBD effort, with many inputs were developed in discrete stages. First, initial requirements guidance documents such as the AoA, ICD, etc., were screened for inputs. The next inputs were developed from four stakeholder perspectives on SSC value: acquirer (craft), operator, builder, and maintainer. Later, inputs arose from the CDD development effort. These ideas were merged with early cuts at the candidate Response Variables. Later still this set was synchronized with the final Response Variables remaining at the end of Process 10, producing a set of measurable attributes (measures) for the SDM to review and update for the evaluation in Process 17.

Processes 12: Compile Feasible Design Combinations with Substantiating Data; Process 13: Develop Candidate Response Variables (RV); and Process 14: Sync RVs and Measures. Compile Feasible Design Combinations with Substantiating Data commenced the Design Integration phase of the SBD effort. At this point the DIT and the SEMs had done their best in reducing the available trade space based on the SBD principles. The next step needed was a DIT-led set of decisions about remaining non-dominated solutions and low-impact factors. Candidate designs at the craft level were developed by combining feasible alternatives from across each of the elements. The remaining combinations (design configurations) were then filtered for craft level feasibility using the Balance Loop Software developed for the purpose.

Process 15: Review Measures & Seek Oversight Board Approval. Prior to the comparative design evaluations of **Process 16**, the set of Measures was rounded out by the DIT to accommodate platform level scoring and presented to the Oversight Board for review and approval.

Process 16: Implement Logical Decisions Scoring Model. Using the approved measures for comparative design evaluation, and the commercially available Logical Decisions Software a scoring model was implemented. Three set of preferences were defined to offer a wide range of sensitivity analysis regarding the relative importance of the measures to overall craft value.

Process 17: Evaluate Alternatives using Approved Measures & Logical Decisions Software. Using the approved Measures the Integrated Designs were comparatively scored. The process of evaluating these design alternatives involved many filters and data checks leading up to the evaluation in the approved measures. Several iterations were required to iron out the errors in the data trail verify the filters and calculations.

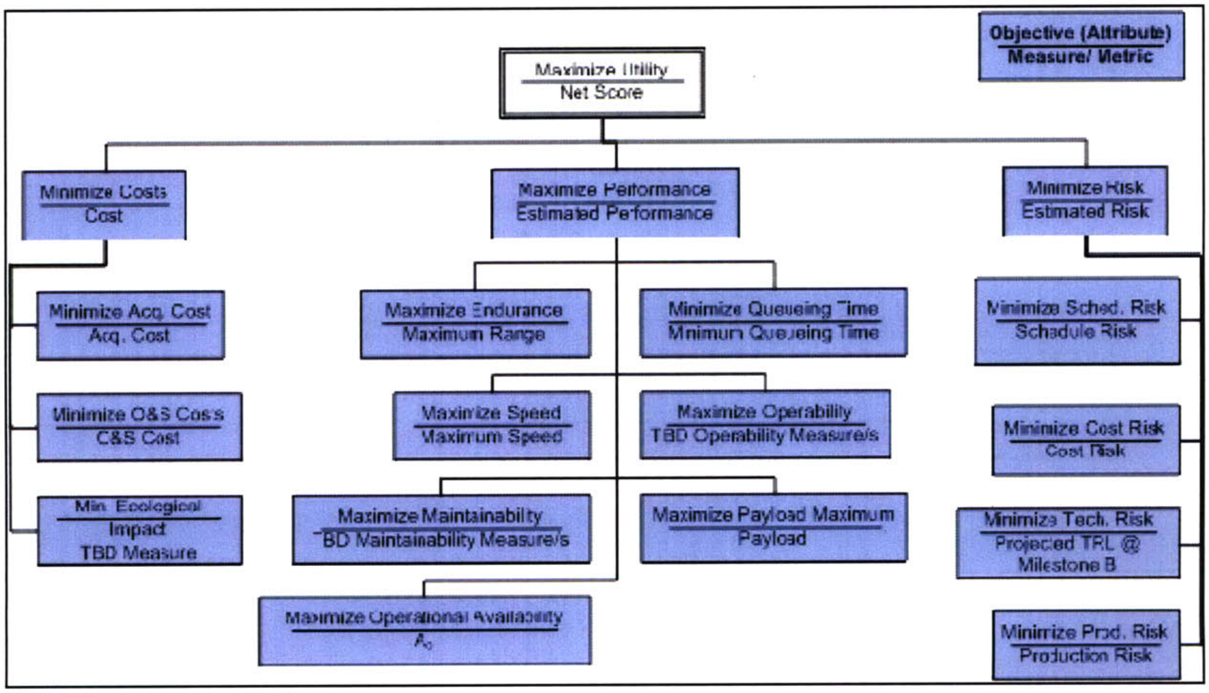
Process 18: Compile "Best" Designs, Impacts of Key Design Decisions, And Substantiating Data. The better scoring designs were evaluated to identify and finalize key design factors and highest value element options.

Process 19: Down Select to Preferred Baseline Design. Based on the output of Process 18, a Baseline Design was developed with backups for key design factor options identified and substantiated with SBD results documentation.

Appendix B: SSC Program Attributes and Measures

The development of measures started with the candidate key design parameters identified by the SEMs at the start of SBD. For these candidate key design parameters, candidate craft level response variables (attributes) needed to assess the relative importance of these design parameters were then identified. The response variables were tempered with attributes from multiple stakeholder perspectives. The response variables were also bounced against the Key System Attributes (KSAs) coming out of the CDD development. The remaining response variables were finally converted into measurable attributes (measures) for the multi-attribute utility evaluation. Like the design of the SBD process, development of the measures was evolutionary and is described in more detailed in the sections below.

The figure below represents a snapshot in time during the development cycle.



Appendix C: Initial Submarine Elements/Factors/Options

Hull						
Trade Categories	**Candidate Key Design Parameters**	**Specific Options, Variable Ranges of Study**				**Discrete/ Continuous**
Hull	Material	SS	HY80	HY100	Composite	Discrete
	Type of Hull	Single BOR	Double BOR	Single NBOR	Double NBOR	Discrete
	Structures - Bulkhead Spacing	Varies				Continuous
	Structures - Stiffener Spacing	Varies				Continuous
	Structures - Stiffener Sizing	Varies				Continuous
	Hull Treatments	% of Hull	Type			Discrete
Geometry	L/D	6	11			Continuous
	Diameter	25	32	40		Discrete
	PH Volume	Varies				Continuous
	Deck Rafting (% of decking)	Location	Type			Continuous
	# of Decks	2	3	4		Discrete
	Curvature Factor	Varies but generally between 1-1.37				Continuous
	Frame Factor	Varies but generally between 1-1.10				Continuous
Misc.	Special Hull Penetrations	Varies				Discrete
	Superstructure	Length	Volume	Contents		Discrete

Performance

Trade Categories	Candidate Key Design Parameters	Specific Options, Variable Ranges of Study			Disc./ Cont.
Operational	Endurance Days	15	90		Cont.
	Crew Size	20	80		Cont.
	Design Depth	600	1000		Cont.
Armament	Torpedo Type	MK54	CVLWT	MK48	Discrete
	Number of Torpedo Tubes	0	2	4	Discrete
	Tube Location	Internal	External		Discrete
	Torpedo Room Arrangement	Reconfigurable			Discrete
Defensive	Countermeasure Types	Varies			Discrete
	Countermeasure Locations	Varies			Discrete
Stealth	Acoustic Silencing	% of Equipment			Cont.
Sail	Sail Design	Varies			Discrete
	Mast Selection	# of Masts	Location		Discrete
Maneuvering	Aft Control Planes	Cruciform	X-Plane		Discrete
	Fwd Control Planes	Bow	Fairwater		Discrete
C4N	Visual sensor	Optics Mast	Photonics Mast		Discrete
	Aural sensor	Dome/ Conformal	HF Sail/Bow	Flank	Discrete
	Towed Array	None	TB-16	TB-23/9	Discrete
	Radio Suite	Individual Components	CSRR		Discrete
	Fire control suite	Hardware Configuration	# of consoles		Discrete
	Control Room Arrangement	Varying			Discrete
	Sonar Suite	Hardware Configuration	# of consoles		Discrete

Power and Propulsion

Trade Cat.	Candidate Key Design Parameters	Specific Options, Variable Ranges of Study					Discrete / Cont.
Power	Energy converter	DG	CCD	Stirling Engine			Discrete
	Battery	Pb Acid	Adv Li-Ion	Flywheel			Discrete
	Fuel Cell	PEM FC	HT Phosphoric Acid PEM	Alkaline FC	SOFC	MCFC	Discrete
	Fuel Stowage (Diesel)	Internal	External				Discrete
	Fuel Stowage (Fuel Cell)	Internal	External				Discrete
	Fuel Cell Fuel Desulfurization	None	Onboard	Shoreside			Discrete
	Fuel Cell Fuel Reformation	None	Onboard	Shoreside			Discrete
	Power Production	1000 kw	10000 kw				Cont.
Elec. Dist.	Electrical Distribution	LVDC	MVDC	LVAC	MVAC	HFAC	Discrete
Propulsion	Motor	DC	Synchronous	Induction	Perm. Magnet	HTSC	Discrete
	Propulsor	Propeller	Pods	Waterjet			Discrete
	# of shafts	0	1	2			Discrete

Auxiliary

Trade Categories	Candidate Key Design Parameters	Specific Options, Variable Ranges of Study	Discrete/Continuous
DC	Fire Suppression Options	Automated vs. Manual	Discrete
Habitability	HVAC System Options	# of Plants, Capacity	Discrete
Auxiliary	Fuel Tank Configuration	1, 2, or 3 Tanks	Discrete
Auxiliary	Air Compressors	# of Plants, Capacity	Discrete
Habitability	Distilling System Options	Type, Location	Discrete
Habitability	Atmosphere Control Options	#, types of units	Discrete
Auxiliary	Ship Service Hydraulic	Electric vs. Hydraulic	Discrete
Auxiliary	External Hydraulic	Electric vs. Hydraulic	Discrete
Habitability	Oxygen Generating/Storage	Varies	Discrete
Auxiliary	Hovering System	Capacity, Type of Pump	Discrete
Auxiliary	Trim &Compensation Pumps	Automated vs. Manual	Discrete
Auxiliary	Secondary Propulsion Motors	1 or 2	Discrete

Payloads

Candidate Key Design Parameters	Specific Options, Variable Ranges of Study	Discrete/Continuous
Missile Tube (BM)	4 - 16	Discrete
VLS (Tomahawk)	4 - 12	Discrete
Lockout Chambers	2 Options	Discrete
UUV	3 Options	Discrete
AUV	2 Options	Discrete
Mine Warfare	2 Options	Discrete
SOF Equipment	Varies	Discrete

Appendix D: Balance Filter Equations

The balance filter is built around use of parametric equations taken from Burcher and Rydill Concepts in Submarine Design as shown throughout this appendix.

Volumes

This is the first section of the balance filter and represents the starting point for the filter. From the 10 design parameters and ranges available from the element screening, those mapped to volume include diameter, endurance, crew size, and payload volume.

The Payload Volume (PL_v) is assumed to be 28% of the internal volume of the pressure hull. This value provides a good first order estimate in the conventional submarine design. Tankage, propulsion equipment, and auxiliaries are not counted in the payload volume.

$$PH_{net}[m^3] = \frac{PL_v[m^3]}{0.28}$$

Internal tankage for the trim and compensation system in then determined taking into account the minimum and maximum saltwater densities (ρ) the submarine will encounter.

$$TC[m^3] = \left[\frac{PH_{net}[m^3](\rho_{\max} - \rho_{\min})[t/m^3]}{\rho_{sw}[t/m^3]} + \frac{W_{stores}[t]}{\rho_{sw}[t/m^3]} \right] \frac{1}{UF}$$

Additional variables include the Utility Factor (UF), taken as 95% to account for tank permeabilities and ullage (full/empty margins) and the weight of stores (W_{stores}) which are determined from:

$$W_{stores}[t] = N_{crew} * E[days] * w_s[t]$$

The W_{stores} contains two of the four design parameters. These are the number of crew (N_{crew}) and the number of endurance days (E). The weight factor (w_s) is taken as 25 kg per man.

With PH_{net} and TC now calculated, a total internal volume of the pressure hull can now be calculated.

$$PH_{in}[m^3] = PH_{net}[m^3] + TC[m^3]$$

To estimate the external volume for the pressure hull, the PH_{in} is increased by a factor (K1). For concept design, this factor is taken to be 15% and accounts for frame spacing, hull curvature, etc. that has to be added to the internal volume to form the external pressure hull.

$$PH_{ex}[m^3] = PH_{in}[m^3] * (1 + K1)$$

This volume is then added to a Main Ballast Tank (MBT) volume to obtain the envelope volume. The percentage of MBT that comprises the PH_{ex} is called the Reserve Buoyancy (RB). A value of 15% is used for concept design.

$$MBT[m^3] = PH_{ex}[m^3] * (RB) * \frac{1}{UF}$$

The addition of the PH_{ex} and MBT volumes results in the envelope volume. An additional factor (K2) is applied to account for volumes such as superstructure, appendages, and the sail of the submarine and is applied a value of 15%.

$$TotalVolume[m^3] = \left(PH_{ex}[m^3] + MBT[m^3]\right) * (1 + K2)$$

The fourth design factor is then varied to determine the resulting length that the total volume would represent.

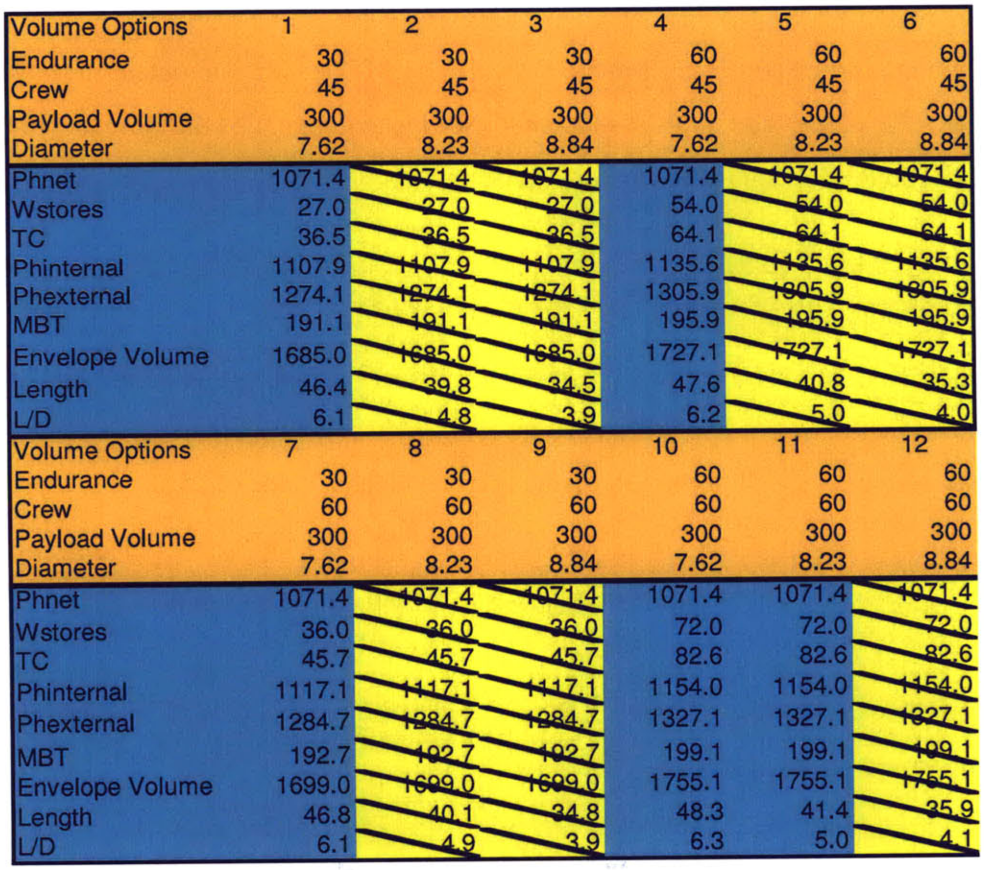
$$Length[m] = \frac{\frac{TotalVolume[m^3]}{K3}}{\pi * \left(\frac{D[m]}{2}\right)^2}$$

A conversion factor (K3) is applied to account for the forward and after shaping factors. K3 is derived from analysis of operational diesel electric submarines and takes the value of 0.796. The associated Length to Diameter (L/D) ratio is:

$$\frac{L}{D} = \frac{Length[m]}{Diameter[m]}$$

Pass Criteria: The four design parameters in the volume section yield 36 possible combinations. Any combination that resulted in an L/D ratio less than six or greater than 11 was eliminated.

The results from this analysis are presented below.



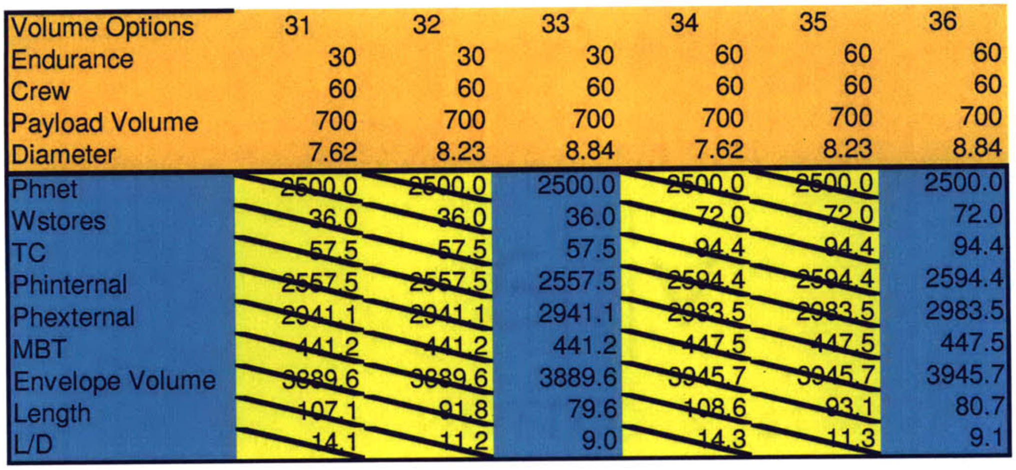
Volume Options	1	2	3	4	5	6
Endurance	30	30	30	60	60	60
Crew	45	45	45	45	45	45
Payload Volume	300	300	300	300	300	300
Diameter	7.62	8.23	8.84	7.62	8.23	8.84
Phnet	1071.4	~~1071.4~~	~~1071.4~~	1071.4	~~1071.4~~	~~1071.4~~
Wstores	27.0	~~27.0~~	~~27.0~~	54.0	~~54.0~~	~~54.0~~
TC	36.5	~~36.5~~	~~36.5~~	64.1	~~64.1~~	~~64.1~~
Phinternal	1107.9	~~1107.9~~	~~1107.9~~	1135.6	~~1135.6~~	~~1135.6~~
Phexternal	1274.1	~~1274.1~~	~~1274.1~~	1305.9	~~1305.9~~	~~1305.9~~
MBT	191.1	~~191.1~~	~~191.1~~	195.9	~~195.9~~	~~195.9~~
Envelope Volume	1685.0	~~1685.0~~	~~1685.0~~	1727.1	~~1727.1~~	~~1727.1~~
Length	46.4	~~39.8~~	~~34.5~~	47.6	~~40.8~~	~~35.3~~
L/D	6.1	~~4.8~~	~~3.9~~	6.2	~~5.0~~	~~4.0~~

Volume Options	7	8	9	10	11	12
Endurance	30	30	30	60	60	60
Crew	60	60	60	60	60	60
Payload Volume	300	300	300	300	300	300
Diameter	7.62	8.23	8.84	7.62	8.23	8.84
Phnet	1071.4	~~1071.4~~	~~1071.4~~	1071.4	1071.4	~~1071.4~~
Wstores	36.0	~~36.0~~	~~36.0~~	72.0	72.0	~~72.0~~
TC	45.7	~~45.7~~	~~45.7~~	82.6	82.6	~~82.6~~
Phinternal	1117.1	~~1117.1~~	~~1117.1~~	1154.0	1154.0	~~1154.0~~
Phexternal	1284.7	~~1284.7~~	~~1284.7~~	1327.1	1327.1	~~1327.1~~
MBT	192.7	~~192.7~~	~~192.7~~	199.1	199.1	~~199.1~~
Envelope Volume	1699.0	~~1699.0~~	~~1699.0~~	1755.1	1755.1	~~1755.1~~
Length	46.8	~~40.1~~	~~34.8~~	48.3	41.4	~~35.9~~
L/D	6.1	~~4.9~~	~~3.9~~	6.3	5.0	~~4.1~~

Volume Options	13	14	15	16	17	18
Endurance	30	30	30	60	60	60
Crew	45	45	45	45	45	45
Payload Volume	500	500	500	500	500	500
Diameter	7.62	8.23	8.84	7.62	8.23	8.84
Phnet	1785.7	1785.7	1785.7	1785.7	1785.7	1785.7
Wstores	27.0	27.0	27.0	54.0	54.0	54.0
TC	42.4	42.4	42.4	70.0	70.0	70.0
Phinternal	1828.1	1828.1	1828.1	1855.8	1855.8	1855.8
Phexternal	2102.3	2102.3	2102.3	2134.1	2134.1	2134.1
MBT	315.3	315.3	315.3	320.1	320.1	320.1
Envelope Volume	2780.3	2780.3	2780.3	2822.4	2822.4	2822.4
Length	76.6	65.6	56.9	77.7	66.6	57.8
L/D	10.0	8.0	6.4	10.2	8.1	6.5

Volume Options	19	20	21	22	23	24
Endurance	30	30	30	60	60	60
Crew	60	60	60	60	60	60
Payload Volume	500	500	500	500	500	500
Diameter	7.62	8.23	8.84	7.62	8.23	8.84
Phnet	1785.7	1785.7	1785.7	1785.7	1785.7	1785.7
Wstores	36.0	36.0	36.0	72.0	72.0	72.0
TC	51.6	51.6	51.6	88.5	88.5	88.5
Phinternal	1837.3	1837.3	1837.3	1874.2	1874.2	1874.2
Phexternal	2112.9	2112.9	2112.9	2155.3	2155.3	2155.3
MBT	316.9	316.9	316.9	323.3	323.3	323.3
Envelope Volume	2794.3	2794.3	2794.3	2850.4	2850.4	2850.4
Length	76.9	66.0	57.2	78.5	67.3	58.3
L/D	10.1	8.0	6.5	10.3	8.2	6.6

Volume Options	25	26	27	28	29	30
Endurance	30	30	30	60	60	60
Crew	45	45	45	45	45	45
Payload Volume	700	700	700	700	700	700
Diameter	7.62	8.23	8.84	7.62	8.23	8.84
Phnet	~~2500.0~~	~~2500.0~~	2500.0	~~2500.0~~	~~2500.0~~	2500.0
Wstores	~~27.0~~	~~27.0~~	27.0	~~54.0~~	~~54.0~~	54.0
TC	~~48.3~~	~~48.3~~	48.3	~~75.9~~	~~75.9~~	75.9
Phinternal	~~2548.3~~	~~2548.3~~	2548.3	~~2575.9~~	~~2575.9~~	2575.9
Phexternal	~~2930.5~~	~~2930.5~~	2930.5	~~2962.3~~	~~2962.3~~	2962.3
MBT	~~439.6~~	~~439.6~~	439.6	~~444.3~~	~~444.3~~	444.3
Envelope Volume	~~3875.6~~	~~3875.6~~	3875.6	~~3917.7~~	~~3917.7~~	3917.7
Length	~~106.7~~	~~91.5~~	79.3	~~107.9~~	~~92.5~~	80.2
L/D	~~14.0~~	~~11.1~~	9.0	~~14.2~~	~~11.2~~	9.1



Volume Options	31	32	33	34	35	36
Endurance	30	30	30	60	60	60
Crew	60	60	60	60	60	60
Payload Volume	700	700	700	700	700	700
Diameter	7.62	8.23	8.84	7.62	8.23	8.84
Phnet	~~2500.0~~	~~2500.0~~	2500.0	~~2500.0~~	~~2500.0~~	2500.0
Wstores	~~36.0~~	~~36.0~~	36.0	~~72.0~~	~~72.0~~	72.0
TC	~~57.5~~	~~57.5~~	57.5	~~94.4~~	~~94.4~~	94.4
Phinternal	~~2557.5~~	~~2557.5~~	2557.5	~~2594.4~~	~~2594.4~~	2594.4
Phexternal	~~2941.1~~	~~2941.1~~	2941.1	~~2983.5~~	~~2983.5~~	2983.5
MBT	~~441.2~~	~~441.2~~	441.2	~~447.5~~	~~447.5~~	447.5
Envelope Volume	~~3889.6~~	~~3889.6~~	3889.6	~~3945.7~~	~~3945.7~~	3945.7
Length	~~107.1~~	~~91.8~~	79.6	~~108.6~~	~~93.1~~	80.7
L/D	~~14.1~~	~~11.2~~	9.0	~~14.3~~	~~11.3~~	9.1

Weights:

The next module moved to determine the weight associated with three design parameters: Diving Depth (DD), Payload Weight (PL_{wt}), and material (σ_y). This begins by looking at the structural weight. This is proportional to the design depth and the external volume of the pressure hull. A constant K4 is representative of steel and is taken as 0.125.

$$PW_{wt}[t] = K4 * \frac{DD[m]}{\sigma_Y[MPa]} * TotalVolume[m^3] * \rho_{steel}[t/m^3]$$

To calculate total weight, an initial estimate of the total weight is calculated using the third design factor, payload weight.

$$W_{tot}[t] = \frac{PL_{wt}[t]}{0.09}$$

With an initial estimate of payload weight, an approximate value for Machinery Weight (M_{wt}), Accommodation Weight (A_{wt}), and Ballast Weight (B_{wt}) is determined based off the initial estimate for the total weight.

$$M_{wt}[t] = 0.35 * W_{tot}[t]$$

$$A_{wt}[t] = 0.04 * W_{tot}[t]$$

$$B_{wt}[t] = 0.08 * W_{tot}[t]$$

Using the weight values from above, a revised total weight of the submarine is calculated.

$$W_{tot}[t] = PL_{wt}[t] + W_{stores}[t] + A_{wt}[t] + B_{wt}[t] + M_{wt}[t] + PH_{wt}[t]$$

Pass Criteria: With the total weight of the ship determined, the filter process looks to eliminate those designs that do not have an initial weight and volume balance within a specified range. This range is a percentage of total ship volume. A summary of the results are contained below:

		1	2	3	4	5	6	7	8
Weight Options	Diving Depth	175	175	175	175	250	250	250	250
	Material	551.7	515	551.7	515	551.7	515	551.7	515
	Payload Weight	300	300	150	150	300	300	150	150
Weight Module	PHwt	~~534.5~~	~~572.6~~	~~534.5~~	572.6	~~763.6~~	~~818.0~~	763.6	818.0
	Wtot initial	~~3333.3~~	~~3333.3~~	~~1666.7~~	1666.7	~~3333.3~~	~~3333.3~~	1666.7	1666.7
	Mwt	~~1166.7~~	~~1166.7~~	~~583.3~~	583.3	~~1166.7~~	~~1166.7~~	583.3	583.3
	Awt	~~133.3~~	~~133.3~~	~~66.7~~	66.7	~~133.3~~	~~133.3~~	66.7	66.7
Volume	Bwt	~~266.7~~	~~266.7~~	~~133.3~~	133.3	~~266.7~~	~~266.7~~	133.3	133.3
1685.0	Wtot	~~2428.2~~	~~2466.2~~	~~1494.8~~	1532.9	~~2657.2~~	~~2711.6~~	1723.9	1778.3
% Difference		~~-44.1%~~	~~-46.4%~~	~~11.3%~~	9.0%	~~-57.7%~~	~~-60.9%~~	-2.3%	-5.5%
		~~0.0~~	~~0.0~~	~~1.0~~	1.0	~~0.0~~	~~0.0~~	1.0	1.0
	PHwt	~~547.8~~	~~586.9~~	~~547.8~~	586.9	~~782.6~~	~~838.4~~	782.6	838.4
2	Wtot initial	~~3333.3~~	~~3333.3~~	~~1666.7~~	1666.7	~~3333.3~~	~~3333.3~~	1666.7	1666.7
	Mwt	~~1166.7~~	~~1166.7~~	~~583.3~~	583.3	~~1166.7~~	~~1166.7~~	583.3	583.3
	Awt	~~133.3~~	~~133.3~~	~~66.7~~	66.7	~~133.3~~	~~133.3~~	66.7	66.7
	Bwt	~~266.7~~	~~266.7~~	~~133.3~~	133.3	~~266.7~~	~~266.7~~	133.3	133.3
1727.1	Wtot	~~2468.5~~	~~2507.5~~	~~1535.2~~	1574.2	~~2703.3~~	~~2759.0~~	1769.9	1825.7
		~~-42.9%~~	~~-45.2%~~	~~11.1%~~	8.9%	~~-56.5%~~	~~-59.8%~~	-2.5%	-5.7%
		~~0.0~~	~~0.0~~	~~1.0~~	1.0	~~0.0~~	~~0.0~~	1.0	1.0
	PHwt	~~538.9~~	~~577.3~~	~~538.9~~	577.3	~~769.9~~	~~824.8~~	769.9	824.8
3	Wtot initial	~~3333.3~~	~~3333.3~~	~~1666.7~~	1666.7	~~3333.3~~	~~3333.3~~	1666.7	1666.7
	Mwt	~~1166.7~~	~~1166.7~~	~~583.3~~	583.3	~~1166.7~~	~~1166.7~~	583.3	583.3
	Awt	~~133.3~~	~~133.3~~	~~66.7~~	66.7	~~133.3~~	~~133.3~~	66.7	66.7
	Bwt	~~266.7~~	~~266.7~~	~~133.3~~	133.3	~~266.7~~	~~266.7~~	133.3	133.3
1699.0	Wtot	~~2441.6~~	~~2480.0~~	~~1508.3~~	1546.7	~~2672.6~~	~~2727.4~~	1739.2	1794.1
		~~-43.7%~~	~~-46.0%~~	~~11.2%~~	9.0%	~~-57.3%~~	~~-60.5%~~	-2.4%	-5.6%
		~~0.0~~	~~0.0~~	~~1.0~~	1.0	~~0.0~~	~~0.0~~	1.0	1.0
Weight Module	PHwt	~~556.7~~	~~596.4~~	~~556.7~~	596.4	~~795.3~~	~~852.0~~	795.3	852.0
	Wtot initial	~~3333.3~~	~~3333.3~~	~~1666.7~~	1666.7	~~3333.3~~	~~3333.3~~	1666.7	1666.7
	Mwt	~~1166.7~~	~~1166.7~~	~~583.3~~	583.3	~~1166.7~~	~~1166.7~~	583.3	583.3
	Awt	~~133.3~~	~~133.3~~	~~66.7~~	66.7	~~133.3~~	~~133.3~~	66.7	66.7
	Bwt	~~266.7~~	~~266.7~~	~~133.3~~	133.3	~~266.7~~	~~266.7~~	133.3	133.3
1755.1	Wtot	~~2495.4~~	~~2535.1~~	~~1562.1~~	1601.7	~~2734.0~~	~~2790.7~~	1800.6	1857.3
		~~-42.2%~~	~~-44.4%~~	~~11.0%~~	8.7%	~~-55.8%~~	~~-59.0%~~	-2.6%	-5.8%
		~~0.0~~	~~0.0~~	~~1.0~~	1.0	~~0.0~~	~~0.0~~	1.0	1.0

	PHwt	881.9	944.8	881.9	944.8	1259.9	1349.7	1259.9	1349.7
5	Wtot initial	3333.3	3333.3	1666.7	1666.7	3333.3	3333.3	1666.7	1666.7
	Mwt	1166.7	1166.7	583.3	583.3	1166.7	1166.7	583.3	583.3
	Awt	133.3	133.3	66.7	66.7	133.3	133.3	66.7	66.7
	Bwt	266.7	266.7	133.3	133.3	266.7	266.7	133.3	133.3
2780.3	Wtot	2775.6	2838.4	1842.3	1905.1	3153.5	3243.3	2220.2	2310.0
		0.2%	-2.1%	33.7%	31.5%	-13.4%	-16.7%	20.1%	16.9%
		1.0	1.0	0.0	0.0	1.0	1.0	1.0	1.0
Weight Module	PHwt	881.9	944.8	881.9	944.8	1259.9	1349.7	1259.9	1349.7
6	Wtot initial	3333.3	3333.3	1666.7	1666.7	3333.3	3333.3	1666.7	1666.7
	Mwt	1166.7	1166.7	583.3	583.3	1166.7	1166.7	583.3	583.3
	Awt	133.3	133.3	66.7	66.7	133.3	133.3	66.7	66.7
	Bwt	266.7	266.7	133.3	133.3	266.7	266.7	133.3	133.3
2780.3	Wtot	2775.6	2838.4	1842.3	1905.1	3153.5	3243.3	2220.2	2310.0
		0.2%	-2.1%	33.7%	31.5%	-13.4%	-16.7%	20.1%	16.9%
		1.0	1.0	0.0	0.0	1.0	1.0	1.0	1.0
	PHwt	881.9	944.8	881.9	944.8	1259.9	1349.7	1259.9	1349.7
7	Wtot initial	3333.3	3333.3	1666.7	1666.7	3333.3	3333.3	1666.7	1666.7
	Mwt	1166.7	1166.7	583.3	583.3	1166.7	1166.7	583.3	583.3
	Awt	133.3	133.3	66.7	66.7	133.3	133.3	66.7	66.7
	Bwt	266.7	266.7	133.3	133.3	266.7	266.7	133.3	133.3
2780.3	Wtot	2775.6	2838.4	1842.3	1905.1	3153.5	3243.3	2220.2	2310.0
		0.2%	-2.1%	33.7%	31.5%	-13.4%	-16.7%	20.1%	16.9%
		1.0	1.0	0.0	0.0	1.0	1.0	1.0	1.0
	PHwt	895.3	959.1	895.3	959.1	1278.9	1370.1	1278.9	1370.1
8	Wtot initial	3333.3	3333.3	1666.7	1666.7	3333.3	3333.3	1666.7	1666.7
	Mwt	1166.7	1166.7	583.3	583.3	1166.7	1166.7	583.3	583.3
	Awt	133.3	133.3	66.7	66.7	133.3	133.3	66.7	66.7
	Bwt	266.7	266.7	133.3	133.3	266.7	266.7	133.3	133.3
2822.4	Wtot	2815.9	2879.7	1882.6	1946.4	3199.6	3290.7	2266.3	2357.4
		0.2%	-2.0%	33.3%	31.0%	-13.4%	-16.6%	19.7%	16.5%
		1.0	1.0	0.0	0.0	1.0	1.0	1.0	1.0
	PHwt	895.3	959.1	895.3	959.1	1278.9	1370.1	1278.9	1370.1
9	Wtot initial	3333.3	3333.3	1666.7	1666.7	3333.3	3333.3	1666.7	1666.7
	Mwt	1166.7	1166.7	583.3	583.3	1166.7	1166.7	583.3	583.3
	Awt	133.3	133.3	66.7	66.7	133.3	133.3	66.7	66.7
	Bwt	266.7	266.7	133.3	133.3	266.7	266.7	133.3	133.3
2822.4	Wtot	2815.9	2879.7	1882.6	1946.4	3199.6	3290.7	2266.3	2357.4
		0.2%	-2.0%	33.3%	31.0%	-13.4%	-16.6%	19.7%	16.5%
		1.0	1.0	0.0	0.0	1.0	1.0	1.0	1.0
Weight Module	PHwt	895.3	959.1	895.3	959.1	1278.9	1370.1	1278.9	1370.1
10	Wtot initial	3333.3	3333.3	1666.7	1666.7	3333.3	3333.3	1666.7	1666.7
	Mwt	1166.7	1166.7	583.3	583.3	1166.7	1166.7	583.3	583.3
	Awt	133.3	133.3	66.7	66.7	133.3	133.3	66.7	66.7
	Bwt	266.7	266.7	133.3	133.3	266.7	266.7	133.3	133.3
2822.4	Wtot	2815.9	2879.7	1882.6	1946.4	3199.6	3290.7	2266.3	2357.4
		0.2%	-2.0%	33.3%	31.0%	-13.4%	-16.6%	19.7%	16.5%
		1.0	1.0	0.0	0.0	1.0	1.0	1.0	1.0
	PHwt	886.4	949.5	886.4	949.5	1266.2	1356.5	1266.2	1356.5
11	Wtot initial	3333.3	3333.3	1666.7	1666.7	3333.3	3333.3	1666.7	1666.7
	Mwt	1166.7	1166.7	583.3	583.3	1166.7	1166.7	583.3	583.3
	Awt	133.3	133.3	66.7	66.7	133.3	133.3	66.7	66.7
	Bwt	266.7	266.7	133.3	133.3	266.7	266.7	133.3	133.3
2794.3	Wtot	2789.0	2852.2	1855.7	1918.9	3168.9	3259.1	2235.6	2325.8
		0.2%	-2.1%	33.6%	31.3%	-13.4%	-16.6%	20.0%	16.8%
		1.0	1.0	0.0	0.0	1.0	1.0	1.0	1.0
	PHwt	886.4	949.5	886.4	949.5	1266.2	1356.5	1266.2	1356.5
12	Wtot initial	3333.3	3333.3	1666.7	1666.7	3333.3	3333.3	1666.7	1666.7
	Mwt	1166.7	1166.7	583.3	583.3	1166.7	1166.7	583.3	583.3
	Awt	133.3	133.3	66.7	66.7	133.3	133.3	66.7	66.7
	Bwt	266.7	266.7	133.3	133.3	266.7	266.7	133.3	133.3
2794.3	Wtot	2789.0	2852.2	1855.7	1918.9	3168.9	3259.1	2235.6	2325.8
		0.2%	-2.1%	33.6%	31.3%	-13.4%	-16.6%	20.0%	16.8%
		1.0	1.0	0.0	0.0	1.0	1.0	1.0	1.0

Weight Module	PHwt	886.4	949.5	~~886.4~~	~~949.5~~	~~1266.2~~	~~1356.5~~	~~1266.2~~	~~1356.5~~
13	Wtot initial	3333.3	3333.3	~~1666.7~~	~~1666.7~~	~~3333.3~~	~~3333.3~~	~~1666.7~~	~~1666.7~~
	Mwt	1166.7	1166.7	~~583.3~~	~~583.3~~	~~1166.7~~	~~1166.7~~	~~583.3~~	~~583.3~~
	Awt	133.3	133.3	~~66.7~~	~~66.7~~	~~133.3~~	~~133.3~~	~~66.7~~	~~66.7~~
	Bwt	266.7	266.7	~~133.3~~	~~133.3~~	~~266.7~~	~~266.7~~	~~133.3~~	~~133.3~~
2794.3	Wtot	2789.0	2852.2	~~1855.7~~	~~1918.9~~	~~3168.9~~	~~3259.1~~	~~2295.6~~	~~2325.8~~
		0.2%	-2.1%	~~33.6%~~	~~31.3%~~	~~-13.4%~~	~~-16.6%~~	~~20.0%~~	~~16.8%~~
		1.0	1.0	~~0.0~~	~~0.0~~	~~1.0~~	~~1.0~~	~~1.0~~	~~1.0~~
	PHwt	904.2	968.6	~~904.2~~	~~968.6~~	~~1291.6~~	~~1383.7~~	~~1291.6~~	~~1383.7~~
14	Wtot initial	3333.3	3333.3	~~1666.7~~	~~1666.7~~	~~3333.3~~	~~3333.3~~	~~1666.7~~	~~1666.7~~
	Mwt	1166.7	1166.7	~~583.3~~	~~583.3~~	~~1166.7~~	~~1166.7~~	~~583.3~~	~~583.3~~
	Awt	133.3	133.3	~~66.7~~	~~66.7~~	~~133.3~~	~~133.3~~	~~66.7~~	~~66.7~~
	Bwt	266.7	266.7	~~133.3~~	~~133.3~~	~~266.7~~	~~266.7~~	~~133.3~~	~~133.3~~
2850.4	Wtot	2842.8	2907.2	~~1909.5~~	~~1973.9~~	~~3230.3~~	~~3322.4~~	~~2297.0~~	~~2389.0~~
		0.3%	-2.0%	~~33.0%~~	~~30.7%~~	~~-13.3%~~	~~-16.6%~~	~~19.4%~~	~~16.2%~~
		1.0	1.0	~~0.0~~	~~0.0~~	~~1.0~~	~~1.0~~	~~1.0~~	~~1.0~~
	PHwt	904.2	968.6	~~904.2~~	~~968.6~~	~~1291.6~~	~~1383.7~~	~~1291.6~~	~~1383.7~~
15	Wtot initial	3333.3	3333.3	~~1666.7~~	~~1666.7~~	~~3333.3~~	~~3333.3~~	~~1666.7~~	~~1666.7~~
	Mwt	1166.7	1166.7	~~583.3~~	~~583.3~~	~~1166.7~~	~~1166.7~~	~~583.3~~	~~583.3~~
	Awt	133.3	133.3	~~66.7~~	~~66.7~~	~~133.3~~	~~133.3~~	~~66.7~~	~~66.7~~
	Bwt	266.7	266.7	~~133.3~~	~~133.3~~	~~266.7~~	~~266.7~~	~~133.3~~	~~133.3~~
2850.4	Wtot	2842.8	2907.2	~~1909.5~~	~~1973.9~~	~~3230.3~~	~~3322.4~~	~~2297.0~~	~~2389.0~~
		0.3%	-2.0%	~~33.0%~~	~~30.7%~~	~~-13.3%~~	~~-16.6%~~	~~19.4%~~	~~16.2%~~
		1.0	1.0	~~0.0~~	~~0.0~~	~~1.0~~	~~1.0~~	~~1.0~~	~~1.0~~
Weight Module	PHwt	904.2	968.6	~~904.2~~	~~968.6~~	~~1291.6~~	~~1383.7~~	~~1291.6~~	~~1383.7~~
16	Wtot initial	3333.3	3333.3	~~1666.7~~	~~1666.7~~	~~3333.3~~	~~3333.3~~	~~1666.7~~	~~1666.7~~
	Mwt	1166.7	1166.7	~~583.3~~	~~583.3~~	~~1166.7~~	~~1166.7~~	~~583.3~~	~~583.3~~
	Awt	133.3	133.3	~~66.7~~	~~66.7~~	~~133.3~~	~~133.3~~	~~66.7~~	~~66.7~~
	Bwt	266.7	266.7	~~133.3~~	~~133.3~~	~~266.7~~	~~266.7~~	~~133.3~~	~~133.3~~
2850.4	Wtot	2842.8	2907.2	~~1909.5~~	~~1973.9~~	~~3230.3~~	~~3322.4~~	~~2297.0~~	~~2389.0~~
		0.3%	-2.0%	~~33.0%~~	~~30.7%~~	~~-13.3%~~	~~-16.6%~~	~~19.4%~~	~~16.2%~~
		1.0	1.0	~~0.0~~	~~0.0~~	~~1.0~~	~~1.0~~	~~1.0~~	~~1.0~~
	PHwt	~~1229.3~~	~~1317.0~~	~~1229.3~~	~~1317.0~~	1756.2	1881.4	~~1756.2~~	~~1881.4~~
17	Wtot initial	~~3333.3~~	~~3333.3~~	~~1666.7~~	~~1666.7~~	3333.3	3333.3	~~1666.7~~	~~1666.7~~
	Mwt	~~1166.7~~	~~1166.7~~	~~583.3~~	~~583.3~~	1166.7	1166.7	~~583.3~~	~~583.3~~
	Awt	~~133.3~~	~~133.3~~	~~66.7~~	~~66.7~~	133.3	133.3	~~66.7~~	~~66.7~~
	Bwt	~~266.7~~	~~266.7~~	~~133.3~~	~~133.3~~	266.7	266.7	~~133.3~~	~~133.3~~
3875.6	Wtot	~~3123.0~~	~~3210.6~~	~~2189.7~~	~~2277.3~~	3649.9	3775.0	~~2716.5~~	~~2841.7~~
		~~19.4%~~	~~17.2%~~	~~43.5%~~	~~41.2%~~	5.8%	2.6%	~~29.9%~~	~~26.7%~~
		~~1.0~~	~~1.0~~	~~0.0~~	~~0.0~~	1.0	1.0	~~0.0~~	~~0.0~~
	PHwt	~~1242.7~~	~~1331.2~~	~~1242.7~~	~~1331.2~~	1775.3	1901.8	~~1775.3~~	~~1901.8~~
18	Wtot initial	~~3333.3~~	~~3333.3~~	~~1666.7~~	~~1666.7~~	3333.3	3333.3	~~1666.7~~	~~1666.7~~
	Mwt	~~1166.7~~	~~1166.7~~	~~583.3~~	~~583.3~~	1166.7	1166.7	~~583.3~~	~~583.3~~
	Awt	~~133.3~~	~~133.3~~	~~66.7~~	~~66.7~~	133.3	133.3	~~66.7~~	~~66.7~~
	Bwt	~~266.7~~	~~266.7~~	~~133.3~~	~~133.3~~	266.7	266.7	~~133.3~~	~~133.3~~
3917.7	Wtot	~~3163.4~~	~~3251.9~~	~~2230.0~~	~~2318.6~~	3695.9	3822.4	~~2762.6~~	~~2889.1~~
		~~19.3%~~	~~17.0%~~	~~43.1%~~	~~40.8%~~	5.7%	2.4%	~~29.5%~~	~~26.3%~~
		~~1.0~~	~~1.0~~	~~0.0~~	~~0.0~~	1.0	1.0	~~0.0~~	~~0.0~~
	PHwt	~~1233.8~~	~~1321.7~~	~~1233.8~~	~~1321.7~~	1762.6	1888.2	~~1762.6~~	~~1888.2~~
19	Wtot initial	~~3333.3~~	~~3333.3~~	~~1666.7~~	~~1666.7~~	3333.3	3333.3	~~1666.7~~	~~1666.7~~
	Mwt	~~1166.7~~	~~1166.7~~	~~583.3~~	~~583.3~~	1166.7	1166.7	~~583.3~~	~~583.3~~
	Awt	~~133.3~~	~~133.3~~	~~66.7~~	~~66.7~~	133.3	133.3	~~66.7~~	~~66.7~~
	Bwt	~~266.7~~	~~266.7~~	~~133.3~~	~~133.3~~	266.7	266.7	~~133.3~~	~~133.3~~
3889.6	Wtot	~~3136.5~~	~~3224.4~~	~~2203.1~~	~~2291.1~~	3665.2	3790.8	~~2731.9~~	~~2857.5~~
		~~19.4%~~	~~17.1%~~	~~43.4%~~	~~41.1%~~	5.8%	2.5%	~~29.8%~~	~~26.5%~~
		~~1.0~~	~~1.0~~	~~0.0~~	~~0.0~~	1.0	1.0	~~0.0~~	~~0.0~~
	PHwt	~~1251.6~~	~~1340.8~~	~~1251.6~~	~~1340.8~~	1788.0	1915.4	~~1788.0~~	~~1915.4~~
20	Wtot initial	~~3333.3~~	~~3333.3~~	~~1666.7~~	~~1666.7~~	3333.3	3333.3	~~1666.7~~	~~1666.7~~
	Mwt	~~1166.7~~	~~1166.7~~	~~583.3~~	~~583.3~~	1166.7	1166.7	~~583.3~~	~~583.3~~
	Awt	~~133.3~~	~~133.3~~	~~66.7~~	~~66.7~~	133.3	133.3	~~66.7~~	~~66.7~~
	Bwt	~~266.7~~	~~266.7~~	~~133.3~~	~~133.3~~	266.7	266.7	~~133.3~~	~~133.3~~
3945.7	Wtot	~~3190.2~~	~~3279.4~~	~~2256.9~~	~~2346.1~~	3726.6	3854.1	~~2793.3~~	~~2920.7~~
		~~19.1%~~	~~16.9%~~	~~42.8%~~	~~40.5%~~	5.6%	2.3%	~~29.2%~~	~~26.0%~~
		~~1.0~~	~~1.0~~	~~0.0~~	~~0.0~~	1.0	1.0	~~0.0~~	~~0.0~~

Powering:

With the integrated design space now reduced to concepts with a basic volume and weight match, the filter then moves to powering. Although typical concept exploration looks to calculate the Shaft Horsepower (SHP) the propulsion motor must provide, the SBD effort has already explored motors with specified outputs and provided a discrete range of options in the design space. The process then turns to matching the applicable motor to the appropriate integrated design.

Starting with the design parameter applicable to this section, Propulsion Motor (P_{motor}) power, the Effective Horsepower (EHP) along with varying other power requirements is calculated.

$$EHP[kw] = P_{motor}[kw] * PE$$

For the powers calculated below, U_{sub} is 4 kts, U_{snort} is 10 kts, and U_{mean} is 7 kts.

Submerged Power (P_{sub}):

$$P_{sub}[kw] = K_p * TotalVolume^{0.64}[m^3] * U_{sub}{}^{2.9}[m/s]$$

Snort Power (P_{snort}):

$$P_{snort}[kw] = K_p * TotalVolume^{0.64}[m^3] * U_{snort}{}^{2.9}[m/s]$$

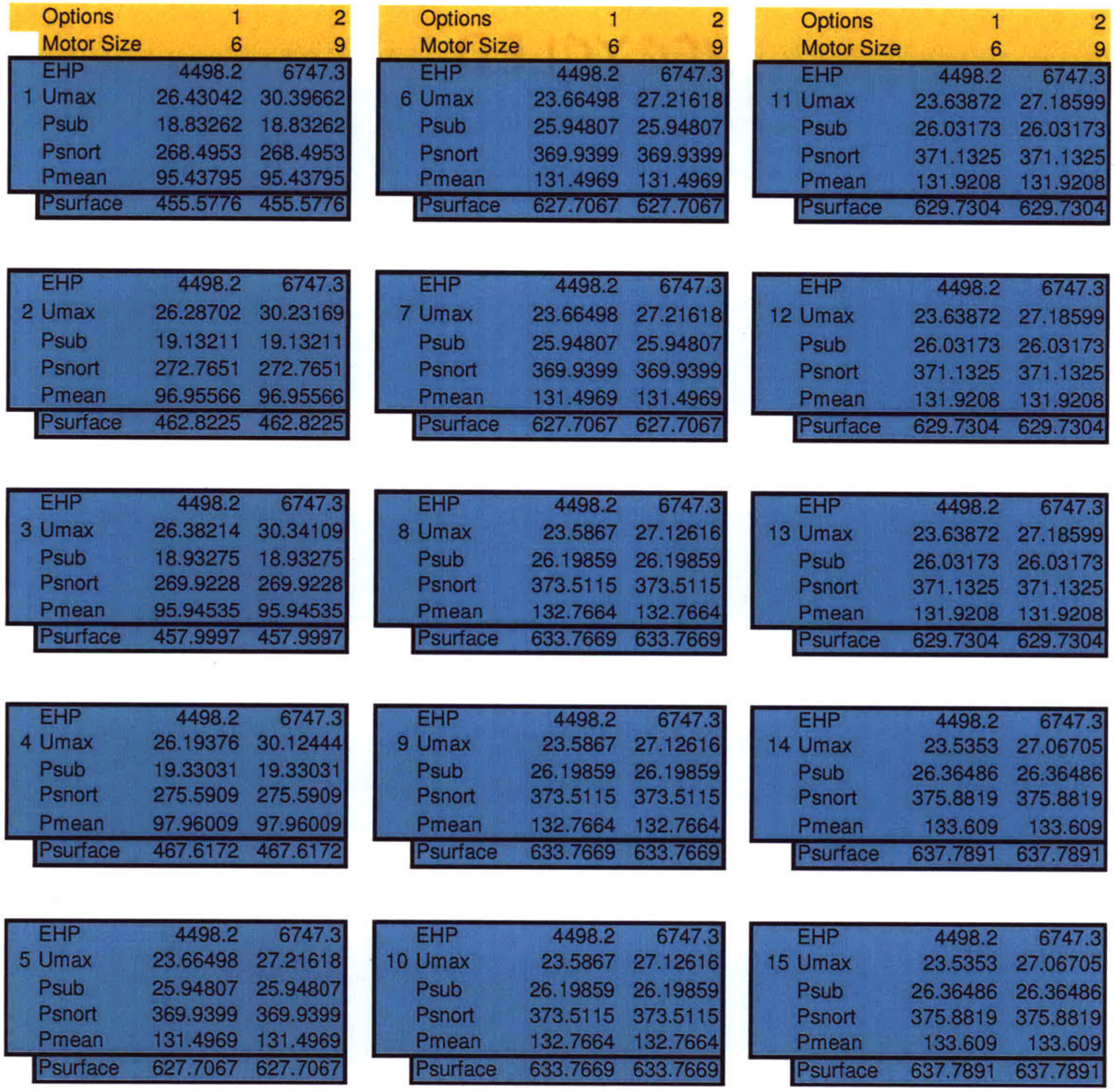
Mean Speed Power (P_{mean}):

$$P_{mean}[kw] = K_p * TotalVolume^{0.64}[m^3] * U_{mean}{}^{2.9}[m/s]$$

PE represents the propulsion efficiency normal comprised of the hull, propeller, relative rotative, and shaft transmission efficiencies. K_p is a factor that takes into account all variables associated with resistance.

Pass Criteria: Although not used in this balance filter, speed requirements and restrictions could be applied to reduce the design space.

Since the only factor involved in this section is based off of total volume, the results, like those in the weight module, are representative of each of the 20 volumes calculated in the volume module. The results are contained below.



	Options	1	2
	Motor Size	6	9
	EHP	4498.2	6747.3
1	Umax	26.43042	30.39662
	Psub	18.83262	18.83262
	Psnort	268.4953	268.4953
	Pmean	95.43795	95.43795
	Psurface	455.5776	455.5776

	EHP	4498.2	6747.3
2	Umax	26.28702	30.23169
	Psub	19.13211	19.13211
	Psnort	272.7651	272.7651
	Pmean	96.95566	96.95566
	Psurface	462.8225	462.8225

	EHP	4498.2	6747.3
3	Umax	26.38214	30.34109
	Psub	18.93275	18.93275
	Psnort	269.9228	269.9228
	Pmean	95.94535	95.94535
	Psurface	457.9997	457.9997

	EHP	4498.2	6747.3
4	Umax	26.19376	30.12444
	Psub	19.33031	19.33031
	Psnort	275.5909	275.5909
	Pmean	97.96009	97.96009
	Psurface	467.6172	467.6172

	EHP	4498.2	6747.3
5	Umax	23.66498	27.21618
	Psub	25.94807	25.94807
	Psnort	369.9399	369.9399
	Pmean	131.4969	131.4969
	Psurface	627.7067	627.7067

	Options	1	2
	Motor Size	6	9
	EHP	4498.2	6747.3
6	Umax	23.66498	27.21618
	Psub	25.94807	25.94807
	Psnort	369.9399	369.9399
	Pmean	131.4969	131.4969
	Psurface	627.7067	627.7067

	EHP	4498.2	6747.3
7	Umax	23.66498	27.21618
	Psub	25.94807	25.94807
	Psnort	369.9399	369.9399
	Pmean	131.4969	131.4969
	Psurface	627.7067	627.7067

	EHP	4498.2	6747.3
8	Umax	23.5867	27.12616
	Psub	26.19859	26.19859
	Psnort	373.5115	373.5115
	Pmean	132.7664	132.7664
	Psurface	633.7669	633.7669

	EHP	4498.2	6747.3
9	Umax	23.5867	27.12616
	Psub	26.19859	26.19859
	Psnort	373.5115	373.5115
	Pmean	132.7664	132.7664
	Psurface	633.7669	633.7669

	EHP	4498.2	6747.3
10	Umax	23.5867	27.12616
	Psub	26.19859	26.19859
	Psnort	373.5115	373.5115
	Pmean	132.7664	132.7664
	Psurface	633.7669	633.7669

	Options	1	2
	Motor Size	6	9
	EHP	4498.2	6747.3
11	Umax	23.63872	27.18599
	Psub	26.03173	26.03173
	Psnort	371.1325	371.1325
	Pmean	131.9208	131.9208
	Psurface	629.7304	629.7304

	EHP	4498.2	6747.3
12	Umax	23.63872	27.18599
	Psub	26.03173	26.03173
	Psnort	371.1325	371.1325
	Pmean	131.9208	131.9208
	Psurface	629.7304	629.7304

	EHP	4498.2	6747.3
13	Umax	23.63872	27.18599
	Psub	26.03173	26.03173
	Psnort	371.1325	371.1325
	Pmean	131.9208	131.9208
	Psurface	629.7304	629.7304

	EHP	4498.2	6747.3
14	Umax	23.5353	27.06705
	Psub	26.36486	26.36486
	Psnort	375.8819	375.8819
	Pmean	133.609	133.609
	Psurface	637.7891	637.7891

	EHP	4498.2	6747.3
15	Umax	23.5353	27.06705
	Psub	26.36486	26.36486
	Psnort	375.8819	375.8819
	Pmean	133.609	133.609
	Psurface	637.7891	637.7891

Options	1	2
Motor Size	6	9
EHP	4498.2	6747.3
16 Umax	23.5353	27.06705
Psub	26.36486	26.36486
Psnort	375.8819	375.8819
Pmean	133.609	133.609
Psurface	637.7891	637.7891

Options	1	2
Motor Size	6	9
EHP	4498.2	6747.3
18 Umax	21.94006	25.23242
Psub	32.31641	32.31641
Psnort	460.7328	460.7328
Pmean	163.7696	163.7696
Psurface	781.7623	781.7623

Options	1	2
Motor Size	6	9
EHP	4498.2	6747.3
20 Umax	21.90556	25.19274
Psub	32.46423	32.46423
Psnort	462.8403	462.8403
Pmean	164.5188	164.5188
Psurface	785.3383	785.3383

EHP	4498.2	6747.3
17 Umax	21.99238	25.29259
Psub	32.09395	32.09395
Psnort	457.5612	457.5612
Pmean	162.6423	162.6423
Psurface	776.3809	776.3809

EHP	4498.2	6747.3
19 Umax	21.97486	25.27245
Psub	32.1682	32.1682
Psnort	458.6198	458.6198
Pmean	163.0186	163.0186
Psurface	778.177	778.177

Electrical Load:

This section of the filter took into the account the remaining design parameters: the type of battery (associated attribute being cell power P_{cell}) and varying levels of payload power (PL_p). This begins with the determination of the submerged hotel load (HL).

$$HL[kw] = 0.75 * PL_P[kw] + 0.075 * PH[m^3]$$

Using this load combined with the propulsive load, the number of batteries is then calculated.

$$No.ofBatt = \left(\frac{P_{sub}[kw] + HL[kw]}{P_{cell}[kw]} \right) * (1 + K5)$$

K5 is the battery safety margin. P_{cell} is the maximum power capacity of a single cell. The next step is to determine the diesel generator power.

$$P_{diesel}[kw] = \left[\frac{(1+m)}{1000} * I_{\max}[A] * V_{\max}[Volts] * N + HL[kw] + \frac{P_{snort}[kw]}{\eta_e * PE} \right] * \frac{1}{\eta_{conv}}$$

In this relation, the power output of the diesel generator is P_{diesel} is the power output of the generator set, m is an oversizing factor of 15%, and Imax and Vmax are the maximum charging current and voltage, respectively, for a single cell. The efficiencies η_e and η_{conv} are taken as 0.95 and 0.98 respectively. The former is associated with the power losses from the generator to the propulsion motor and the second with the efficiency of electrical energy conversion in the generator

The results are contained below. The results thus far yield 324 results. This is made up of volume (20) x weight (8) = 160 reduced to 44. Each of the 44 combinations has power combinations (2) resulting in 88 configurations. Each of these 88 configurations has four possible electrical loadings resulting in the 324 possible configurations.

		1	2	3	4
	Battery Power	2	4	2	4
	Payload Power	150	150	200	200
1	Hotel Load	238.9	238.9	276.4	276.4
	# of Batteries	193.3	96.6	221.4	110.7
	Diesel Power	3184.5	1917.2	3591.7	2139.9
2	Hotel Load	242.0	242.0	279.5	279.5
	# of Batteries	195.9	97.9	224.0	112.0
	Diesel Power	3228.2	1943.8	3635.3	2166.5
3	Hotel Load	239.9	239.9	277.4	277.4
	# of Batteries	194.1	97.1	222.3	111.1
	Diesel Power	3199.1	1926.1	3606.2	2148.8
4	Hotel Load	244.1	244.1	281.6	281.6
	# of Batteries	197.6	98.8	225.7	112.9
	Diesel Power	3257.2	1961.6	3664.3	2184.3
5	Hotel Load	321.0	321.0	358.5	358.5
	# of Batteries	260.2	130.1	288.4	144.2
	Diesel Power	4299.8	2593.4	4706.9	2816.1
6	Hotel Load	321.0	321.0	358.5	358.5
	# of Batteries	260.2	130.1	288.4	144.2
	Diesel Power	4299.8	2593.4	4706.9	2816.1
7	Hotel Load	321.0	321.0	358.5	358.5
	# of Batteries	260.2	130.1	288.4	144.2
	Diesel Power	4299.8	2593.4	4706.9	2816.1
8	Hotel Load	324.2	324.2	361.7	361.7
	# of Batteries	262.8	131.4	290.9	145.5
	Diesel Power	4341.9	2618.8	4749.0	2841.4
9	Hotel Load	324.2	324.2	361.7	361.7
	# of Batteries	262.8	131.4	290.9	145.5
	Diesel Power	4341.9	2618.8	4749.0	2841.4
10	Hotel Load	324.2	324.2	361.7	361.7
	# of Batteries	262.8	131.4	290.9	145.5
	Diesel Power	4341.9	2618.8	4749.0	2841.4
11	Hotel Load	322.1	322.1	359.6	359.6
	# of Batteries	261.1	130.5	289.2	144.6
	Diesel Power	4313.8	2601.9	4720.9	2824.5
12	Hotel Load	322.1	322.1	359.6	359.6
	# of Batteries	261.1	130.5	289.2	144.6
	Diesel Power	4313.8	2601.9	4720.9	2824.5
13	Hotel Load	322.1	322.1	359.6	359.6
	# of Batteries	261.1	130.5	289.2	144.6
	Diesel Power	4313.8	2601.9	4720.9	2824.5
14	Hotel Load	326.3	326.3	363.8	363.8
	# of Batteries	264.5	132.2	292.6	146.3
	Diesel Power	4369.9	2635.7	4777.0	2858.3
15	Hotel Load	326.3	326.3	363.8	363.8
	# of Batteries	264.5	132.2	292.6	146.3
	Diesel Power	4369.9	2635.7	4777.0	2858.3
16	Hotel Load	326.3	326.3	363.8	363.8
	# of Batteries	264.5	132.2	292.6	146.3
	Diesel Power	4369.9	2635.7	4777.0	2858.3
17	Hotel Load	403.2	403.2	440.7	440.7
	# of Batteries	326.4	163.2	354.6	177.3
	Diesel Power	5384.5	3243.9	5791.6	3466.6
18	Hotel Load	406.3	406.3	443.8	443.8
	# of Batteries	329.0	164.5	357.1	178.6
	Diesel Power	5425.7	3268.6	5832.8	3491.3
19	Hotel Load	404.2	404.2	441.7	441.7
	# of Batteries	327.3	163.6	355.4	177.7
	Diesel Power	5398.3	3252.2	5805.4	3474.8
20	Hotel Load	408.4	408.4	445.9	445.9
	# of Batteries	330.7	165.3	358.8	179.4
	Diesel Power	5453.2	3285.0	5860.3	3507.7

Performance:

The last module adds detail to each of the 324 configurations. These additional performance characteristics are defined below:

Fuel volume is determined based off of the range the submarine will travel as well as other variables defined below.

$$F_{vol}[m^3] = \left[\frac{Range[nm]}{U_{snort}} * P_{mean}[kw] * sfc\left[\frac{kg}{kWh}\right]\right] * \frac{1}{\rho_{fuel}[kg/m^3]}$$

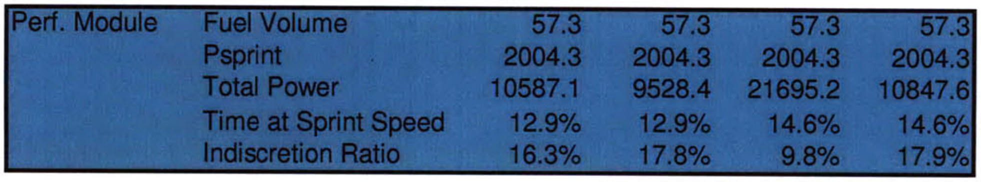
Sprint speed (U_{snort}) is defined as 20 knots. The amount of time the submarine can stay at sprint speed is defined below.

$$TimeAtSprintSpeed = \frac{\#ofBatteries * P_{cell}[kw] * \eta_{batt}}{P_{sprint}[kw/hr] + HL[kw/hr]}$$

The indiscretion ratio is a ratio of recharge time to total cycle time.

$$IndiscretionRatio = \frac{RechargeTime}{RechargeTime + SubmergedTime}$$

The results for four configurations are shown below. Similar results are compiled for the remaining 320 configurations.



Perf. Module	Fuel Volume	57.3	57.3	57.3	57.3
	Psprint	2004.3	2004.3	2004.3	2004.3
	Total Power	10587.1	9528.4	21695.2	10847.6
	Time at Sprint Speed	12.9%	12.9%	14.6%	14.6%
	Indiscretion Ratio	16.3%	17.8%	9.8%	17.9%