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Concept exploration for a future frigate/destroyer size warship platform

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THESIS

CONCEPT EXPLORATION FOR A FUTURE FRIGATE/DESTROYER SIZE WARSHIP PLATFORM

by

Ralf Trappe

March 2001

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The purpose of this thesis is to make a clean sheet of paper approach to develop a platform for a future frigate/destroyer size warship based on the operational requirements in the context of future crisis management and constrained resources. The envisioned timeframe is the beginning of the next decade, i.e. 2010 +.

Basic operational requirements regarding the bare warship platform will be weighted and discussed. The study is concentrating on the hull and propulsion configuration to support the derived operational needs. All weapons and control systems will be handled as interchangeable modules, hence only spaces and interfaces will be discussed in this thesis. Special emphasis is given to Total Ownership Costs and the risk from incorporating not yet introduced technologies.

In addition to the classical monohull approach, Catamaran, Trimaran, SWATH and the O'Neill hull form configurations will be investigated as well. In comparison to the Combined Diesel and Gas Turbine (CODAG) and Combined Diesel or Gas Turbine (CODOG) propulsion Diesel Electric, Gas Turbine Electric and possible combinations of these propulsion concepts will be evaluated.

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CONCEPT EXPLORATION FOR A FUTURE FRIGATE/DESTROYER SIZE WARSHIP PLATFORM

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Submitted in partial fulfillment of the
requirements for the degree of

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The author would like to acknowledge the support of Mr. David A. Walden of the Caderock Division, Naval Sea Systems Command. He provided vital data for the O'Neill hull form from towing tank tests at the David Taylor Research Center. This information served as the basis for performance predictions of the proposed design.

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I. INTRODUCTION

A. PURPOSE

In today's fast changing political environment our current naval assets do not sufficiently meet current and future requirements, dictated by a full spectrum of possible crises in a global scenario, ranging from humanitarian help to full scale major conflicts. Current assets do not incorporate state of the art technologies and their support needs do not match current constraints due to declining resources.

This thesis will outline today's technically obtainable solutions to build and operate a future frigate/destroyer size warship to replace current aging assets. The research will be based on current and future operational requirements and a market review of ship's hull and propulsion concepts available to meet these requirements. High emphasis will be on the implementation of supportability and upgradeability concepts.

The proposed vessel shall satisfy operational requirements expected in the years 2010 + and shall be upgradeable in an efficient way to satisfy operational requirements evolving during their minimum 30 year service life. The study specifically concentrates on the hull and propulsion configuration to support the derived operational needs. All weapons and control systems will be handled as interchangeable modules, hence only spaces and interfaces will be discussed in this thesis.

Total ownership costs will be one of the key focus areas during the whole selection and design process.

B. RESEARCH QUESTIONS

The primary research question is: What are today's possible solutions to design a warship platform that will satisfy the current and future operational requirements with special regard to all aspects of total ownership costs?

This leads to the following secondary research questions:

1. Hierarchical investigation of operational requirements. What performance characteristics does a battle space commander expect of a frigate/destroyer size ship and how are they going to be ranked to each other? What operational requirements for future warships are defined and mandatory today?

2. What configurations of hull shapes and propulsion systems would support the needs derived from question 1., utilizing materials, technologies and manufacturing processes, which will have matured by 2010? All solutions will be evaluated with regard to most efficient use of available resources, total ownership costs and a proposed program schedule.

3. What are the elements of the total ownership costs for a naval warship?

4. What would a future naval combat vessel look like as a synthesis of the answers to these questions?

C. THESIS OUTLINE

Operational requirements concerning the performance characteristics of a naval war-fighting platform will be derived from the current and expected future mission needs. These requirements will be weighted against each other to obtain a balanced hierarchy that will serve as a basis for the selection of possible hull and propulsion concepts.

Basic ship hull, propulsion and warfare support concepts will be discussed. The feasibility and availability of innovative solutions for the hull type and the propulsion plant will be evaluated with the means of calculations and market survey. Warfare support concepts will be investigated with regard to survivability, supportability and upgradeability. One of the underlying concepts in the design will be the use and definition of modules and their required interfaces. The idea of replaceable modules will be used for all propulsion, auxiliary, weapon and control systems where possible.

Total Ownership Costs (TOC), i.e. the cost incurred from acquisition including R&D through life cycle support up to demilitarization and disposal, will be defined for a naval ship. These definitions will be used for the assessment of possible design solutions for the future warship. Major emphasis will be on the supportability and efficient operation during the vessel's deployment.

Possible candidate concepts for hull, propulsion and warfare support will be assessed by their ability to satisfy the derived operational requirements and their expected total ownership costs.

A possible synthesis of the results to obtain a reliable, supportable and upgradeable platform for a future naval combat vessel will be presented and discussed.

D. METHODOLOGY

The methodology used in this thesis research will consist of the following steps.

1. Review German and U.S. Mission Need Information concerning future frigate/destroyer size warships.
2. Review today's available technologies for ship's hulls, propulsion and support systems and search for innovative warfare system support concepts.
3. Review all aspects of Total Ownership Costs.
4. Evaluate operational requirements.
5. Evaluate hull types, propulsion and warfare support systems.
6. Estimate the impact of these concepts with regard to Total Ownership Costs.
7. Analyze possible combinations of all appropriate candidate systems with special respect to their ability to satisfy the stated Mission Needs.
8. Synthesize the results into a proposed design.
9. Formulate conclusions of the findings and recommendations for the German Ministry of Defense and the U.S. Department of Defense.

E. EXPECTED BENEFITS OF THIS THESIS

The thesis will show possible solutions for the design of a future frigate/destroyer size naval surface vessel to replace our current aging assets. Due to the modular concepts employed, this might serve as the basic common platform for a whole family of efficient future naval combat vessels for different missions. The focus on total ownership costs at the design stage is one of the key focus areas for all future military assets.

This thesis will not provide the ultimate exactly defined solution to the design problem but it will show possible solutions derived from the requirements. One major focus within the thesis is the process applied to select, evaluate and synthesize components for a proposed ship design. The final design would be left to the contractor(s) based on defined performance specifications issued by the government.

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II. BACKGROUND

A. INTRODUCTION TO A FUTURE MISSION NEED IN THE YEAR 2010 +

1. Change in the Global Environment

Since the end of the Cold War era the global political environment has changed significantly. Most of today's crises occur affecting naval warfare in the littoral environment and they can happen virtually anywhere around the world. Compared to the bipolar scenario of the past, today's conflicts are smaller in scale but they come at very short notice and require a flexible and precisely tailored response towards the individual crisis. Due to the fact that the composition of the forces with regard to their nationalities varies from conflict to conflict, interoperability becomes one of the key challenges for success.

2. Future Missions for the Navy

The navies of tomorrow will be confronted with the following missions:

- Antisubmarine Warfare (ASW)
- Above Water Warfare (AWW), i.e. Anti Air Warfare (AAW) + Anti Surface Warfare (ASuW)
- Theater Air Defense (TAD)
- Theater Ballistic Missile Defense (TBMD)
- Littoral Warfare / Naval Surface Fire support (NSFS)

- Embargo Operations
- Humanitarian Missions
- Mine Warfare (MW)

3. Assets Needed to Fulfill the Missions

Looking at the current assets of the German Navy, the following missions are covered: Anti Submarine Warfare (ASW), Above Water Warfare (AWW), Embargo Operations, Humanitarian Missions and Mine Warfare (MW). Theater Air Defense (TAD) was partly covered by destroyers class 103 ("LUTJENS" class, similar to US "CHARLES F. ADAMS" class) which are being taken out of service. Littoral Warfare, especially Naval Surface Fire Support, is only covered by assets carrying a 76-mm gun. Theater Ballistic Missile Defense (TBMD) is presently not covered at all. Beginning in 2002, the frigate class 124 will provide the TAD mission capabilities currently provided by the destroyer class 103. The frigate class 122 ("BREMEN" class), which covers mainly ASW, AWW and Embargo Operations will be at the end of their 30 year service life in 2012 and the following years. Due to this development there will be a need to replace these eight frigates beginning in 2012. Since the roles of TBMD and NSFS particularly need to be created or enhanced and the capabilities of the "BREMEN" class need to be replaced, eight new ships are required to close the gap. A possible option is to design a primarily AWW version and a primarily ASW version on the basis of a common hull. The AWW version then has to be able to perform the TBMD and the NSFS role as well.

B. OPERATIONAL REQUIREMENTS

1. The Following Operational Capabilities are Required to Fulfill these Future Missions:

- The ship shall be capable of detecting and tracking air, surface, and subsurface contacts in order to support the prescribed concept of operations in the defined operational environment.
- The ship shall provide command and control capability to support the concept of Network-Centric-Warfare [Ref.1].
- The ship shall be fully interoperable with all forces at joint and combined levels.
- The ship shall employ advanced weapon systems to the highest extent possible while also using common NATO Standard ammunition to allow cross supplies within a multi-national force.
- The ship shall achieve or exceed the maneuverability, speed of advance and range required to keep up with combined naval forces, e.g., NATO Standing Naval Forces Atlantic (STANAVFORLANT).
- The ship shall be designed to meet Level III Survivability criteria specified in U.S. OPNAVINST 9070.1 or corresponding foreign national instructions.

2. System Requirements Concerning the Platform:

No	Requirement	Rationale
1	The design shall comply with or exceed all relevant military and commercial standards for ocean going ships at the time of lead ship delivery with no exemption.	Since the international standards, especially those concerning safety, waste and emissions are getting very tight, there would be huge future costs for retrofitting the required systems. The extensive use of commercial standards where applicable allows the use of commercial off-the-shelf (COTS) components and subcomponents.
2	State-of-the-art automation, built-in test systems and central computerized data logging system shall be provided.	Manpower is one of the major cost drivers in the operation of a warship today and it will be in future. Any reasonable investment to reduce manpower up front will significantly lower the total ownership costs.
3	The ship shall have integrated electric power generation, distribution and propulsion system.	This ensures optimum load condition and hence efficiency for the prime movers. With an electric drive system more flexibility in internal arrangement of all machinery is gained. It increases the overall redundancy and versatility by automatic re-routing and re-allocation of loads in emergency situations. It provides the high electric power needs required by future generations of weapon systems.

4	The high and low speed maneuverability in harbor and at sea shall be high.	The ship has to be able enter or leave harbor and secure alongside without external assistance, i.e. tugs or personnel. Both might not be available in a future crisis scenario. The ship has to keep up with combined naval forces in any threat environment.
5	Modular design shall be implemented to the maximum extent possible.	The benefits are the ease of replacement in case of failure or battle damage, upgradeability to accommodate future state-of-the-art systems and capability for exchange systems to enable the ship to perform different roles.
6	The design shall provide 10 % margin for displacement growth. This shall include a 0.5 m margin for the vertical center of gravity (KG).	The ship has to have a service life allowance to permit displacement growth, in order to accommodate weight increases, incl. topweights, caused by future upgrades.
7	Cables, pipes and vents shall be designed to support the modular concept. The number of cables, pipes and vents has to be sufficient for a reasonable future growth and to provide redundancy in case of failure.	The full benefits of a modular design can only be utilized, if the ship's technical infrastructure supports a "plug-and-play" like operation, hence requiring a standardized supply of electrical power, data transfer, ventilation and cooling water.
8	Commercial state of the art data processing bandwidth shall be employed.	Since all future combat systems rely on permanent transfer of huge amounts of data, the ships must be provided with the maximum bandwidth reasonable available.

9	The platform shall be prepared to support an open architecture integrated computer network.	The system has to ensure compatibility with all relevant IT standards at the time of lead ship delivery and has to allow for future growth and updates. Hence the final decision about detail design of hardware and software has to be postponed until about three years before ship delivery.
10	Stealth technology has to be used to the maximum extent practicable.	The key to "high tech" warfare is to avoid any detection and hence possible damage from enemy hits as long as possible. Therefore all emissions, including the magnetic, electro-magnetic, heat, radar, noise, visual and even the wake signatures of the ship have to be as small as possible.
11	The damaged stability characteristics shall allow for flooding of at minimum three adjacent compartments without sinking.	The loss of compartments can occur due to battle damage, grounding, collision or internal accidents. In all cases the ship and her crew shall survive without external assistance.
12	The platform shall survive medium caliber gunfire or one (EXOCET equivalent) missile hit.	Since the ship might be on its own it has to remain at least in a reduced mission capable status after a hit as long as possible.
13	The ship shall have underwater acoustic detection capability suitable to the mission requirements.	Even in the non-ASW role some capability similar to today's sonar is required for self defense. For the deep-sea ASW role more advanced capability can be installed as one of the modules.

14	Support of a minimum of 2 helicopters, or 1 helicopter and two UAVs shall be provided by the platform.	Helicopters and or drones are required for reconnaissance or as weapon carriers. At least one helicopter is required for personnel and casualty transfer in any kind of operation.
15	NATO standard RAS equipment, automated means to handle all liquid and solid supplies as well as means to deliver fuel shall be provided.	The RAS capability is essential to ensure the required operational endurance. An automated supply handling system is required to transport solid goods in a fast, safe and efficient way within the ship with minimum personnel. The fuel delivery capability is required to supply smaller units like Fast Patrol Boats (FPBs) and Corvettes during an operation. This will be done alongside only.
16	There have to be two rigid boats rigged such that they can easily be deployed, one of which has to be equipped with a cabin.	The boats are required for special forces operations, evacuations, search and rescue and as a means to commute between ship and shore if the ship cannot stay in a harbor. The covered boat is required for casualty transfers.
17	An accommodation margin shall be provided for at least 30 personnel above ship's force level.	Within the ships design roles, it has to be able to deploy special forces, accommodate casualties, perform evacuations and serve as a training platform for officer candidates.
18	State-of-the-art corrosion protection	Design flaws in the corrosion protection of the platform cause manpower intensive actions and increase the total ownership costs significantly.

19	Operational availability for the system shall be 0.90 or greater.	The operational availability, which is a function of all system Mean Times Between Maintenance (MTBMs) and the respective down times, is a vital key to fulfill the mission need with a limited number of assets.
20	System supportability and upgradeability shall be possible via currently available infrastructure.	The system has to be supported within the currently available infrastructure. Major module replacements either for repair, change of role or for upgrades shall be performed in any harbor with container handling capabilities.

2. Key Performance Parameters:

CRITERIA	THRESHOLD	OBJECTIVE
Top Speed (to be sustained up to sea state 7)	28 kn.	35 kn.
Acceleration (0 – 25 kn.)	90 sec.	60 sec.
Maximum Range	4,000 nm.	7000 nm.
Endurance	21 days	28 days
High Speed Transit	4,000 nm @ 18 kn	5,000 nm @ 24 kn
Max sea state for boat operation	6	7
Max sea state for helicopter/UAV operation	8	9
Min floodable length in adjacent compartments	3	4
Crew required to operate ship	180	120

C. TECHNOLOGY CONCEPTS

1. Hull Types

The following hull types could in theory be used to serve as a platform for a future warship:

a. Monohull; b. Catamaran; c. Trimaran; d. SWATH; e. Combinations of these

a. Monohull

The conventional monohull is the basis for most military vessels at the moment. One of the major benefits is that there is a lot of expertise available concerning all aspects of hull design and construction. Another is the low wetted surface area to displacement ratio, which pays off with low skin friction that governs the majority of the resistance at lower speeds. There are advanced versions of monohulls that manage to reduce the wave making resistance by means of special shapes to the bow and stern of the vessel. A planning hull offers higher speed capability, but is presently not feasible for ship sizes discussed in this thesis at economical power levels.

b. Catamaran

The catamaran offers a large deck area but is restricted in the capability to accommodate large changes in weight. It is more efficient at high speeds due to lower wave-making resistance, but gets penalized by a higher wetted surface area to displacement ratio, which basically results in higher total ship's resistance at low speeds compared to a monohull of similar displacement. The dynamic transverse stability of a catamaran is better compared to a similar sized monohull. Enhanced seakeeping ability can be achieved by wave piercing bow designs.

c. Trimaran

In theory many facts relevant to the catamaran apply to the trimaran as well. Most trimarans have a center hull that is much larger than the side hulls, which results in some of the monohull features. In practice there hasn't been any significant development in large-scale trimarans until quite recently. The first serious project in this direction is the British 'RV Triton'. Since the total loss of one side hull due to battle damage may not necessarily be catastrophic for the ship survival, this design offers some not yet explored benefits in survivability.

d. SWATH (Small Waterplane Area Twin Hull)

The SWATH ship has the advantage of minimum wave making resistance but has a high wetted surface area and hence high skin friction at a given displacement. It's primary benefits in seakeeping are that it shows relatively lower motions in waves, assuming a such that they won't expose the lower hulls nor touch the bottom of the cross-structure connecting the upper hulls. Similar to the catamaran, this type offers a high amount of deck area but is even more limited in its capability to accommodate large weight changes. Most SWATH ships today need a stabilizer system to ensure sufficient dynamic longitudinal stability.

e. Combinations

There are feasible combinations like the O'Neill design that basically consists of one fully submerged main hull and two additional side hulls to ensure the required transverse stability. This design attempts to lower the wetted surface area compared to a SWATH ship without loosing all the benefits of lower wave making resistance.

Other hull form types such as hydro-foils, air cushion and surface effect vehicles are not likely to yield an efficient solution as a platform for a frigate / destroyer sized surface warship due to their inefficient power to weight ratio.

2. Power Systems

a. Mechanical Drive Systems

Pure mechanical drive systems in this context are all propulsion systems that rely on a direct mechanical connection between the prime movers and the propellant systems. This might be single or multi shaft arrangement, as well as a Schottel or Voith-Schneider vertical axis propeller or even a water jet. The key element of all mechanical systems driven by more than one prime mover is a gearbox including the necessary coupling devices. The prime movers could be Diesel engines, gas turbines or any combination of both. For ships with mechanical drive systems, running their engines at a constant design load condition is the most efficient way of propulsion. An additional, separate electrical power generation system for ship service power is required.

b. Partial Electric Drive Systems

In today's warship design, there are two major varieties of partial electric drive systems. The first is the combination of an electric motor connected to the shaft for low speeds (some ships achieve up to 16 kn.) and a gas turbine connected to the same shaft for high speeds. There are different arrangements possible. The second one, especially used for smaller Mine Warfare Vessels, is the combination of a completely mechanical drive system with an electric-driven Schottel propeller to achieve noise-free propulsion at very low speeds (up to 5 kn.). As for the pure mechanical drive system, separate prime movers are required to power the electrical and the main propulsion system.

c. Fully Electric Drive Systems

In a fully electric drive system, any prime mover can be combined with any propelling system. There are no constraints about the physical location/distance of prime mover and propeller. The electric drive motor can be placed completely external of the hull, as is done with podded drive systems. One of the benefits is the possibility of selecting the prime movers, which are connected to the power grid such that they are always running at a very efficient load. The resultant lower specific fuel consumption will compensate for efficiency losses due to energy transformations. For future designs in particular, the fully electric drive approach provides the option of using fuel cells as the source of electric energy. The major benefits of an integrated electric power generation and propulsion system are the redundancy of prime movers and the versatility in load sharing for propulsion and non-propulsion purposes.

Any kind of conventional steam driven systems are not evaluated in this study because they are too manpower and maintenance intensive. The use of a nuclear propulsion system is neither an efficient nor a desired solution for displacements in the region of 5,000- 6,000 tons.

3. Warfare System Support Concepts

For the purpose of this study the warfare system support concepts are split into 4 generations by the author of this thesis.

a. 1st Generation

In the past most weapon, command and control systems were tailored for a specific use on a specific platform. Even if similar systems were used for different platforms via utilization of a configuration management and logistic support system, they were not interchangeable without assistance from specialists within a shipyard.

b. 2nd Generation

Today's systems are designed such that a core system is common for all applications. The interfaces between the weapon, command or control system and the platform side have to be modified whenever a system gets updated or replaced by another system.

c. *3^{rd} Generation*

All systems are completely modular. Interfaces are defined by standards. Ships crew is able to swap modules in a 'plug and play' like environment; i.e. all war-fighting modules comply with the interface standard and are replaceable or interchangeable with reasonable effort. The platform has to provide the interfaces in the form of a central bus system to support all possible needs of the module concerning data transfer, power supply, cooling water as well as air pressure and ventilation. For guns, fire control and radar systems in particular, the platform provides an automatic (maybe laser based) alignment method.

d. *4^{th} Generation*

In the future, many close range rapid-fire weapon systems will be replaced by concentrated energy / laser weapons. These systems will probably have a need of electric energy that is far beyond the electric power generation capacity of most of today's surface combat ships. An efficient way to satisfy these high electric energy needs would be an integrated electric power generation and propulsion system. In such a configuration the high but short period electric power needs by weapons could be provided easily by the power generation system without exceeding the ship's electric power generation capacity.

D. TOTAL OWNERSHIP COST

Especially in times of increasing needs and decreasing funds, Total Ownership Cost is the "buzzword" in all large system acquisitions. Today's rapidly increasing operation and support costs are consuming the funds we need for investments in the modernization of our fleet. Before the cost impacts of a system's design features can be evaluated later in this study, the individual components of the total ownership cost for a warship have to be identified.

1. Development

The expenditure of funds begins long before the actual procurement of a system. During the planning process for an acquisition program a program office is set up, studies have to be performed and with the evolving program the requirement for manpower increases. These are all indirect costs which are not necessary counted towards the budget of the program. Additional, relatively smaller expenses in the development phase frequently result in high payoffs later in the life cycle.

2. Acquisition

This includes all cost from the earliest design stage up to the delivery/hand over of the finished ship to the Navy. It covers costs like material, manufacturing (including overhead), an initial set of software, testing (from components up to sea trials) and a basic set of spares.

3. Manpower and Social Cost

Manpower consists of two main cost drivers, salaries and training. Just the salaries of the crew for a German class 122 frigate (220 crewmembers) are in the order of at least $ 50,000,000 per year. Due to rotation, permanent training programs are required to keep a high operational readiness of the crew. In addition to the time spent in training by the crew, huge funds for training facilities including the teaching staff have to be allocated. Other secondary costs of personnel that cannot be neglected are health benefits and retirement payments. This study recognizes manpower as one of the key aspects for cost reduction, but does not determine those costs in detail.

4. Maintenance

For the purpose of this study maintenance has to be broken down further. The basic two categories are labor and materials. Labor has to be split down into three different levels, operational, intermediate and depot, with each having different capabilities, rates and overheads. It has to be decided whether a two-layer system, i.e. operational and depot level only is a cost effective alternative. Particularly for maintenance actions that require expensive test and/or tool sets, a consolidation of these actions at a higher maintenance level could significantly reduce tool and maintenance costs.

5. Operating Consumables

In today's surface warships, consumption at unit level accounts for about 25 % of the total Operation and Support (O&S) cost. Petroleum, Oil and Lubricants (POL) account for more than 50 % of these, hence ~ 12.5 % of the total O&S cost. The other 50% of the consumption at unit level are caused by repair parts, depot level support, training expendables and support services.

6. Downtime

It has to be realized that a reduction in total downtime, which translates into an increase in operational availability per unit, will enable the navy to satisfy the same mission need with fewer assets. To achieve the maximum operational availability, the cycle times for maintenance, modernization and training have to be optimized, i.e., the turn-around times in maintenance have to be minimized. A modular design will support shorter downtimes. Systems with high Mean Times Between Maintenance (MTBMs), either preventive or corrective, will support longer intervals between shipyard overhauls. All downtimes caused by maintenance, modernization or training have to be synchronized.

7. Upgrades, Modernization

With respect to the expected lifetime of a naval ship, which will be in excess of 30 years, there is no way to avoid upgrades and modernization. Most of these will concern the payload, i.e. weapons and electronics. In the past, changes to the main platform, i.e. the hull, and the propulsion system have occurred only occasionally.

Command and control systems in particular in our current ships are often buried deep inside the hull. Replacement of parts that are too bulky and/or heavy to be moved through the passageways requires an enormous effort in dismantling and reinstalling other installations. To avoid excessive downtimes and costs, all major command and control systems should be installed with adequate access routes to replace them with minimum effort. Most weapon systems are installed in an inherently more accessible location anyway. To further enhance the upgradeability, all systems should be provided with standardized interfaces that support a "plug-and-play" concept.

8. Software Support

The number of systems that work completely independent of any software is decreasing rapidly. Changes to the software in order to upgrade a system, to enhance the interoperability between systems or just to remove initial bugs and insufficiencies are very time consuming and expensive. The use of standard off-the-shelf versus customized software has to be evaluated for each individual application.

9. Demilitarization, Disposal

If the design process is oriented towards minimizing total ownership cost, the demilitarization and or disposal cost at the end of the service life can also be minimized. The major cost driver at the disposal stage is the initial choice of the materials. A high risk is caused by the chance that today's non-hazardous materials may become hazardous materials in the future (Example: the use of asbestos in past systems).

III. EMPIRICAL STUDY

A. HIERARCHICAL EVALUATION OF THE OPERATIONAL REQUIREMENTS

Before discussing and evaluating proposed alternatives for hull designs, propulsion systems and power generation arrangements, all relevant system requirements and key performance parameters have to be ranked. Those requirements and performance parameters with the highest ranking will be given the highest priorities in the evaluation of the proposed concepts.

1. Ranking of System Requirements

The weighing matrix in Appendix A was developed as follows. The 20 system requirements concerning the platform for future warship, as defined in the previous chapter, are compared to each other using a "pairwise" approach, i.e. on a one to one basis. The result of this comparison is expressed in a scale of three possible results.

- An entry of 1.0 means the requirement listed in the column is more important than the requirement listed in the matching row, i.e., if limited funds are available to support these two, the requirement listed in the column has priority over that in the row.

- An entry of 0.5 means both requirements are of equal importance or there is no conflict between these requirements. In the case of funding constraints available funds shall be split evenly among both.
- An entry of 0.0 means the requirement listed in the column is less important than that listed in the row. In this case the requirement listed in the row has higher priority in case of funding constraints.

The results in the lower triangle of the matrix are just a mirror image of the developed results in the upper triangle. This mirror image is needed for the automatic EXCEL spreadsheet calculation of the totals. The column totals are calculated and divided by the sum of the totals to derive their percentage contribution. The final step is to assign priorities and to list the top 10 requirements according to their ranking.

(11) Design stability	1
(12) Survivability	2
(4) High maneuverability	3
(10) Stealth technology	4
(19) Operational availability	4
(3) Integrated electric power system	5
(5) Modular design	6
(9) Open architecture computer network	6
(20) Supportability, Upgradeabilty	6
(14) Support of helicopters/UAVs	6

Table 3.1, Priorities of System Requirements

The result of this weighting process clearly shows the high emphasis on stability and survivability. Thus there is a priority on the ability of the projected ship and her crew to survive severe damage either by military action, terrorist attack or in the form of any kind of accident, without external help. The platform is to remain at least in a reduced mission capable state for as long as possible. In combination with the required Stealth capability, which got priority 4, these results show the need for some fundamental changes in the conceptual design of the ship compared to our current assets. Maneuverability on rank 3 and Stealth, which is kind of a measure for detectability, on rank 4, highlight the need to avoid hits.

The next five requirements in the priority list (operational availability, integrated electric power system, modular design, open architecture computer network and supportability / upgradeability) are interrelated as well. Operational availability in essence means if the system works reliably for most of the time, than fewer backup or redundant systems are needed to fulfill the mission. To keep the operational availability at a high level the system must be supportable and upgradeable, which is enabled by modular design and the open architecture computer network. The integrated electric power system ensures the required design flexibility to support the modular concept. It also ensures a high thermal efficiency over a wide range of possible load conditions and it provides the resources for future growth in electrical power needs of future weapon systems. Also these five requirements underline the concept of controlling the total ownership costs early in the design stage. In past ship designs the neglect of these areas from the above priority list developed into huge life cycle cost drivers.

The requirement to support helicopters and/or Unmanned Air Vehicles (UAVs) shows the dependency of modern combat platforms on these assets. Since there is a movement towards UAVs and even Unmanned Combat Air Vehicles (UCAVs), all preparations for the special needs of UAVs, like launch and recovery facilities as well as ground control units, have to be incorporated in the design of the proposed combat ship.

2. Ranking of Key Performance Parameters (KPPs)

The method used to evaluate the KPPs is the same as described above for the system requirements. A total number of 9 KPPs are weighted against each other. The weighing matrix for the KPPs is shown in Appendix A Table 2 and the result is shown in Table 3.2.

(8) Min floodable length in adjacent compartments	1
(9) Reduction of crew required to operate ship	2
(5) High Speed Transit	3
(3) Maximum Range	4
(4) Endurance	4
(1) Top Speed	5
(6) Max sea state for boat operation	6
(7) Max sea state for helicopter operations	6
(2) Acceleration (0 – 25 kn.)	7

Table 3.2, Priorities of KPPs

The result as shown in Table 3.2 sets the highest priority to the floodable length, which is consistent with the first priorities of the systems requirements evaluation, the design stability and the survivability. The next rank is given to the reduction of crew required to operate the ship. Manpower is the most expensive part of the total ownership costs. Automation and ergonomic design belong to the key criteria during the selection process of all systems for war fighting as well as for support purposes.

The results for high-speed transit, maximum range and endurance are very close to each other. This underlines the need for global deployment within minimum achievable transit times. A high range and endurance are required to perform single ship missions independent of support assets. Compared to the last three performance parameters, the top speed is of less importance. There is no desire to outperform any kind of fast coastal vessels. The acceleration of the vessel is of even less importance due to the same reasons.

Especially in littoral crisis scenarios and in embargo operations, the deployment of boats and helicopters can be much more essential than the use of weapons. The values of these assets on board the platform and hence the value of the platform itself is close to zero, if they can't be operated due to adverse weather conditions.

B. EVALUATION OF HULL TYPES

The study concentrates on the hull types previously described in Section II.C.1. These hull types are evaluated on the basis of how suitable they are to support the previously derived and weighted performance parameters and system requirements. To compare the hull types, they are assumed to carry a similar payload, hence the actual displacements of the different hull types to function as a warship platform and to satisfy the stated requirements will vary. The individual designs are assigned a score according to the following scale:

- An entry of 1.0 means, this design is extremely suitable to support the performance parameter/system requirement.
- An entry of 0.5 means, this design will adequately support the performance parameter/system requirement.

- An entry of 0.0 means, this design will not specifically support this performance parameter/system requirement.
- No entry means, this performance parameter or system requirement is of no relevance to the design.

The final scores are shown in Table 3.3. In the following paragraphs some of the strengths and weaknesses of the different hull types will be highlighted.

System Requirements :		Monohull		Catamaran		Trimaran		SWATH		O'Neill	
	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
(11) Design stability	8.7	0.5	4.4	0.0	0.0	1.0	8.7	0.0	0.0	1.0	8.7
(12) Survivability	8.4	0.5	4.2	0.5	4.2	1.0	8.4	0.5	4.2	1.0	8.4
(4) High maneuverability	7.6	0.5	3.8	1.0	7.6	1.0	7.6	1.0	7.6	1.0	7.6
(10) Stealth technology	6.8	0.5	3.4	0.5	3.4	0.5	3.4	1.0	6.8	1.0	6.8
(19) Operational availability	6.8										
(3) Integrated electric power system	6.6										
(5) Modular design	5.2	0.5	2.6	1.0	5.2	1.0	5.2	1.0	5.2	1.0	5.2
(9) Open architecture computer network	5.2										
(20) Supportability, Upgradeabilty	5.2	0.5	2.6	1.0	5.2	1.0	5.2	1.0	5.2	1.0	5.2
(14) Support of helicopters/UAVs	5.2	0.5	2.6	1.0	5.2	1.0	5.2	1.0	5.2	1.0	5.2
Total:			**23.6**		**30.8**		**43.7**		**34.2**		**47.1**
Key Performance Parameters :		**Monohull**		**Catamaran**		**Trimaran**		**SWATH**		**O'Neill**	
	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
(8) Min floodable length	20.8	0.5	10.4	0.0	0.0	1.0	20.8	0.0	0.0	1.0	20.8
(9) Reduction of crew	18.2										
(5) High Speed Transit	13.9	0.5	7.0	0.5	7.0	0.5	7.0	1.0	13.9	1.0	13.9
(3) Maximum Range	12.5	1.0	12.5	0.5	6.3	0.5	6.3	0.5	6.3	0.5	6.3
(4) Endurance	12.5	1.0	12.5	0.5	6.3	0.5	6.3	0.5	6.3	0.5	6.3
(1) Top Speed	8.3	0.5	4.2	1.0	8.3	1.0	8.3	0.5	4.2	0.5	4.2
(6) Max sea state for boat operation	5.6	0.0	0.0	0.5	2.8	0.5	2.8	1.0	5.6	1.0	5.6
(7) Max sea state for helicopter ops.	5.6	0.0	0.0	0.5	2.8	0.5	2.8	1.0	5.6	0.5	2.8
(2) Acceleration (0 – 25 kn.)	2.8	0.5	1.4	1.0	2.8	1.0	2.8	0.5	1.4	0.5	1.4
Total:			**47.9**		**36.2**		**57.0**		**43.2**		**61.2**

Table 3.3, Evaluation of Hull Types

1. Monohull

The monohull is a proven standard hull type design. It scores an average 0.5 for most of the criteria. One of the obvious weaknesses is the behavior at low speed or when stationary in heavy sea conditions. Compared to a multi-hull of comparable displacement its roll and pitch motions at sea are such that, for example, the deployment and recovery of boats from its side can be very difficult and dangerous.

The main advantage of the monohull is the ability to more easily accommodate relatively large weight changes. Due to the relatively high waterplane area, the change in draft for a given change in weight is within reasonable limits. Also the performance and behavior of a monohull is less dependent on the actual draft as it is for multi-hull designs. This is vital to provide a ship with the capability to accommodate enough stores and fuel to ensure the required endurance.

2. Catamaran

Looking at the performance parameters, the major strengths of catamarans are high speeds, acceleration and maneuverability especially in calm water. Wave piercing bow designs will enhance the rough water high-speed capabilities. The catamaran like all other multi hull designs offers a relatively larger main deck area, permitting the installation of systems beside each other on the same deck level with less need to stack them on top of each other in several layers as is sometimes necessary on monohulls. This arrangement is ideal for one layer of modules, containing all vital systems that are required to satisfy the operational requirements. In case of changes to the operational requirements, or just for support purposes, the modules could be replaced without any need to cut through several deck layers.

Due to relatively small angles of rolling in adverse weather conditions, this design results in a much more stable platform to support boat and helicopter/UAV missions. However, even though the angles are small at the outer deck edges, high linear accelerations have to be considered, which can result in unfavorable working conditions.

The weakest part of any kind of twin hull design is the ability to survive a hit in one of the hulls. Due the transverse distance between the center of the lost buoyancy and the center of the remaining buoyancy, which actually moves quiet significantly towards the intact, i.e. opposite hull, any flooding will cause extreme angles of heel. This would drastically reduce the maneuverability of the damaged platform.

3. Trimaran

Many features discussed for the catamaran, like high speeds, maneuverability and small roll angles, apply to the trimaran as well. The trimaran also provides a large main deck area to support the concept of relatively easily exchangeable and upgradeable modular systems.

The major difference between most trimarans and any twin-hull design is the concentration of displaced volume in the center hull. The larger the center hull is in relation to the side hulls, the more some characteristics in the ships behavior will be along the lines of a monohull. Looking at survivability, the trimaran clearly outperforms the monohull as well as the twin-hull, i.e. catamaran and SWATH.

The high transverse stability of this design concept allows for a much greater topside weight growth margin compared to a monohull. This feature would support the upgradeability towards more sophisticated sensor and weapon modules to be installed at the mast or on the upper deck levels. Due to the combination of high transverse stability, even in higher sea states, and an increased deck area, this design would be an excellent platform for helicopter and UAV operations.

Looking at the British "Triton" project, even though solid results from the first sea trials are not yet available, the designers expect a significant reduction of total overall hull resistance due to the narrow center hull, despite the added resistance of the two minimal side hulls. As a result less power needs to be installed compared to a similar sized monohull. They estimate the savings for an escort-sized vessel to be in the order of 18% at a speed of 28 kn. [Ref. 2]

Since the RV "Triton" is the first large-scale trimaran demonstrator, there is very little data available about trimaran performance and behavior compared with that for monohulls and catamarans.

4. SWATH

Due its design, i.e. two fully submerged hulls and very narrow struts supporting the superstructure, the major advantage of a SWATH is the much better seakeeping ability. As proven with various SWATH ships, mainly ferries, oceanographic and military vessels, the pitch and roll angles as well as the associated accelerations for a small SWATH are similar to those of much bigger monohulls. A SWATH has the ability to maintain its normal cruising speed even with rough head seas, as long as the wave height does not exceed the height of the struts, i.e. before cross structure slamming occurs. For this reason the SWATH, scores even better in the support of boats, helicopters and UAVs than the catamaran and the trimaran.

Due to their reduced waterplane area, SWATH vessels have a reduced wave making resistance, which in combination with reduced motion (rolling and pitching) results in reduced rough water resistance at high transit speeds. On the other hand this design has a much higher wetted surface area compared to mono hull or conventional multi hull of equal displacement. This leads to a higher frictional resistance, which governs the total resistance in calm water conditions at lower speeds.

Also as a result of the small waterplane area, the required transverse stability (the righting moment) can only be achieved by increasing the beam (the righting arm). As a result SWATH vessels need a greater beam than conventional multi-hulls and hence they are shorter in length, assuming similar displacements. This reduced length in turn causes increased dynamic longitudinal instability, which must be compensated for by some kind of fins or control surfaces.

In general, the SWATH design is very sensitive to weight changes. Due to the small waterplane area, the adding or removal of weight will result in a high change in draft and any significant deviation from the design draft will reduce the SWATH-unique benefits in performance and behavior. Another problem is the high list caused by any off-center loading or flooding; hence this design is very vulnerable to any kind of hit in one of its side hulls. To use the submerged hulls for fuel and hence to increase range and endurance to the maximum possible extent, either a compensated fuel system or an equivalent clean ballast capacity is required. If the latter option is selected, the ship will need to be relatively larger in size.

5. O'Neill Design

The last hull type in this study is a hybrid between the SWATH concept and a trimaran. The basic design consists of a fully submerged center hull supported by a small waterplane area strut and two small side hulls. The center hull contains about 80 to 90% of the displaced volume. By concentrating the majority of the underwater volume in one center hull the total wetted surface area and hence the frictional part of the resistance is much less than if the volume would be distributed over three hulls of equal volume. This design does not lose too much of the seakeeping abilities of a SWATH but gains longitudinal and transverse stability, which reduces the need for the installation of fins or other horizontal control surfaces.

The concept of three long but narrow waterplane areas reduces the wave making resistance and results in a net decrease in total resistance at higher speeds. However there is not much information from model tests and no full-size ship trial data to make exact quantitative statements about the resistance of different shaped O'Neill designs.

Like the SWATH the O'Neill design offers ideal storage for liquid loads in the submerged center hull. As previously discussed the use of this capability to its maximum extent requires the installation of a compensated fuel system or clean ballast system. Problems with such a system will be discussed later.

The maneuverability of this hull type depends on the question of whether the side hulls have a propulsion unit installed or not. The installation of auxiliary propulsion units in the side hulls would drastically increase maneuverability. For an O'Neill as well as for a SWATH vessel, the installation of a conventional, i.e. gas turbine or diesel engine main propulsion plant in the submerged hull will be difficult due to the reduced accessibility through the strut. This problem could be solved with a fully electric drive since there is no need for a direct mechanical connection between any kind of prime mover and the actual drive unit, i.e. cabling is all that is required.

Similar to the trimaran, the O'Neill concept is tolerant of severe damage to one of the side hulls. Due to the small contribution to the overall buoyancy, shifting liquid loads from the center hull into the intact side hull can relatively easily compensate for the opposite's side damage or partial flooding.

An essential consideration concerning the design stability is the question of docking. One alternative is to design the ship with sufficient structural strength such that the center hull alone can support the docking loads of the entire ship, including the side hulls. However, this would significantly increase the structural weight fraction of the ship. The other alternative is to provide separate supports for each side hull as well as for the center hull in drydock, which reduces the weight penalty but significantly complicates the docking process.

Most of the criteria to achieve maximum stealth capabilities can be achieved by all of the hull designs discussed so far. In addition the SWATH and the O'Neill design offer the chance for extremely quiet main propulsion system. With a large diameter, slow revolving, highly efficient propeller driven by an electric motor in the aft end of a fully submerged hull, the noise caused by propulsion could be reduced to a level currently not known to surface ships.

C. EVALUATION OF POWER SYSTEMS

For the purpose of this study the power systems are divided into power generating systems and propulsion systems. These two categories will be evaluated first. The next step is the evaluation of power systems as part of a total ship power concept with primary emphasis on propulsion needs. The use of electrical power for command, control and weapon systems will be discussed in part D. of this chapter.

1. Power Generation

System Requirements :		**Gas Turbine**		**Diesel**		**Fuel Cell**	
	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
(11) Design stability	8.7						
(12) Survivability	8.4						
(4) High maneuverability	7.6	1	7.6	0.5	3.8	0.5	3.8
(10) Stealth technology	6.8	0	0	0.5	3.4	1	6.8
(19) Operational availability	6.8	0.5	3.4	0.5	3.4	1	6.8
(3) Integrated electric power system	6.6	0.5	3.3	0.5	3.3	1	6.6
(5) Modular design	5.2	0.5	2.6	0.5	2.6	0.5	2.6
(9) Open architecture computer network	5.2						
(20) Supportability, Upgradeabilty	5.2	0.5	2.6	0.5	2.6	0.5	2.6
(14) Support of helicopters/UAVs	5.2						
Total :			**19.5**		**19.1**		**29.2**

Key Performance Parameters :		**Gas Turbine**		**Diesel**		**Fuel Cell**	
	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
(8) Min floodable length	20.8						
(9) Reduction of crew	18.2	0.5	9.1	0.5	9.1	1	18.2
(5) High Speed Transit	13.9	0.5	6.95	0.5	6.95	1	13.9
(3) Maximum Range	12.5	0.5	6.25	0.5	6.25	1	12.5
(4) Endurance	12.5	0.5	6.25	0.5	6.25	1	12.5
(1) Top Speed	8.3	1	8.3	0.5	4.15	0.5	4.15
(6) Max sea state for boat operation	5.6						
(7) Max sea state for helicopter operations	5.6						
(2) Acceleration (0 – 25 kn.)	2.8	1	2.8	0.5	1.4	0.5	1.4
Total :			**39.7**		**34.1**		**62.7**

Table 3.4, Evaluation of Power Generation Systems

a. Gas Turbine

Looking at currently available systems, the gas turbine has the best power to weight ratio. Used for propulsion it provides maximum acceleration and top speeds and used for electrical power generation it can easily cope with rapid load changes. Gas turbines are available in proven, supportable and reliable designs, hence ensuring a high operational availability.

The gas turbines currently in service have a relatively high specific fuel consumption, i.e. greater than 0.330 kg/kW and this fuel consumption is only achieved within a very narrow band around the design load condition. New developments like the Rolls Royce WR 21 regenerative cycle gas turbines reach significantly better fuel consumption, i.e. in the order of 0.250 kg/kW, and they provide this efficiency over a wider range of load conditions. The penalties for this increase in efficiency are increases in weight, size and procurement cost.

b. Diesel Engines

Compared to gas turbines, diesel engines are much more efficient over a much wider range of loads, i.e. in the order of 0.220 kg/kW. Some large, slow revolving two-stroke diesel engines, as used for commercial ships, are even more efficient, but due to their size and weight they are not a viable alternative for the use on a combat platform. Diesel engines are also readily available in proven, supportable and reliable designs, hence offering a high operational availability. The penalties associated with diesel engines are high weight and lower responsiveness to load changes compared to the gas turbine.

Looking at stealth capabilities of a diesel engine, it generates less emission and exhaust heat than a gas turbine, but still has an Infra Red (IR) signature detectable by some missile seekers. The emission of noise for diesel engines can be controlled to some extent by noise absorbing mounting and encapsulation, however, the under water noise signatures generally remain quiet significant.

c. Fuel Cell

The fuel cell seems to solve all problems with gas turbines and diesel engines, but it is not yet available in the required module size, at least in the weight range of a diesel engine and there is no experience about the supportability and reliability. Since there are nearly no moving parts inside the actual fuel cell and cooling can easily control the low reaction temperature, the reliability is expected to be high. Due to the basic concept of the fuel cell, there is no exhaust gas apart from steam, which can be discharged under water, without violating any emission regulations. This would drastically reduce the IR signature of the platform.

Small-scale fuel cell modules, as designed for the German class 212 submarine (300 kW), are available already. At a current price of about $ 10,000/kW, as quoted by Siemens in 1998 [Ref. 3], just the power generation system able to supply all electric power inclusive of propulsion for a frigate size warship (~ 50,000 kW) would result in procurement costs of about US $ 0.5 billion. At a current power to weight ratio of 5.6 kg/kW as quoted by Daimler Chrysler in 1997 [Ref. 4] this plant would have a total weight of 280 tons, which makes it impractical at this stage of development.

The fuel cell can only be used in combination with electric propulsion, since there is no mechanical, rotational output available to drive a shaft.

2. Propulsion Systems

System Requirements :		Shaft + Propeller		Podded Drive		Water Jet	
	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
(11) Design stability	8.7		0		0		0
(12) Survivability	8.4		0		0		0
(4) High maneuverability	7.6	0.5	3.8	1	7.6	1	7.6
(10) Stealth technology	6.8	1	6.8	0.5	3.4	0	0
(19) Operational availability	6.8	1	6.8	0.5	3.4	0.5	3.4
(3) Integrated electric power system	6.6	0.5	3.3	0.5	3.3	0.5	3.3
(5) Modular design	5.2	0.5	2.6	1	5.2	0.5	2.6
(9) Open architecture computer network	5.2		0		0		0
(20) Supportability, Upgradeabilty	5.2	0.5	2.6	0.5	2.6	0.5	2.6
(14) Support of helicopters/UAVs	5.2		0		0		0
Total :			25.9		25.5		19.5

Key Performance Parameters :		Shaft + Propeller		Podded Drive		Water Jet	
	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
(8) Min floodable length	20.8		0		0		0
(9) Reduction of crew	18.2		0		0		0
(5) High Speed Transit	13.9	0.5	6.95	0.5	6.95	0.5	6.95
(3) Maximum Range	12.5	1	12.5	0.5	6.25	0	0
(4) Endurance	12.5	1	12.5	0.5	6.25	0	0
(1) Top Speed	8.3	0.5	4.15	0.5	4.15	0.5	4.15
(6) Max sea state for boat operation	5.6		0		0		0
(7) Max sea state for helicopter operations	5.6		0		0		0
(2) Acceleration (0 – 25 kn.)	2.8	0.5	1.4	0.5	1.4	1	2.8
Total :			37.5		25.0		13.9

Table 3.5, Evaluation of Propulsion Systems

a. Direct Shaft Propeller Arrangement

The classic shaft propeller arrangement is still an efficient means of ship propulsion. A steam turbine, internal combustion engine or an electric motor could power the shaft. The most efficient version would be one fixed blade large diameter propeller, driven by a shaft without gearbox, powered by low speed (< 120 rpm) large stroke volume 2-cycle diesel engine, as is done in large merchant ships. The drawbacks of this configuration would be that it is optimized and hence efficient only at its design load, i.e. cruising speed and the maneuverability is minimized in all its aspects. Also due to large weight and size, this is no feasible solution for naval surface combatants in the size of a frigate or destroyer.

The use of two shafts and controllable pitch propellers at medium speeds, i.e. 100 to 250 rpm, increases the maneuverability significantly. The maneuverability of these designs also depends on the position, size and hydrodynamic effectiveness of the rudders.

In this design there are two major sources of under water noise. The first is engine noise transmitted via the gearbox, shaft and propeller and the second is cavitation noise produced by the relatively small but high speed propellers. There are systems available and already in use to reduce the noise caused by cavitation with a bleed air system at the propeller blades. The optimum efficiency and noise characteristic could be achieved with large diameter propellers rotating at slow speeds, i.e. less than 100 rpm.

b. Podded Drive

The podded drive was developed from the purely mechanic Schottel drive, where the motor itself is mounted inside the hull and the rotational power is transferred via a vertical connection shaft into a propulsion unit, that can be turned to direct its horizontal thrust in any direction. In case of today's podded drive system an electric motor is inside an external pod underneath the hull, driving one or two propellers. Podded drive systems are currently available up to 20 MW per unit.

The losses resulting from transformation of rotational energy into electrical power and back into rotational energy are more than offset by gains in hydrodynamic efficiency. This is achieved due to the unobstructed flow of water towards the podded drive unit. In case of a two-propeller unit, this enhances the hydrodynamic efficiency of the forward propeller. [Ref. 5]

The major benefits are the high maneuverability, no need for an additional rudder and a huge gain of space in the aft part of the ship, usually occupied by propulsion machinery. The modular design allows a quick exchange of the whole propulsion system for repairs or upgrades. The negative aspect is that any kind of support, like preventive or corrective maintenance has to be done when the ship is in dry dock. This can only be avoided when the unit itself has a reasonable high reliability.

Since these systems have only been installed on commercial ships, there is not much data available concerning the noise transmitted into the water. The diameters of the propellers and the rotational speeds are in the range of those used for conventional shaft propeller arrangements. In theory a bleed air system could be installed as well to reduce cavitation and hence underwater noise. Also the reaction of the drive unit to shock loads from a close-to-the-ship weapon detonation, has not yet been tested.

c. *Waterjet*

The waterjet propulsion can be powered by any combustion engine or by an electric motor. It provides excellent responsiveness to power changes and maneuverability. The waterjet unit itself has a lower diameter than a propeller delivering the same thrust, hence it can be installed when space is a limiting factor, i.e. it provides the ideal propulsion for low draft vessels in shallow water.

The efficiency achieved by today's waterjets is significantly lower than the efficiency of shaft propeller propulsions or podded drives. New developments of water-jets with greater impeller diameters and higher efficiencies are in development. These waterjet units will not be completely enclosed within the hull and hence increase the draft of the vessel. [Ref. 6]

Due to the extremely low diameter of the impeller and the high rotational speeds, the under water noise exceeds the values of noise generated by the conventional shaft propeller arrangement or the podded drive unit. Future concepts concerning linear electric propulsion in the form of a water jet, i.e. water would be accelerated by a magnetic field with no need for an impeller, would significantly enhance the efficiency and reduce the noise. This technology mainly depends on the development of superconducting wires at higher temperatures. Today these concepts are not mature enough to be included as an option in the study.

3. Power System Concepts

System Requirements :		Mechanical Drive		Partial Electric Drive		Fully Electric Drive	
	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
(11) Design stability	8.7						
(12) Survivability	8.4	0	0	0.5	4.2	1	8.4
(4) High maneuverability	7.6						
(10) Stealth technology	6.8	0	0	0.5	3.4	1	6.8
(19) Operational availability	6.8	0.5	3.4	0.5	3.4	1	6.8
(3) Integrated electric power system	6.6	0	0	0.5	3.3	1	6.6
(5) Modular design	5.2	0	0	0.5	2.6	1	5.2
(9) Open architecture computer network	5.2						
(20) Supportability, Upgradeabilty	5.2	0	0	0.5	2.6	1	5.2
(14) Support of helicopters/UAVs	5.2						
Total :			**3.4**		**19.5**		**39**

Key Performance Parameters :		Mechanical Drive		Partial Electric Drive		Fully Electric Drive	
	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
(8) Min floodable length	20.8	0.5	10.4	0.5	10.4	1	20.8
(9) Reduction of crew	18.2	0	0	0.5	9.1	1	18.2
(5) High Speed Transit	13.9	1	13.9	0.5	6.95	0	0
(3) Maximum Range	12.5	0.5	6.25	0.5	6.25	0.5	6.25
(4) Endurance	12.5	0.5	6.25	1	12.5	1	12.5
(1) Top Speed	8.3	1	8.3	0.5	4.15	0	0
(6) Max sea state for boat operation	5.6						
(7) Max sea state for helicopter operations	5.6						
(2) Acceleration (0 – 25 kn.)	2.8	1	2.8	0.5	1.4	0	0
Total :			**47.9**		**50.6**		**57.8**

Table 3.6, Evaluation of Power System Concepts

a. Mechanical Drive

A common propulsion design used in today's warships are two controllable pitch propellers, each driven by a shaft via a reduction gearbox, powered either by a medium to high speed diesel engine, i.e. 1000 – 1500 rpm, and/or a gas turbine. These configurations are widely known as Combined Diesel or Gas Turbine (CODOG) and Combined Diesel and Gas Turbine (CODAG). There are also designs using two sizes of gas turbines, Combined Gas Turbine and Gas Turbine (COGAG). The medium to high speed diesel engines as well as the gas turbines, especially when combined with a controllable pitch propeller, provide a reasonable responsiveness to power changes. In the two-shaft arrangement they achieve a fairly high maneuverability as well.

With regard to modularity and hence supportability, the designer's flexibility is constrained by a mechanical drive system. Prime mover, reduction gearbox and shaft including all the auxiliary and ancillary machinery in frigate/destroyer sized platforms occupy the lower compartment levels from amidships nearly to the stern. Combustion air and exhaust gases have to be ducted over great distances from the outside to the prime movers.

Perfect noise isolation between the prime movers and the drive train is nearly impossible. Hot exhaust gases exit the ship close to amidships, hence attracting missiles with IR seekers towards the center of the platform.

A completely separate and independent set of prime movers is required for the electrical power generation. There is no possibility to feed excess power form the propulsion plant into the electrical grid and vice versa.

b. Partial Electric Drive

The partial electric drive configuration is a mechanical arrangement of combustion engines and electric motors to act either on the same or on separate shafts to drive the ship. A partial electric drive configuration, as, for example, used for the British "Duke" class (Type 23), allows an efficient and relatively silent cruise up to 15 kn. To reach the maximum speed of 28 kn the two gas turbines drive the ship via a mechanical reduction gear and shaft system. One of the major benefits of this configuration is the avoidance of extreme low load conditions for the prime movers. These low load conditions would cause a very high specific fuel consumption. A gas turbine in a comparable size to the Rolls Royce SPEY SM1A can easily exceed 1kg/kW under unfavorable load conditions. Benefits from a possible integrated power system for propulsion and the general electric power supply will be discussed under "Fully Electric Drive".

Similar to the mechanical drive the partial electric drive system is still constrained in the location of most of its components. Only the prime movers used to generate the power for the electrical propulsion can be located independent of the drive shaft. Today, in all designs of frigate or destroyer sized ships, the mechanical and the electrical drive are combined on the same shaft(s). In theory it is possible, and it has already been done for smaller vessels like mine warfare vessels, to separate the electric propulsion unit completely from the mechanic propulsion unit, i.e. a conventional mechanical driven shaft propeller and a separate electric driven Schottel drive or podded drive.

c. Fully Electric Drive

In this design concept the propeller, podded drive or water jet is driven by an electric motor, which is located as close as possible to the propeller/impeller. The prime mover generating the required electric power can be located anywhere.

There are two basic concepts for the fully electric drive. In the past, electrically powered ships had one electric power grid with prime mover generator sets for propulsion and a different one with its own prime movers to feed the ship's electrical power distribution system. A more efficient way is to create an integrated electric power generation and distribution net that feeds the propulsion system and all other electric consumers as well. This allows a high flexibility in shifting the power allocation continuously between propulsion and, for example, weapons systems with regard to operational needs. The prime movers would always run very close to their design load conditions, which will significantly increase the overall efficiency. Since the total capacity for the power generation system will be largely determined by the propulsion requirements, this design offers an enormous growth potential for all other future electrical applications, as in, for example, directed energy weapons.

The redundancy gained by a fully integrated electric system would significantly increase the operational availability. Since the amount of mechanical components in the propulsion system determines the maintenance, operation and hence manning requirements, electric propulsion offers real potential for crew reduction in the engineering department.

The flexibility of internal arrangement of the components allows one to have a very quiet electric propulsion system, since no noise/vibrations will be transmitted from the prime mover or the gearbox to the propeller. In the mechanical drive arrangement, there was a limitation on the shock mountings due to alignment requirements between shaft, gearbox and the engines. In the electrical drive configuration, a much better sound insulation of the prime movers is possible, hence the total noise level is reduced. Positioning the gas turbine generator sets close to the stern of the platform, and hence leading the hot exhaust gases aft of the ship can change the IR signature drastically.

The fully electric propulsion concept facilitates a modular design of its components. A gas turbine generator set with self contained combustion air inlet and exhaust gas outlet, built into a container at the ship's main deck level, would reduce the time to replace this module down to a few hours.

A ship powered by an integrated electrical system offers the potential for a future upgrade to fuel cells. Industries involved in the development of fuel cells expect the technology to mature into efficient and reliable systems by the beginning of the next decade, or well within the service life of any ship built today or in the near future.

D. EVALUATION OF WARFARE SYSTEM SUPPORT CONCEPTS

A warship can be divided into two basic physical components, the platform and the payload. The boundary between these has to be defined as clearly as possible. The purpose of this section is to identify the interfaces between platform and payload.

The payload are all systems on board the ship, required to satisfy the mission need as defined in Chapter II. A. Such systems are any kind of weapon as well as command and control systems, any kind of manned or unmanned aircraft for reconnaissance, surveillance, combat or transport purposes, and any additional accommodation, catering or medical services in addition to those required by the ship's crew. The payload is the reason for the existence of the ship.

In the past, platforms have been tailored around the desired payload. This is the efficient solution, if the ship is used for the originally specified purpose for its whole service life and no modifications or upgrades will be required. Since today's development cycle for the technology in the weapon and control sector is much shorter than the expected service life of a naval platform, a design for upgradeability and supportability is vital. A completely modular configuration would also allow for fast changes of the payload in response to changes in the mission, and hence in the operational requirements. The ability to adapt the available assets to a variety of different missions can significantly reduce the total number of assets needed.

There are two key design criteria to be examined with regard to a modular approach. The first is the physical arrangement, i.e. location of the modules and its accessibility, and the second is the required connections to the module.

1. Physical Arrangement

The location of a warfare system is a function of its interaction with the environment and the required accessibility. For example a towed array sonar system has to be located at the stern of the ship, all weapon, radar and antenna systems have be on or directly under the top surface of the ship's hull, command and control systems have to be sufficiently sheltered and easily accessible for the operators. If too many modules are stacked on top of each other, it is very time-consuming to replace the bottom ones. The ideal arrangement is possible on platforms with a relatively large deck area, as provided by multi-hull ships. The size for the modules that contain the systems should be standardized to increase the flexibility in the physical arrangement of the required systems to satisfy the then current operational requirements. If possible, commercial container standards should be used.

To avoid time consuming adjustments, all systems/modules containing direction sensitive weapons or antennas should be fitted with an automatic alignment system.

2. Module Connections

The interfaces between the systems and the platform have to provide the means for data exchange between the systems as well as between a system and the platform. In addition, the systems have to be provided with electric power, ventilation, chilled water, high-pressure air and in case of power generating systems, fuel is needed as well. The location of the connections shall be at the same standardized position in all module spaces. There has to be enough redundancy to survive the loss of some of these connections as result of a hit.

Data transfer cables should be installed with enough growth margin to cope with any future systems that might be installed during the service life of the platform. The module spaces should be pre-wired to provide point-to-point connections between the systems as well as a connection by a central data bus to support an open architecture computer network. The data bus system will be integrated into the platform, but the computer systems will part of the upgradeable payload. Detailed specifications for the required data connections still have to be developed in further studies.

All radar and communication systems shall be located such as to minimize the distance of high voltage cables between the transmitter/receiver units and their antenna arrays.

E. IMPACTS ON TOTAL OWNERSHIP COSTS (TOCs)

1. Hull Type

With regard to development and acquisition, any deviation from the conventional monohull will increase these costs. Any multi-hull structure, especially the SWATH and the O'Neill design require more material for the hull than a similar sized, i.e. comparable payload, monohull. During the construction there is more scaffolding required and the building dock has to be significantly wider than for a monohull of similar displacement. With regard to the maintenance of the underwater hull surface, the required effort is directly proportional to the total surface area of the vessel; hence the monohull would be the best choice.

Looking at the POL part of the operating consumables, the use of an advanced multi-hull design could significantly reduce these costs. Even though the calm water resistance is still comparable to a monohull, the resistance for a SWATH or O'Neill in rough water will be lower. If the greater deck area of a multi hull is used to support a modular concept, which allows placement of the majority of systems beside each other instead of on top of each other, time and effort for the replacement of any system could be drastically reduced. As long as the hull is built from mild steel instead of aluminum, high tech alloys or composites, the risk is very low that it will cause significant costs for a future demilitarization and disposal. Hazardous materials shall be avoided for installations in the ship's hull, as well as for all internal and external coatings, i.e. paint.

2. Power Generation and Propulsion

Since manpower with all its associated costs is a great chunk of the Total Ownership Costs, the reduction of ship's crew is one of the design priorities. Any mechanical or partial electric drive system requires significantly more personnel for operation and maintenance. Hence, the integrated electric power generation and propulsion system in combination with state-of-the art automation will achieve the greatest possible reduction in manning requirements for the engineering department on the platform.

An integrated power generation and propulsion design also enhances the concept of modularity, which reduces time (labor and down time), effort and hence costs for any support actions, like corrective and scheduled maintenance as well as upgrades and modernization.

Due to more efficient operation and less need for lubrication of moving parts, the POL consumption of the fully electric drive and its associated costs will decrease as well. The best efficiency and hence lowest operating cost could be achieved with the fuel cell as power source.

3. Warfare System Support

If the platform provides the means to support a completely modular arrangement for warfare systems, future O&S costs can be reduced, due to shorter down times for maintenance, upgrades and modernization. If the modularity enables fast role changes, just by swapping completely modular systems, either the total number of assets or the number of different systems as part of the payload for the individual platform could be reduced. By adopting the commercial container standard for the module size, the systems could be exchanged in any container terminal around the globe, assuming the necessary agreements to perform such actions in a foreign harbor are in place. The transfer could be arranged via commercial shipping lines at minimum cost. This would also reduce the need for the platform itself, to spend extended periods in naval shipyards.

This concept will increase the operational availability at ship level, if there are sufficient additional replacement systems available. The number of the required replacement, i.e. spare systems depends on the number of assets requiring the systems, their turn-around times for maintenance, upgrade or modernization and on the system's reliability. With regards to the TOC, this leads to the conclusion that a careful trade-off has to be done between the additional system cost and the savings from increased operational availability due to a much shorter turn-around time for the platform as a whole.

One of the major problems concerning the disposal costs of today's warships is the insulation and shielding for cables. Previously used materials have primarily been chosen to enhance the resistance against heat and fire. With regard to their disposal, the majority of these materials are hazardous. There are two ways to reduce this cost risk in the future. First, especially in a modular design, many wiring connections will be redundant, hence the conceptual design of the wiring harness has to be optimized to minimize the total amount of wiring required, but still satisfying the needs to support the system modularity.

The idea of demilitarization of the platform at the end of its service life is enhanced by a modular design, since sensitive equipment can easily be separated from the main hull.

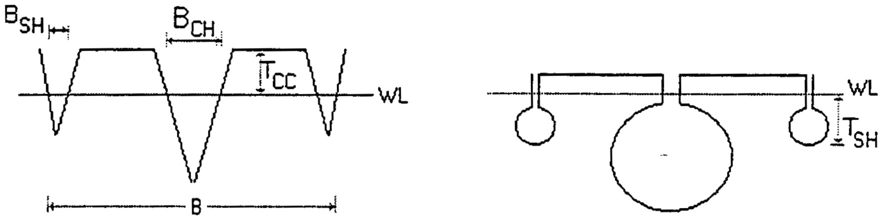
IV. RESULTS

This chapter discusses one possible design solution as a synthesis of the results from the evaluations in the previous chapter. The decision is based on the total scores derived from the weighing of the requirements and KPPs, and the evaluation of hull types, power generation systems, propulsion systems and drive concepts based on those weight factors. The candidate platform will be a trimaran/O'Neill hull, powered by a mix of diesel and gas turbine powered generators with fully electric propulsion. Since there are many possible variations, further details will be derived and discussed in the following paragraphs.

A. THE HULL

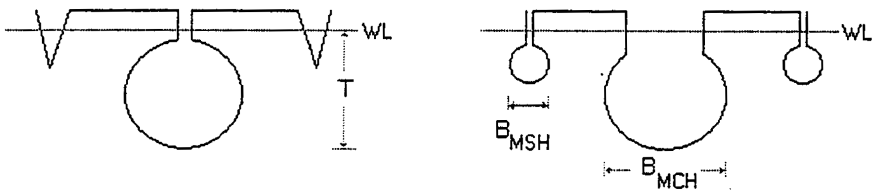
There are many possible variations in hull shape between the conventional trimaran, as used for the British "Triton" project [Ref. 2], and the O'Neill hull form. There are several parameters that can be varied for any three-hull semi submerged marine platform [see Figure 4.1].

As for any other ship, one of the design targets for a modern combat platform is to minimize the frictional as well as the residuary resistance, i.e. mainly wave making resistance, and hence to reduce the amount of power that has to be installed to operate efficiently at the required speeds under specified load conditions. The design has to satisfy the requirements for longitudinal and transverse stability as well as for mechanical strength, for the intact and damaged platform. The platform has to be producible and serviceable with reasonable effort, i.e. the designer shall think about docking and berthing as well.



A , Conventional Trimaran

B , O'Neill with Small Waterplane Area Sidehulls



C , O'Neill with conventional Sidehulls

D , O'Neill with Small Waterplane Sidehulls
and Medium Waterplane Center Hull

Figure 4.1, Basic Hull Cross Sections

For further reference to discuss the hull shape parameters in this study, four basic cross-sections are shown in Figure 4.1. With regard to the cross sections, the following quantities are used to describe the dimensions:

B = ship's beam in the design waterline
B_{CH} = center hull beam in the design waterline
B_{SH} = side hull beam in the design waterline
B_{MCH} = maximum breath of the center hull
B_{MSH} = maximum breath of the side hull
T = center hull draft
T_{SH} = side hull draft
T_{CC} = Clearance between cross structure and waterline

1. Hydrodynamic Characteristics of the O'Neill Hull Form

The first parameter is the distribution of displacement among the center and the side hulls. Looking only at the total wetted surface area for a given displacement, a large center hull and minimal side hulls would be the optimum solution. Further reduction in waterplane area is possible by just building the center hull without side hulls, but due to transverse stability concerns the waterplane area then had to be increased, which would result in a conventional monohull.

The next parameter is the total waterplane area and its distribution among the three hulls. Specifically, the total waterplane area is a measure of the capability of the platform to accommodate weight changes, either caused by fuel consumption or by changes in the combat systems payload due to different mission requirements. For a given shape at a given speed the residuary resistance is a function of the waterplane area, i.e. the greater the waterplane area the higher is the residuary resistance. Relatively low waterplane area for the individual hulls results in reduced accessibility to the submerged part of the hull. Very thin struts would also cause problems in structural strength. The distribution of the waterplane area among and within the hulls governs the longitudinal and transverse stability of the platform. The higher the longitudinal and transverse moments of inertia of the waterplane area, the higher the stability will be. A low moment of inertia in longitudinal direction, combined with large submerged hulls will result in dynamic pitching, as experienced with initial SWATH designs without control surfaces close to the bow of the hulls [Ref. 7]. A high longitudinal moment of inertia does not necessary mean three long struts, it can also be achieved by a high longitudinal setback of the outer hulls in relation to the center hull. A triangular arrangement of the three waterplane areas would allow shorter struts and still ensure a high longitudinal and transverse stability. The end of the center hull and strut can be forward of the outer hull struts. Examples are the ARGO design study in 1989 [Ref. 8] and the studies and towing tank experiments performed at the David Taylor Research Center in 1988 [Ref.9].

As shown by the towing tank experiments at the David Taylor Research Center, an outer hull setback has significant influence on the residuary resistance. The outer hulls should be behind the Kelvin wake zone, which was in this specific experimental setup within 19° 28' on either side of the stem of the center hull as shown in Figure 4.2.

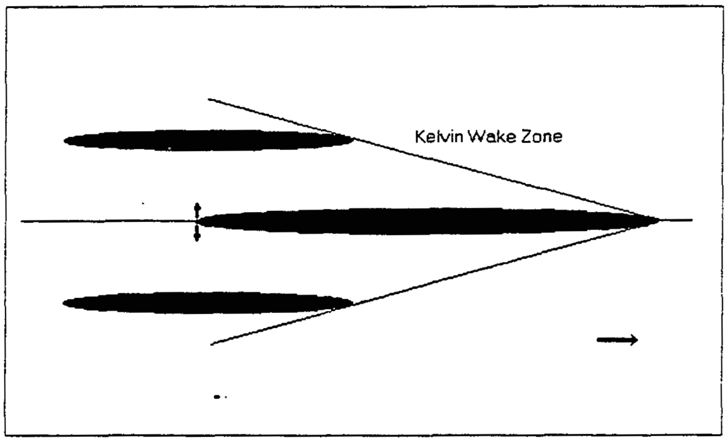


Figure 4.2, Outer Hull Setback

The ARGO design study, which was performed as a software based simulation, pointed out that the shape of the struts in the waterline is of less significance on the residuary resistance apart from speeds from 6 – 13 kn for their design, which equates to Reynolds numbers from $93*10^6$ to $202*10^6$. They examined different shapes for the underwater hulls as well and found a shape with two distinct maxima in cross-section achieved the best performance. [Ref. 8, page 599]

The response to sea state, also is a function of the waterplane area, especially at the outer ends of the platform. To be less affected by wave heights smaller than the clearance between cross-section and waterline, these areas should be minimized. Hence a tradeoff has to be done between the actual water plane areas of the various hull portions and their distance to each other to achieve the required longitudinal and transverse moments of inertia. With these parameters optimized, the O'Neill hull can outperform a similar sized monohull with regard to its seakeeping characteristics.

For a notional O'Neill hull displacing 4328 tons [Ref.9, page 3], the results of the experiments at the David Taylor Research Center predicted a power requirement of 30,440 kW at 30 kn in the most favorable condition, i.e. Model 5355-2 (New outer hulls in aft position) [Ref. 9, Table 6]. This power requirement is comparable to a conventional frigate hull like the German F-122 class. Calculations to equate the power requirements to the difference in displacement are attached in Appendix B.

2. Physical Design Considerations

A further benefit from a shorter center hull, i.e. a center hull that ends forward of the aft end of the platform, is the space gained to lower, operate and tow any equipment like a Variable Depth Sonar (VDS) or a Towed Array Sonar (TAS) without interfering with the rudder and propeller.

A significant outer hull setback influences the main deck layout as well. The platform will have a fairly narrow bow that could accommodate a gun and a missile launch system, and a wide aft body to provide the space for warfare, power generation and supply systems/modules. The topside of the aft platform can serve as helicopter or

UAV/UCAV flight deck. The topside weight growth potential for future modifications and updates depends on the waterplane area of the side hulls.

With a given limit in total draft and change in trim, the total waterplane area is one measure that determines the platform's capability to compensate for weight changes. This may become a constraint for the amount of fuel that can be consumed before ballasting has to occur; hence it has significant influence on the range and endurance of the vessel. If this leads to a need for compensated fuel tanks, the design of these tanks has to ensure a reliable operation in compliance with environmental protection rules, e.g., a zero discharge policy.

If the lower hulls are mainly loaded with POL, the beam of the side hulls B_{SH} is governed by hydrodynamic and structural considerations in the first place; in addition there will be auxiliary propulsion units installed, which only require limited space and access. The beam of the center hull B_{CH} is also governed by accessibility factors. Even with all power generating modules installed at main deck level, the main propulsion motor has to be accessible. If the required accessibility can't be achieved for one large electric motor, an arrangement of several smaller motors could solve the problem.

3. Proposed Hull Design

Based on the results and discussion in the previous chapters, the 105 m 4,700 ton O'Neill hull as shown in Appendix C was designed. This is a first iteration that has to mature through several additional iterations to reach the final design stage. The following decisions were made for this design:

The width of the center strut is 4 m. This allows enough access to the lower center hull but still reduces the center hull's waterplane area significantly compared to a monohull of similar displacement. The flat bottom of the center hull reduces the draft at design displacement to 7 m, and is also beneficial for easier dry-docking. The narrow end of the center strut improves the degree of symmetrical flow towards the main propeller.

The main purpose of the side hulls is to ensure sufficient transverse stability with a minimum of wetted surface area. This leads to the choice of a triangular cross-section with its maximum width in the waterline. The waterplane area and its transverse offset govern the transverse stability. Details about the dimensions are listed in Appendix D. Figure 4.3 shows the effect of increase in beam on the vertical position of the metacenter.

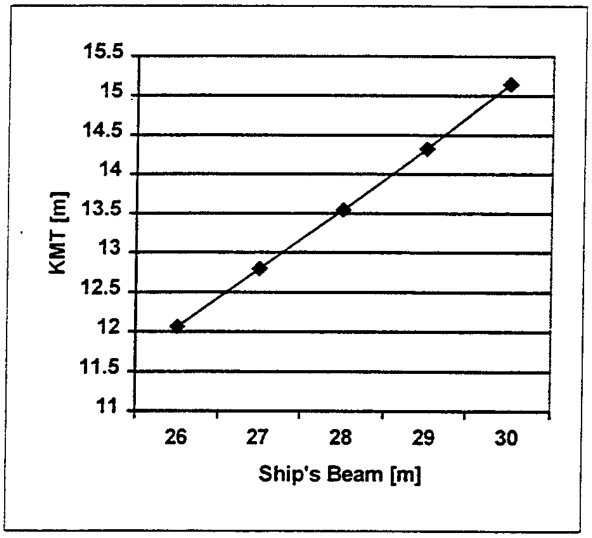


Figure 4.3, Increase of KM_T with increase of B

The outer hull setback ensures that these hulls stay within the Kelvin Wake Zone. The exact setback has to be determined in towing tank trials. The extension of the outer hulls aft of the center hull supports the main deck aft of the main propeller. This configuration provides enough distance between the main propeller and any towed gear like VDS or TAS. The wave piercing bow design of the side hulls is a proven design feature from high-speed catamarans.

To share the total buoyant volume among three fully submerged geometrically similar hulls would be disadvantageous with respect to the wetted surface area per ton displacement. The better solution is to concentrate most of the displaced volume in one small-waterplane center hull with two relatively small side hulls to provide the rest of the buoyancy and the required transverse stability. In the proposed design the center hull accounts for approximately 90 % and each side hull for 5% of the displacement. The wetted surface area for the proposed design is about 3,400 m^2, which is in between the wetted surface area of a typical frigate monohull with 2,500 – 2,800 m^2 and a SWATH with a approximately 4,000 – 4,200 m^2 for an equivalent sized ship.

A 4 m clearance between waterline and cross-structure provides an acceptable behavior up to sea state 6. Since the occurrence of cross-structure slamming depends on more than just the cross-structure clearance and, as mentioned before, there is no data from full size O'Neill hulls, results from a large scale demonstrator are vital to make valid predictions. The location of all living spaces and most working spaces in the center of the ship reduces the motion and acceleration to be experienced by the ship's crew in adverse weather conditions. If the platform is used for any kind of floating hospital mission, this will greatly enhance the ability to perform complicated surgery on board.

The depth of the cross-structure under the main deck supports the accommodation of standard 20-ft and 40-ft container modules up to a maximum non standard height of 11 ft, i.e. 3.35 m, underneath the flight deck and up to 12 ft, i.e. 3.63 m in front of the deckhouse. There will be at least one 40-ft container bay directly aft of the hangar reaching down into the lower center hull. Depending on the arrangement of the forward container bays, one additional 'deep' bay could be build in front of the deckhouse. These bays can be used for heavy machinery equipment or ammunition storage to lower the center of gravity. Boat access and torpedo storage and launch systems will be provided in the side hulls. Crew accommodation and support, hangar and all spaces required for C_4I (Command, Control, Communication, Computing & Intelligence) will be provided within and underneath the deckhouse. Access to bulky modules in the deckhouse, e.g. switch boards, computer racks and operator stations, will be provided through the hangar. The deep container bay aft of the hangar will provide access to the decks underneath the deckhouse. All container bays have to be separated by suitable gastight and watertight bulkheads to ensure maximum capability to survive any damage by weapon hits or accidents.

Since performance of the O'Neill hull, as for most other advanced multi-hull designs as well, suffers significantly when not operated at the design draft, the maximum lifetime allowance for growth in displacement is governed by a 0.6 m maximum increase in draft. With a waterplane area of 520 m^2 this results in possible weight increase of ~ 320 tons. Another option to compensate for later weight increases is to give up some of the ~ 1,245 tons initially assigned to POL. Every meter increase in length for the whole ship, i.e. center hull and side hulls, would increase the displacement at the original design waterline by 66 tons.

To minimize the radar reflection signature all usually external installations such as boats, life rafts, capstans and guardrails have to be integrated or covered. All active and passive antenna devices should be mounted as flat arrays on the surface or inside a composite shell. One of the benefits of the proposed O'Neill hull form is the possibility to enhance the stealth characteristic of the ship by a significant tumblehome beginning right at the waterline without decreasing the transverse stability.

B. PROPULSION AND CONTROLS

The power required for propulsion of an O'Neill hull can be estimated roughly to be in the range of similar sized monohulls (see comparison of power requirements for a German class 122 frigate and a notional O'Neill hull in Appendix B). If there is no appropriate information from towing tank tests available, this is a reasonable approach. Since there was some data available for an O'Neill hull model, which provides reasonable similarity to the proposed hull, the following approach was chosen. The residuary resistance coefficient was adopted from the O'Neill hull towing tank experiments at the David Taylor Research center [Ref. 9], the frictional resistance coefficient was derived from the wetted surface of the proposed O'Neill hull, and finally the total resistance and hence the required EHP for a given speed was calculated. The SHP for the required propulsion plant can be derived from the EHP via the efficiency of propulsion system. Figure 4.4 shows an approximation for EHP versus speed for an O'Neill hull as specified in Appendices C and D. Calculations and assumptions are attached in Appendix E.

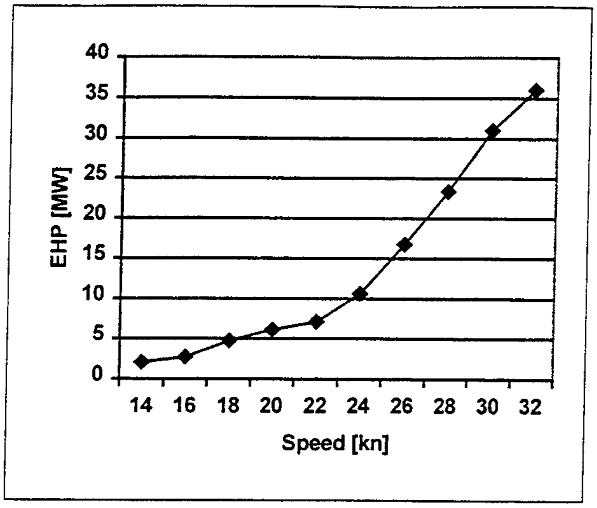


Figure 4.4, EHP versus Speed

A single large diameter propeller that rotates at relatively low speeds will achieve the most efficient and silent propulsion. This configuration would result in a very low maneuverability at slow ship speeds. To increase the maneuverability both side hulls have to be equipped with auxiliary propulsion units.

Due to the shape of the center hull one large and efficient electric motor driving a single or two in-line counter-rotating propellers will be the best solution. The decision as to whether a single or a set of counter-rotating propellers is chosen depends on the effective horsepower required to drive the ship and the maximum diameter and rotational speed allowed for the propeller(s). Relatively compact electric propulsion motors are currently in development. A key technology to decrease size and increase efficiency is the high-temperature superconductor, or HTS, wire [Ref. 10]. Assuming the total propulsive efficiency of the main propulsion to be at least 70% would result in a SHP requirement of 37 MW to achieve the threshold of 28 kn. A reasonably high but efficient transit speed would be 22 kn., requiring 11.5 MW of SHP. With an estimated specific fuel consumption of 0.25 kg/kWh a total of ~ 650 tons or ~ 780 m^3 of Diesel fuel would be needed to achieve the objective of 5,000 NM.

Suitable auxiliary propulsion for the side hulls could be provided by electrically powered waterjets with directed thrust capability. Even with a propulsive efficiency as low as 50% a total SHP of 6.6 MW would be sufficient to power both waterjets for ship speeds up to 14 kn without use of the main propulsion system in the center hull [see Appendix E]. Due to their high transverse moment arms, this propulsion power capability in the side hulls would provide a high maneuverability at low speeds and even when stationary. The auxiliary propulsion units can support the main propulsion plant during acceleration and deceleration of the ship.

Instead of a rudder at or aft of the stern of the center hull, "spoilers" at the side hulls could be used as directional control surfaces. At low speeds the required maneuverability is ensured by the waterjets. At higher speeds the spoilers would only be engaged when a course change is necessary, when not engaged the control surfaces would be fully retracted into the surface of the adjoining structure, and hence it would generate neither resistance nor noise. Due to the extension of the outer hulls aft of the center hull, the ship has a high degree of directional stability. To achieve a smaller turn radius at higher speeds, the waterjets could be used to supplement the spoilers.

C. POWER GENERATION

Since the vessel's drive system will be electric, the power generation has to supply sufficient power for propulsion as well as for all other electrical requirements. As previously discussed, there are three candidate systems for electrical power generation on board a future naval combat platform. Two of these are available in a variety of configurations today. These are the gas turbine that offers the best power to weight ratio and the diesel engine that offers the best efficiency. The fuel cell is in a very rapid development, so it might become a feasible alternative by the beginning of the next decade. Independent of today's decision, the overall power generation concept of the future platform is structured to be as modular as possible to prepare for future upgrades and modifications.

Before a decision is made on what size and what mix of power generator modules to choose, the power requirement has to be analyzed further. As derived in the previous paragraph, the total power requirement for propulsion to achieve the threshold of 28 kn is ~ 37 MW. Allowing maximum load on the main and on the auxiliary propulsion systems simultaneously at least 44 MW should be provided. Experience on the German class 122 and 123 frigate show that the actual electrical power consumption for the ship at combat stations is in the range of 800 to 1,200 kW. The installation of 3,000 kW or 4,000 kW for the class 124 frigate was necessary to provide the required redundancy. This lead to the decision that a total of 48 MW installed SHP should be sufficient for today's electrical power needs. Since the power generation is provide by exchangeable modules, later upgrades and modifications according to changes in power requirements can easily be adopted.

The mix of different output capacities should be optimized with respect to partial load conditions, and the location depends on the actual module weights and ambient air requirements. Components that are used in current applications in the German fleet should be used to enhance spare part and maintenance expertise consolidation. For the initial installation of power generation modules the following arrangement is chosen:

- Two MTU 20V 1163 TB93 diesel generator sets, each with a maximum rated SHP of 7.4 MW, to be placed at the bottom of the deep container bay(s) aft of the hangar, i.e. just above the POL tank top level. The combustion air will be supplied from intakes at the aft sides of the hangar, the exhaust will be discharged from the center strut underneath the cross-structure.
- Two GE 7 LM 2500 PF/MLG gas turbine generator set, with a maximum rated SHP of 23.5 MW each, are to be placed in the port and starboard side outer container bays at the aft end of the flight deck. The combustion air intake for this module will be at the topside of the side hull, the exhaust will be discharged through the transom of the ship.
- Two MWM TBD 602 V 16 K diesel generator sets, each with a maximum rated SHP of 1.14 MW, one to be placed in the port and starboard container bays in front of the deckhouse. Combustion air intake will be at the side of the deckhouse, the exhaust will be discharged underneath the cross-structure. For use alongside in harbor or when at anchor, an alternate exhaust discharge for these diesel engines will be provided to the top of the deckhouse.

This configuration provides sufficient power for all electrical needs including propulsion up to ~ 22 kn at a reasonable specific fuel consumption using the two main diesel engines only. One gas turbine alone would provide enough power to propel the ship at 24 kn and satisfy all other electrical needs at the same time. Both gas turbine generator sets combined with the two main diesel engine generator sets would provide enough power for ship speeds up to 32 kn.

The high flexibility in power generation provided by an integrated electric plant means the ship will be able to operate under all possible load conditions much more efficiently than currently available power generation systems. The fully integrated electrical power system combined with state-of the-art automation will also significantly reduce the manning requirements for the ship's engineering department.

D. RISK ASSESSMENT

Since the O'Neill hull-based platform will be a stand-alone development, there is a high risk, compared to the evolutionary development for the most recent frigates in the German Navy, i.e. from the 122 class via the 123 class and finally to the 124 class. To reduce the risk, a final decision to choose the O'Neill hull for a frigate-sized surface combatant should be preceded by further towing tank trials and the evaluation of a large scale demonstrator, i.e. ½ to $^2/_3$ in linear dimensions of the proposed ship. The demonstrator would also provide data about the actual construction costs for this fairly complicated hull structure. After completion of the trials, the demonstrator could be used for training and support purposes. Since there is no data available from similar ships, effects of material aging caused by the dynamic loads, especially those that the cross-structure has to withstand throughout its planned 30-year service life, need to be assessed via finite element methods. Due to the "open systems" approach and highly modular concept of the platform, the risk concerning the choice of engine and warfighting systems is low. Assuming an early and comprehensive interface specification is established and enforced, the decision about the individual systems can occur closer to the final delivery date than would be possible with a non modular approach. In case any system proves during the operational phase to be unsatisfactory, suboptimal, or a much better technology has emerged, a modification can still be done with limited effort. As shown in the stability calculations in Appendix D the initial GM of 4.75 m offers a high top-weight growth margin to accommodate future weapon and sensor systems.

Rapid changes in the global political situation and hence in the mission and threat environment can be accommodated by exchanging the payload. For humanitarian missions, war-fighting modules could even be exchanged for medical treatment or accommodation units for casualties, hence creating a large capacity floating hospital.

The overall dimensions, i.e. length, beam and draft, are still very conservative. An optimized design with much greater beam and hence more deck space area would be possible, but it would cause additional constraints with respect to berthing and to dry-docking. Choosing a circular cross-section could reduce the wetted surface area of the center hull, but this would significantly increase the draft. Much greater draft and beam, like $T = 10$ m and $B = 35$ m or more, could result in significant operational constraints especially when operating in the littoral. The proposed dimensions of $L_{OA}=105$ m, $B=26$ m and $T=7$ m would still fit the existing shore-based support infrastructure, hence the investment into new infrastructure to support the ship could be minimized.

Even though the propulsive power requirement will be in the same range as for similar sized monohulls in calm water, the performance in rough water will be superior as long as no cross-structure slamming occurs. In the case of the proposed ship at the design displacement of 4,700 tons, this will probably not occur until sea state 6. This leads to one of the major constraints of the design: best performance and behavior at sea will be achieved within a very small margin around the design displacement. As a consequence the ship has to be fitted with a compensated fuel system or sufficient clean water ballast tanks. Since a compensated fuel system based on current technology without mechanical separation between fuel and seawater does not comply with the zero discharge policy, this is not a feasible option. A clean water ballast system requires much more ship volume, therefore it would constrain the maximum fuel capacity and hence range and endurance of the ship. A clean compensated fuel system, based on either a membrane or bladder to separate seawater and fuel, has not yet been built in the required scale. Even though such a system is eventually expected to be possible, further development has to be performed. Since the initial POL capacity of the proposed design (see Appendix D) is more than sufficient to support the required range an endurance a clean water ballast system could be used until these technologies mature.

The estimation of propulsive power, as shown in Appendix E, was done using the actual physical dimensions of the proposed design to derive the frictional resistance coefficient (C_F). The residuary resistance coefficient (C_R) was obtained from towing tank trials of a slightly different O'Neill hull, but with similar values for the wetted surface area and the length and relative positioning of the three hulls. The reason for adopting these values was simply that they were the only results available for a ship of the proposed size and shape. The risk concerning the validation of this C_R for the proposed hull is to be assessed as medium. The true resistance and hence the EHP for the proposed hull is expected to be within an error margin of 12 %.

The choice for prime movers, as shown in the previous section, bears a very low risk. All these engines are currently available, matured designs. The maintenance and support infrastructure is readily available in the German Navy, hence the operational availability is expected to exceed the required 90%. Possible upgrades to a gas turbine generator set based on the Rolls Royce – Northrop Grumman WR 21 have still to be investigated. Even though the specific fuel consumption is lower than for the chosen GE turbine, the total ownership costs (TOC) will be increased significantly by the need to establish a new maintenance and support infrastructure in the German Navy. Additionally the WR 21 module is significantly greater in weight and volume. Looking at past operational profiles and the ability to operate the ship up to 22 kn by the more efficient diesel engines alone, the overall use of the gas turbines and hence the amount of fuel burned will be in an acceptable range. Hence it will probably be a better decision to use currently introduced engines, jump the generation of intercooled and recuperated gas turbines and replace the current engines by fuel cells when the technology is matured.

E. DISCUSSION

The proposed design offers many advantages as well as challenges. As previously discussed, the optimum performance of the vessel is achieved at points very close to design draft only and hence depends on a load compensating system such as a compensated fuel system or a clean ballast system. Also, due to the high sensitivity in draft changes, it is not feasible to provide a 10% or greater service life allowance for weight growth without any performance penalties. If a weight growth allowance is required, the platform has to be designed to the maximum allowable displacement from the beginning and the missing weight has to be compensated by ballast. This ballast could be provided by additional fuel, such that the required minimum range is achieved with the amount of fuel left when the maximum allowable weight has been installed, i.e. at commissioning the ship would have a much greater range than required. As previously discussed, their is enough margin to trade initial POL capacity for later weight increases.

Looking at the stability estimate in Appendix D, the calculated metacentric height of 4.75 m offers risks as well as options. The major risk will be that the ship becomes very stiff, i.e. crew and equipment will experience small amplitude motions but fairly high accelerations, increasing with the distance from the center of the ship. When this metacentric height is accepted it offers a high top-weight growth margin. If, based on a validation of these prediction with demonstrator trials, it is decided to reduce the metacentric height, it could be done by placing some of the existing modules, e.g. the main diesel engines at a higher location, or simply by reducing the length and hence the waterplane area of the side hulls. The later method would reduce the frictional and residuary resistance, which in turn could lead to reduced operating costs.

The integrated electric power generation, distribution and drive system allows maximum flexibility in internal arrangement of its components and increases the overall redundancy of the electric power supply as well as the propulsion system in emergency situations. It also significantly reduces the required manning levels. The choice of the prime movers was made with high emphasis on currently available systems in the German Navy. This leads to easier Navy-wide configuration management and avoidance of costs for creating a new maintenance, support and training infrastructure.

The highly modular, "open systems" arrangement of all systems on board ensures simplified exchange of the modules, for the purpose of scheduled or corrective maintenance, modernization/upgrades or to prepare the ship for changes concerning its mission. To achieve a maximum flexibility in system transportation and handling, the components should comply with standard 20 ft or 40 ft container dimensions.

From the perspective of helicopter and/or UAV handling this design provides a much more stable platform and a significantly larger flight deck compared to monohulls of similar displacement. The flight deck dimensions of 18 m by 42 m would even allow one helicopter to take off or land while the second one is still on the flight deck, or handle helicopters with higher weight than could be done by today's monohull frigates, assuming suitable structure to support the flight deck. Since nearly the whole area is used for container bays to accommodate machinery or war-fighting systems, the "lids" above the modules not only have to provide a watertight and fueltight seal with the flight deck, they also have to provide the structural strength and a flat continuous surface for helicopter operations.

To realize a surface combatant based on such a radically different hull type, many problems and challenges have to be solved, including those that might not be known at the current stage of development. Since there isn't much information, or even experience with O'Neill hulls, further towing tank trials and experiments with a large-scale demonstrator have to be performed. Looking at an envisioned delivery date of 2012 there is not much time left for experiments and their evaluation. Assuming a total construction time of 3 years, including the lead-time for some component manufacturing, and 4 years for detail design, the decision on proceeding with an O'Neill hull has to be made not later than 2005. To allow at least 2 years for data collection and evaluation, a demonstrator has to be launched by 2003. This is only feasible if further in-depth studies of design details including towing tank tests are started straight away.

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V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This study provides a structured approach containing the necessary reasoning to select a concept that satisfies a given set of requirements based on technologies that are available today or will become available in the near future, i.e. within the next 10 years. It is not meant to be even a preliminary design level study for a frigate. Many assumptions were derived from the information available at the time of the study. It is expected that more data will become available from ongoing programs investigating advanced hull designs and powering concepts. To adapt to any changes in policy and requirements, the weighing matrices for system requirements and key performance parameters can be revised, which may result in different weighed scores and priorities.

Today's key concerns in warship design are Total Ownership Costs (TOC) and operational availability. Both aspects have to be addressed as early as possible in the conceptual design stage, well before any detail design and subsystem development. To avoid the use of components and systems that are obsolete at the time of ship delivery, due to fast paced technological development, the timing of critical decisions has to be optimized. On the other hand a trade-off has to be done, comparing advantages from new technologies with benefits from systems currently in use in the German Navy, i.e. with their support infrastructure already in place. As highlighted in Chapter IV, reliance on a late decision can significantly increase the overall program risk.

Since the proposed design, as described in Chapter IV, is radically different from a conventional monohull, the available tables for relationships between payload, displacement and power requirement could not be applied. At the time of this study, there was no experience-based data available for such estimates. The exact relationships have to be determined through several detailed iterations based on the actual payload requirements.

The current development trends in existing programs for frigate / destroyer sized warships, like the U.S. Navy's DD 21 and the Royal Navy's Type 45 destroyer, show a general movement towards an integrated electrical power generation, distribution and propulsion system. This is made possible by developments in power electronic components during the past 10 to 15 years. Hence, with respect to the platform, other key decisions concern the hull type and shape, the propulsion arrangement and the choice of the prime movers.

For the purpose of this study, all warfighting systems are viewed as variable payload. The modular approach to the arrangement of systems within the ship is the logical response to the rapid developments in weapon, sensor, communication and computing technology. To ensure a 'plug and play' like operation of interchangeable modular systems, high emphasis has to be put into exact and comprehensive interface specifications. One of the key parameters to support an open architecture systems approach is the initially installed bandwidth.

In general, advanced multi-hull designs offer many performance features not provided by similar sized monohulls. Based on the available trials and evaluations, there is not much gain in total resistance compared to monohulls over a wide range of speeds in calm water conditions. The major advantage is the superior performance at sea states up to the limit when cross-structure slamming occurs. Especially for combatant ships, any three-hull design is superior to twin-hulls due to the higher ability to compensate buoyancy losses caused by a hit on one side of the ship

One major disadvantage of all advanced multi-hulls is their high sensitivity to draft and hence load changes. Means to compensate these load changes have to be provided in the design; otherwise the multi-hull's overall performance would suffer significantly. The use of initial excess POL capacity for later weight increases, as discussed in Chapter IV, could solve this problem.

B. RECOMMENDATIONS

To deviate from the conventional monohull evolution to a radically different advanced multi-hull type requires significant lead times for exploratory design studies, towing tank tests and large scale demonstrators. The total lead-time, depending on the specific design, will be in the range of 10 to 12 years.

The evaluations and discussions in this study show that an O'Neill hull is a feasible design solution for a future frigate or destroyer. The final decision to use such a design clearly depends on the results of large-scale demonstrator sea trials. When a delivery date of 2012 is envisioned to deliver the first ship, preliminary design and towing tank tests have to commence immediately.

A conventional trimaran would also provide a suitable platform for a future warship hull. Due to the relatively lower wetted surface area, the resistance at lower speeds will be lower than that of the proposed O'Neill hull. Since the British RV "Triton" is currently the only large-scale trimaran, the results from the sea trials currently underway should be closely monitored. [Ref. 2]

C. SUGGESTIONS FOR FURTHER STUDIES

Before concentrating only in the direction described in this study, basic studies exploring non-material solutions as well as completely different approaches to satisfy the stated mission needs have to be done. Another possible approach would be the consolidation of the naval assets within a multi-national force. This approach might be the most cost-effective solution, but results in decreased national independence in crisis decisions.

During all studies of details and alternatives, as proposed later in this section, the cost implementations of design decisions have to be closely monitored. Factors like manpower and operating costs like POL are key areas when it comes to the selection of any system to be installed on board the platform as well as with respect to broad conceptual decisions.

Further design studies have to be performed to optimize the internal arrangement of all necessary components and modules, and to finalize the outer structure, its dimensions and hence the final power requirements. These studies should be performed by a dedicated design team, with one team member will be responsible solely for keeping track of all weight added to the ship, its exact location and influence on the stability, due to the criticality of weight control to the success of the O'Neill hull form. Another vital part of the study will be the structural strength calculation, which could be performed using finite element methods to model the complicated structure of an O'Neill hull form.

A series of towing tank tests should be performed to validate the calculations of the power requirements attached in Appendix E. As part of these tests, the shape, size and relative location of the center hull and the side hulls including the struts should be varied to determine the optimum configuration.

The design of the shipwide electrical power and data network, and the specification of all relevant interfaces have to be studied and evaluated in depth. This includes decisions about the physical and electromagnetic protection of the network, alternative routes for redundancy and an automatic re-routing control system to provide instant response in any emergency situation. The development of a fully automated alignment system would drastically reduce the time required for the exchange of weapon and sensor systems.

Design studies and corresponding material tests have to be performed to find and evaluate possible solutions for a mechanical water-fuel separation systems, which can be used for 'clean' compensated fuel systems. This might be a membrane, a bladder or anything else suitable to keep both fluids permanently apart, allowing a maximum percentage of tank use for either one of them.

A boat launch system has to be developed that can be integrated in the stealth structure without degrading the radar reflection signature. The system should provide safe boat launch and recovery up to sea state 6, i.e. wave heights of up to 4 m. The design is not constrained to a sidebased system, it could as well be a sternbased system similar to those used on offshore search and rescue vessels. Similarly, the RAS gear for liquid and solid replenishment at sea in compliance with current NATO standards has to be integrated into the surface as well. For the long-term, alternative ways to perform replenishment should be investigated.

A study should be performed to investigate the required manning levels to perform the anticipated missions. This study should also define the required accommodation standards. The arrangement of all accommodations should be optimized with regard to quality of living and functional aspects as well. Today on most naval ships the accommodation for the crew is according to the rank structure. The study should include the question whether a more functional or team-oriented arrangement of living spaces would be beneficial. This might include consideration about the effect of massive personnel losses due to an unexpected hit.

Studies and trials could be performed on existing multi-hulls as to determine whether a spoiler system attached to the outer hulls could completely replace one or more conventional rudders. The benefit of a surface integrated spoiler would be that it does not generate any noise or resistance when no directional correction is necessary.

Table A.1, System Requirements Evaluation

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
(1) Compliance with standards		1.0	1.0	0.5	1.0	0.5	0.5	0.5	0.5	1.0	0.5	1.0	0.5	0.5	0.5	0.5	0.5	0.5	1.0	1.0	
(2) State-of-the-art automation	0.0		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1.0	1.0	0.5	0.5	0.5	0.5	0.0	0.5	1.0	1.0	
(3) Integrated electric power system	0.0	0.5		0.5	0.5	0.5	0.0	0.0	0.5	0.5	1.0	0.5	0.0	0.0	0.0	0.0	0.0	0.5	1.0	0.5	
(4) High maneuverability	0.5	0.5	0.5		0.5	0.0	0.0	0.0	0.0	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.5	
(5) Modular design	0.0	0.5	0.5	0.5		0.0	0.5	0.5	0.5	1.0	1.0	1.0	0.5	0.5	0.5	0.5	0.0	0.5	0.5	0.5	
(6) Design displacement reserve	0.5	0.5	0.5	1.0	1.0		0.0	0.0	1.0	1.0	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1.0	1.0	0.5	
(7) Cables, pipes and vents	0.5	0.5	1.0	1.0	1.0	1.0		0.5	0.5	1.0	1.0	1.0	0.5	1.0	0.0	1.0	0.5	0.5	1.0	0.5	
(8) Fiber optics	0.5	0.5	1.0	1.0	0.5	1.0	0.5		0.5	0.5	1.0	1.0	0.5	1.0	0.0	1.0	0.5	0.5	1.0	0.5	
(9) Open architecture computer network	0.5	0.5	0.5	1.0	0.5	0.0	0.5	0.5		0.5	1.0	0.5	0.0	0.5	0.0	0.5	0.5	0.5	0.5	0.5	
(10) Stealth technology	0.0	0.5	0.5	0.5	0.0	0.0	0.0	0.5	0.5		0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	1.0	0.5	
(11) Design stability	0.5	0.0	0.0	0.5	0.0	0.5	0.0	0.0	0.0	0.5		0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
(12) Survivability	0.0	0.0	0.5	0.5	0.0	0.0	0.0	0.0	0.5	0.5	0.5		0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	
(13) Hull mounted sonar	0.5	0.5	1.0	1.0	0.5	0.5	0.5	0.5	1.0	0.5	1.0	1.0		0.5	0.0	0.5	0.0	0.5	0.5	0.5	
(14) Support of helicopters/UAVs	0.5	0.5	1.0	1.0	0.5	0.0	0.0	0.0	0.5	0.5	1.0	1.0	0.5		0.0	0.5	0.5	0.0	0.5	0.5	
(15) RAS capability	0.5	0.5	1.0	1.0	0.5	0.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0		0.5	0.5	0.0	0.5	0.5	
(16) Boats	0.5	0.5	1.0	1.0	0.5	0.0	0.0	0.0	0.5	1.0	1.0	1.0	0.5	0.5	0.5		0.5	0.0	1.0	0.5	
(17) Additional quarters and storage	0.5	1.0	1.0	1.0	1.0	0.5	0.5	0.5	0.5	1.0	1.0	1.0	1.0	0.5	0.5	0.5		0.5	1.0	1.0	
(18) Corrosion protection	0.5	0.5	0.5	0.5	0.5	0.0	0.5	0.5	0.5	1.0	1.0	1.0	0.5	1.0	1.0	1.0	0.5		0.5	0.5	
(19) Operational availability	0.0	0.0	0.0	1.0	0.5	0.0	0.0	0.0	0.5	0.0	1.0	0.5	0.5	0.5	0.5	0.0	0.0	0.5		0.5	
(20) Supportability, Upgradeabilty	0.0	0.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1.0	1.0	0.5	0.5	0.5	0.5	0.0	0.5	0.5		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Subtotal :	6.0	8.5	12.5	14.5	10.0	6.0	5.5	6.0	10.0	13.0	16.5	16.0	8.0	10.0	5.0	8.5	4.5	7.0	13.0	10.0	190.5
Percentage :	**3.1**	**4.5**	**6.6**	**7.6**	**5.2**	**3.1**	**2.9**	**3.1**	**5.2**	**6.8**	**8.7**	**8.4**	**4.2**	**5.2**	**2.6**	**4.5**	**2.4**	**3.7**	**6.8**	**5.2**	100.0
Priority:			**5**	**3**	**6**				**6**	**4**	**1**	**2**		**6**					**4**	**6**	

Results from Ranking:

(11) Design stability	1
(12) Survivability	2
(4) High maneuverability	3
(10) Stealth technology	4
(19) Operational availability	4
(3) Integrated electric power system	5
(5) Modular design	6
(9) Open architecture computer network	6
(20) Supportability, Upgradeabilty	6
(14) Support of helicopters/UAVs	6

0.0 means vertical feature is less important than horizontal, 1.0 means it is more important and 0.5 means it is equally important or there is no conflict. Weights for columns are added at the bottom and normalized by dividing by the sum of all weights.

Table A.2, Key Performance Parameter Evaluation

	1	2	3	4	5	6	7	8	9	
(1) Top Speed		0.0	1.0	1.0	1.0	0.5	0.5	0.5	0.5	
(2) Acceleration (0 – 25 kn.)	1.0		1.0	1.0	1.0	0.5	0.5	1.0	1.0	
(3) Maximum Range	0.0	0.0		0.5	1.0	0.0	0.0	1.0	1.0	
(4) Endurance	0.0	0.0	0.5		1.0	0.0	0.0	1.0	1.0	
(5) High Speed Transit	0.0	0.0	0.0	0.0		0.5	0.5	1.0	1.0	
(6) Max sea state for boat operations	0.5	0.5	1.0	1.0	0.5		0.5	1.0	1.0	
(7) Max sea state for helicopter/UAV operations	0.5	0.5	1.0	1.0	0.5	0.5		1.0	1.0	
(8) Min floodable length in adjacent compartments	0.5	0.0	0.0	0.0	0.0	0.0	0.0		0.0	
(9) Reduction of crew required to operate ship	0.5	0.0	0.0	0.0	0.0	0.0	0.0	1.0		
	1	2	3	4	5	6	7	8	9	
Subtotal :	3.0	1.0	4.5	4.5	5.0	2.0	2.0	7.5	6.5	36.0
Percentage :	**8.3**	**2.8**	**12.5**	**12.5**	**13.9**	**5.6**	**5.6**	**20.8**	**18.1**	100.0
Priority:	5	7	4	4	3	6	6	1	2	

Results from Ranking:

(8) Min floodable length in adjacent compartments	1
(9) Reduction of crew required to operate ship	2
(5) High Speed Transit	3
(3) Maximum Range	4
(4) Endurance	4
(1) Top Speed	5
(6) Max sea state for boat operations	6
(7) Max sea state for helicopter/UAV operations	6
(2) Acceleration (0 – 25 kn.)	7

0.0 means vertical feature is less important than horizontal, 1.0 means it is more important and 0.5 means it is equally important or there is no conflict. Weights for columns are added at the bottom and normalized by dividing by the sum of all weights.

APPENDIX B: POWER COMPARISON OF MONOHULL AND O'NEILL HULL

Since the best results of the proposed O'Neill hull form in Ref. 3 were achieved with a new outer hull in far aft position, these results were used to compare the power requirements to a conventional monohull. Since the conventional monohull for which the exact powering data were available is the German F-122 class with a displacement of 3,600 tons and the predictions derived from the trials at the David Taylor Research Center are for a displacement of 4328 tones the results have top be compared using a linear scaling factor (λ).

$$\lambda^3 = \frac{V_{O'Neill}}{V_{122}} = \frac{4{,}328 tons}{3{,}600 tons} = 1.2022$$
$$\lambda = \sqrt[3]{1.2022} = 1.06331$$

The power is a function of the square of this scaling factor, hence the experienced power requirements for the 122 class frigate of SHP~31,000 kW at 30 kn (measured at the shaft between reduction gear and thrust bearing) has to be multiplied by λ^2 to obtain the power requirement at 30 kn of an equivalent monohull. To equate this t the effective horsepower a propulsive coefficient of 0.8 was assumed.

$$\lambda^2 = 1.13063$$
$$EHP = 0.8 * 1.13063 * 31{,}000 kW = 28{,}040 kW$$

Comparing the 28,040kW for the monohull with the proposed 27,190kW for the O'Neill hull (see Ref. 3 page 17), it can be stated that the O'Neill hull will at least be in the same region of power requirement, maybe with some advantages in adverse sea state conditions.

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APPENDIX C: DRAWINGS

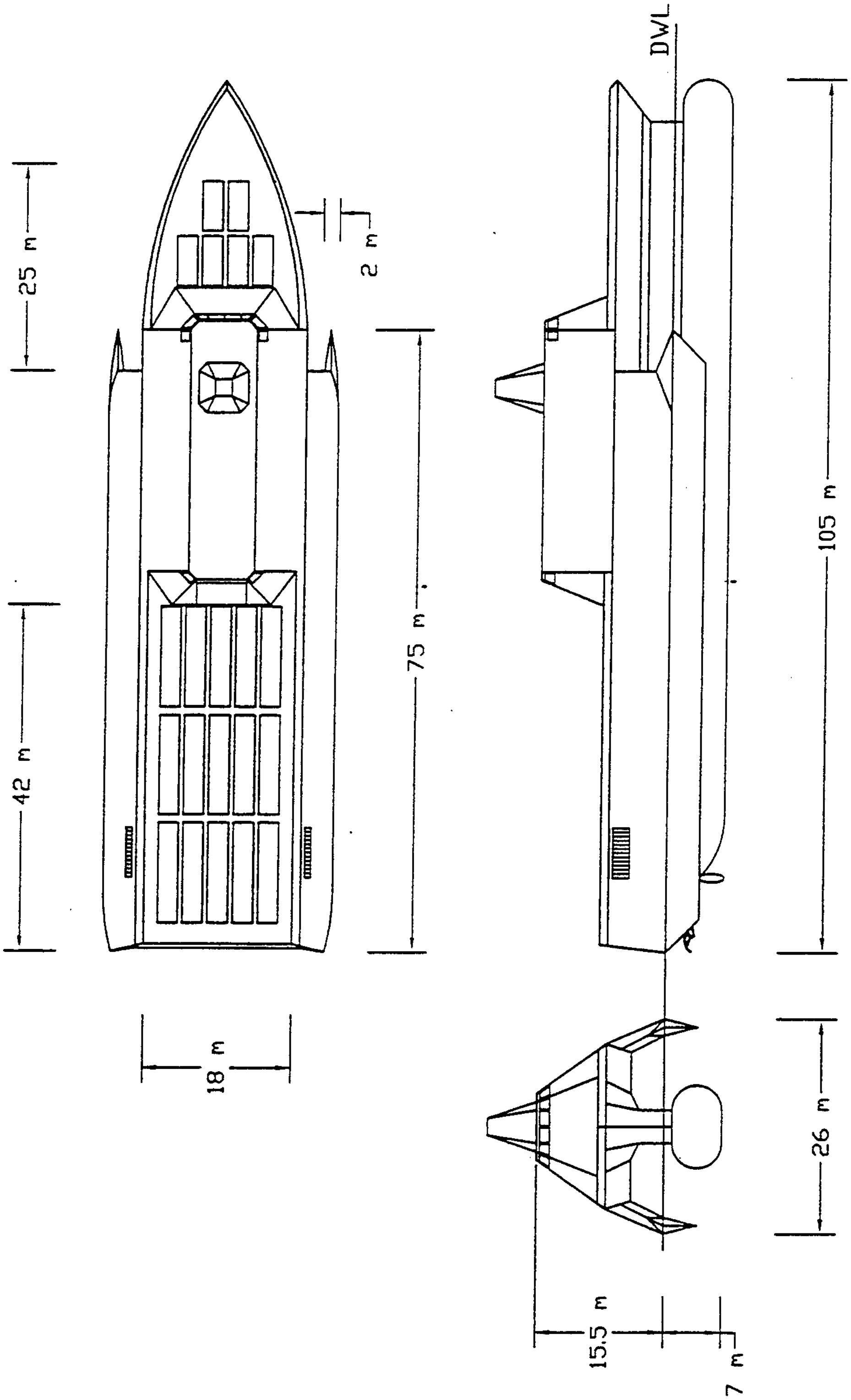

Figure C.1, 3 Side View of the Hull

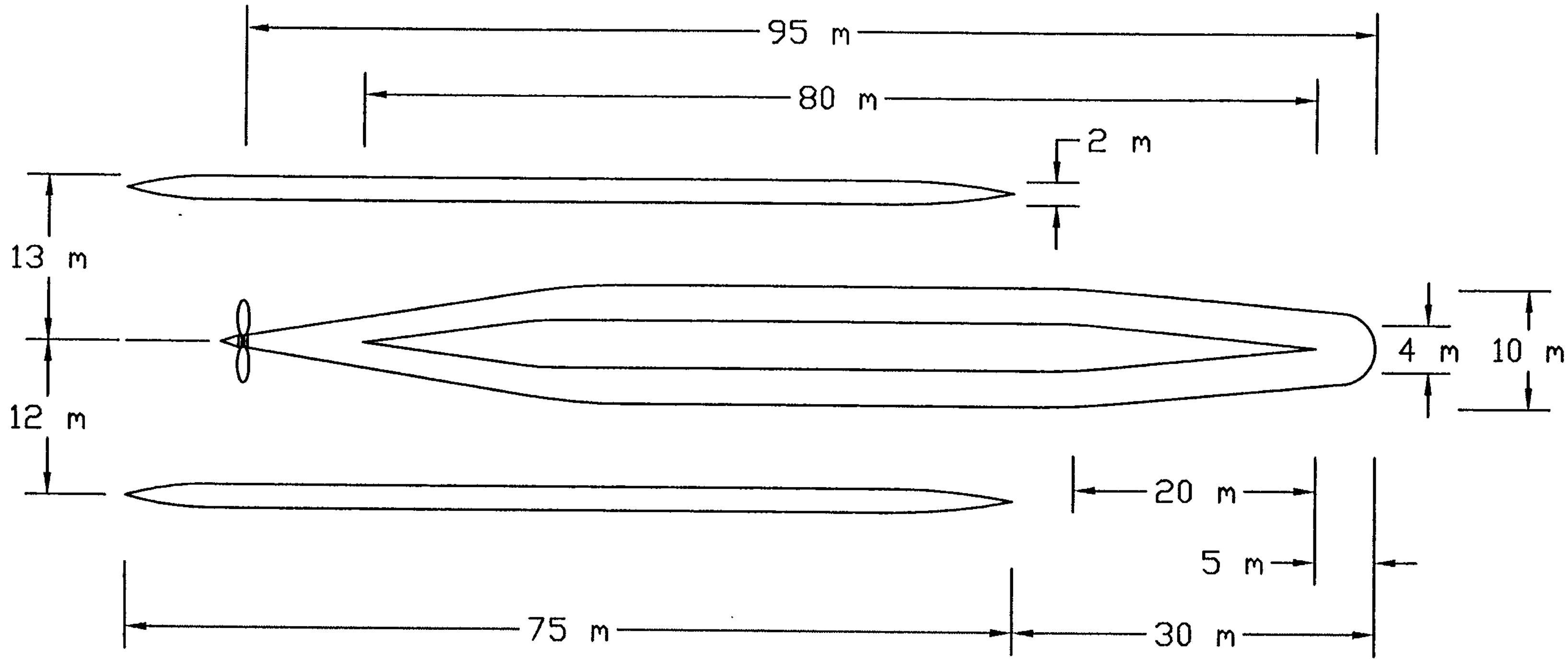

Figure C.2, Waterplane Section View

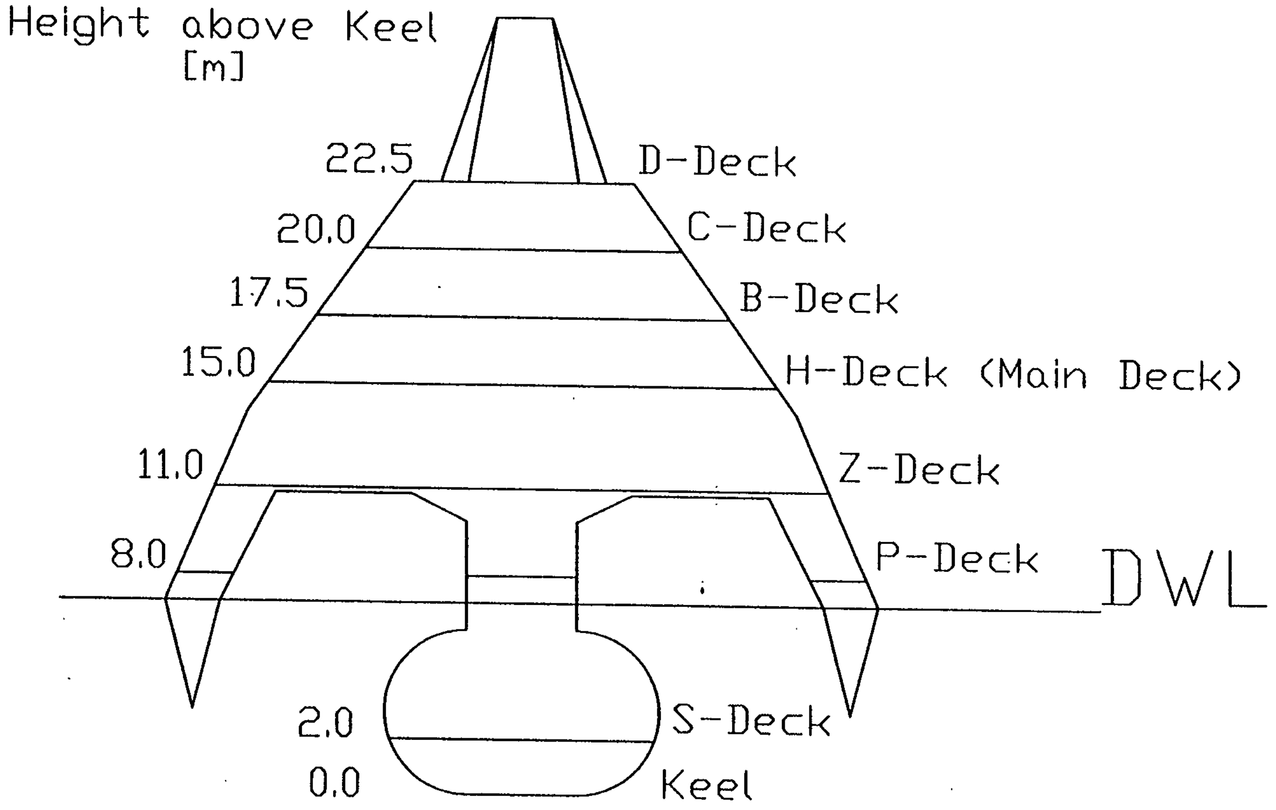

Figure C.3, Deck-Level Arrangements

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APPENDIX D: CALCULATIONS

1. CALCULATIONS OF HULL PARAMETER

Basic linear Dimensions:

Total Length of the Ship	L_{OA}	= 105 m
Total Beam	B	= 26 m
Center Hull Draft	T	= 7 m
Cross-Structure Clearance	T_{CC}	= 4 m
Total Depth of the Hull	D	= 15 m

Center Hull:

Total Length	L_{OA}	= 95 m
Length at Waterline	L_{WL}	= 80 m
Beam at Waterline	B_{CH}	= 4 m
Max Breadth	B_{MCH}	= 10 m
Depth of Center Float	D_{CF}	= 6 m

Side Hull:

Length at Waterline (=L_{OA})	L_{WL}	= 75 m
Beam at Waterline	B_{SH}	= 2 m
Side Hull Draft	T_{SH}	= 4 m

Displaced Volume (*V*):

$$V_{CH} = \frac{1}{3} * 52.27m^2 * 28m + 52.27m^2 * 48m + \frac{1}{2} * (52.27m^2 + 28.27m^2) * 20m + 250m^2 * 1m$$

$$V_{CH} = 4{,}5052.21m^3$$

$$V_{SH} = \frac{1}{3} * 4m^2 * 10m + 60m * 4m^2 + \frac{1}{3} * 4m^2 * 5m$$

$$V_{SH} = 260m^3$$

$$V = 4{,}5052.21m^3 + 2 * 260m^3 = \underline{4{,}572.21m^3}$$

Waterplane Area (A_W):

$$A_{W_{CH}} = 45m * 4m + \frac{1}{2} * 4m * 15m + \frac{1}{2} * 4m * 20m = 250m^2$$

$$A_{W_{SH}} = 11m * \frac{1}{2} * 2m + 60m * 2m + 5m * \frac{1}{2} * 2m = 135m^2$$

$$A_W = 250m^2 + 2 * 135m^2 = \underline{520m^2}$$

Wetted Surface Area (*S*):

$$S_{CH} = 362.52m^2 + 1{,}288.8m^2 + 444.74m^2 + 28.27m^2 + 160m^2 - 250m^2 = 2{,}034.33m^2$$

$$S_{SH} = 2 * 75m * 4.47m = 670.50m^2$$

$$S = 2{,}034.33m^2 + 2 * 670.5m^2 = \underline{3{,}375.33m^2}$$

Displacement (Δ)

Assuming density of seawater $\rho = 1.025\frac{\text{tons}}{\text{m}^2}$

$$\Delta = 4{,}572.21m^3 * 1.025\frac{tons}{m^3} = \underline{4{,}686.52tons}$$

Tons per Centimeter Immersion (*TPC*)

$$TPC = \frac{A_W}{100} * \rho = \frac{520m^2}{100cm} * 1.025\frac{tons}{m^3} = \underline{5.33\frac{tons}{cm}}$$

2. CALCULATION OF TRANSVERSE STABILITY

Transverse Metacenter ($\underline{KM}$)

$$I_T = T_{T_{CH}} + 2*(I_{T_{SH}} + y^2 A_{W_{SH}})$$

$$I_{T_{CH}} = \frac{15m*4^3m^3}{48} + \frac{45m*4^3m^3}{12} + \frac{20m*4^3m^3}{48} = 286.67m^4$$

$$I_{T_{SH}} = \frac{10m*2^3m^3}{48} + \frac{60m*2^3m^3}{12} + \frac{5m*2^3m^3}{48} = 42.50m^4$$

$$I_T = 286.67m^4 + 2*(42.50m^4 + 12^2m^2*135m^2 = 39,251.67m^4$$

$$\overline{BM} = \frac{I_T}{V} = \frac{39,251.67m^4}{4,572.21m^3} = 8.58m$$

	Location [m]	Volume [m³]	Moment [m⁴]
	3.00	3,802.21	11,406.63
	6.50	250.00	1,625.00
	5.66	520.00	2,943.20
Σ =		**4,572.21**	**15,974.83**

$$\overline{KB} = \frac{15,974.83m^4}{4,572.21m^3} = 3.49m$$

$$\overline{KM} = \overline{KB} + \overline{BM} = 8.58m + 3.49m = \underline{12.07m}$$

Effect of an Increase in Beam

Beam [m]	I_T [m⁴]	BM [m]	KM [m]
27	42,559.11	9.31	12.80
28	46,001.67	10.06	13.55
29	49,579.11	10.84	14.33
30	53,291.67	11.66	15.15

Table D.1, BM and KM versus Ship's Beam

Center of Gravity (*KG*)

Assumptions concerning the hull structure:

All steel plating used for the estimation of the bare hull center of gravity is given an additional 40% weight margin for stiffeners. The density for steel is assumed to be 7.9 tons/m2. The location is the center height over keel.

Item	Thickness [mm]	incl. Margin [mm]	Area [m^2]	Volume [m^3]	Mass [tons]	Location [m]	Moment [tons x m]
Top Side Deck (external)	6	8.4	250	2.1	16.6	22.5	373.3
Top Side Walls (external)	6	8.4	720	6.0	47.8	18.0	860.0
C - Deck	5	7.0	180	1.3	10.0	20.0	199.1
C - Deck Walls	3	4.2	360	1.5	11.9	21.3	253.8
B - Deck	5	7.0	250	1.8	13.8	17.5	241.9
B - Deck Walls	3	4.2	360	1.5	11.9	18.8	224.0
H - Deck (Main Deck)	8	11.2	1700	19.0	150.4	15.0	2256.2
H - Deck Walls	5	7.0	360	2.5	19.9	16.3	323.5
Cross-Structure Walls (external)	6	8.4	750	6.3	49.8	13.0	647.0
Z - Deck	8	11.2	1600	17.9	141.6	11.0	1557.2
Z - Deck Walls	5	7.0	1080	7.6	59.7	13.0	776.4
Center Strut Walls (external)	8	11.2	590	6.6	52.2	8.5	443.7
P - Deck	6	8.4	250	2.1	16.6	8.0	132.7
P - Deck Walls	5	7.0	200	1.4	11.1	9.5	105.1
Center Float Walls (external)	10	14.0	1650	23.1	182.5	3.0	547.5
S - Deck (Tank Top)	8	11.2	800	9.0	70.8	2.0	141.6
S - Deck Walls	5	7.0	350	2.5	19.4	4.5	87.1
Tank Walls	6	8.4	450	3.8	29.9	1.0	29.9
Keel Plate	15	21.0	250	5.3	41.5	0.0	0.0
Side Hulls (external)	6	8.4	2880	24.2	191.1	8.0	1528.9
					1148.4		**10729.0**

Height of Center of Gravity above Keel (KG) in [m] =	**9.34**

Schaded cells are calculated automatically.

Table D.2, Center of Gravity for Hull Structure

Assumptions:

Unless their exact center of gravity is known, all loads are applied at an average height of 1 meter above the respective deck level. Furnishings and fixed installations accounts for all minor equipment, cables, pipes and vents (S-Deck incl. auxiliary machinery). The container infrastructure accounts for the container basement as well as for all cable, pipe and vent interfaces.

Item	Deck	Load	Area	Volume	Mass	Location	Moment
		[kg/m^2]	[m^2]	[m^3]	[tons]	[m]	[tons x m]
Furnishing and fixed installations	C	150	180		27	21	567
	B	150	250		37.5	18.5	693.75
	H	150	650		97.5	16	1560
	Z	200	800		160	12	1920
	P	150	250		37.5	9	337.5
	S	300	800		240	3	720
Container Infrastructure (21x)	Z				105	12	1260
Crew (~ 180 x 150 kg)	H				27	16	432
Radar/Antenna Dome	D				10	25	250
Main Diesel Generators (2x)	S				80	4	320
Electric Propulsion Machinery	S				50	3	150
Propeller + Shaft	S				10	3	30
Water Jet Units (2x)	Side Hulls				10	5	50
Gas Turbine Generator Sets (2x)	Z				40	13	520
Auxiliary Diesel Generators (2x)	Z				16	13	208
POL	A			1500	1245	1	1245
Fresh Water	A			90	90	1	90
Provisions	P				200	9	1800
Store and Spare Parts	P				400	9	3600
Boats, Liferafts, Capstans, ...	H				40	16	640
Empty Hull Total					1148.4	9.34	10729.0
					4070.9		27122.2

Height of Center of Gravity above Keel (KG) in [m] = 6.66

Table D.2, Center of Gravity for Platform

Assumptions concerning the payload:

The platform provides all means of transportation, support and personnel.
The exact payload is defined by the exact mission requirements.

Item	Deck	Mass	Location	Moment
		[tons]	[m]	[tons x m]
Platform Total		4070.9	6.66	27122.2
War-fighting Modules, Containers	Z	400	13	5200
(13 x 40 ft + 4 x 20 ft)				
C^4I Systems outside Containers	C	20	21	420
	Z	50	13	650
Hull mounted Bow Sonar	S	10	3	30
Ammunition for Gun	S	100	4	400
Torpedos in Side Hulls	P	12	8	96
Helicopter / UAV / UCAV	H	24	17	408
		4686.9		**34326.2**

Height of Center of Gravity above Keel (KG) in [m] =	**7.32**

Table D.2, Center of Gravity for Total Ship

With the calculated KM of 12.07m the final metacentric height GM is 4.75m.

APPENDIX E: CALCULATIONS OF POWER REQUIREMENTS

Assumptions:

At the time of this study there was no data available concerning the performance and power requirement data of a full size O'Neill hull and only limited data from model tests. To enable a rough estimate for power requirements, Froude similarity to an O'Neill hull model tested at the David Taylor Research Center was assumed. Their model gave the closest match to the proposed hull form with the original outer hulls in aft position; see Ref. 3 page 13 to15. Hence the residuary resistance coefficients from the table on page 15 in the Ref. 3 was chosen for the following calculations. For the calculation of the friction resistance the ITTC 1957 Line was used. The required dimensions for the ship are those derived in Appendix D.

$$R_{TS} = C_{TS} * (\frac{1}{2} * \rho * v^2 * S)$$

$$\mathrm{Re} = \frac{v * L_{WL}}{\nu}$$

$$C_{TS} = C_{FS} + C_{RS} + C_A$$

$$C_{FS} = \frac{0.075}{(\log_{10} \mathrm{Re} - 2)^2}$$

$$EHP = R_{TS} * v$$

$$L_{WL} = 80m$$

$$\rho = 1.025 \frac{tons}{m^3}$$

$$v = 14kn - 32kn$$

$$\nu = 1.18831 * 10^{-6} \frac{m^2}{\mathrm{sec}}$$

$$S = 3{,}375.33m^2$$

$$C_A = 0.0005$$

Speed	Speed	Re	C_{FS}	C_{RS}	C_{TS}	R_{TS}	EHP	SHP
[kn]	[m/sec]					[N]	[kW]	[kW]
14	7.20	484871605.7	0.001677942	0.001093	0.003270942	293505	2114	3322
16	8.23	554138978	0.001649207	0.000747	0.002896207	339435	2794	4390
18	9.26	623406350.2	0.00162447	0.00139	0.00351447	521305	4827	7586
20	10.29	692673722.4	0.00160281	0.001167	0.00326981	598783	6161	9681
22	11.32	761941094.7	0.001583587	0.000792	0.002875587	637175	7211	11332
24	12.35	831208466.9	0.001566338	0.001212	0.003278338	864497	10674	16773
26	13.38	900475839.2	0.001550718	0.002021	0.004071718	1260119	16855	26486
28	14.40	969743211.4	0.001536464	0.002524	0.004560464	1636862	23578	37051
30	15.43	1039010584	0.00152337	0.002808	0.00483137	1990673	30723	48279
32	16.46	1108277956	0.001511272	0.002645	0.004656272	2182857	35935	56469

Table E.1, Speed versus Effective and Shaft Horse Power

Including a safety margin of 10 % and a propulsive efficiency of 0.7 results in the following requirements for installed shaft horsepower (SHP).

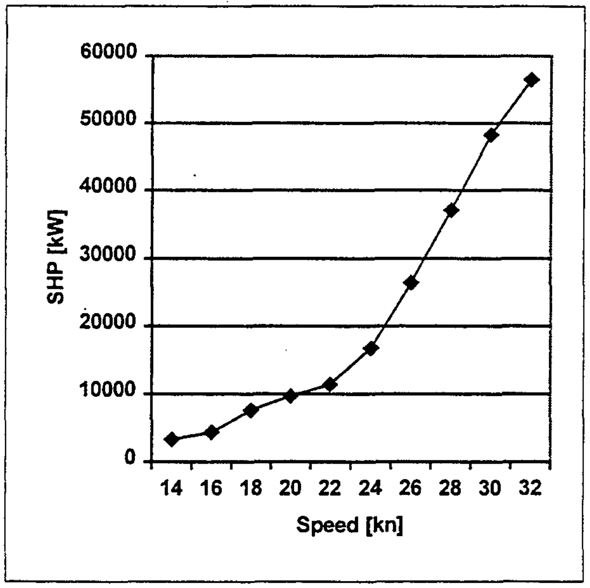

Figure E.1, Speed versus Shaft Horse Power

GLOSSARY OF ACRONYMS, ABREVIATIONS AND DIMENSIONS

A. ACRONYMS AND ABREVIATIONS

AAW	Anti Air Warfare
ASuW	Anti Surface Warfare
ASW	Anti Submarine Warfare
AWW	Above Water Warfare (incl. AAW and ASuW)
C_4I	Command Control Communication Computing Intelligence
CODAG	Combined Diesel and Gas Turbine
CODOG	Combined Diesel or Gas Turbine
COGAG	Combined Gas Turbine and Gas Turbine
COTS	Commercial Off-The-Shelf
FPB	Fast Patrol Boat
IR	Infrared
IT	Information Technology
KPP	Key Performance Requirements
MTBM	Mean Time between Maintenance
MW	Mine Warfare
NATO	North Atlantic Treaty Organization
NSFS	Naval Surface Fire Support
O&S	Operation and Support
POL	Petrol Oil Lubricants
RAS	Replenishment at Sea
R&D	Research and Development
rpm	Revolutions per Minute
SWATH	Small Waterplane Area Twin Hull
STANAVFORLANT	Standing Naval Force Atlantic

TAD	Theater Air Defense (Incl. AAW)
TAS	Towed Array Sonar
TBMD	Theater Ballistic Missile Defense
TOC	Total Ownership Cost
UAV	Unmanned Air Vehicle
UCAV	Unmanned Combat Air Vehicle
VDS	Variable Depth Sonar
WL	Waterline

B. DIMENSIONS

	Units	
A_W	$[m^2]$	Waterplane area
B	[m]	Ship's beam in the design waterline
B_{CH}	[m]	Center hull beam in the design waterline
BM	[m]	Height of metacenter above center of buoyancy
B_{MCH}	[m]	Maximum breath of the center hull
B_{MSH}	[m]	Maximum breath of the side hull
B_{SH}	[m]	Side hull beam in the design waterline
C_A		Correlation allowance
C_{FS}		Frictional resistance coefficient
CH		Center hull
C_{RS}		Residuary resistance coefficient
C_{TS}		Total resistance coefficient
D	[m]	Depth of the hull
EHP	[W]	Effective horsepower
GM	[m]	Height of metacenter above center of gravity
I_T	$[m^4]$	Transverse moment of inertia

KB	[m]	Height of center of buoyancy above keel
KG	[m]	Height of center of gravity above keel
KM	[m]	Height of metacenter above keel
L_{OA}	[m]	Length over all
L_{WL}	[m]	Length at waterline
Re		Reynolds number
R_{TS}	[N]	Resistance of total ship
S	[m^2]	Wetted surface area
SH		Side hull
SHP	[W]	Shaft horsepower
T	[m]	Center hull draft
T_{CC}	[m]	Clearance between cross-structure and waterline
TPC	[tons]	Tons per centimeter immersion
T_{SH}	[m]	Side hull draft
V	[m^3]	Displaced volume
v	[m/sec], [kn]	Ship's speed
Δ	[tons]	Displacement
λ		Scaling factor
ν	[m^2/sec]	Kinematic viscosity
ρ	[tons/m^3]	Mass density

Conversions

Length: 1 m = 3.281 ft

Area: 1 m^2 = 10.76 ft^2

Volume 1 m^3 = 35.32 ft^3

Mass: 1 ton = 1,000 kg = 2,205 lbs. = 0.984 LT

Power 1 W = 1 Nm/sec = $1.341 * 10^{-3}$ hp

Speed 1 m/sec = 1.944 kn

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