

**NAVAL POSTGRADUATE SCHOOL  
Monterey, California**



**THESIS**

**APPLICATION OF NUMERICAL  
OPTIMIZATION TECHNIQUES TO  
SURFACE COMBATANT DESIGN  
SYNTHESIS**

by

Neil E. Meister

September 1998

Thesis Advisors:

Matthew D. Kelleher  
Charles N. Calvano

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TECHNIQUES TO SURFACE COMBATANT DESIGN  
SYNTHESIS**

Neil E. Meister  
Lieutenant, United States Coast Guard  
B.S., University of California Santa Barbara, 1988

Submitted in partial fulfillment of the  
requirements for the degree of

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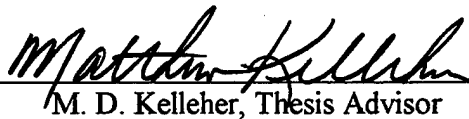
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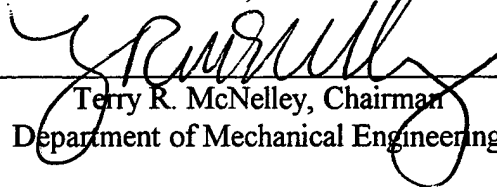
Approved by:



M. D. Kelleher, Thesis Advisor



C. N. Calvano, Thesis Advisor



Terry R. McNelley, Chairman  
Department of Mechanical Engineering



## ABSTRACT

This thesis presents the effort to incorporate a numerical optimizer into an existing ship design synthesis math model. The goal is to improve the functionality of the model while retaining the intrinsic value of the model's friendly user interface, which is greatly advantageous for its use as a learning tool. A description of the math model and its origin and intent are presented along with a discussion of numerical optimization techniques and tools. The integration and linking software is described along with the actual Integrated Ship Design System. Results of comparison and sensitivity studies are also presented.



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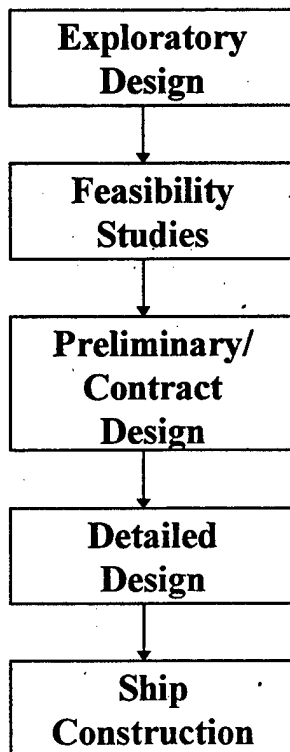


## I. INTRODUCTION

### A. BACKGROUND

The process of designing a modern combatant ship is an exceptionally complicated and intricate undertaking. The challenge of the ship designer is to engineer a total ship system that fulfills rigorous requirements within certain constraints, such as the laws of nature, the limits of technology and especially in today's environment, limited budgets. This requires the ship designer to have an in depth knowledge of numerous engineering disciplines and possesses a special ability to bring together or synthesize these diverse areas to create a balanced ship design.

The ship design process can be divided into several phases, each which increases in detail and resource expenditure as the process proceeds;



A successful ship design starts with a set of operational requirements generated by the end user. These requirements typically include a nominal mission profile and payload specifics (i.e. combat systems). The next step requires defining the initial concepts for the overall ship configuration. While the operational requirements may dictate a specific ship type (i.e. an oil tanker should be a monohull to maximize cargo capacity), the surface combatant can take on many forms (monohull, multihull, wave piercer, etc.), each of which may have advantages and disadvantages but still fill the mission need. The same is true for the propulsion system; numerous permutations may meet the requirements, but the designer must choose wisely to produce the most balanced design. This leads to the implementation of feasibility studies, the objective of which is to conduct trade-off studies between capabilities, cost and risks which are then presented as whole-ship solutions. The whole-ship solution consists of the hull form type, its gross characteristics such as beam, draft, length, a gross cost estimate and the areas of major technical risk. These whole-ship solutions come about through the use of a traditional iterative design spiral as shown in Figure 1. It is the improvement of this portion of the design process that is the focus of this thesis. The remainder of the design process is dedicated to refining the chosen design(s) and completing detailed engineering studies that eventually lead to the production of the ship [Ref.1].

It is during the feasibility study phase of the design process that having an ability to examine many different designs in a rapid, but consistent manner is highly desirable. A multitude of variables must be considered and evaluated using proven techniques that have been developed and refined through years of use. Sophisticated computer aided combatant ship design tools have been extensively developed over the years. The primary system

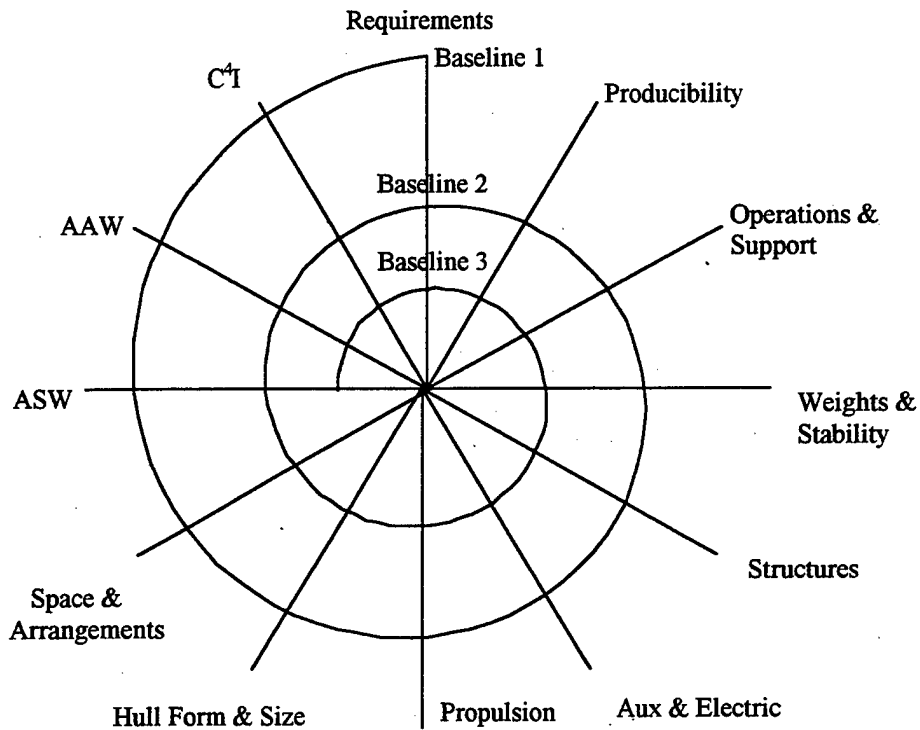


Figure 1. Iterative Ship Design Spiral [Ref. 1].

being used by the U. S. Navy is the Advanced Ship System Evaluation Tool (ASSET) [Ref. 2]. But for the student, these design tools are really too far removed from the basics needed to learn and understand the fundamentals of ship design.

Efforts at the Department of Ocean Engineering at the Massachusetts Institute of Technology in the 1970s produced several naval combatant ship synthesis models. Those developed by Reed [Ref. 3], and Graham and Hamly [Ref. 4] are particularly relevant in that they form the basis of the model used in this thesis. The Simplified Math Model for the Design of Naval Frigates was adapted from these original models and has been revised several times throughout the years to add additional features and to keep pace with rapidly changing software. The model in its current form is written in Mathcad, which presents an



easy to read and understand object oriented environment for equations, while maintaining powerful evaluation capabilities.

## **B. OBJECTIVES**

The simplified math model generates the basic data for a first order design, though it requires the designer to check manually and adjust numerous parameters to ensure they fall within the feasible range designated within the model. It is then up to the designer to choose what parameters to change if the results are infeasible, and this can lead to extended or fruitless searches in the wrong direction. To aid the designer in more rapidly reaching a reasonable design, it is possible to use the techniques of numerical optimization to drive the model to the best design for a given specific objective and set of constraints. For example, the designer may wish to minimize the displacement of a ship given a fixed payload, and that the principle dimensions (beam, draft, length) are constrained so that the ship will fit into existing dry dock facilities. The objective function becomes the mathematical expression for displacement, which must be minimized such that it does not violate the constraints placed on beam, draft, and length. This approach has an added benefit that it aids the student in understanding what variables and constraints control the design.

The use of numerical optimization is not new in the realm of ship design, and the literature records numerous efforts to incorporate optimization techniques stretching back to the 1960s. MIT demonstrated early leadership in the efforts to apply the methods of numerical optimization to practical ship designs. Chryssostomidis [Ref. 5] investigated commercial containership preliminary design, choosing a least cost criterion as the optimization goal. His study found that payload (i.e. cargo) volume and weight were

driving the overall operational costs, and his optimization of design focused on the development of vessels designed to the discrete sizing of shipping containers.

This type of study lent itself well to the easily quantifiable economic factors considered in the design of single-purpose commercial ships. Optimizing economic factors alone for multi-mission naval vessels on the other hand, is not so easily done due to the difficulty of quantifying missions that are not of an economic nature. Holmes [Ref. 6], and Wagner [Ref. 7] attempted to apply the least cost criterion to the design of a naval auxiliary and salvage tug. They found that military mission effectiveness cannot be readily measured in economic terms unless each ship's missions are completely specified. Also a numeric value for effectiveness must be applied and remain consistent when selecting between different designs.

These early efforts to apply optimization to ship design shared a common optimization technique, the exponential random search method, developed by Mandel and Leopold [Ref. 8]. It is essentially a brute force method that randomly generates guesses within the constrained design space for the design variables, and computes the objective function and compares it to the previous value. If the new value is less than the old, the new value replaces the old and the process is repeated until convergence. Development of more sophisticated optimization algorithms in the 1980s permitted further applications to ship design.

Jenkins [Ref. 9] applied the COPES/CONMIN optimization program developed by Vanderplatts [Ref. 11] to the Reed Ship Synthesis Model [Ref. 3]. This optimization program utilized more advanced techniques such as the method of conjugate directions for locally unconstrained problems and the method of feasible directions for the locally

constrained problem [Ref. 10]. The use of this sophisticated code permitted more rapid convergence of the ship synthesis program, which fulfilled the goal of allowing more designs to be considered during the preliminary design phase.

Improving the functionality of the MIT Simplified Math Model by adding an optimization capability is the central challenge of this research effort. The objective then, of this thesis is to incorporate proven numerical optimization tools into the MIT Simplified Math Model and have the system deliver an optimal and reasonable design under various payload conditions.

### **C. COMPUTER PROGRAM OVERVIEW**

To successfully meet the objective requires the integration of several distinct computer modules, each in its own computer language, which alone cannot communicate with each other. The ship's payload data is generated using an Excel spreadsheet, the Simplified Math Model uses Mathcad to evaluate the ship design and the numerical optimizer is a Matlab program. To enable these disparate modules to pass data among themselves in a logical and meaningful manner, an integration and linking program called MathConnex is utilized. Through the use of MathConnex, all the necessary design variables can be generated, passed between modules and selected results displayed, all while remaining in a consolidated and user friendly work space. A MathConnex representative overview of the computer program is shown in Figure 2.

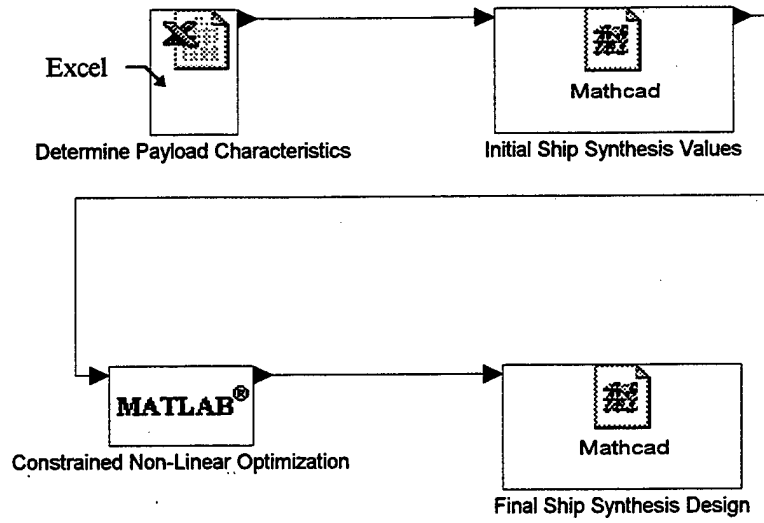


Figure 2. MathConnex Computer Program Overview.



## II. MIT SIMPLIFIED MATH MODEL

### A. ORIGIN AND INTENT

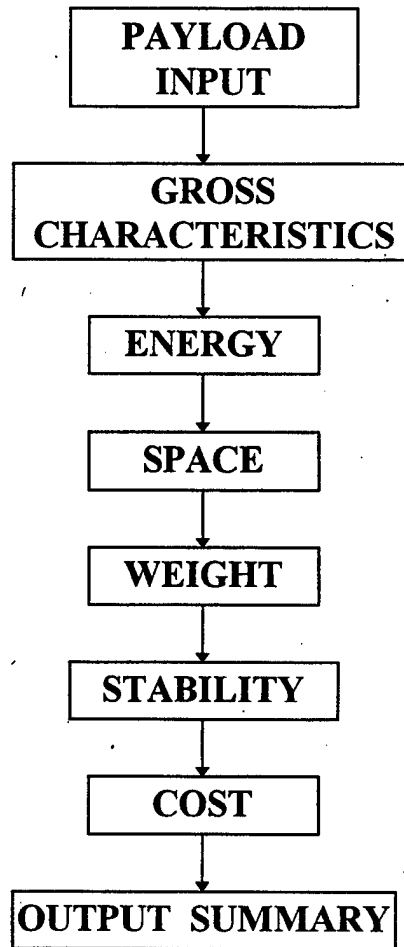
In the past, students of naval engineering were required to wade through pages of hand calculations, and stacks of tables and charts, (examples are contained in the Appendix C which are part of the Math Model documentation), to complete each iteration in the ship design spiral. The modern personal computer presents a means by which some of the drudgery can be eliminated while still providing a meaningful learning experience. The Department of Ocean Engineering at the Massachusetts Institute of Technology (MIT) has spent the past two decades developing a simplified math model for ship design. The current model traces its origins to the work completed by Reed [Ref. 3], which in turn drew heavily upon the Navy's destroyer design model, DD07, and the Center for Naval Analyses Conceptual Design of Ships Model (CODESHIP) developed in the 1960s. Since the personal computer has become ubiquitous and more powerful, the model has been converted from a main frame environment and major revisions have continued to be made to keep pace with hardware and software developments throughout the 1980s and 1990s.

The model is the central design tool utilized in the Principles of Naval Ship Design course offered at MIT. In its current form, the model is presented in a programming language called Mathcad [Ref. 13], which displays equations and relations in an easy to read object oriented format, while still performing high powered mathematical calculations. The visual interface allows students to work through problems as they would on a sheet of paper, but they can easily vary different parameters and quickly see the impact on the design, while not getting bogged down in routine calculations. This

allows more designs to be evaluated, and the student gains a greater appreciation for the ship design process.

## **B. PROGRAM DESCRIPTION**

The Mathcad display of the model is very easy to read and understand, since it looks just like a sheet of equations, with actively updated graphs, tables and a summary of output. Mathcad reads from left to right, and from the top to bottom of the page, which allows the model to be organized according to the following macro flow diagram.



Most of the user-supplied payload data is generated using an Excel spreadsheet which contains weight, center of gravity, area and electrical power requirements for

current and near future surface combatant systems. Additional inputs such as crew size, type of power plant and speed requirements are generated by the user and all this data is then manually input to the model. The gross characteristics of the ship are then generated using the form coefficient values and displacement, which are varied by the user in the output summary section. Energy requirements for propulsion and electrical service load are calculated to ensure the installed power plant is sufficient and to provide the fuel weight and volume for the given endurance. Area, volume and weight calculations for the rest of the ship follow. Finally, the static, intact stability is calculated and a simplified cost model generates the lead ship cost.

The model's summary section contains the ship design form coefficients that are set by the designer. These coefficients are limited in range due to the constraints imposed when using Taylor Standard Series hull resistance data [Ref. 12]. There are four coefficients that are manipulated by the designer; the Prismatic Coefficient  $C_P$ , the Maximum Transverse Section Coefficient  $C_M$ , the Beam-to-Draft Ratio  $C_{BT}$ , and the Displacement-to-Length Ratio  $C_{\Delta L}$ . These coefficients are assigned as global variables and fix the basic characteristics for the design being considered. The model uses these fixed values along with a designer-provided estimate of the displacement,  $W_{FL}$ , to generate values for the beam, draft, and length, which in turn generates a new displacement,  $W_T$ .

To initiate use of the model, all the user-supplied data is input in the first section and in the output summary page. For the first iteration, the displacement is calculated assuming the payload weight is ten percent of the full load displacement and is entered in the summary page as  $W_{FL}$ . The model then generates a new displacement,  $W_T$  which is compared to the previous displacement,  $W_{FL}$ . After each iteration, several values in the



model must be checked to ensure the design is valid, and these are highlighted by the double pound sign (##) in the right margin. If all the checks are satisfactory, the next iteration is completed by changing  $W_{FL}$  to the value in  $W_T$ . Once the displacement error is sufficiently small, usually around one percent, and the checks throughout the model are satisfactory, the model has converged. If the values to be checked in each iteration are not satisfactory, then the designer must change one or more of the variables to bring the design into compliance. The form coefficients are the variables that are manipulated for a fixed payload, and it is here that the student can best see the impact of these on the overall design. Once a form coefficient is altered, the design iteration process is repeated until convergence is reached. A detailed model description containing the symbol lists and micro flow diagrams is contained in Appendix C.

### **C. LIMITATIONS AND MODIFICATIONS**

The model clearly fills its intended purpose of providing an easy to use and understand design tool for the student of naval engineering. It requires the designer to pay close attention to the details of each iteration, preventing a “black box” mentality where numbers are input in one end and get spit out the other, without knowing what really goes on in between. The drawback is that all this manual manipulation does not lend itself to the inclusion of a numerical optimizer, which by definition must search through the entire design space and is iteration intensive. If each iteration required the designer to manually check for compliance within the design variable constraints, the optimization process would be agonizingly slow and its use would be deterred.

To best leverage the advantages of the model in conjunction with the optimizer and the payload generation spreadsheet, the transfer of data between them must be

improved. The MathConnex program fills the very well. MathConnex provides the channels through which the data flows between the different applications using simple variable designators and click-and-drag connections. The Mathcad model was modified so that the entire payload is automatically loaded from the Excel spreadsheet each time the model is run. Likewise, the values of the design variables generated by the optimizer are passed back into the model for the final design synthesis.

One of the checks required in the model is to ensure that the depth at the midship station,  $D_{10}$  is greater than the minimum calculated for the sheer line (see Section IV of the model). This was modified so that  $D_{10}$  will always be one foot larger than  $D_{10min}$ , thus ensuring compliance with the sheer line criterion. The remainder of the model remains in its original form.



### III. NUMERICAL OPTIMIZER

#### A. OPTIMIZATION THEORY AND TECHNIQUES

The desire to provide the best solution to a design problem has always been a primary goal of designers. As our engineered systems have increased in complexity, producing just a feasible design can require significant effort. With the advent of the high speed computer, numerical mathematical methods have evolved that permit the designer to produce not only a feasible design, but through proper application of these mathematical methods, the designer can find the best or optimal solution to the problem with little additional effort.

For proper analysis, the design problem must be posed in a manner consistent with typical numerical optimization methods. A widely accepted form for a nonlinear constrained optimization problem is presented by Vanderplatts [Ref. 10];

Minimize:	$F(\mathbf{X})$		objective function
Subject to:	$g_j(\mathbf{X}) \leq 0$	$j=1,m$	inequality constraints
	$h_k(\mathbf{X}) = 0$	$k=1,l$	equality constraints
	$X_i^l \leq X_i \leq X_i^u$	$i=1,n$	side constraints
	$\mathbf{X} = \{X_1 X_2 X_3 \dots X_n\}$		design variables

The vector  $\mathbf{X}$  contains the minimum number of design variables that describe the system to be optimized. The objective function is the relationship that expresses the interdependence of the design variables and is the function to be optimized. The constraint functions, explicit or implicit functions of the design variables, limit the design space that is searched to ensure feasibility of the solution. It should be noted that these functions and their first derivatives must be continuous in  $\mathbf{X}$ .

Nonlinear constrained optimization requires the use of sophisticated algorithms which for the purposes of this research are described in detail in the Matlab Optimization Toolbox Handbook [Ref. 14]. It is worthwhile, though, to investigate a simple constrained optimization problem to demonstrate the basic concepts in the hope of creating a better understanding of the larger problem.

As a hypothetical example, consider the two dimensional problem using the ship's beam (B) and draft (T) as the design variables. The side constraints require the beam to be greater than 30 feet but less than 70 feet, and the draft greater than 10, but less than 30 feet. An inequality constraint uses the beam to draft ratio, which is no less than 2.8 and no greater than 3.7. In the standard form the problem would be expressed like this;

Minimize:	$F(B,T)$	objective function
Subject to:	$2.8 \leq B/T \leq 3.7$	inequality constraint
	$30 \leq B \leq 70$	
	$10 \leq T \leq 30$	side constraints
	$X = \{B \ T\}$	design variables

The objective function can be any continuous function of the design variables B and T. This usually represents some characteristic of the ship, such as displacement, cost, or payload fraction, which is to be optimized. The constraints bound the region of the design space and control the search so that only feasible solutions are returned. An unconstrained search might return the mathematical minimum as a negative displacement, which is obviously infeasible. Figure 3 defines the design space, and it is easy to see that the feasible range for the objective function is contained within the outlined area and that the optimal minimal value is unique. This graphical representation clearly shows the

location of the optimum, but most design problems are much more complex and do not lend themselves to such an easy solution. As complexity of the design space increases, the only reasonable means to solve the optimization problem lies in the use of numerical methods.

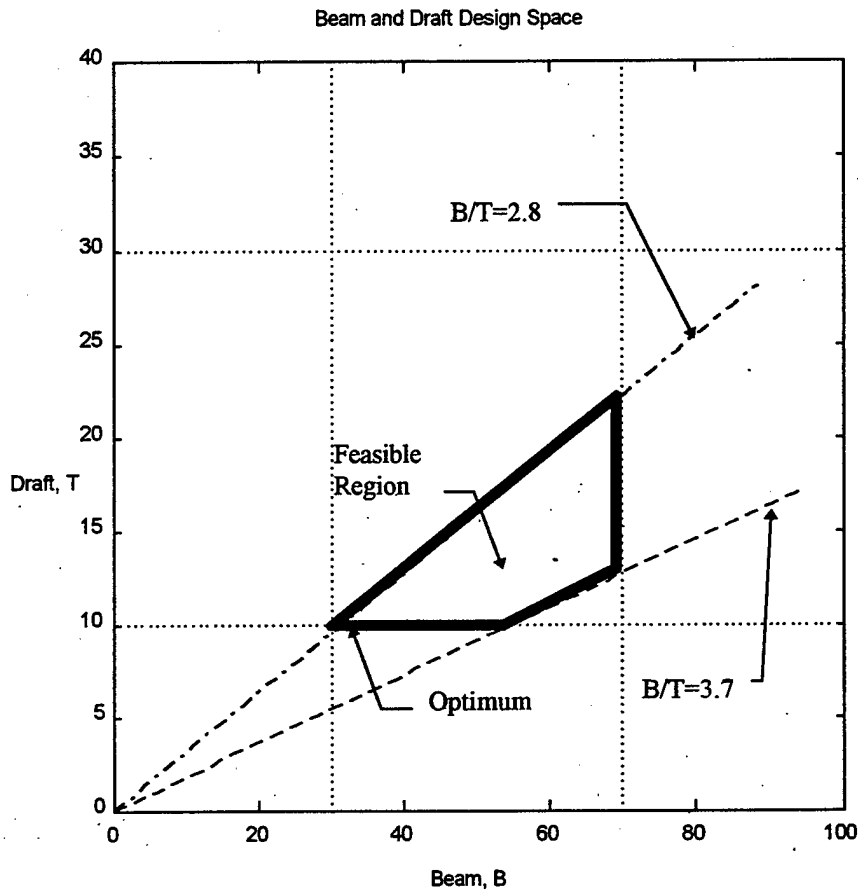


Figure 3. Two Dimensional Design Space

The optimization problem requires a sequential search of the design space to find the optimum, and this causes the process to be iterative by nature. The problem can then be reduced to two remaining tasks; find in which direction to search, and how big a step to take in that direction. The iterative form is then defined as;

$$\mathbf{X}^q = \mathbf{X}^{q-1} + \alpha \cdot \mathbf{S}^q$$

where  $q$  is the iteration number,  $S$  is a vector search direction, and  $\alpha^*$  is a scalar that defines the step size of the move in the direction  $S$ . The search direction must be chosen so that it will reduce the objective function while not violating any constraints. The step size must be appropriately chosen so that the problem converges efficiently but accurately. The core remainder of optimization theory is therefore concerned with the details of choosing the best search direction and step size. References 10 and 14 provide in-depth discussion and analysis on this and many other optimization topics. Reference 14 is particularly helpful in describing the algorithms used within the Matlab optimizer.

## **B. MATLAB OPTIMIZER DESCRIPTION**

Matlab invokes the constrained nonlinear optimizer by using the command "constr". The problem is posed in the standard form and is input into Matlab in the following format;

```
x = constr('function',x0,options,vlb,vub,[ ],p1,p2...)
```

- $x$  is the vector of returned optimized design variables.
- 'function' is the M-file containing the objective function and constraints.
- $x_0$  is the initial guess of the design variables.
- options controls output displays and termination criteria.
- vlb/vub are the upper and lower boundaries on the design variables or the side constraints.
- $p_1, p_2$  are additional variables to be passed into the 'function' M-file.

The 'function' M-file must be properly formatted to work with the optimizer;

function [f,g]=function name(input variables)

- f is the value of objective function.
- g is the value of the constraint vector.

## C. OPTIMIZER FUNCTION DESCRIPTION

### 1. Objective Function

The choice to use full load displacement as the objective function was reached by weighing several factors. Previous optimization studies provided very good rationale for using displacement as the objective function when designing surface combatants [Ref. 9]. Additionally, the calculation of the displacement requires the use of all the major modules within the math model, which have subsequently been incorporated into the Matlab optimizer as function M-files. This will ease future research by allowing use and modification of existing function M-files and permitting them to be tailored to calculate different objective functions.

### 2. Design Variables

The choice of design variables is derived from the choice of the objective function. A close study of the math model uncovered that all the derived weights that make up the displacement are a function of only five variables; beam, draft, length at waterline, prismatic coefficient and the maximum transverse section coefficient. Working carefully through the model, calculations that were independent of the design variables are calculated in the math model and passed as-is to the optimizer, while those calculations that are dependent on the design variables are calculated in separate Matlab function M-files and all are brought together as the objective function to be optimized. The design



variables change names between the different applications so Table 1 provides a cross reference of the variable names to aid in navigating though the different applications.

Design Variable	Mathcad Variable Name	Matlab Variable Name
Beam	B	x(1)
Draft	T	x(2)
Length at Waterline	LWL	x(3)
Prismatic Coefficient	$C_P$	x(4)
Maximum Transverse Section Coefficient	$C_X$	x(5)

Table 1. Design Variable Description.

### 3. Constraints

The constraints that are incorporated into the optimizer are real, rational, engineering limitations on the design variables. They define what is a feasible design. The math model provides acceptable ranges for several coefficients and ratios and displays them in parentheses next to the current value on the summary page. These ranges are necessary to keep the designs within the valid range of the Taylor Standard Series [Ref. 12] for resistance calculations. The ranges are then converted to constraints for use in the optimizer. Inequality constraints include; Beam-to-Draft ( $C_{BT}$ ), Length-to-Beam( $C_{LB}$ ), GM-to-Beam ( $C_{GMB}$ ), and Displacement-to-Length ( $C_{AL}$ ). The acceptable ranges for the design variables  $C_P$  and  $C_X$  are included as side constraints in the “vlb, vub” command in Matlab. The side constraints for the remaining design variables are generated from design experience. Table 2 contains a summary of the constraints used in the optimizer. Note that Matlab requires the ranges to be split up and formatted as upper and lower inequality constraints.

Coefficient or Ratio	Range	Mathcad	Matlab Constraint Equation
Beam-to-Draft Ratio	2.8 - 3.7	$C_{BT}$	$g(1)=(2.8*x(2)/x(1))-1$ $g(2)=(x(1)/(3.7*x(2)))-1$
Length-to-Beam Ratio	7.5 - 10	$C_{LB}$	$g(3)=(x(1)*7.5/x(3))-1$ $g(4)=(x(3)/(x(1)*10))-1$
GM-to-Beam Ratio	0.09 - 0.122	$C_{GMB}$	$g(5)=(0.09*x(1)/GM)-1$ $g(6)=(GM/(0.122*x(1)))-1$
Displacement-to-Length	45 - 65	$C_{\Delta L}$	$g(7)=(45*((x(3)/100)^3/f))-1$ $g(8)=(f/(((x(3)/100)^3)*65))-1$
Prismatic Coefficient	0.54 - 0.64	$C_P$	$v_{lb} = 0.54, v_{ub} = .064$
Max Transverse Section	0.7 - 0.85	$C_X$	$v_{lb} = 0.7, v_{ub} = 0.85$

Table 2. Constraint Summary.



## IV. INTEGRATION AND LINKING OF COMPUTATIONAL SYSTEMS

### A. MATHCONNEX PROGRAM DESCRIPTION

The MathConnex environment allows the user to integrate and link several types of application programs and data sources to form a single computational system. It uses a visual interface and it greatly simplifies the task of creating an integrated ship design synthesis program, which could otherwise be hobbled by the cumbersome data transfer requirements of the disparate computational elements.

MathConnex is capable of handling the three different applications used in the ship design program; Excel spreadsheets for the payload, Mathcad worksheets for the design synthesis, and the Matlab numerical optimizer. Each application is displayed as an icon on the worksheet with the associated data transfer "wires" connecting it to the other applications, see Figure 3. This plainly defines the program logic flow which follows the arrows on the wires. To view the contents of an application, one need only double click on the icon and the contents are displayed within the fully functional application window. When one is done with an application, clicking elsewhere on the worksheet collapses it back into an icon. This allows the inclusion of large application files and makes them easy to manipulate while keeping the overall program uncluttered on the MathConnex worksheet.

The data to be passed between applications is calculated and collected within each application for transfer to the next. It should be noted that each application is restricted to only four input and output ports, thus requiring most data to be gathered into arrays and assigned an appropriate transfer variable name, i.e. Input1, Ouput0, etc. Data transfer between the applications is handled by using click-and-drag wire connections between the

input/output ports on each icon. Once the data has been transferred, a similar variable transformation is accomplished to reassign the elements of the transfer arrays to the appropriate variable names in the next application.

At certain points during program processing it is desirable to view the intermediate results to ensure that the applications are generating useful data. The manner in which this is accomplished is the same as data transfer between applications, except the desired data is output to a view box on the worksheet.

MathConnex has enabled the integrated ship design system to fulfill the original intent of providing the student a design tool with a user friendly interface while greatly expanding the capabilities of the MIT Simplified Math Model through the addition of the numerical optimizer.

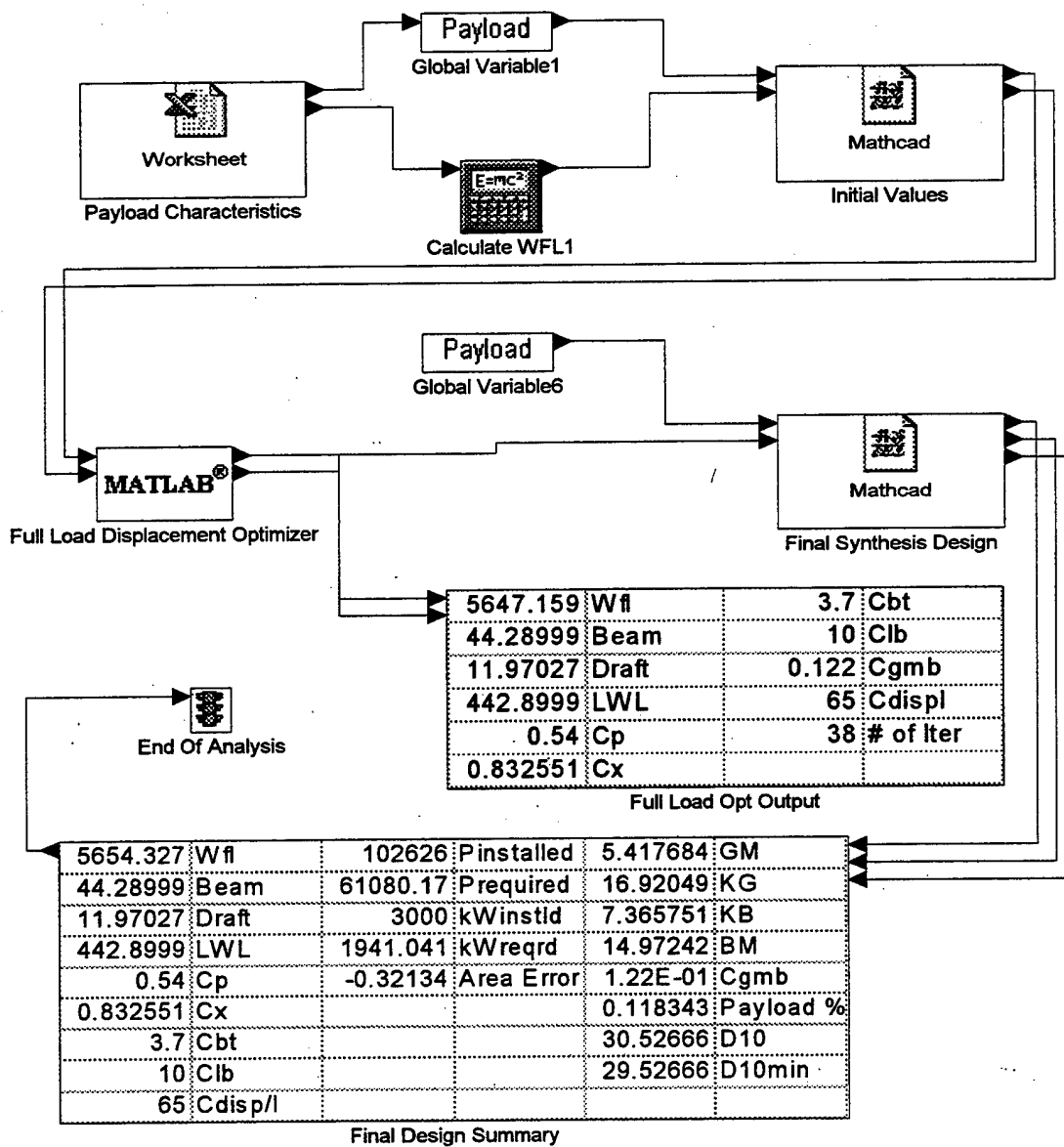


Figure 4. MathConnex Worksheet.



## V. INTEGRATED SHIP DESIGN SYSTEM

### A. PROGRAM DATA AND LOGIC FLOW

The previous section presented the general view of the operation and layout of the MathConnex worksheet. This section will present the detailed, step-by-step procedures that are executed in the Integrated Ship Design System (ISDS) worksheet as shown in Figure 4. Appendix G is a user's manual for the designer that provides the hands-on mechanics for proper set-up and use of the ISDS.

The ISDS MathConnex worksheet starts in the upper left hand corner with the Payload Characteristics contained in an Excel spreadsheet. By double-clicking on the icon, the Payload Characteristics spreadsheet is displayed on the screen. The designer then proceeds through the list of combat systems, modifying it to meet the specific payload for the desired design. The Excel spreadsheet then generates weight, area, stability and power data for the payload and transfers the array to Global Variable 1 and 6, "Payload", in the MathConnex worksheet. The total payload weight from the Excel spreadsheet is passed to the "Calculate WFL1" module to provide an initial guess of displacement.

The payload array and the displacement are then passed to the first Mathcad module, "Initial Values". This uses the math model to generate the initial values of the design variables and the non-design variable dependent weights and center of gravity information for use in the optimizer. Range, speed and manning data input by the designer are also passed to the optimizer and the "Final Synthesis Design" Mathcad module.

The Matlab module uses the transferred data to initialize the non-linear constrained optimizer to calculate the optimal minimal displacement and the associated design variable



values. This data, along with the constraint values and the number of optimizer iterations are output to the worksheet to provide intermediate evaluation of the design, and for later comparison to the final design synthesis results to check consistency. Additional detailed output from the optimizer can be viewed in a Matlab editor screen outside of the MathConnex environment. This data file, "outopt", contains important input data such as the initial guess for the design variables, and their side constraints. Output data includes updates of the objective function value for every six iterations, the magnitude of the constraint violation, and specifics regarding the algorithm search method. A message is also displayed which indicates if the optimization has successfully converged and identifies which constraints are active.

The optimal values of the design variables along with the original payload are transferred to the "Final Synthesis Design" Mathcad module. The math model calculates the final design and outputs selected design attributes to the screen. The complete design summary and all the calculations can be viewed by simply double-clicking on the "Final Synthesis Design" Mathcad module and scrolling through the pages. The stop light automatically toggles off the calculation.

## **B. DESIGN EXAMPLE**

### **1. Payload Description**

The effort required to define the payload and mission profile that the ship must fulfill is no trivial task. The guiding document, which is developed by the end user, is the Mission Needs Statement (MNS). This far-reaching document provides critical guidance, not only for the ship designer, but other acquisition programs, formulators of service and joint doctrines and cooperative efforts with our allies. The MNS that is utilized in this design example provides the requirements for expeditionary force surface combatants for the 21<sup>st</sup> century (i.e. SC-21) as modified at MIT for use in the Principles of Naval Ship Design (Course 13.412) when it was offered in the fall of 1997. The MNS lays the foundation for the DD-13A Background and Requirements Document, which provides a summary of combat systems that are arrayed into three variants to meet escalating needs.

This design example uses the DD-13A Medium Variant (Payload #2) with the following additional modifications;

- ⇒ Manning: 15 Officers, 135 Enlisted
- ⇒ Average Deck Height: 9 feet
- ⇒ Sustained Speed: 27 knots
- ⇒ Endurance: 7500 nautical miles
- ⇒ Stores Period: 45 days
- ⇒ Fin Stabilizers: None
- ⇒ CPS System: Full
- ⇒ Propulsion: Mechanical Drive LM-2500, 2 per shaft, 2 shafts, no APU's

⇒ Ship's Service Power: DDA 501-K34

The MNS, the DD-13A Background and Requirements Document, and the payload spreadsheet are contained in Appendix B.

## **2. Optimized Design Results**

Before the initial run through the optimizer, the designer must assign values to the side constraints for the first three design variables in the Matlab module on the MathConnex worksheet. An upper and lower value for the beam, waterline length and draft will come from experience, but can be guided by real world constraints such as limiting the maximum beam to allow passage through the Panama Canal, or restricting maximum draft to allow transit to different ports around the world. The setting of these side constraints limits the design space to be searched by the optimizer, and creates the possibility that a local, vice global minimum may be returned if the side constraints are too limiting. Expanding and contracting the side constraints to investigate the full design space should be attempted for every design considered. The side constraints for  $C_P$  and  $C_X$  are fixed by the acceptable ranges permitted in the math model.

The optimizer should be sufficiently robust that any initial guess of the design variables returns the same optimum value of the objective function and design variables. The ISDS uses the data generated by the "Initial Values" Mathcad module for the first guess of the design variables ("x0") in the optimizer. This first guess can be easily changed by toggling on the designer-provided guess line in the Matlab module.

The optimizer will return a solution to the MathConnex worksheet even if the constraints force an infeasible solution, though the Matlab command window output data file will print a warning that no feasible solution has been found. The designer must

remain keenly aware when reviewing solutions in MathConnex to cross check the command window to ensure the optimizer has returned a feasible solution that has converged.

Six different runs with the ISDS were completed using the previously described payload to capture all the above possibilities. Detailed results of the Mathcad math model and optimizer outputs are in Appendix E, the combined results are in Table 3.

Design Attribute	Initial Run		Expand Side Constraints		High Value Initial Guess	
	Results	vlb-vub	x0	Results	vlb-vub	x0
Displacement, Wfl (lton)	6123.424			6123.424		6123.424
Beam, B (ft)	45.50163	40 to 70	55.745	45.50163	20 to 90	55.745
Draft, T (ft)	12.29774	10 to 30	16.892	12.29774	5 to 40	16.892
Waterline Length, LWL (ft)	455.0163	400 to 700	495.3	455.0163	200 to 800	495.3
Prismatic Coefficient, Cp	0.54	.54 to .64	0.6	0.54	.54 to .64	0.6
Max Transverse Section, Cx	0.787983	.70 to .85	0.75	0.787983	.70 to .85	0.75
Beam-to-Draft, Cbt	3.7			3.7		3.7
Length-to-Beam, Clb	10			10		10
GM-to-Beam, Cgmb	0.122			0.122		0.122
Displacement-to-Length, Cdl	65			65		65
Number of Iterations	31			31		109

Design Attribute	Low Value Initial Guess		Constrained Above Optimum		Constrained Below Optimum	
	Results	vlb-vub	x0	Results	vlb-vub	x0
Displacement, Wfl (lton)	6123.424			7182.628		4729.255
Beam, B (ft)	45.50163	40 to 70	0	50	50 to 90	55.745
Draft, T (ft)	12.29774	10 to 30	0	15	15 to 40	16.892
Waterline Length, LWL (ft)	455.0163	400 to 700	0	500	500 to 800	495.3
Prismatic Coefficient, Cp	0.54	.54 to .64	0	0.54	.54 to .64	0.6
Max Transverse Section, Cx	0.787983	.70 to .85	0	0.770449	.70 to .85	0.75
Beam-to-Draft, Cbt	3.7			3.333333		3.860366
Length-to-Beam, Clb	10			10		10.10579
GM-to-Beam, Cgmb	0.122			0.122		-0.33549
Displacement-to-Length, Cdl	65			57.46102		70.42378
Number of Iterations	49			32		37

Table 3. Results from Optimizer Using Constant Payload.

Warning:  
No feasible  
solution found.

The initial run used the output values from the "Initial Value" Mathcad model to provide the first guess of the design variables. The side constraints were set assuming a sufficient range to cover the expected size of the ship. The optimization converged successfully with four constraints remaining active ( $g(2)$ ,  $g(4)$ ,  $g(6)$ ,  $g(8)$ ). To ensure that this was not a local minimum, the next run increased the range of the side constraints to cover more of the design space, while keeping the initial guess constant. The results were exactly the same, so this does appear to be a global minimum.

To check the performance capabilities of the optimizer, unrealistically high values for the initial guess were used, while the side constraints remained constant. The optimizer performed very well; it found the same optimum, but it took almost four times the number of iterations to converge on the solution. Correspondingly, the initial guess was set at zero to see if it would find the same optimum from below, which it did using only half the number of iterations required for the high initial guess.

As a final check of the capabilities of the optimizer, the side constraints were changed to exclude the location of the global minimum in the design space. When the lower side constraints were moved above the global minimum, a new local minimum was found that was equal to the new lower side constraints. This is an expected and feasible result, and one which should alert the designer to expand the design space and continue to search for the global optimum. Finally, the upper side constraint for draft was set lower than the optimal value. This resulted in no feasible solution being found, and the optimizer discontinued the search and printed the appropriate warning message. Note that the optimizer did output results, but that most of the constraints are quite obviously violated.

and this should alert the designer to double check the Matlab command window data file output for warning messages.

The previous effort has definitively located the global minimal displacement for the given payload and constraints using the Matlab optimizer. A few additional checks must be made to ensure that the final design is feasible within the constraints of the math model. The final design summary in MathConnex contains data that needs to be compared to ensure the design is feasible; these include the installed versus required propulsion power and ship service electrical power and area and weight errors. If any of these are outside the designer-defined limits, adjustments to the characteristic inputs in the payload and math model must be made and the optimization process started again.

### **3. Comparison of Optimized versus Non-Optimized Design Results**

The previous section demonstrates the ability of the ISDS to successfully link the Matlab optimizer with the MIT Math Model and produce a feasible design. The ISDS also behaved predictably when tested with unrealistic constraints and initial design variable guesses. The next logical question is does the ISDS produce a ship design of less displacement than if one used the MIT Math Model alone?

When using the MIT Math Model without the optimizer, several of the coefficient values are held fixed. The values assigned to these coefficients are chosen at the middle of the acceptable range to reduce any bias for this example;

$$C_P = .59, C_X = .775, C_{BT} = 3.25, C_{\Delta L} = 55.$$

Six iterations were required to bring the weight error below one percent and Table 4 shows the results of the optimized versus non-optimized design.

The non-optimized design is nearly feasible with the exception that  $C_{GMB}$  is outside of the acceptable range, the ship's service power requirement is slightly high and the area requirement is overstated by 20 percent. Though it is nearly feasible, it is not optimal, there is a 36 percent difference in displacement, a 26 percent reduction in payload fraction and almost an eight and one half percent increase in cost. The greatest difference between the optimized and non-optimized models is in the value of GM, a 127 percent difference. GM is defined as;

$$GM := KB + BM - KG$$

A closer look reveals that KG has a minimal difference between the two methods, the biggest changes are in KB and BM. BM is a cubic function in beam;

$$BM := \frac{LWL \cdot B^3 \cdot C_{IT}}{12 \cdot V_{FL}}$$

so small changes in beam result in large changes in BM. Beam is a function of displacement and the variable form coefficients  $C_P$ ,  $C_X$ , and  $C_{BT}$ ;

$$B \equiv \sqrt{\frac{C_{BT} \cdot V_{FL}}{C_P \cdot C_X \cdot LWL}}$$

and by fixing the values of the form coefficients in the middle of the range the, beam is forced to remain fairly large.

To demonstrate the sensitivity of B, BM, and GM, the starting displacement is held constant from before and moderate changes to the values of the form coefficients ( $\pm 10\%$ ) are made and the results tabulated in Table 5. The results show that changes to the form coefficients are almost one-for-one to changes in the beam (-15%), while draft and length remain essentially constant. The greatest difference though is in stability; GM



and BM drop dramatically, 55% and 31% respectively and these changes produce a feasible design, with the exception of area which can be adjusted for with minimal overall impact to the rest of the design.

This clearly demonstrates the influence of the coefficients of form in the math model, and how advantageous it is to have an ability to easily manipulate them during the design process. The ISDS provides this capability through its use of the optimizer which enables the entire design space to be considered simultaneously, instead of one small piece when the MIT Math Model is used alone.

Non-Optimized	Design Attribute	Non-Optimized	Percent Difference
8359.500026	Wfl (lton)	7879.850351	-5.73777946
62.24414674	Beam (ft)	53.12115024	-14.65679422
19.15204515	Draft (ft)	18.97183937	-0.940921866
532.1307151	LWL (ft)	533.66969	0.289209927
0.59	Cp	0.64	8.474576271
0.775	Cx	0.85	9.677419355
3.25	Cbt	2.8	-13.84615385
8.549088436	Cib	10.04627512	17.51282251
55 (fixed)	Cdisp/l	55 (fixed)	
102626	Pinstalled (hp)	102626	
85806.67845	Prequired (hp)	85232.82952	-0.668769539
3000	kWinstld (kW)	3000	
3023.538718	kWreqrd(kw)	2745.998472	-9.179318373
0.204919419	Area Error	0.264553987	
-0.008626356	Weight Error	0.060870401	
12.68761149	GM (ft)	5.654802214	-55.43052198
19.66127644	KG (ft)	19.66713065	0.029775361
11.95711557	KB (ft)	11.34806536	-5.093621459
20.39177236	BM (ft)	13.9738675	-31.47301148
2.04E-01	Cgmb	1.06E-01	-47.77618486
8.064060715	Payload %	7.994497279	-0.862635325
1103.21963	Cost, \$Mil	1087.107089	-1.46050164
6	# of Iterations	1	

Table 5. Comparison of Modified Coefficients of Form in MIT Math Model.  
(Note, shaded results violate model constraints.)



## VI. CONCLUSIONS AND RECOMMENDATIONS

### A. CONCLUSIONS

The goal of this research effort was to improve the functionality the MIT Simplified Math Model by adding a numerical optimization capability that would deliver optimal and reasonable ship designs. This goal has been met, and even exceeded in some respects. MathConnex enables the ISDS to use all three application programs simultaneously in a singular, user friendly environment and presents consolidated results that can be easily checked for reasonableness and accuracy. This aids the designer in the ability to investigate more designs in the same amount of time than when using the MIT Math Model alone.

The ISDS and the MIT Math Model both produce feasible and reasonable designs, though they solve the problem in a fundamentally different way. The MIT Math Model takes a displacement and calculates the gross characteristics of beam, draft and length for a given set of fixed coefficients of form. The ISDS, though using the same mathematical basis for calculation, uses the gross characteristics and variable, but constrained, coefficients of form to calculate the displacement. This makes the ISDS a more flexible design tool through its ability to consider the entire design space during the feasibility study.

It is the Matlab optimizer that permits ISDS this flexibility. Its ability to take a multivariable, constrained design problem and return an optimum displacement value using fairly simple user supplied algorithms is key to the system's success. It is the positive synergistic effects of mating the math model with the optimizer that makes this such a powerful design tool.

## **B. RECOMMENDATIONS**

This study was limited to investigating only one objective function, displacement. Efforts were focused on successfully integrating the different applications in the MathConnex environment and translating the Mathcad algorithms into Matlab function M-files in the optimizer. Fine tuning the optimizer to return consistent results with the MIT Math Model also required significant effort. The function M-files in the optimizer should lend themselves to easy manipulation for follow-on studies to develop different objective functions for optimization. A particularly relevant objective function in the current fiscal environment would be cost minimization. Another interesting area would be investigating the feasibility of power limited designs and comparing them to the current practice payload limited designs.

In conclusion, the ISDS is a design tool that possesses numerous characteristics that make it very attractive to the student and designer. As with any software program, understanding how the elements operate and interact is crucial to ensuring valid results. Gaining a thorough working knowledge of the MIT Math Model and ISDS User's Guide in Appendix G is the best way to guarantee that the optimum design is returned.

## APPENDIX A. GLOSSARY

**Coefficients of Form:** Geometric qualities of the ship that can be related as ratios or dimensionless coefficients. Useful in comparing certain performance characteristics associated with hydrodynamic phenomena.

**Prismatic Coefficient ( $C_P$ ):** The ratio of the volume of displacement ( $\nabla$  or  $V_{FL}$ ) to the volume of a prism having waterline length (LWL) and a cross section equal in area to that of the maximum section at the designated waterline.

**Maximum Transverse Section Coefficient ( $C_X$ ):** The ratio of the maximum transverse section area to the product of the beam (B) and draft (T) at this section.

**Beam-to-Draft Ratio ( $C_{BT}$ ):** Ratio of the beam (B) to the draft (T).

**Displacement-to-Length Ratio ( $C_{\Delta L}$ ):** The ratio of the full load displacement, in long tons, ( $\Delta_{FL}$  or  $W_{FL}$ ) to the waterline length (LWL) in feet.

$$C_{\Delta L} := \frac{\Delta_{FL}}{\left(\frac{LWL}{100}\right)^3}$$

**Length-to-Beam Ratio ( $C_{LB}$ ):** Ratio of the waterline length (LWL) to the beam (B).

**Sheer Line:** The line of intersection of the main or weather deck with the side of the ship.

**Objective Function:** The relationship that expresses the interdependence of the design variables and is the function to be optimized.

**Constraint Function:** Explicit or implicit functions of the design variables that limit the design space that is searched to ensure feasibility of the solution.

**Active Constraint:** An active constraint is one where the optimal solution lies on the constraint boundary.

**Function M-file:** Matlab file that allows the designer to create new mathematical functions that are added to the existing library of Matlab functions. A function M-file passes arguments in and out of its local workspace to reduce clutter in the main working environment.

**GM:** The distance between the ship's vertical center of gravity and its metacenter.

**KB:** The distance between the ship's baseline or keel and the vertical center of buoyancy.

BM: The distance between the ship's vertical center of buoyancy and its metacenter.

KB: The distance between the ship's baseline or keel and the vertical center of buoyancy.

Transverse Waterplane Inertia Coefficient ( $C_{IT}$ ): The ratio of the moment of inertia of the waterplane area to that of the circumscribing rectangle in the transverse direction.

Underwater Volume ( $V_{FL}$ ): The volume of water displaced at full load.

**APPENDIX B. MIT SIMPLIFIED MATH MODEL PAYLOAD SPREADSHEET**



**DD13A  
PAYLOAD**

PAYLOAD NAME	WT KEY	WT	VCG DATUM	VCG FT AD	AREA KEY	HULL FT2	DKHS FT2	CRUISE KW	BATTLE KW
STEEL LANDING PAD (ON HULL) - SH-60 CAPABLE	W111	10.7	36.717	0.20	NONE	0	0	0	0
128 CELL VLS ARMOR - LEVEL III HY-80	W164	56	38.31575	-10	NONE	0	0	0	0
VGAS HY-80 ARMOR LEVEL II	W164	3	33.4	18.3	NONE	0	0	0	0
SQS-53C 5M BOW SONAR DOME	W165	85.7	0	-1.5	NONE	0	0	0	0
GROUP 100	WP100	155.4				0	0	0	0
CIC W/UYO-44 & 2X LSD	W410	19.34	0	35.58	A1131	1953	448	45.03	45.03
NAVIGATION SYSTEM	W420	7.29	51	14.00	A1132	0	848.3	55.99	53.5
ADVANCED DIGITAL C4I (JTIDS/LINK 16/LINK22/TADIXS/TACINTEL)	W440	37.91	51	-46.84	A1110	1230.6	1270.4	35.76	39.67
SPS-67 SURFACE SEARCH RADAR	W451	1.81	51	-10.00	A1121	0	70	8	0
ADVANCED IFF	W455	2.32	51	-5.00	NONE	0	0	3.2	4
SPY-1D MFAF -- SINGLE TRANSMITTER	W456	58.67	33.4	15.84	A1121	0	1828	291.4	345.18
X-BAND RADAR AND FOUNDATION, 110 FT ABOVE BL	W456	4.11	0	113.00	NONE	0	0	220.16	220.16
SQS-53C 5M BOW SONAR DOME ELEX	W463	57.7	0	9.3	A1122	1942	0	39	39
LIGHTWEIGHT BROADBAND VARIABLE DEPTH SONAR (LBVDS)	W464	0.24	36.717	-6.20	A1142	200	0	3	4.2
SSQ-61 BATHYTHERMOGRAPH	W465	0.31	36.717	-10.90	A1122	85.5	0	0	0
SSQ-28 SONOBUOY PROCESSING SYSTEM	W466	5.26	51	-44.86	NONE	0	0	1.15	1.15
ADVANCED INTEGRATED ELECTRONIC WARFARE SYSTEM (AIEWS)	W472	4.4	33.4	20.60	NONE	0	0	6.4	6.4
AN/SLO-25A NIXIE	W473	0.24	36.717	-6.20	A1142	200	0	3	4.2
MK36 DLS W/6 LAUNCHERS	W474	0.96	33.4	5.39	NONE	0	0	2.4	2.4
MINEHUNTING AUV / REMOTE MINEHUNTING SYSTEM	W478	0.24	36.717	-6.20	A1142	200	0	3	4.2
AEGIS-BASED VGAS GFCS (UYO-21 + UYK-44)	W481	3.32	33.4	0.00	NONE	0	0	9.84	11.77
AN/SWG-1 HARPOON CONTROL IN CIC	W482	1.14	38.31575	10.80	NONE	0	0	0	4.9
MK99 GMFCS W/CEC W/3 SPG-62 ILLUM	W482	14.29	33.4	20.90	A1220	0	959	13.4	30.88
VLS WEAPON CONTROL SYSTEM	W482	0.7	38.31575	-7.80	A1220	56	310	13.62	19.69
ADVANCED TACTICAL WEAPON CONTROL SYSTEM (ATWCS)	W482	5.8	33.4	-7.80	NONE	0	0	13.27	13.27
ASW CONTROL SYSTEM w/SSTD (ASWCS)	W483	3.75	33.4	-12.60	A1240	320	0	8.61	8.61
COMBAT DF	W495	8.26	33.4	21.00	A1141	0	448	15.47	19.34
ELECTRONIC TEST & CHECKOUT	W499	1.1	38.31575	10.80	NONE	0	0	0	0
GROUP 400	WP400	238.96				6187.1	6181.7	791.7	877.55
FWD 64-CELL VLS MAGAZINE DEWATERING SYSTEM	W529	7	35.0585	-0.46	NONE	0	0	0	0
AFT 64-CELL VLS MAGAZINE DEWATERING SYSTEM	W529	7	35.0585	-0.46	NONE	0	0	0	0
COOLING EQUIPMENT FOR SPY-1D	W532	9	33.4	-34.00	A1121	0	960.8	0	0
COOLING ADJUSTMENT FOR X-BAND RADAR	W532	4.43	0	9.81	A1121	47.85	0	13.64	13.64
LAMPS MKIII AVIATION FUEL SYS	W542	4.86	35.0585	-11.00	A1380	30	0	2	2.9
LAMPS MKIII RAST/RAST CONTROL/HELO CONTROL	W588	31.1	35.0585	-1.80	A1312	219	33	4.4	4.4
GROUP 500	WP500	63.39				296.85	993.8	20.04	20.94
SQS-53C 5M BOW SONAR DOME HULL DAMPING	W636	6.7	0	-2.5	NONE	0	0	0	0
LAMPS MKIII AVIATION SHOP AND OFFICE	W665	1.04	35.0585	-4.50	A1360	194	75	0	0
GROUP 600	WP600	7.74				194	75	0	0
VGAS 155 MM	W710	10.2	33.4	18.30	A1214	0	533	10	34
2X HARPOON SSM QUAD CANNISTER LAUNCHERS	W721	4.1	33.4	1.17	A1220	0	0	0	1.6
FWD MK41 VLS 64-CELL	W721	107.72	35.0585	1.14	A1220	128	0	69.65	69.65
AFT MK41 VLS 64-CELL	W721	107.72	35.0585	1.14	A1220	128	0	69.65	69.65
2X MK32 SVTT ON DECK	W750	5.55	33.4	2.20	A1244	0	368	2	5
GROUP 700	W7	235.29				256	901	151.3	179.9
VGAS AMMO -- 680 RDS	WF21	11.3	33.4	13.60	NONE	0	0	0	0
HARPOON MISSILES -- 8 RDS IN CANNISTERS	WF21	3.78	33.4	5.00	NONE	0	0	0	0
AFT MK 41 LAUNCHER MISSILE LOADOUT (ESSM, SM, VLA, TLAM, ATACMS)	WF21	144	35.0585	0.34	A1220	1420	720	0	0
FWD MK 41 LAUNCHER MISSILE LOADOUT (ESSM, SM, VLA, TLAM, ATACMS)	WF21	144	35.0585	0.34	A1220	1420	720	0	0
MK46 LWT ASW TORPEDOES -- 6 RDS IN SVTT TUBES	WF21	1.36	33.4	2.50	A1240	368	0	0	0
MK36 DLS SRBOC CANNISTERS - 100 RDS	WF21	2.2	33.4	11.60	NONE	0	0	0	0
SMALL ARMS AMMO - 7.62MM + 50 CAL + PYRO	WF21	4.1	33.4	-6	NONE	0	0	0	0
LAMPS MKIII 18 X MK46 TORP & SONOBUOYS & PYRO	WF22	9.87	35.0585	4.80	A1374	0	588	0	0
LAMPS MKIII 2 X SH-60B HELOS, UAV'S, AND HANGAR (BASED)	WF23	12.73	35.0585	4.50	A1340	0	3406	5.6	5.6
LAMPS MKIII AVIATION SUPPORT AND SPARES	WF26	9.42	35.0585	5.00	A1390	357	0	0	0
BATHYTHERMOGRAPH PROBES	WF29	0.21	36.717	-6.00	NONE	0	0	0	0
GROUP WF20	WF20	342.97				3565	5434	5.6	5.6
LAMPS MKIII:AVIATION FUEL (JP-5)	WF42	63.8	0	10.4	A1380	0	0	0	0
VARIABLE MILITARY PAYLOAD (WF20+WF42)	WVP	406.77							
ARMAMENT (WP500,WP600,W7,WF20)						4311.85	7403.8		
TOTAL PAYLOAD	WP	1107.6				10499	13585.5	968.64	1083.99
<b>DATUM DEFINITIONS:</b>									
	DEPTH0	47.445		VCG P:	0.00				
	DEPTH3	43.232		VCG VP:	0.00				
	DEPTH6.5	38.316							
	DEPTH10	33.4							
	DEPTH15	35.059							
	DEPTH20	36.717							
	BL	0							
	MAST BAS	51							

**APPENDIX C. MIT SIMPLIFIED MATH MODEL MATHCAD WORKSHEET  
SUPPORTING DOCUMENTATION**

MASSACHUSETTS INSTITUTE OF TECHNOLOGY  
Department of Ocean Engineering

13.412 Handout

SIMPLIFIED MATH MODEL  
FOR THE DESIGN OF  
NAVAL FRIGATES

Adapted from the US Navy Synthesis Model by  
C. Graham  
R. Hamly  
September, 1975

Revised by  
C. Graham and J. Reed: September, 1986

D. Peer: 16 July 1990

C.B. Sweeney: August, 1991

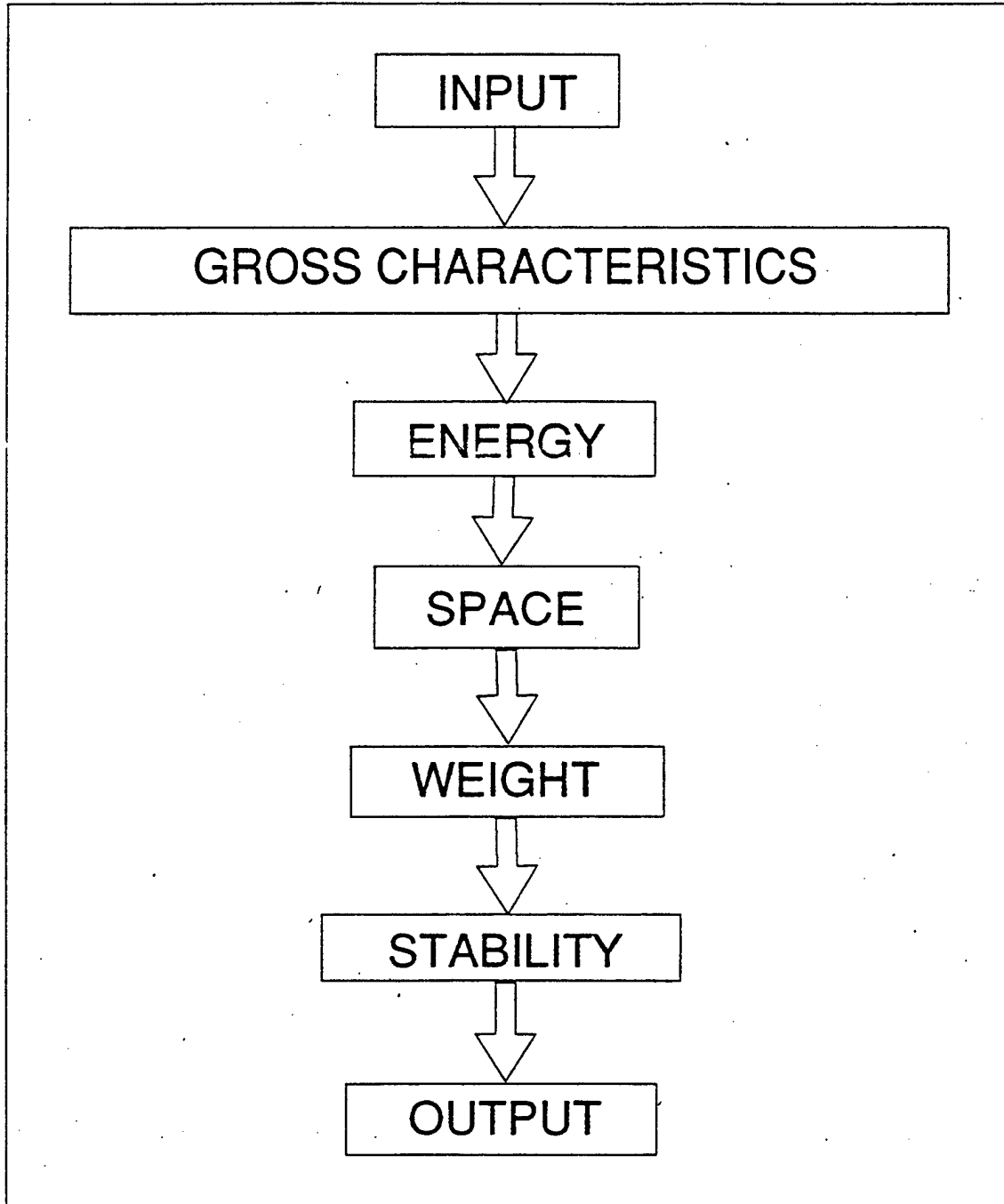
## LIST OF REVISIONS

Rev	Author	Date	Description
1	G. Hottel K. McCoy	24 Dec 88	General Revision
2	D. Peer	4 Jun 90	-Added table of Revision -Changed L/D limit to 15 -Corrected hull vol avail to account for volume of auxiliaries -Moved donar dome water from load weights to weight group 4 -Changed bearing weight to account for propeller weight
3	C.B Sweeney	1 Aug 91	Clarifications added, general revision and conversion to Word Perfect 5.1 files

### List of Enclosures

- Enclosure (1): Math Model Macro Flow Diagram
- Enclosure (2): Symbols Used in Math Model
- Enclosure (3): Micro Flow Diagrams for Frigate Math Model
- Enclosure (4): Taylor Standard Series Made Easy
- Enclosure (5): Energy Balance Module

# MATH MODEL MACRO FLOW DIAGRAM



**SYMBOLS USED IN MATH MODEL**

**L INPUT SYMBOLS**

$A_{DFA}$	Payload deck area in deckhouse - armament, ft <sup>2</sup>
$A_{DFC}$	Payload deck area in deckhouse - command/control, ft <sup>2</sup>
$A_{HFA}$	Payload deck area in hull - armament, ft <sup>2</sup>
$A_{HFC}$	Payload deck area in hull - command/control, ft <sup>2</sup>
$B_{MB}$	Width of machinery box, ft
$C_A$	Correlation coefficient = 0.0005
$E$	Endurance range at $V_e$ , nautical miles
$EP_{CHL}$	Endurance period chilled provisions, days
$EP_{DRY}$	Endurance period dry goods, days
$EP_{FRZ}$	Endurance period frozen provisions, days
$EP_{GSM}$	Endurance period general stores, days
$FR$	Propulsion fuel rate at $V_e$ , lbs/SHP-hr
$FR_G$	Generator fuel rate, lbs/kW-hr
$H_T$	Height between decks, ft
$H_{MB}$	Height of machinery box, ft
$kW_B$	Battle electrical load, kW
$kW_{24}$	Average 24 hour electrical load, kW
$L_{MB}$	Length of machinery box, ft
$N_E$	Number of enlisted accommodations
$N_O$	Number of officer accommodations
$N_S$	Number of shafts
$N_T$	Total number of accommodations
$PC$	Propulsive coefficient
$P_I$	Installed shaft horsepower
$V_e$	Endurance speed, knots
$V_s$	Maximum sustained speed, knots
$W_A$	Ammo weight, tons
$W_H$	Helo weight, tons
$W_{HF}$	Weight of helo fuel, tons
$W_{LO}$	Weight of lube oil, tons

$W_{MT}$	Weight of masts, tons
$W_P$	Payload weight
$W_{PA}$	Payload weight - armament, tons
$W_{PC}$	Payload weight - command and control, tons
$W_{SD}$	Weight of sonar dome, tons
$W_{SW}$	Weight of sea water in sonar dome, tons
$\gamma$	Specific volumes, ft <sup>3</sup> /ton
$V_{VOID}$	Tankage volume, voids, ft <sup>3</sup>

## II. GROSS CHARACTERISTICS SYMBOLS

$A_m$	Area of maximum section, ft <sup>2</sup>
B	Ship beam, ft
$C_M$	Midship section coefficient, $C_M = C_x$
$C_T$	Prismatic coefficient, $\nabla_{HV}/(A_m \cdot L)$
$C_V$	Volumetric coefficient
$C_x$	Maximum section coefficient, $A_m/(B \cdot T)$
L	Ship length, ft
T	Ship draft, ft
$V/L^3$	Speed to length ratio, knot $\sqrt[3]{ft}$
$\Delta_{FL}$	Full load displacement, tons
$\Delta_L$	Displacement to length ratio, ton/ft <sup>3</sup>
$\Delta_{HV}$	Underwater hull volume, ft <sup>3</sup>

## III. ENERGY SYMBOLS

$D_p$	Propeller diameter, ft
$P_s$	Effective horsepower = $PC \cdot SHP = V \cdot R_T / 325.6$
$EHP_{BH}$	Bare hull effective horsepower
$EHP_{BHT}$	Bare hull effective horsepower predicted by Taylor Series
$P_e$	Propulsive power at $V_e$ , shaft horsepower
$P_i$	Installed power, shaft horsepower
$P_R$	Shaft horsepower required to be installed to meet demand
$P_s$	Propulsive power at $V_s$ , shaft horsepower
$R_T$	Total ship resistance, lbs
$W_F$	Endurance fuel weight, tons

#### IV. SPACE SYMBOLS

$A_{DA}$	Deck area available in deckhouse, ft <sup>2</sup>
$A_{DB}$	Deck area in deck house for bridge and chartroom, ft <sup>2</sup>
$A_{DL}$	Deck area in deck house for living, ft <sup>2</sup>
$A_{DM}$	Deck area in deck house for maintenance and access, ft <sup>2</sup>
$A_{DPR}$	Total payload deck area required in deck house, ft <sup>2</sup>
$A_{DR}$	Total arrangement deck area required in deck house, ft <sup>2</sup>
$A_{DSF}$	Deck area in deck house for "ship" functions, ft <sup>2</sup>
$A_{HA}$	Deck area available in hull, ft <sup>2</sup>
$A_{HAB}$	Habitability allowance, ft <sup>2</sup> /man
$A_{HL}$	Deck area in hull for living, ft <sup>2</sup>
$A_{HPR}$	Total payload deck area required in hull, ft <sup>2</sup>
$A_{HR}$	Total arrangement deck area required in hull, ft <sup>2</sup>
$A_{HS}$	Stores deck area in hull, ft <sup>2</sup>
$A_{HSF}$	Deck area in hull for "ship" functions, ft <sup>2</sup>
$A_{MB}$	Cross sectional area of machinery box, ft <sup>2</sup>
$A_{PRO}$	Projected area of hull above water, ft <sup>2</sup>
CN	Cubic number = $L * B * D_{AV} * 10^{-5}$ , ft <sup>3</sup>
$C_{TMB}$	Prismatic coefficient of machinery box = $V_{MB} / (L_{MB} * A_{MB})$
$D_{AV}$	Average hull depth, ft
$D_{MB}$	Hull depth in vicinity of machinery box, ft
$D_0$	Depth at station 0, ft
$D_{10}$	Depth at station 10, ft
$D_{10R}$	Depth at station 10; roll criteria, ft
$D_{10MB}$	Depth at station 10; machinery box criteria, ft
$D_{10BC}$	Depth at station 10; bending moment criteria, ft
D20	Depth at station 20, ft
faux	Auxiliary space factor; class dependent
$f_r$	Flare factor
$F_{AV}$	Average freeboard, ft
$F_0$	Freeboard at station 0, ft
$F_{10}$	Freeboard at station 10, ft
$F_{20}$	Freeboard at station 20, ft



$H_A$	Helo deck area in the hangar, $ft^2$
$I_{VD}$	Intake volume, deckhouse, $ft^3$
$I_{VH}$	Intake volume, hull, $ft^3$
$K_1$	Allowance factor for structure
$K_2$	Allowance factor for expansion
$W_W$	Weight of potable water, tons
$V_{aux}$	Volume of auxiliary spaces, $ft^3$
$V_D$	Deck house volume, $ft^3$
$V_{DR}$	Total arrangement volume required in deck house, $ft^3$
$V_{HA}$	Hull arrangement volume available, $ft^3$
$V_{HAW}$	Hull volume above water, $ft^3$
$V_{HR}$	Total arrangement volume required in hull, $ft^3$
$V_{HT}$	Total hull volume available, $ft^3$
$V_{MB}$	Volume of machinery box, $ft^3$
$V_T$	Total ship volume available, $ft^3$
$V_{TA}$	Total arrangement volume available, $ft^3$
$V_{TK}$	Tankage volume, $ft^3$
$V_{TR}$	Total arrangement volume required, $ft^3$

**V. WEIGHT SYMBOLS (All weights in long tons, 2240 lbs)**

$f_m$	Deck house material factor
$kW_I$	Installed electrical capacity, kW
$W_B$	Shaft bearing weight
$W_{BA}$	Weight of basic auxiliary systems
$W_{BH}$	Weight of basic hull
$W_{BM}$	Weight of basic machinery
$W_C$	Weight of crew
$W_{CC}$	Weight of cable for command and control equipment
$W_{CG}$	Weight of gyro and interior communications equipment
$W_{CO}$	Weight of other command and control equipment
$W_{DH}$	Weight of deck house
$W_{FD}$	Weight of foundations

$W_s$	Weight margin
$W_{GSM}$	Weight of general stores
$W_L$	Light ship weight
$W_{LD}$	Weight of load items
$W_{margin}$	Weight margin factor
$W_{OFH}$	Weight of hull related outfit and furnishings
$W_{OPP}$	Weight of personnel related outfit and furnishings
$W_{FR}$	Propeller weight
$W_{FRV}$	Weight of provisions
$W_s$	Shafting weight per unit length, tons/ft
$W_s$	Shafting weight
$W_{SS}$	Weight of auxiliary steam system
$W_{ST}$	Weight of total shaft system
$W_{SW}$	Weight of seawater in sonar dome
$W_T$	Total weight
$W_w$	Weight of potable water
$W_1$	Hull structure weight
$W_2$	Propulsion machinery weight
$W_3$	Electrical plant weight
$W_4$	Communications and control weight
$W_5$	Auxiliary systems weight
$W_6$	Outfit and furnishings weight
$W_7$	Armament weight

#### VI. STABILITY SYMBOLS

$A_w$	Area of waterplane, ft <sup>2</sup>
BM	Metacentric radius, ft
$C_{IT}$	Transverse (area) inertia coefficient = $I_w/(L*B^3)$
$C_w$	Waterplane area coefficient = $A_w/(B*L)$
GM	Ship transverse metacentric height, ft
$I_w$	Transverse area moment of inertia of the waterplane = $BM*\nabla_{HV}$
KB	Ship vertical center of buoyancy, ft

$KG$	Ship vertical center of gravity, ft
$KG_L$	KG of Light Ship with KG margin
$KG_{LD}$	KG of loads
$KG_{Lsm}$	KG of Light Ship without KG margin
$KG_{margin}$	Margin on light ship KG
$M_{LD}$	Moment of loads relative to base line, ft-tons (use subscripts corresponding to individual load item)
$M_T$	Total moment of all weight groups (includes margins), ft-tons
$M_{wg}$	Moment of weight group relative to baseline, ft-tons (use subscripts corresponding to individual weight group)
$VCG_{wg}$	Vertical Center of gravity of weight group above baseline, ft (use subscripts corresponding to individual weight group)

# MICRO FLOW DIAGRAMS FOR FRIGATE MATH MODEL

## I. INPUT

**Input: Owner - Performance Requirements, Constraints, and Design Philosophy expressed in Top Level Requirements**

**Designer - Component/Subsystem Selection, Design Standards and Practices, Specific Design Parameters and Design Philosophy**

TLR (Owner)  
Design Philosophy

I1. "Design to" Requirements (Goals, Thresholds)  
"Design to" Constraints"



I2. Component/Subsystems  
Design Philosophy



Adjustment to Model



I3. Design Practices and Standards  
Design Philosophy



Adjustment to Model



I4. Specific Design Parameters  
Design Philosophy



Adjustment to Model



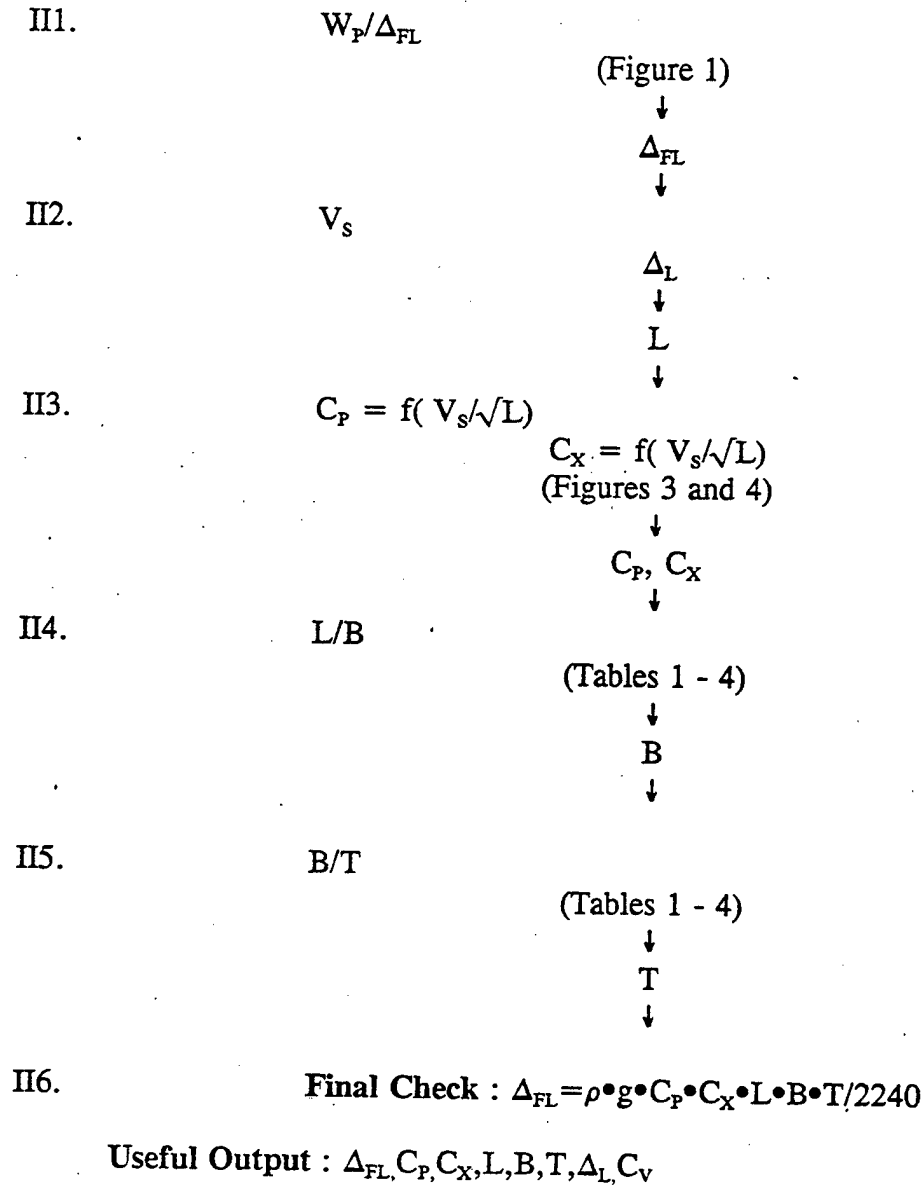
Useful Output : Input file for specific ships

Micro Flow Diagrams  
(Continued)

**II. GROSS CHARACTERISTICS**

**Input:**  $W_P, V_S$

$$W_P = W_{PA} + W_{PC} + W_A + W_H + W_{HF}$$



Micro Flow Diagrams  
(Continued)

II. GROSS CHARACTERISTICS RELATIONSHIPS

II1.  $W_p = \text{Given}$

$$\Delta_{FL} = \text{Pick}$$

$$V_s = \text{Given}$$

II2.  $\Delta_L = \Delta_{FL} / (0.01 \cdot L)^3$

II3.  $L = \text{Pick}$

$$C_p = \text{Pick}$$

$$C_x = \text{Pick}$$

II4.  $B = \text{Pick}$

II5.  $T = \text{Pick}$

II6.  $g = \text{Given}$

$$\rho = \text{Given}$$

$$V_{HV} = C_p \cdot C_x \cdot L \cdot B \cdot T$$

$$C_v = V_{HV} / L^3$$

$$\text{Final Check: } \Delta_{FL} = \rho \cdot g \cdot C_p \cdot C_x \cdot L \cdot B \cdot T / 2240$$

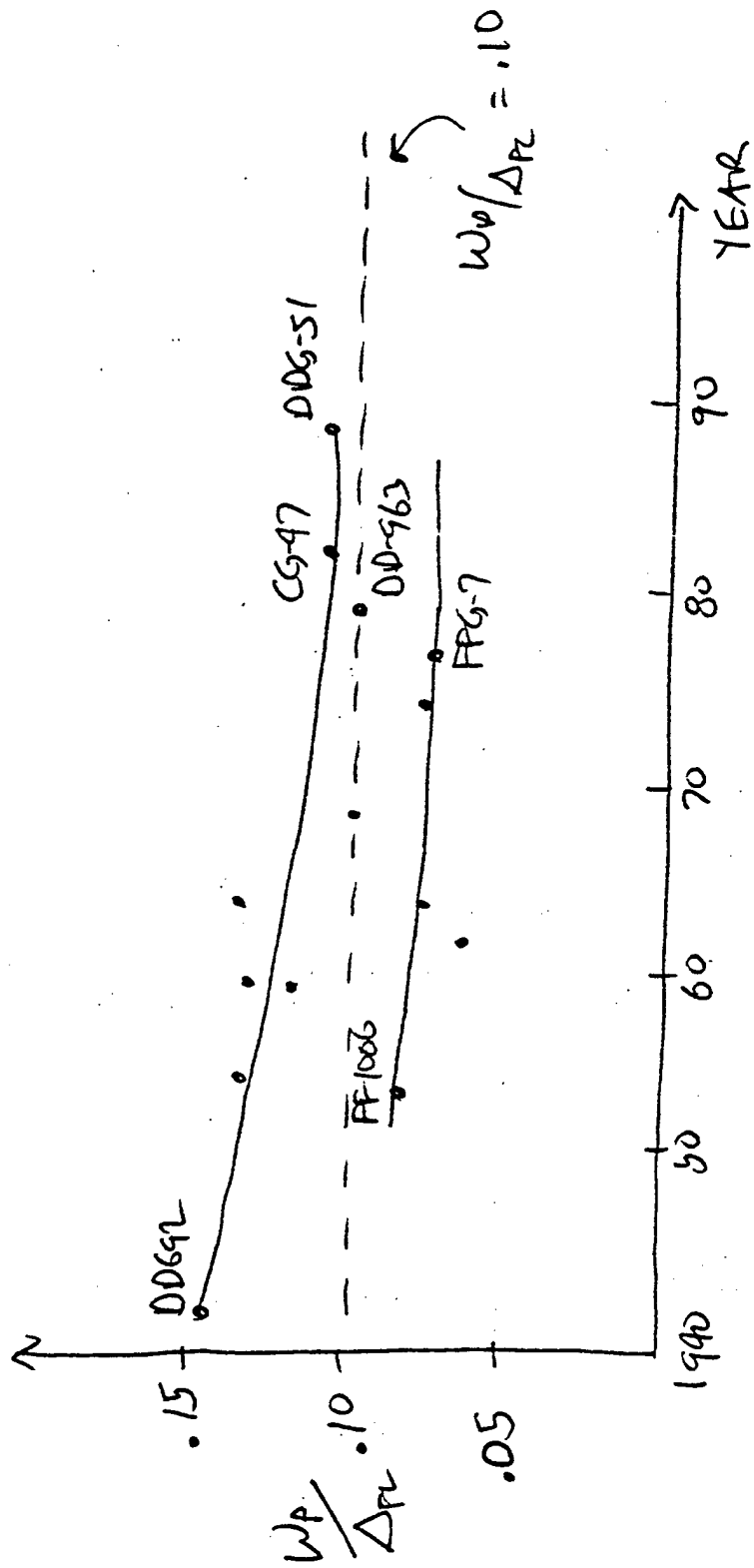
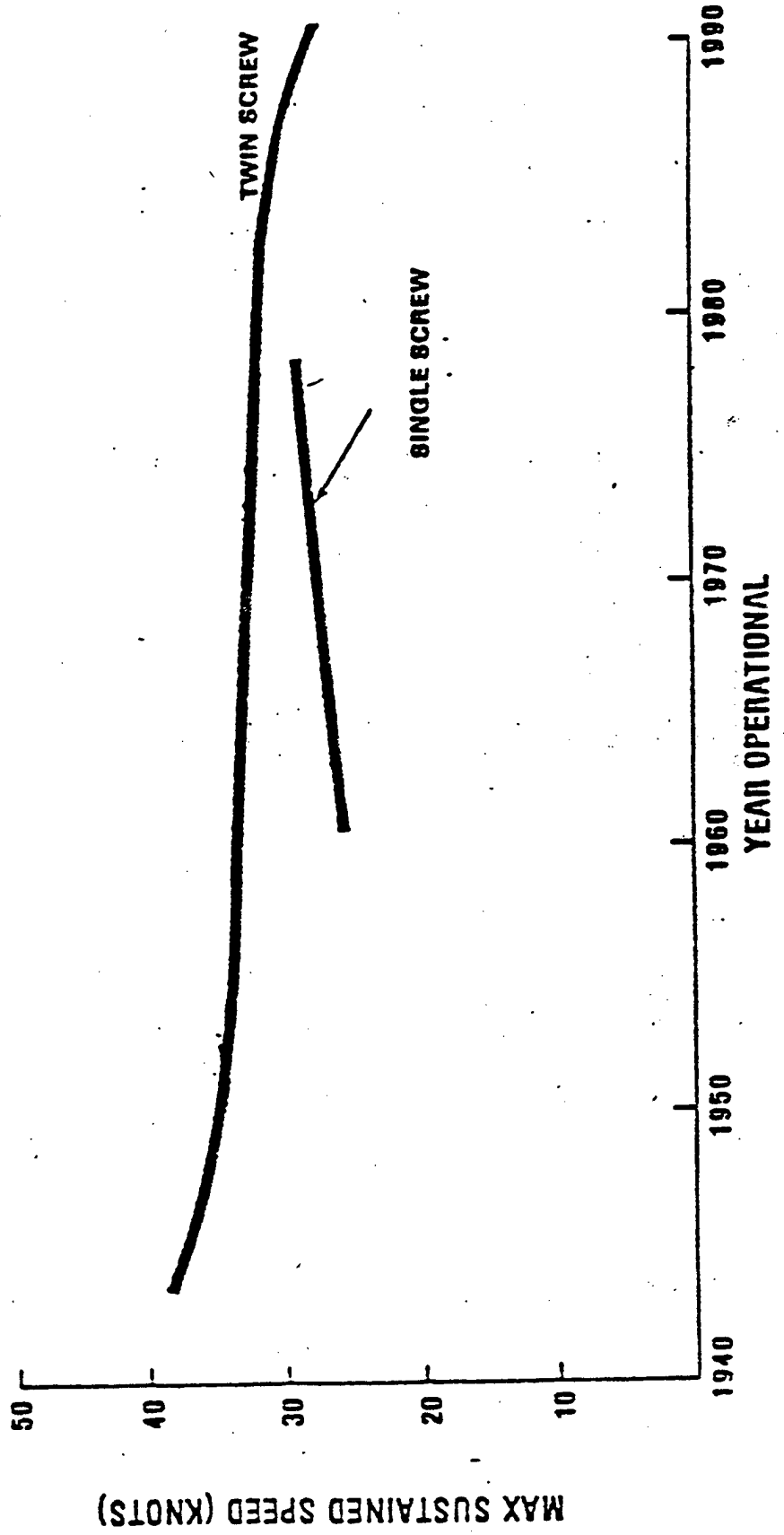


Fig. 1. PAYLOAD WEIGHT FRACTION

Fig 2

# SPEED TREND



MAX SUSTAINED SPEED (KNOTS)

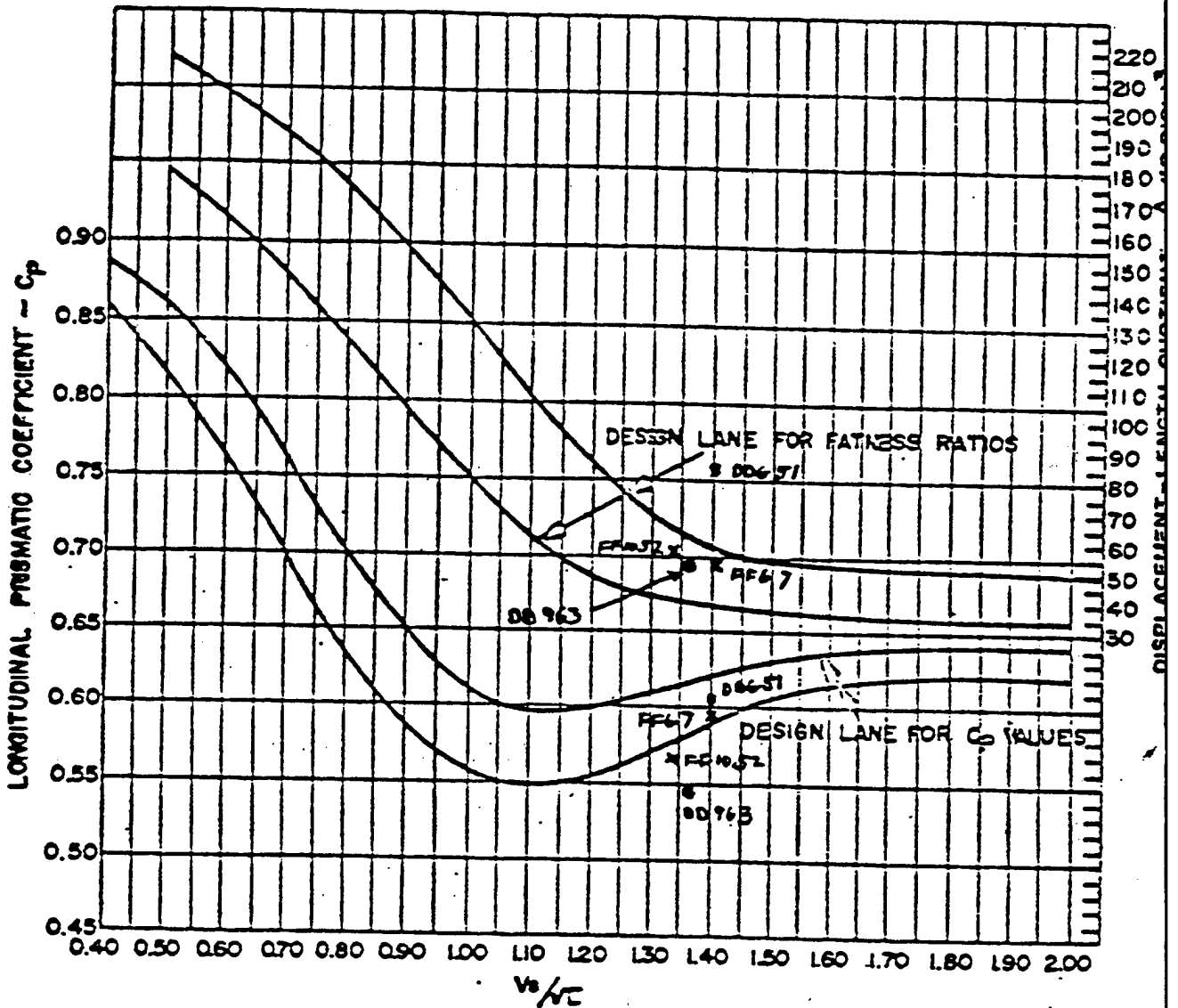
YEAR OPERATIONAL



Fig 3

DESIGN LANES FOR  $\Delta$  +  $C_p$

HYDRODYNAMICS IN SHIP DESIGN



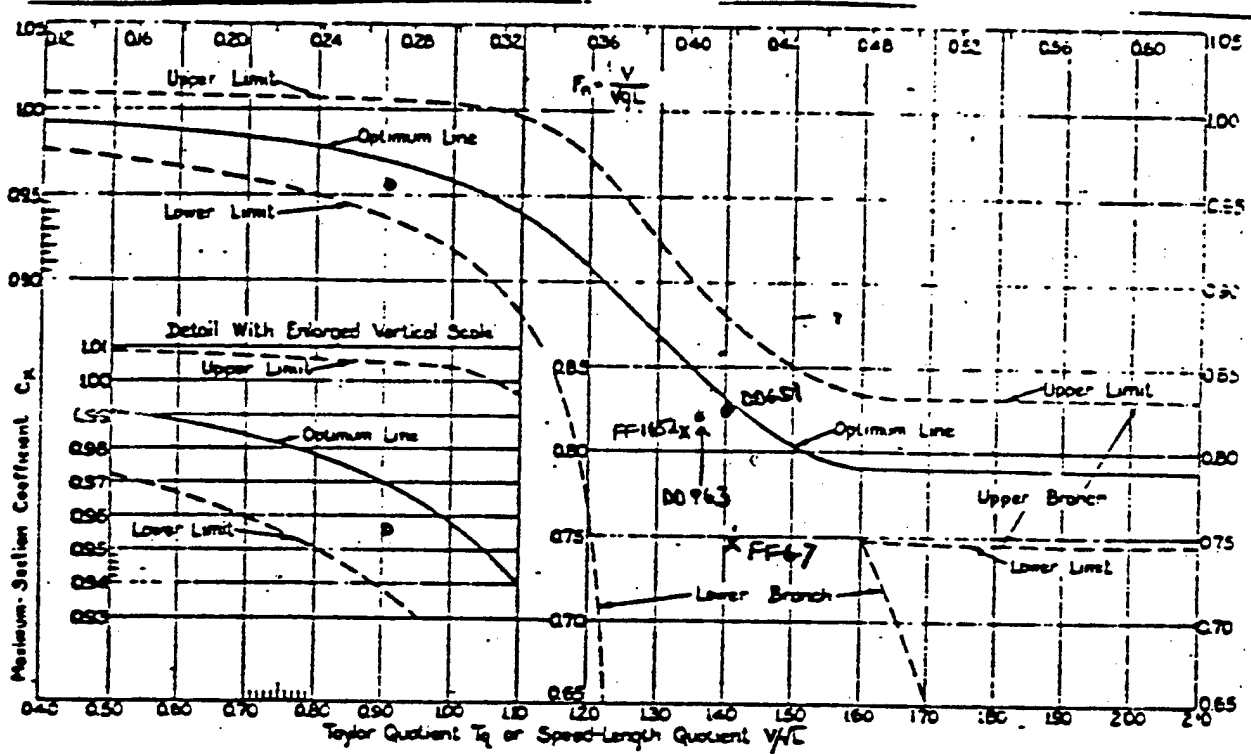
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Ref. Saunders, Hydrodynamics  
in Ship Design. SWAMEE 1957  
Vol II P 416

Fig 4

DESIGN LANES FOR MAXIMUM SECTION COEFFICIENT,  $C_x$



Ref. Saunders  
Vol II p 469

Table 1

VARIATION OF PARAMETERS FOR POST WWII U.S. NAVAL FRIGATE/  
DESTROYER/CRUISER DESIGNS

<u>PARAMETER</u>	<u>RANGE</u>	FFG7	DD963*	DDG51
(S)	6.975-8.95	7.36	7.86	7.19
L/B	7.92-9.92	9.1	9.6	7.5
B/T	2.87-3.21	3.1	3.1	3.1
$C_P$	.56-.636	.593	.547	.604
$C_x$	.747-.835	.747	.823	.825
$\frac{A}{L}$	43.4-65.6	49	46	81
L/D	10.75-17.81	13.6	12.6	11.1
GM/B	.0747-.1227			
$V/\sqrt{L}$	1.24-1.978	1.41	1.37	1.40
$C_{WP}$	.656-.795	.727	.727	.780
$W_P/\Delta$	.0899-.1329	.08	.082	.11
$\Delta/VOL \#/Pt^3$	15.1-28.84			

\*Data represents hull forms  
with a "no-dome" bow.

TABLE 2

## Selected Characteristics\* of Existing Frigates and Frigate Designs

Country	Ships	LWL (ft)	L/B	B/T	C <sub>p</sub>	C <sub>x</sub>	$\Delta/(0.01L)^3$
USA	DE 1006	308	8.4	3.0	0.60	0.80	65
	DE 1037	350	8.7	3.0	-	-	62
	DE 1040	390	8.9	3.0	0.61	0.80	58
	DE 1052	415	8.9	3.1	0.57	0.81	53
	FFG-7	408	9.1	3.1	0.59	0.75	49
	USCG Hamilton	350	8.3	3.1	0.58	0.83	63
U.K.	Leander	360	8.8	3.0	-	-	63
	Type 21	360	8.6	3.3	-	-	59
	Type 22	410	8.5	3.5	0.59	0.82	55
	Type 42	392	8.5	3.7	0.62	0.90	59
Canada	DDH 261	356	8.5	3.0	-	-	63
	DDH 280	398	7.9	3.2	-	-	73
France	C-67A	468	9.4	3.4	0.63	0.81	48
	C-70	423	9.3	3.4	0.63	0.81	49
	C-74						
Netherlands	G.M. Frigate	430	8.9	3.2	-	-	53
	Std. Frigate	400	8.6	3.3	0.59	0.78	55
Germany	Type 101	421	9.6	2.8	-	-	62
	Type 120	344	9.6	2.6	-	-	66
	Type 122	400	8.6	3.3	0.59	0.78	55
Norway	Oslo	308	8.5	3.2	-	-	60
Italy	Audace	432	9.1	3.1	-	-	55
	Lupo	348	9.0	3.2	0.63	0.79	49
	Maestrale	373			0.62	0.78	57
USSR	Krivak	384	8.8	2.8	0.62	0.80	62
	Kashin	440	9.0	3.2	0.62	0.86	58

\*In some cases, values given are approximate; the data sources are, at times, confusing.

TABLE 3

Comparison of FFG 7 Secondary Hull Form Characteristics  
and  
Those Recommended for Small (3000-ton) Frigates

<u>Parameter</u>	<u>FFG 7</u>	<u>Recommended for Minimum Resistance</u>
Forward Section Shape	"UV"	Mild "V", or "UV"
A/A <sub>x</sub> Curve Entrance	Very slightly "hollow"	Slightly "hollow"
$i_E$ Taylor entrance parameter	-	$\approx 0.90$
Section Coefficient at Station 1.0	$\approx 0.64$	$\approx 0.60$
A <sub>20</sub> /A <sub>x</sub>	0.028	0.01 to 0.03
$i_E$ Entrance half-angle	8.0°	6.7° to 8.7°
CWPP Forebody waterplane coeff.	0.610	< 0.62
$\overline{FF}/LWL$	0.556	$\approx 0.57$
B <sub>20</sub> /B <sub>x</sub>	0.513	0.50 to 0.70
CVPF Forebody <sup>vertical</sup> prismatic coeff.	0.720	$\approx 0.70$
CVPA <sup>vertical</sup> prismatic coeff.	0.650	$\approx 0.58$
Aft buttock shape	Almost straight	Little or no "hook"
CPA/CWPA	0.706	$\approx 0.72$

Taken from:

FFG 7 Review of Hydrodynamic  
Design and Performance

NAUSEA Report - 3213-81-20  
Sept 1981

TABLE 4 Primary Characteristics of Selected Destroyer-Type Hull Forms  
(Ordered by Lpp)

Hull Form	Lpp (ft)	Bx (ft)	Tx (ft)	Cp*	Cx	Displ <sup>III</sup> *	Lpp/ D <sub>X</sub>	B <sub>X</sub> /T <sub>X</sub>	Lpp/ T <sub>X</sub>	Lpp/ D <sub>10</sub>	Displ/* (L/100) <sup>3</sup>	C <sub>TP</sub>
NCM (CD)	202.0	38.50	9.50	0.597	0.817	1,030	5.2	4.1	21.3	8.4	125	0.768
NCM (Q.1)	240.0	43.88	11.83	0.575	0.842	1,724	5.5	3.7	20.3	8.3	125	0.756
WHSC	255.0	37.90	13.00	0.500	0.766	1,615	6.7	2.9	19.6	10.9	97	0.768
DE 356	300.0	35.5	10.00	0.620	0.811	1,530	8.5	3.6	30.0	15.0	57	-
DE 1006	308.0	36.50	12.10	0.604	0.803	1,890	8.4	3.0	25.5	15.0	65	0.754
DE 1037	350.0	40.32	13.50	0.580	0.801	2,530	8.7	3.0	25.9	11.8	59	0.721
DE, SCB 199	350.0	39.60	13.00	0.573	0.778	2,297	8.8	3.0	26.9	11.7	54	0.710
DD 692	369.0	40.59	13.00	0.616	0.827	2,833	9.1	3.1	28.4	16.0	56	0.745
Inestrals	374.0	41.01	12.80	0.620	0.780	2,712	9.1	3.2	29.2	13.7	52	0.764
FY 61 DE	375.0	40.40	13.80	0.584	0.781	2,731	9.3	2.9	27.2	12.5	52	0.710
DD 710	383.0	40.59	13.00	0.634	0.815	2,982	9.4	3.1	29.5	16.7	53	0.754
Krivak	383.6	43.31	14.76	0.610	0.820	3,506	8.9	2.9	26.0	11.7	62	0.774
FF 1040'	390.0	43.70	14.50	0.580	0.794	3,245	8.9	3.0	26.9	13.0	55	0.728
Type 62	392.1	45.93	12.14	0.620	0.900	3,406	8.5	3.8	32.3	13.5	58	0.760
Work Study DE	395.0	44.50	14.20	0.562	0.823	3,290	8.9	3.1	27.8	-	54	0.723
SM Frigate	399.6	47.25	13.65	0.612	0.744	3,353	8.5	3.5	29.3	13.4	53	0.720

\* For ships/designs which had a bow-mounted sonar dome, this data represents such hull forms with a "no-dome" bow. |

TABLE 4 (Cont. Inued)

Hull Form	$L_{PP}$ (ft)	$B_X$ (ft)	$T_X$ (ft)	$C_P^*$	$C_X$	Displ <sup>III</sup> *	$L_{PP}/B_X$	$B_X/T_X$	$L_{PP}/T_X$	$L_{PP}/D_{10}$	Displ/ <sup>II</sup> (1./100) <sup>3</sup>	$C_{MP}$
DD 931	407.0	44.38	14.50	0.630	0.828	3,901	9.2	3.1	28.1	16.1	50	0.768
FFG 7	408.0	45.00	14.30	0.593	0.747	3,336	9.1	3.1	28.5	13.6	49	0.727
PFC	410.1	48.23	14.21	0.610	0.800	3,918	8.5	3.4	28.9	13.3	57	0.770
FF 1052	415.0	46.50	15.00	0.569	0.812	3,828	8.9	3.1	27.7	14.4	54	0.734
DDG 2	420.0	47.00	15.00	0.634	0.835	4,477	8.9	3.3	28.0	16.8	60	0.760
C70	423.3	45.93	13.45	0.620	0.793	3,673	9.2	3.4	31.5	14.1	48	0.753
DDGX	433.1	54.06	17.05	0.601	0.847	5,807	8.0	3.2	25.4	13.1	72	0.784
DDG 51 (6.1)	465.9	62.00	20.00	0.604	0.825	8,229	7.5	3.1	23.3	11.1	81	0.780
DL 2	476.0	48.00	14.04	0.611	0.801	4,480	9.9	3.4	33.9	16.9	42	0.746
DIG 9	490.0	50.13	15.75	0.562	0.768	4,775	9.7	3.2	31.1	16.2	41	0.712
F7PE	490.0	49.90	15.80	0.560	0.771	4,770	9.8	3.2	31.0	16.3	41	0.710
CG 16	510.0	53.00	16.50	0.585	0.810	6,041	9.6	3.2	30.9	13.2	46	0.720
DL 1	520.0	53.77	17.62	0.566	0.808	6,435	9.7	3.1	29.5	15.1	46	0.703
CG 26	524.6	54.40	18.80	0.604	0.818	7,561	9.6	2.9	27.9	13.6	53	0.740
DDG FY 67	525.0	61.00	18.25	0.560	0.831	7,700	8.6	3.3	28.8	11.5	54	0.710
DD 963	529.0	55.00	18.00	0.547	0.823	6,731	9.6	3.1	29.4	12.6	46	0.727
DIG(N) 25	540.0	56.86	18.50	0.584	0.794	7,527	9.5	3.1	29.2	13.3	48	0.744

\* For ships/designs which had a bow-mounted sonar dome, this data represents such hull forms with a "no-dome" bow.

W08  
F1

TABLE 4 (Concluded)

Hull Form	$I_{PP}$ (ft)	$B_X$ (ft)	$T_X$ (ft)	$C_P^*$	$C_X$	Displ <sub>DH</sub> <sup>†</sup>	$I_{PP}/B_X$	$B_X/T_X$	$I_{PP}/T_X$	$L_{PP}/D_{10}$	Displ <sup>††</sup> (L/100) <sup>3</sup>	$C_{VP}$
CGN 35	540.0	57.03	20.30	0.614	0.818	8,999	9.5	2.8	26.6	13.3	57	0.760
CGN 38	560.0	61.85	20.50	0.623	0.808	10,210	9.1	3.0	27.3	13.2	58	0.767
CGN 42	560.0	62.50	22.00	0.629	0.845	11,695	9.0	2.8	25.5	13.2	67	0.776
CGN 36	570.0	60.00	20.50	0.603	0.810	9,783	9.5	2.9	27.8	13.9	53	0.760
DLCN (TYPHON)	600.0	62.80	20.50	0.568	0.845	10,595	9.6	3.1	29.3	-	49	0.730
CSCN (Conv.)	666.0	76.70	22.15	0.582	0.897	16,885	8.7	3.5	30.1	15.7	57	0.736
CSCN (VSTOL)**	666.0	80.77	26.60	0.578	0.901	21,308	8.2	3.0	25.0	-	72	0.792
CGN 9	691.8	71.00	21.50	0.578	0.807	14,080	9.7	3.3	32.2	15.4	43	0.710
CA 139	700.0	74.80	24.00	0.616	0.868	19,200	9.4	3.1	29.2	17.6	56	0.745

Note

The hull form characteristics listed in this table are, in some cases, based on the hull form up to the DWL and, in other cases, based on the hull form up to a particular waterline near to, but other than, the DWL (e.g., in some cases the characteristics apply to the hull form up to a waterline at which the hull was model tested) or up to a waterline representing the ship draft in the full-load condition.

\* For ships/designs which had a bow-mounted sonar dome, this data represents such hull forms with a "no-dome" bow.

\*\* Hull form was based on that of the Large-Waterplane version of the CSCN design.



Table 5

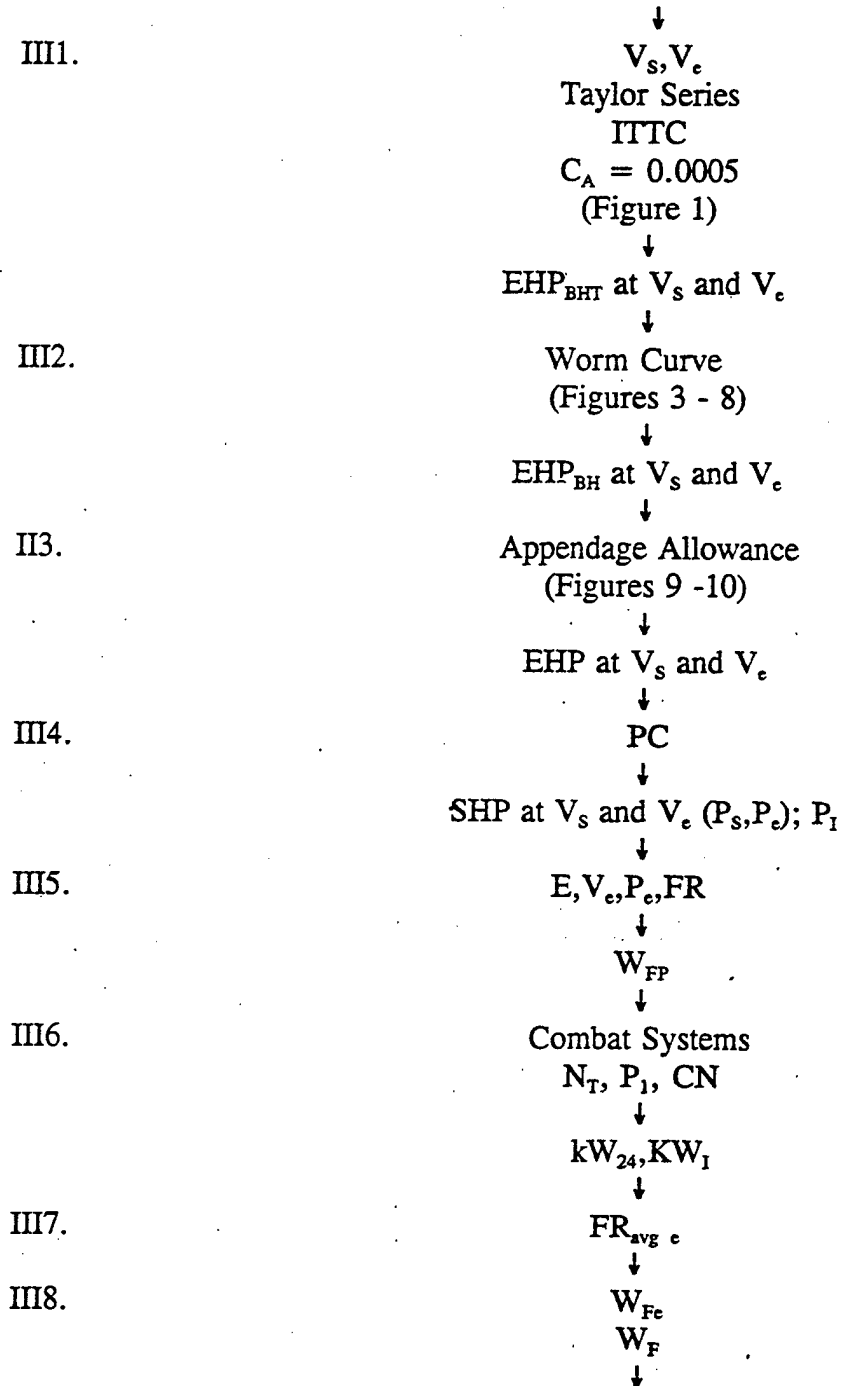
NAVIGATIONAL RESTRICTIONS

A. <u>Ports</u>	<u>Draft (ft)</u>	<u>Length (ft)</u>	<u>Bea</u>
Baltimore, Maryland	23-40	600-810	
Baton Rouge, Louisiana	40	no limit	
Beaumont, Texas	34	600-760	
Boston, Massachusetts	30-38	575-1200	
Brownsville, Texas	34.5	no limit	
Charleston, S. Carolina	30-35	600-705	
Chicago, Illinois	27		
Eureka, California	10-31	200-500	
Freeport, Texas	36	670	
Gulfport, Mississippi	30-32	700	
Hampton-Roads, Virginia	15-38		
Houston, Texas	30-40	600	
Jacksonville, Florida	31-36	600	
Long Beach, California	54	1200	
Los Angeles, California	35-51	226-1895	
New York, New York	20-40	170-1280	
Providence, Rhode Island	34	600	
San Francisco, California	25	300	
B. <u>Canals</u>			
Panama	38.5	835	104
C. <u>Drydocks</u>			
Long Beach Naval Shipyard		1092	144
Norfolk Naval Shipyard		1092	143
National Steel & Shipbuilding Corp., San Diego, CA		965	170
Newport News Shipbuilding and Drydock Corp., Newport News, Virginia		1600	230

Micro Flow Diagrams  
(Continued)

III. ENERGY (Use enclosures 4 and 5 to calculate energy needs)

Input:  $\Delta_{FL}, L, B, T, C_P, C_X, \Delta_L, (C_V), V_S, V_e, E, FR, FR_G, kW_{24}, PC, W_{LO}$



Useful Output :  $P_S, P_e, P_I, kW_{24avg}, kW_I, W_F$

Fig 1 Ca vs  $V_s$   
for FFG-7

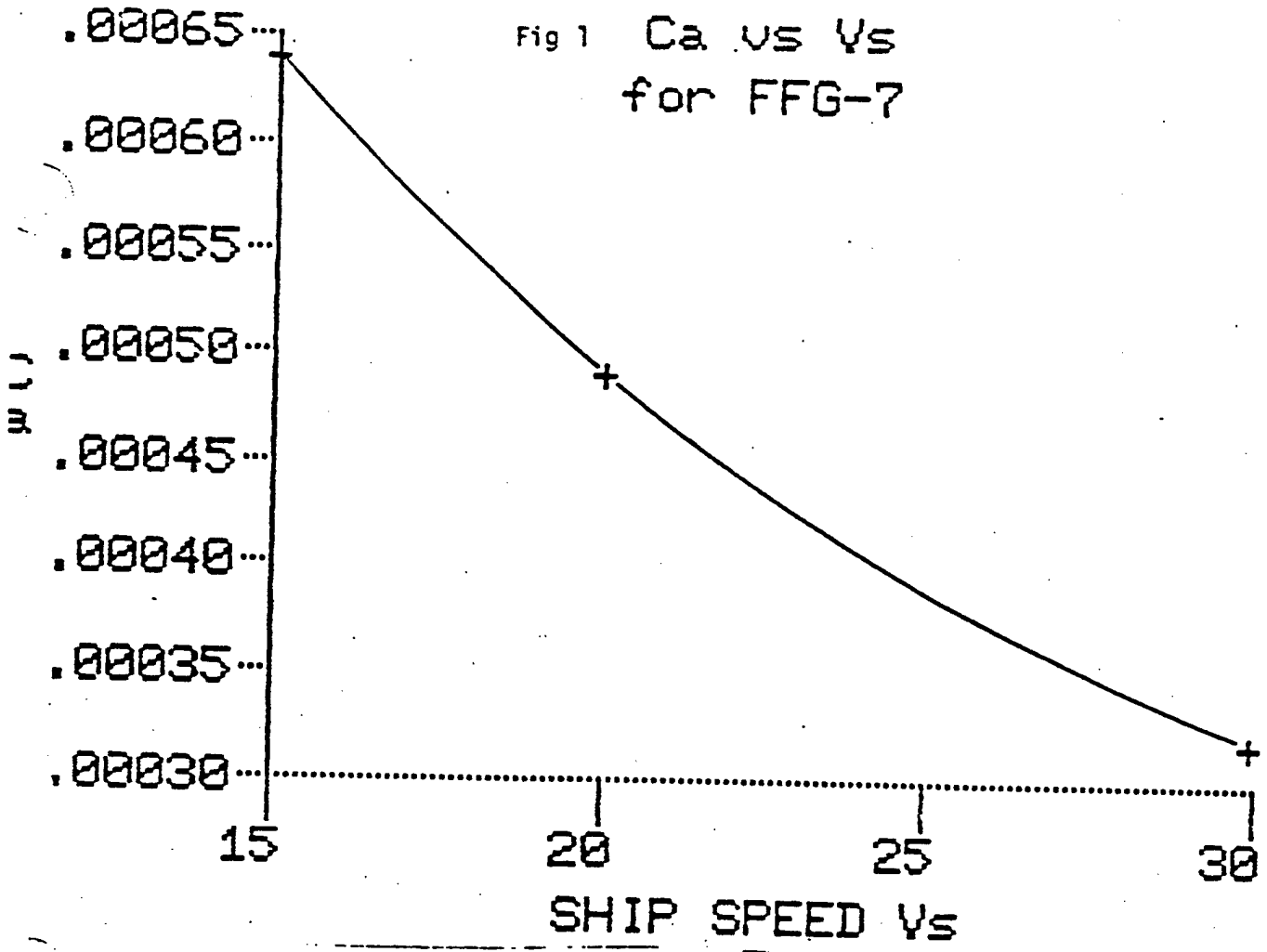
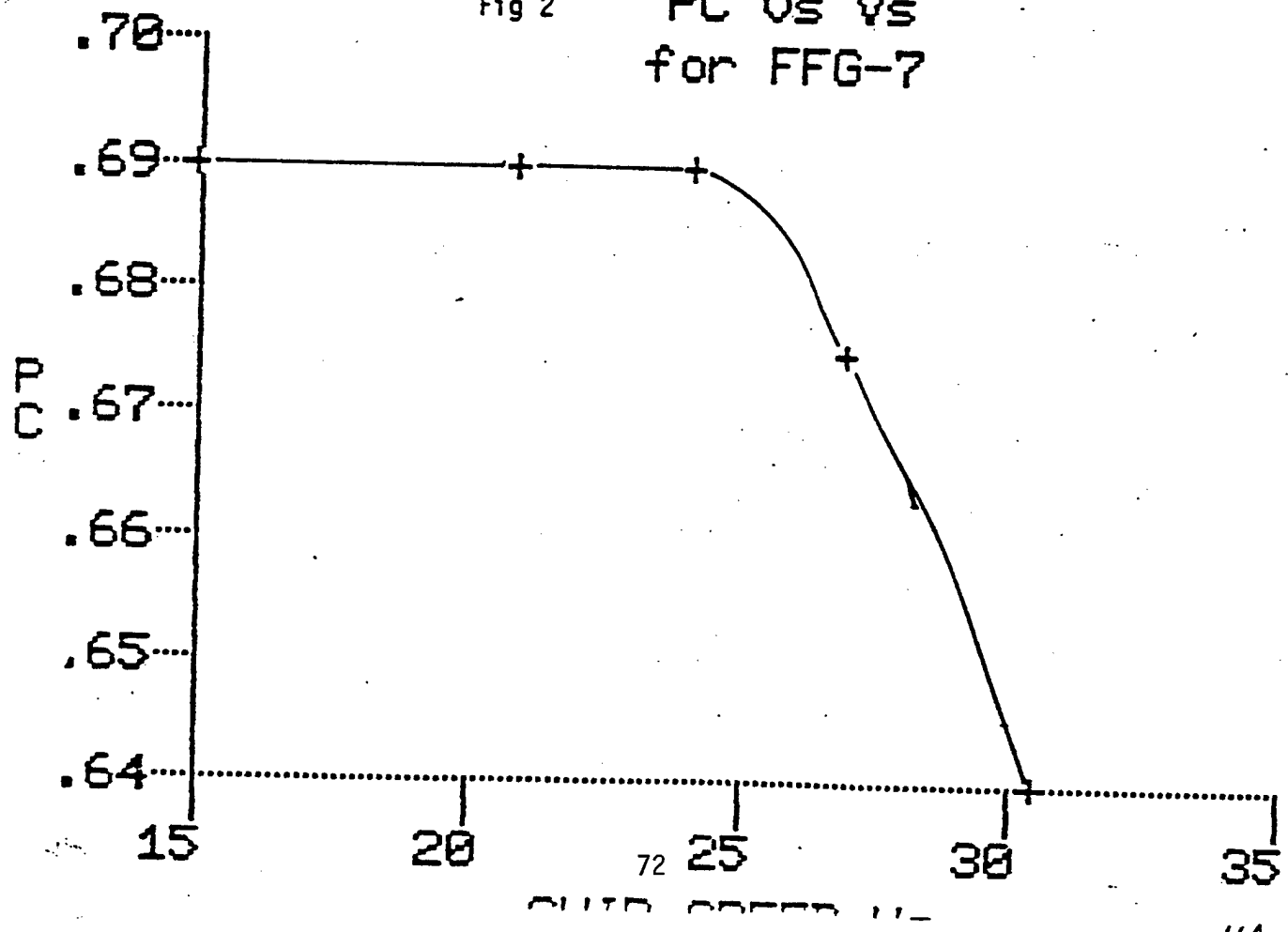


Fig 2 PC vs  $V_s$   
for FFG-7

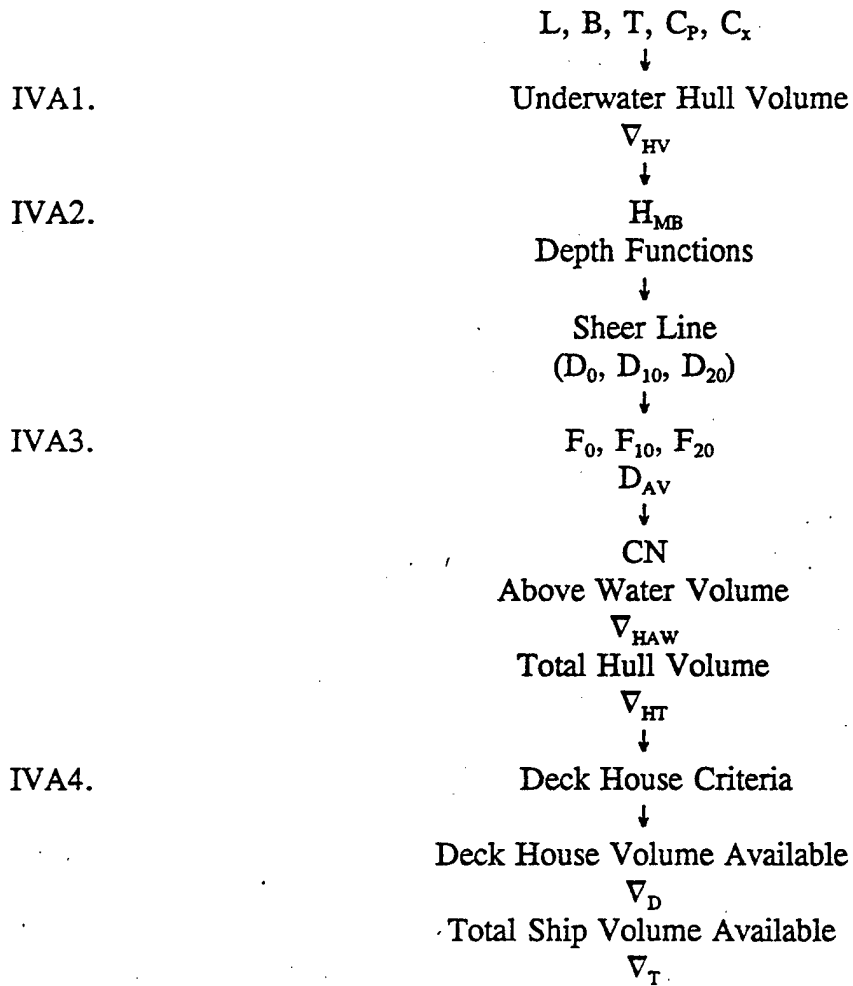


Micro Flow Diagrams  
(Continued)

IV. SPACE

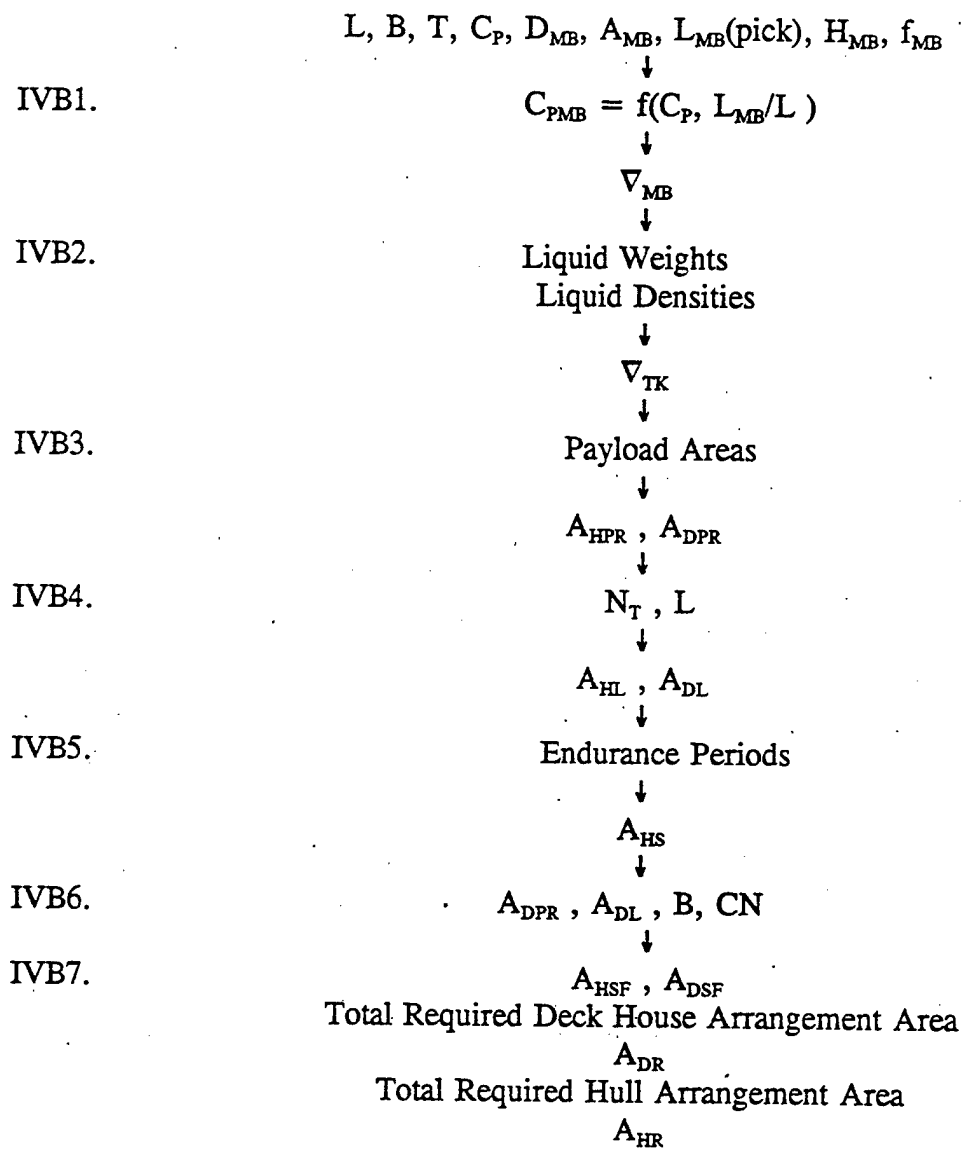
Input:  $L, B, T, C_P, C_x, L_{MB}, H_{MB}$ , Liquid Densities,  $W_F, W_{LO}, W_{HF}, N_T$   
 $A_{HPA}, A_{HPC}, A_{DPA}, A_{DPC}, EP_{DRY}, EP_{CHL}, EP_{FRZ}, EP_{GSM}, f_{MB}$

A. Available



Micro Flow Diagrams  
(Continued)

B. Required



Micro Flow Diagrams  
(Continued)

C. Balance

IVC1.

$$\nabla_{TK}, \nabla_{MB}, \nabla_{HT}$$



Hull Arrangement Volume Available

$$\nabla_{HA}$$



IVC2.

Hull and Deck House  
Arrangement Area Available

$$H_T, \nabla_{HA}, \nabla_D$$



$$A_{HA}, A_{DA}$$



IVC3.

Compare  $A_{HR}$  and  $A_{HA}$   
Compare  $A_{DR}$  and  $A_{DA}$

**Useful Output :** Machinery box dimensions, deck areas for functions in deck house and hull, tankage volumes and total ship volumes

Micro Flow Diagrams  
(Continued)

IV. SPACE ESTIMATING RELATIONSHIPS

A. Available

IVA1.  $\nabla_{HV} = L \cdot B \cdot T \cdot C_p \cdot C_x$

IVA2. 
$$\begin{aligned} F_{10R} &\geq 0.21 B \\ D_{10R} &= F_{10R} + T \\ D_{10MB} &\geq H_{MB} \\ D_{10BC} &\geq L/15 \end{aligned}$$

Select  $D_{10}$  as largest of  $D_{10R}$ ,  $D_{10MB}$ ,  $D_{10BC}$

$$\begin{aligned} D_0 &\geq 1.011827 \cdot T - 6.36215 \times 10^{-6} \cdot L^2 + 2.780649 \times 10^{-2} \cdot L + T \\ D_{20} &\geq .01 \cdot L \cdot (2.125 + 1.25 \times 10^{-3} \cdot L) + T \end{aligned}$$

Draw faired line through  $D_0$ ,  $D_{10}$  and  $D_{20}$  and submit with report

IVA3. 
$$\begin{aligned} F_0 &= D_0 - T; F_{10} = D_{10} - T; F_{20} = D_{20} - T \\ A_{PRO} &= L \cdot (F_0 + 4 \cdot F_{10} + F_{20}) / 6 \\ F_{AV} &= A_{PRO} / L \\ D_{AV} &= F_{AV} + T \\ CN &= L \cdot B \cdot D_{AV} \times 10^{-5} \\ C_w &= 0.236 + 0.836 \cdot C_p \\ f_f &= 0.714599 + 0.18098 \cdot D_{AV} / T - 0.018828 \cdot (D_{AV} / T)^2 \\ &\text{If } f_f < 1.0 \text{ then use } f_f = 1.0 \\ \nabla_{HAW} &= L \cdot B \cdot F_{AV} \cdot C_w \cdot f_f \end{aligned}$$

IVA4. 
$$\nabla_{HT} = \nabla_{HV} + \nabla_{HAW}$$

IVA5. Deck house sizing :  $0.001 L^3 < D_{10} < 0.0015 L^3$

IVA6. 
$$\nabla_T = \nabla_{HT} + \nabla_D$$

Micro Flow Diagrams  
(Continued)

B. Required

IVB1.  $C_{PMB} = f(C_P, L_{MB}/L)$   
(Use figure 2 for data, 3 and 4 for comparison)

$$D_{MB} \approx H_{MB}$$

$$A_{MB} = B \cdot T \cdot C_x + B \cdot (D_{MB} - T)$$

$$f_{aux} = \text{given}$$

$$\nabla_{MB} = L_{MB} \cdot A_{MB} \cdot C_{PMB}$$

$$\nabla_{aux} = \nabla_{MB} \cdot f_{aux}$$

IVB2.  $W_w = 0.224 N_T$

$$\nabla_{TK} = K_1 \cdot K_2 \cdot (W_F \cdot \gamma_F + W_{HF} \cdot \gamma_{HF} + W_{LO} \cdot \gamma_{LO}) + K_1 \cdot W_w \cdot \gamma_w + \nabla_{void}$$

where:  $K_1 =$  factor for structure, 1.02

$K_2 =$  factor for expansion, 1.05

$\gamma_F =$  given

$\gamma_{HF} =$  given

$\gamma_{LO} =$  given

$\gamma_w =$  given

IVB3.  $A_{DPR} = 1.15 \cdot A_{DPA} + 1.23 \cdot A_{DPC}$

$$A_{HPR} = 1.15 \cdot A_{HPA} + 1.23 \cdot A_{HPC}$$

where 1.15 and 1.23 are allowances for access

IVB4.  $A_{DL} = 400 \text{ ft}^2$  (for Commanding Officer)

$$A_{HAB} = 48 \text{ ft}^2/\text{man}$$

$$A_{HL} = (A_{HAB} + L/100) N_T - A_{DL}$$

valid for  $150 < N_T < 500$

and  $.06 < N_o/N_T < .091$

IVB5.  $A_{HS} = 300 + 0.0158 \cdot N_T \cdot (2 \cdot EP_{DRY} + 2 \cdot EP_{CHL} + EP_{FRZ} + 4 \cdot EP_{GSM})$

IVB6.  $A_{DM} = 0.15 A_{DPR} + 0.15 A_{DL}$

$$A_{DB} = 16 (B - 18) + 80$$

$$A_{DSF} = A_{DM} + A_{DB}$$

$$A_{HSF} = 2140 \cdot CN - 540$$

IVB7.  $A_{HR} = A_{HPR} + A_{HL} + A_{HS} + A_{HSF} + (I_{VH} / H_T)$

$$A_{DR} = A_{DPR} + A_{DL} + A_{DSF} + H_A + (I_{VD} / H_T)$$

$$A_{TR} = A_{HR} + A_{DR}$$

$$\nabla_{DR} = H_T \cdot A_{DR}$$

$$\nabla_{HR} = H_T \cdot A_{HR}$$

$$\nabla_{TR} = \nabla_{DR} + \nabla_{HR}$$



Micro Flow Diagrams  
(Continued)

C. Balance

$$\begin{aligned} \text{IVC1. } \nabla_{HA} &= \nabla_{HT} - \nabla_{MB} - \nabla_{aux} - \nabla_{TK} \\ \nabla_{TA} &= \nabla_{HA} + \nabla_D \end{aligned}$$

$$\begin{aligned} \text{IVC2. } A_{HA} &= \nabla_{HA} / H_T \\ A_{DA} &= \nabla_D / H_T \end{aligned}$$

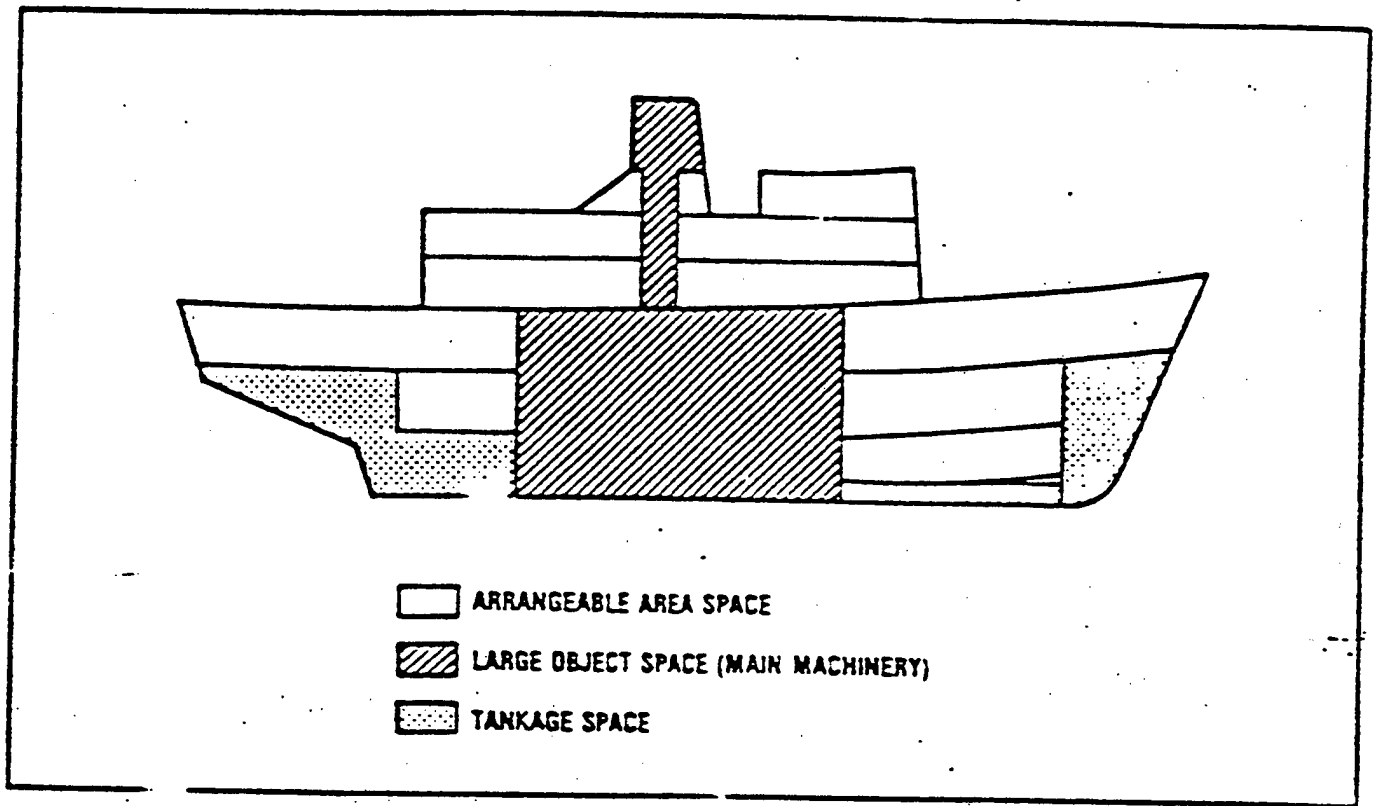
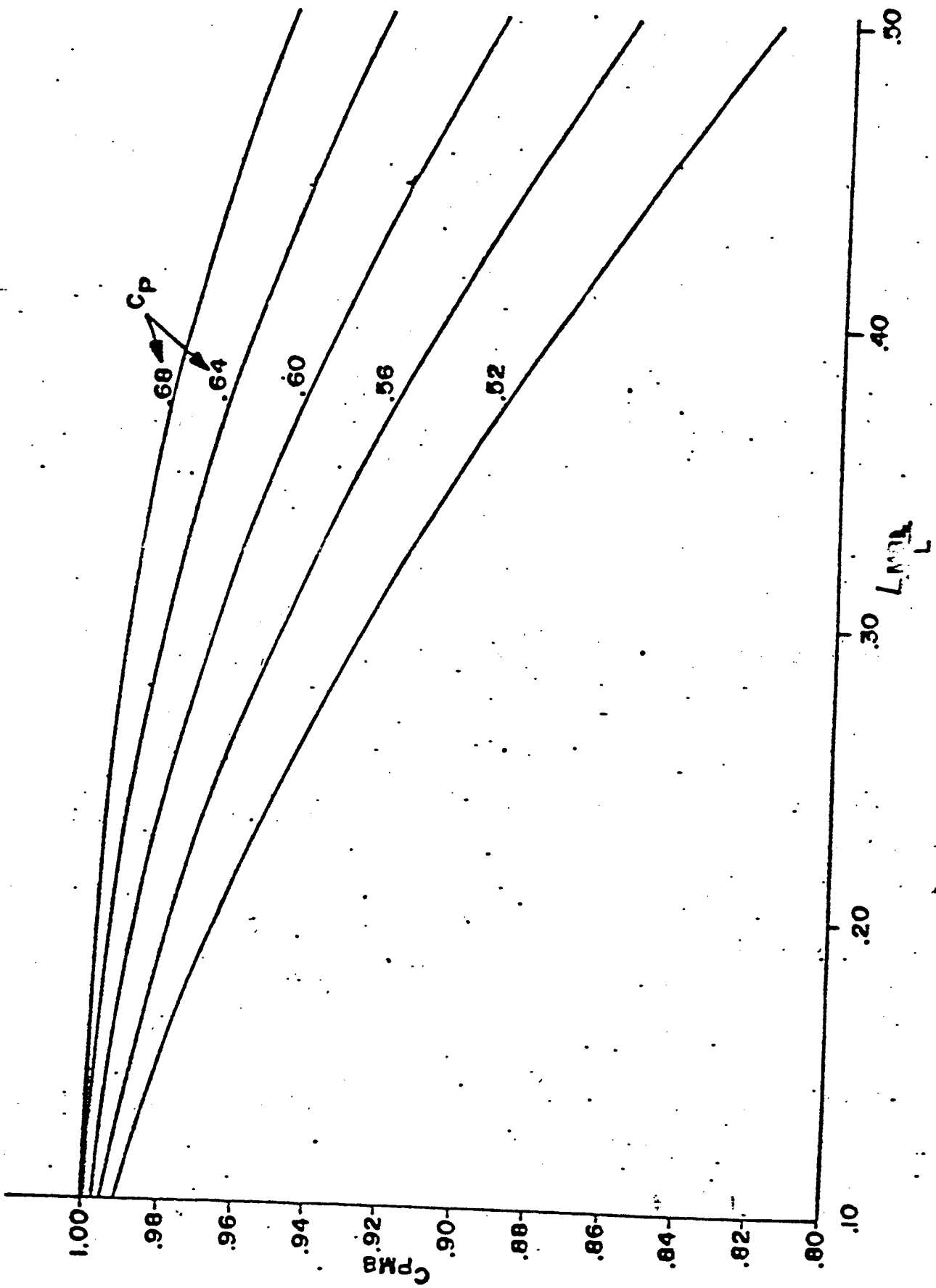


Figure 1 Relationship Among the Three Types of Space

Fig 2 Machinery Box Prismatic Coefficient



Mach Box Vol  
Installed Power

$$\frac{Ft^3}{SHP}$$

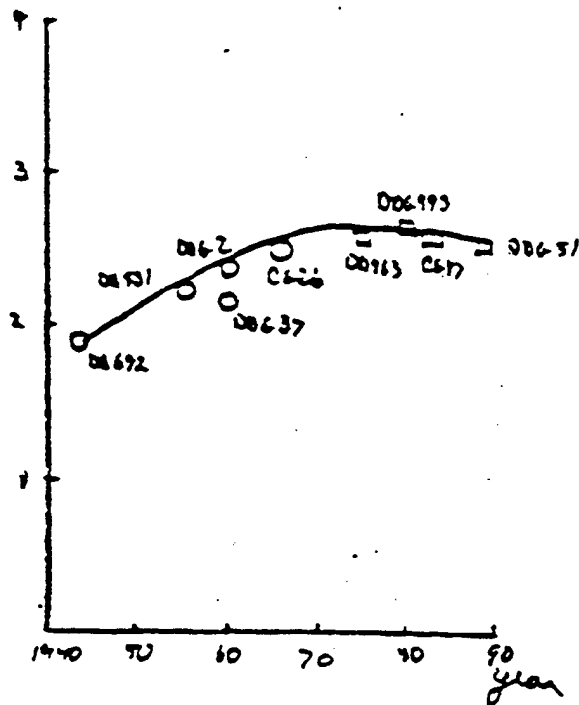
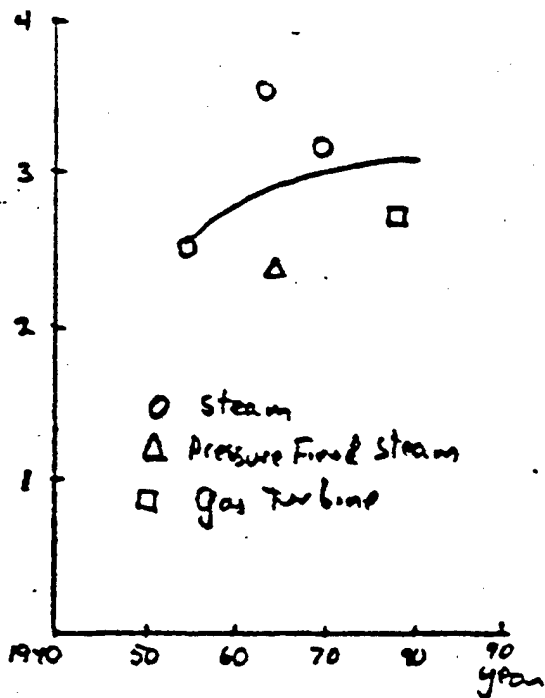


Fig 3 Machinery Box Volume

Fig 4 FRIGATES - SPECIFIC MACHINERY VOLUME

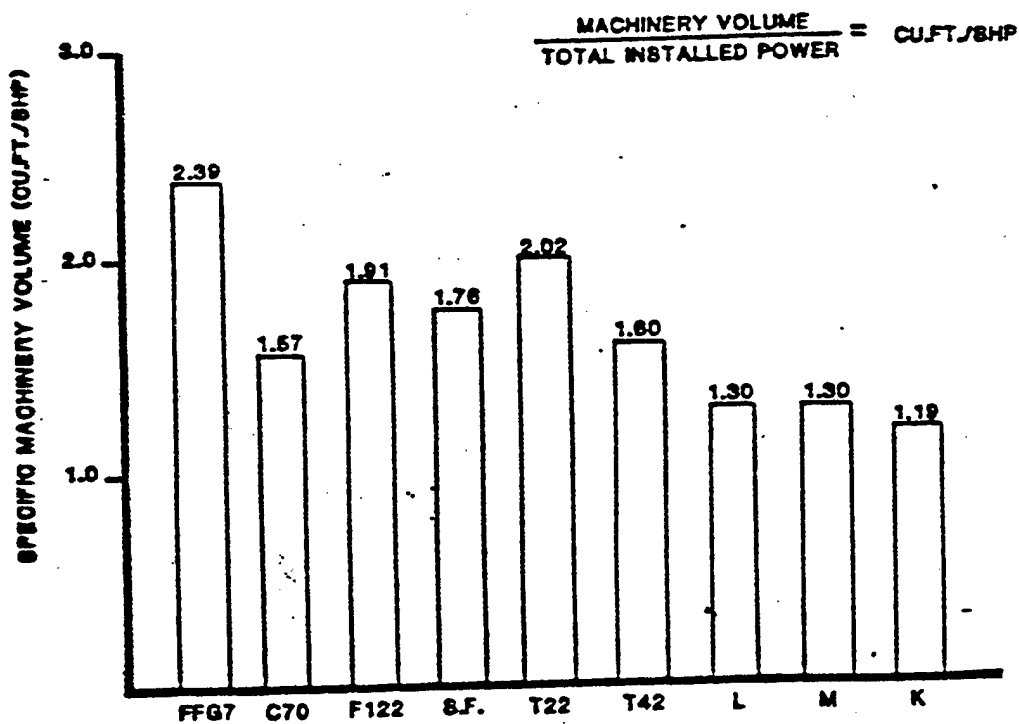


Fig 5

# PAYLOAD TREND

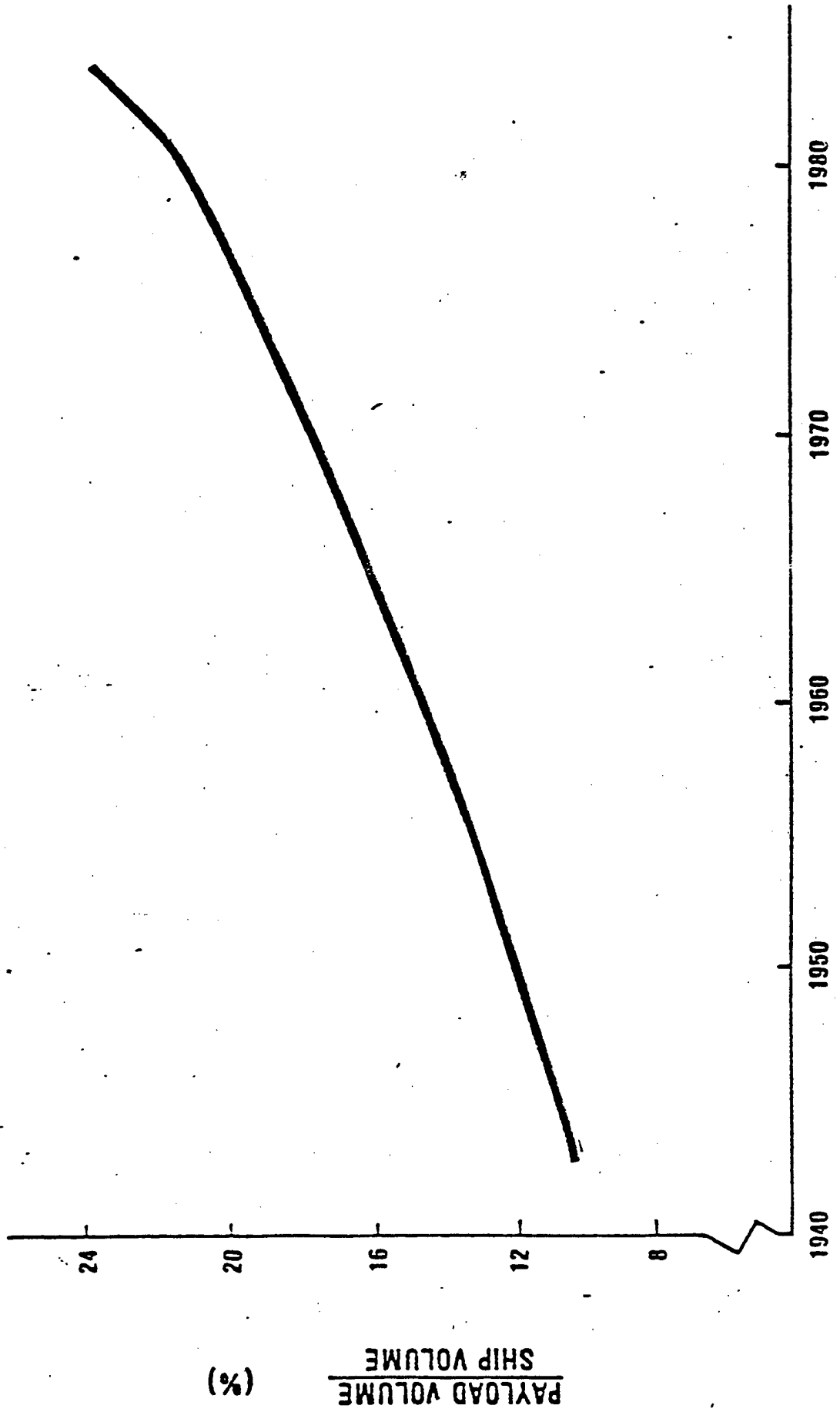


Fig 6 FRIGATES - PAYLOAD VOLUME

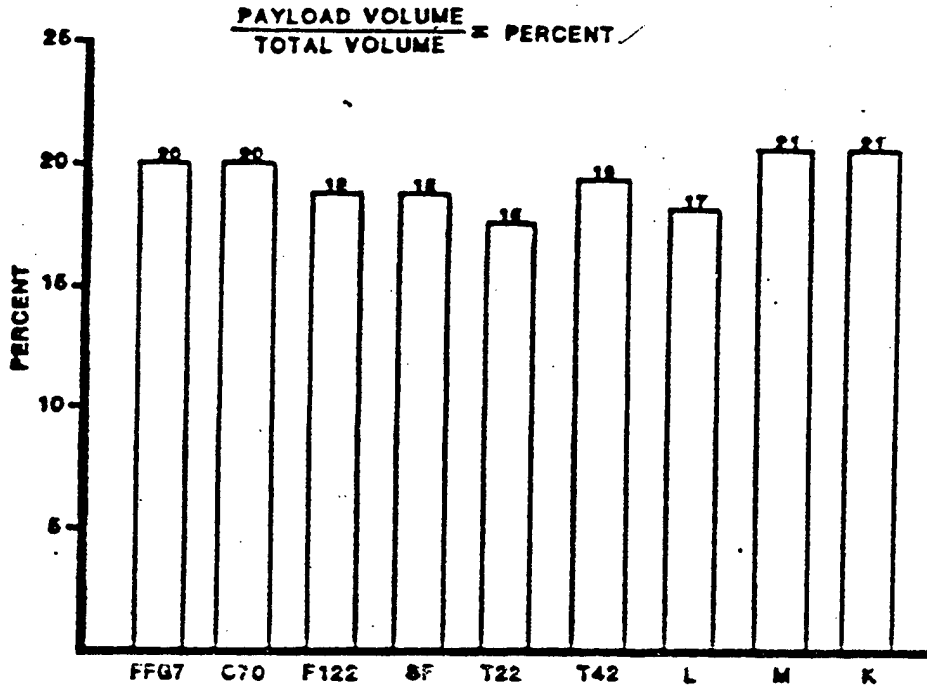
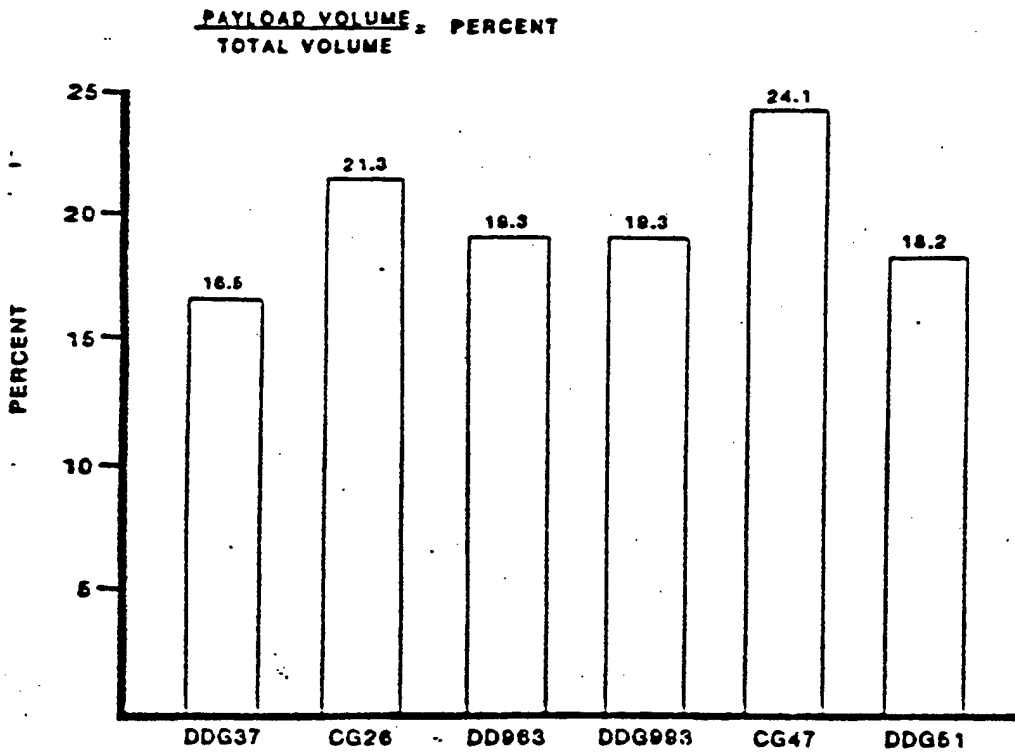
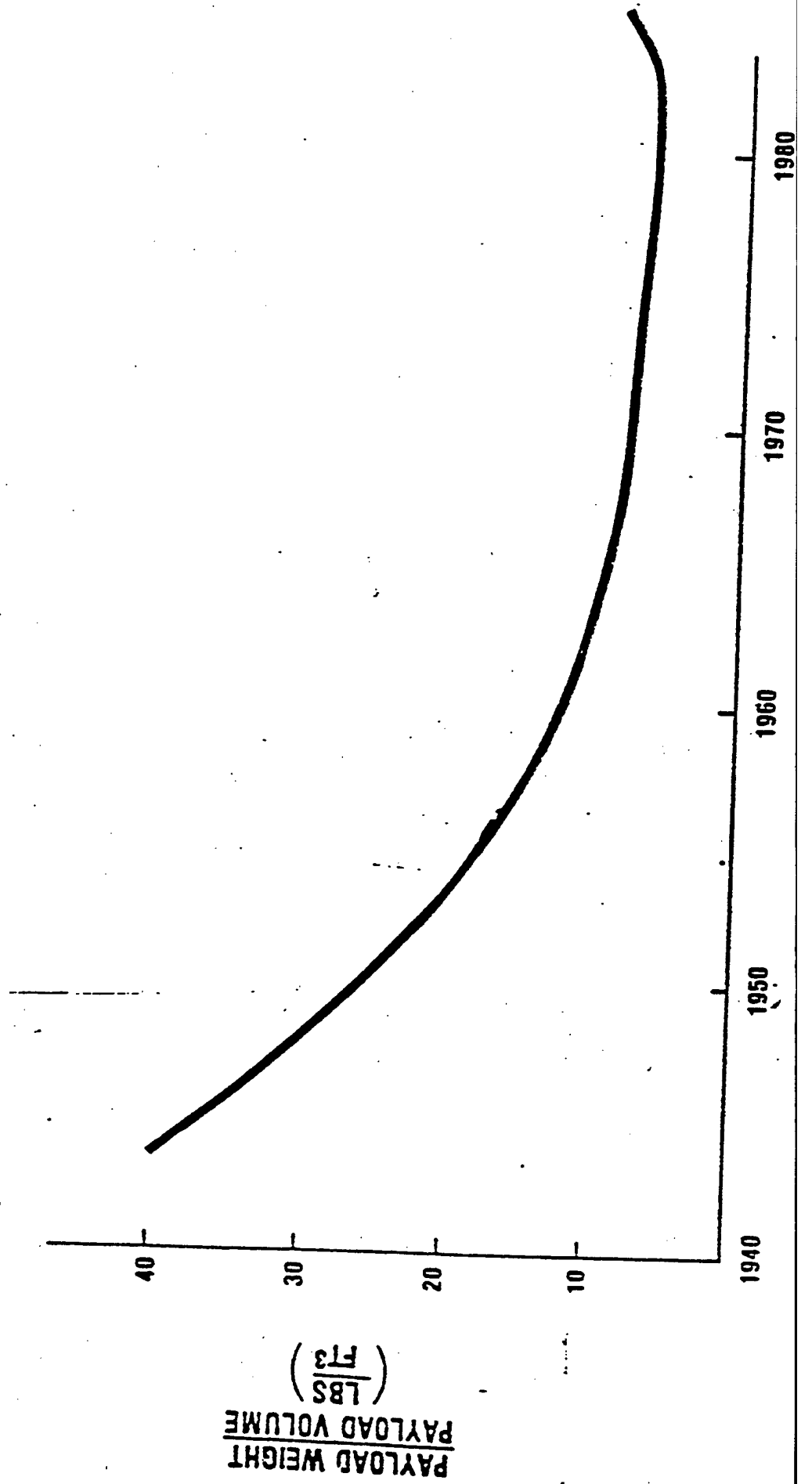


Fig 7 PAYLOAD VOLUME - U.S. SHIPS



# PAYLOAD TREND

FIG 8



PAYLOAD WEIGHT  
(LBS)  
PAYLOAD VOLUME  
(FT<sup>3</sup>)

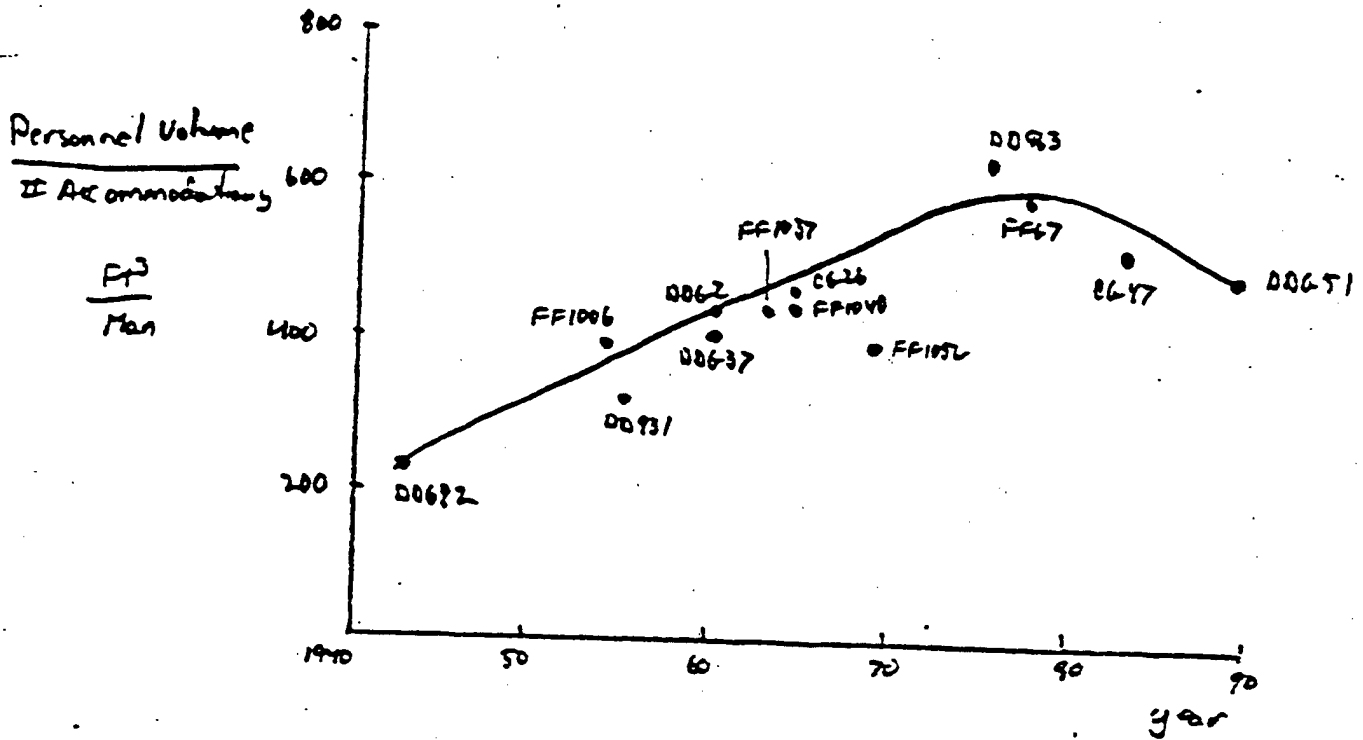


Fig 9 Personnel Volume ✓

Fig 10 HABITABILITY DECK AREA - U.S. SHIPS

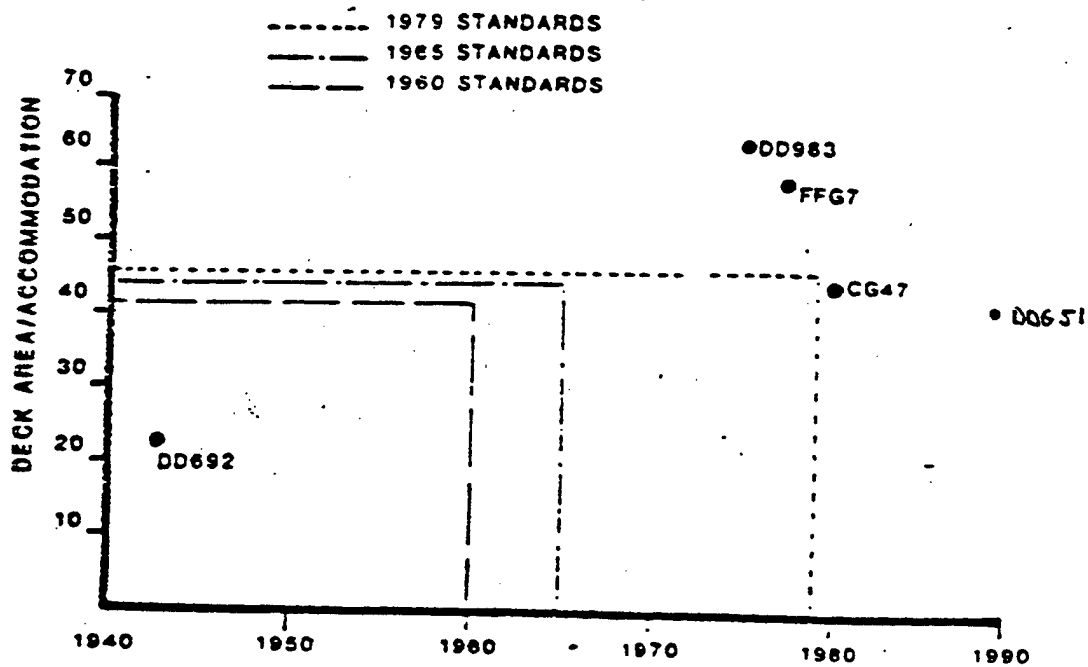




Fig 11

FRIGATES - HABITABILITY SPACE

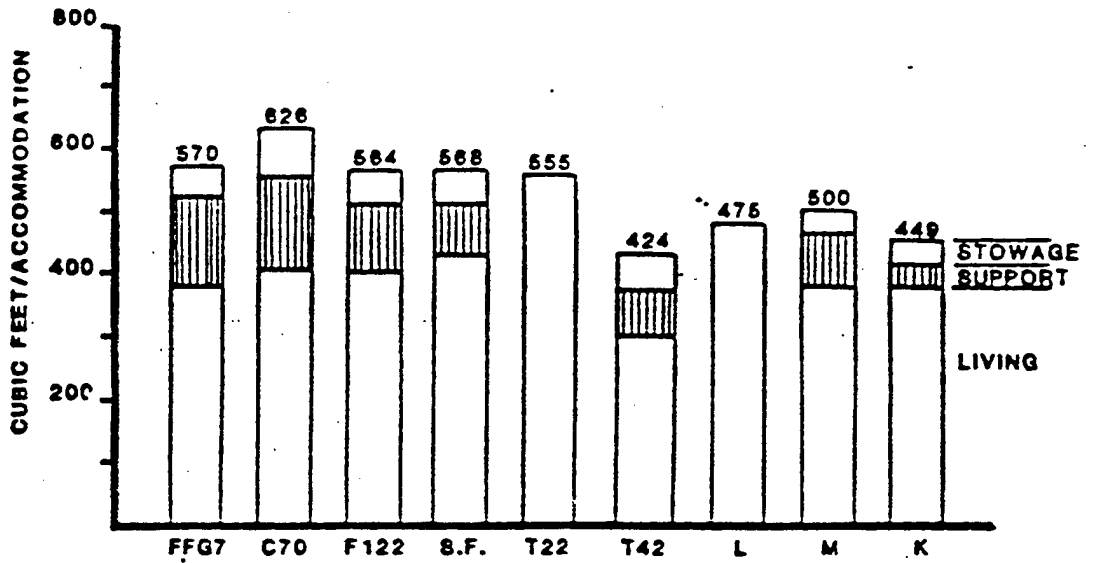


Fig 12

FRIGATES - CREW SIZE

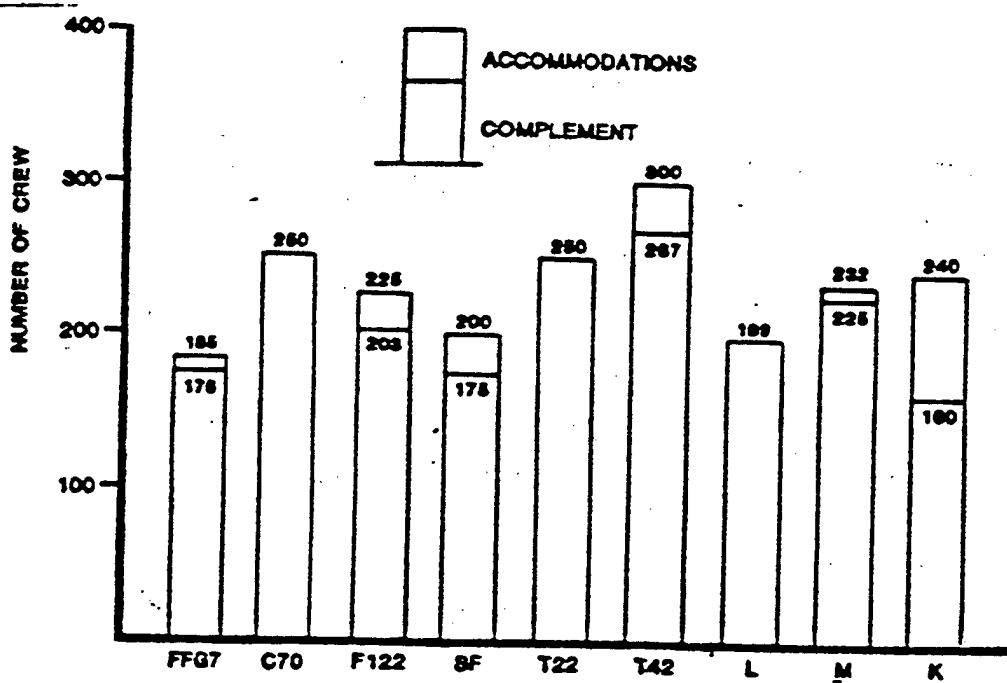
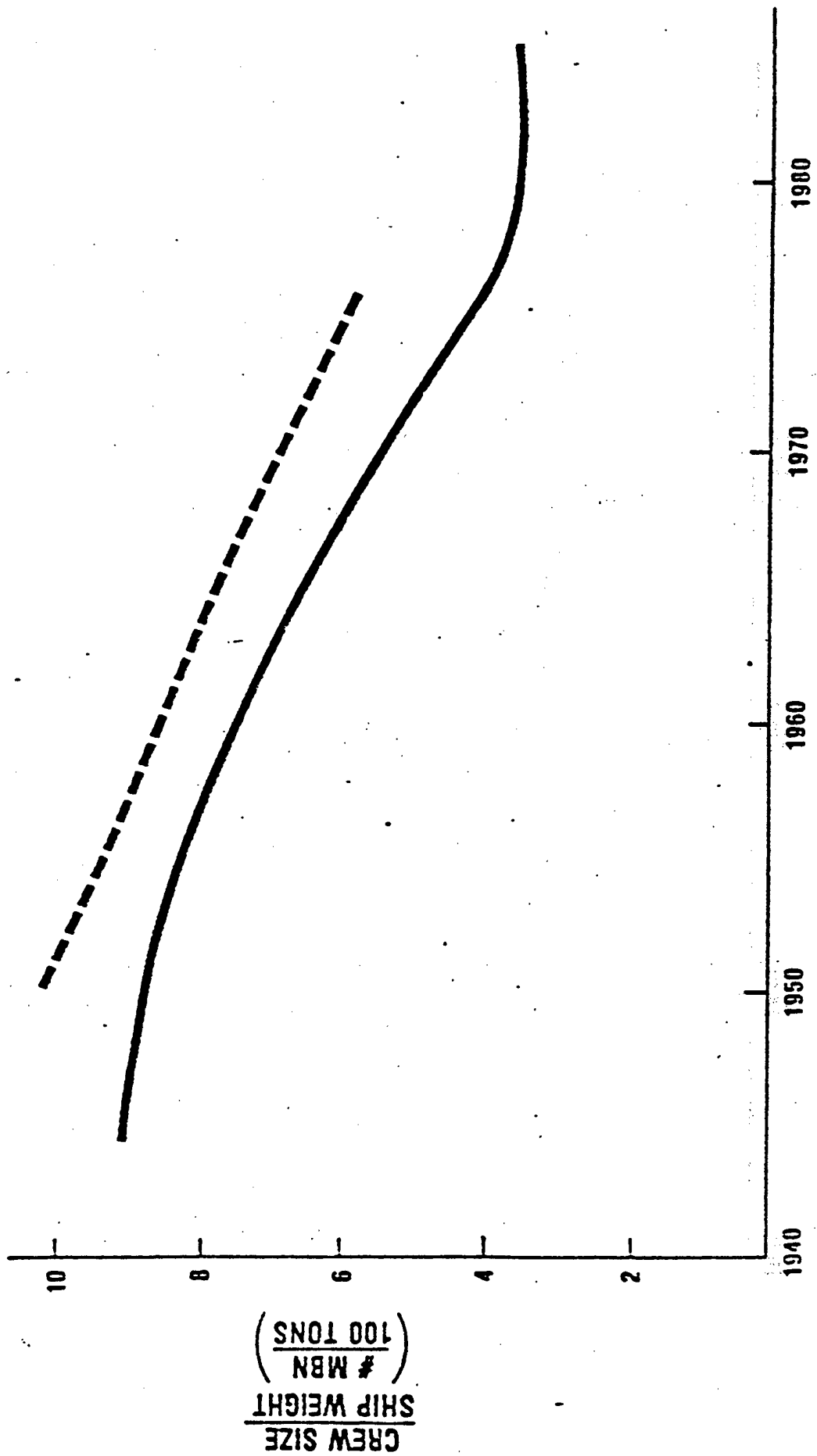


FIG 13 CREW SIZE TREND



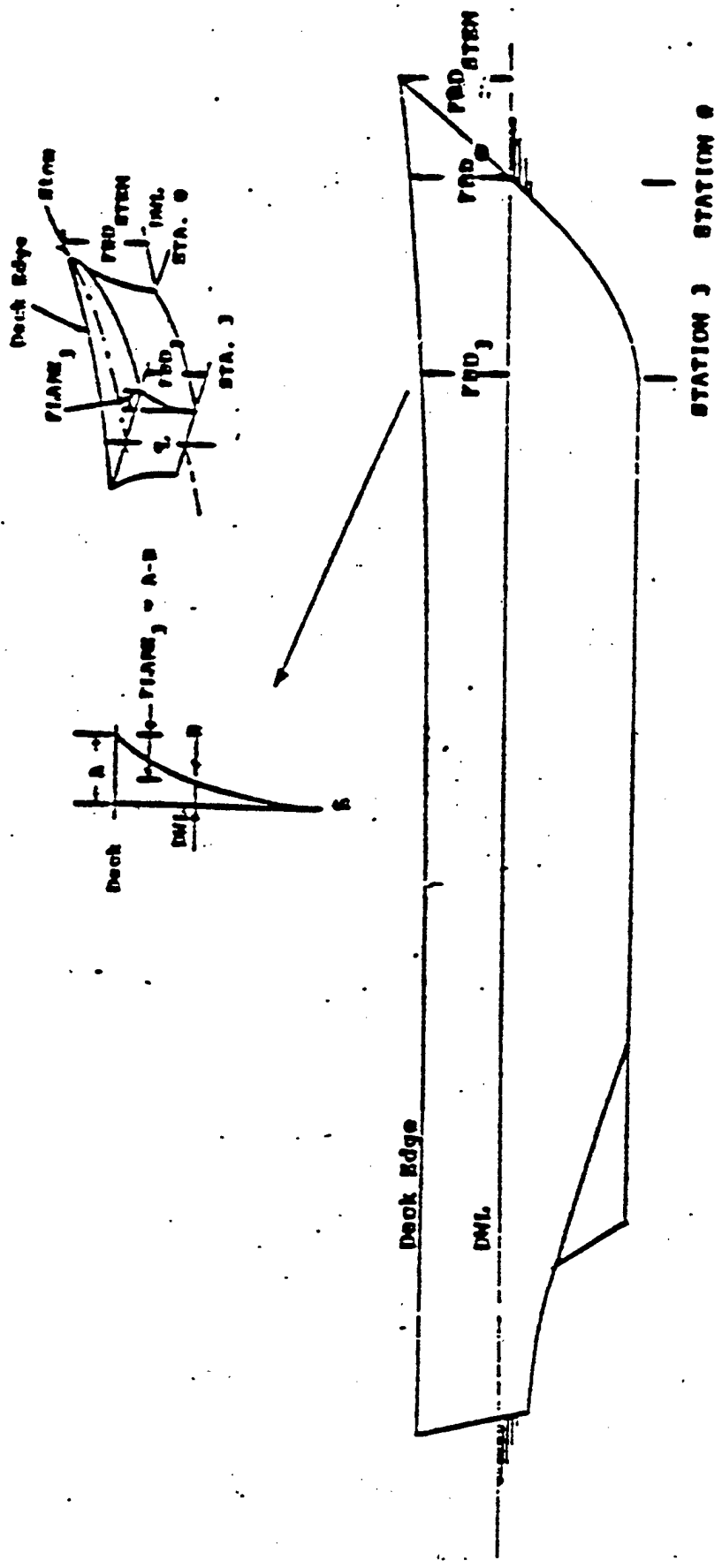


Fig 14 Freeboard and Flare Definitions

NOTE:  $\frac{100 \cdot \text{FBD}_0}{L} = 1.011827 \left(\frac{100T}{L}\right) - 0.000636215(L) + 2.780649$

WHERE T = MOLDED DRAFT, L = LENGTH ON WL, AND  
 $\text{FBD}_0$  = REQUIRED FREEBOARD AT STATION 0.

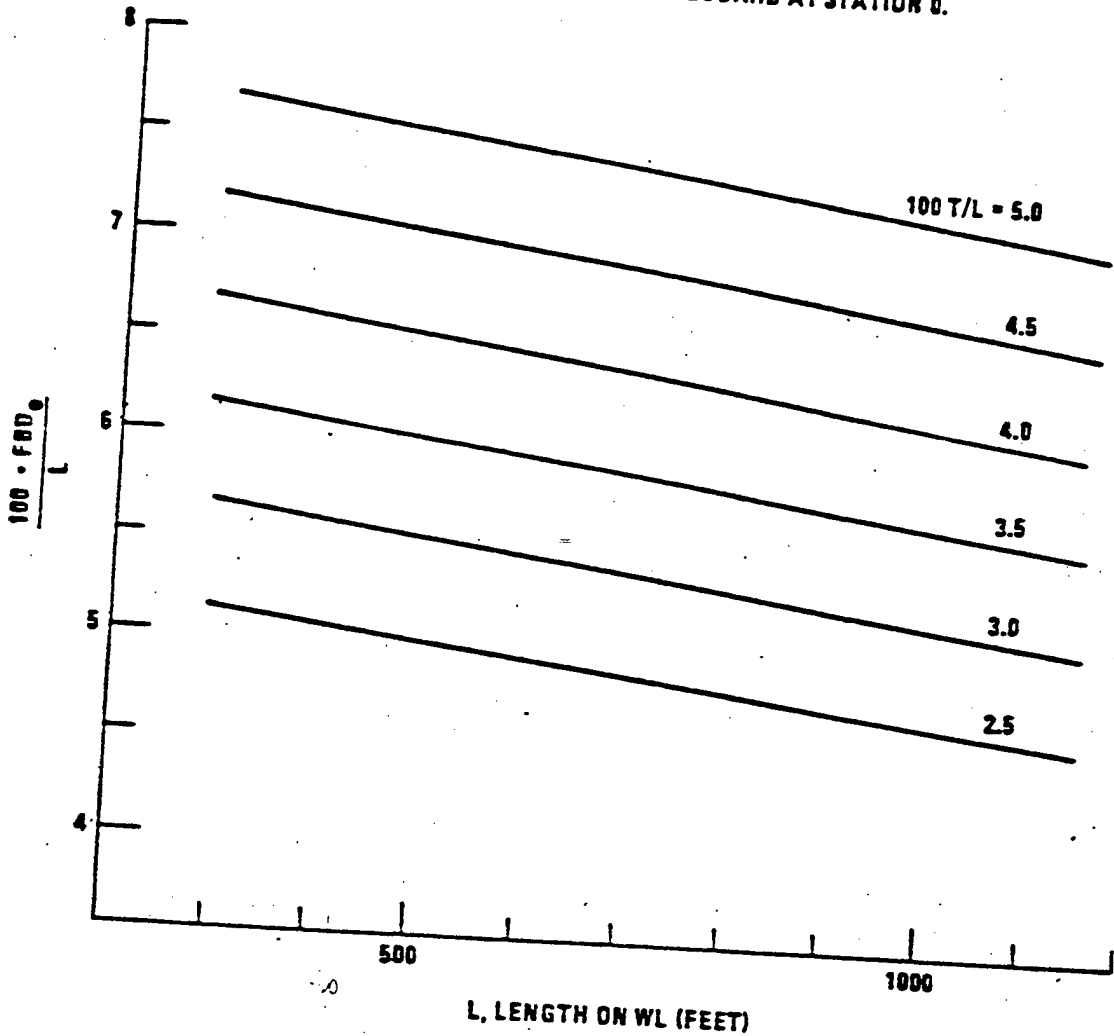


Fig 15 A Criterion for Bow Freeboard for Cruiser/Destroyer Ships

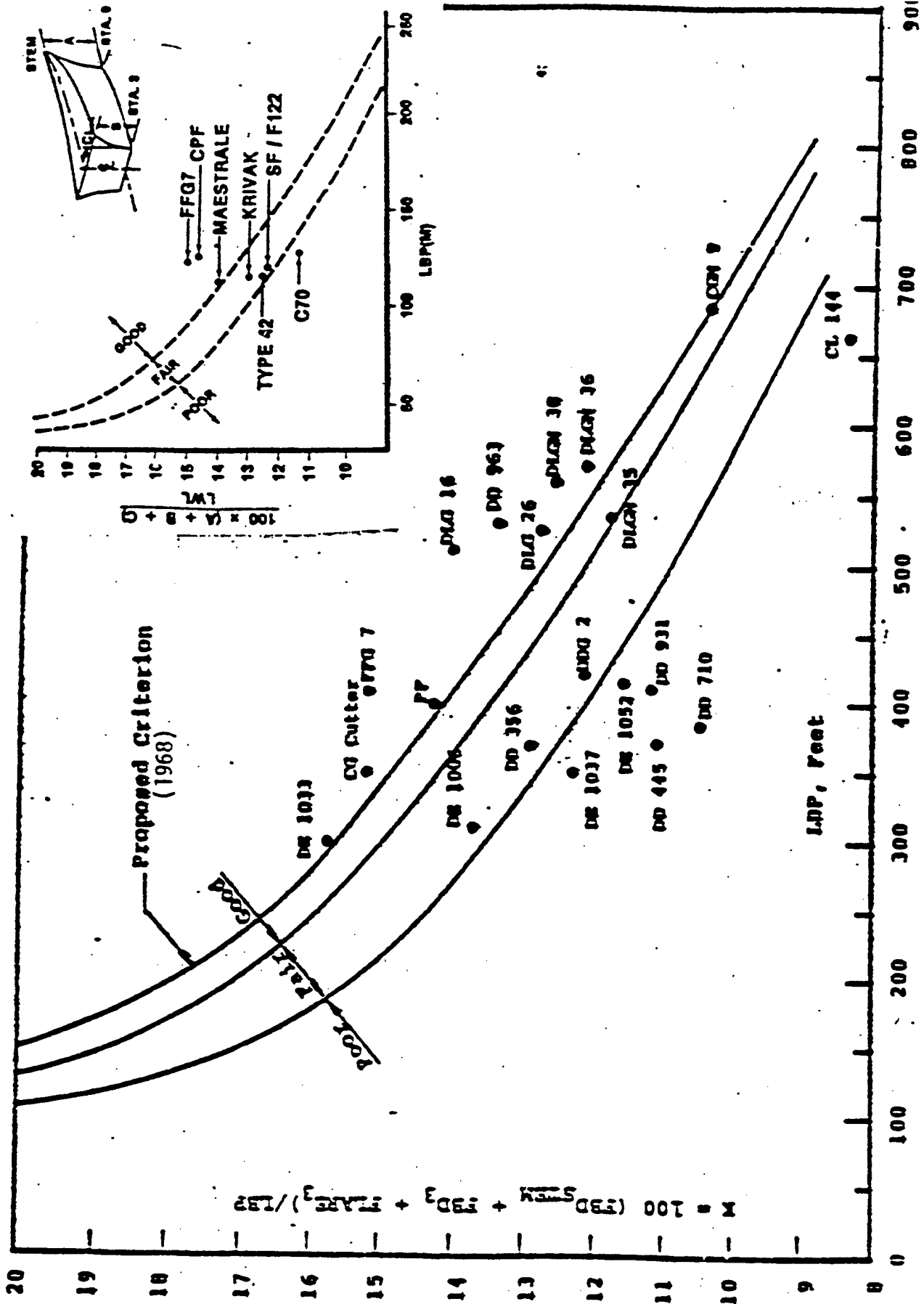


Fig 16 Combined Freeboard and Flare for Destroyer Type Ships.

SOURCE: DDS 079-2

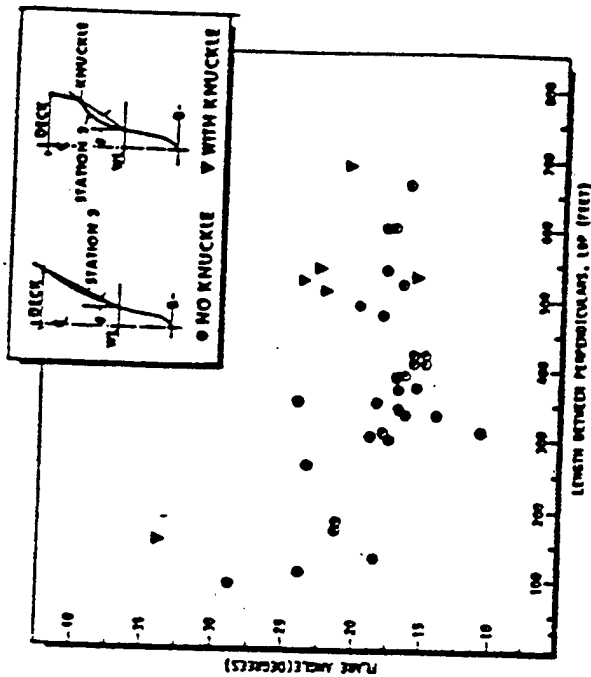


Figure 3. Correlation between FLARE and SHIP LENGTH.

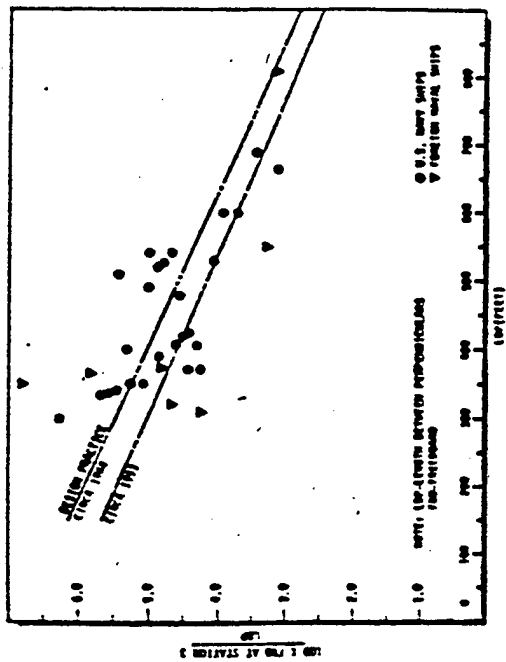
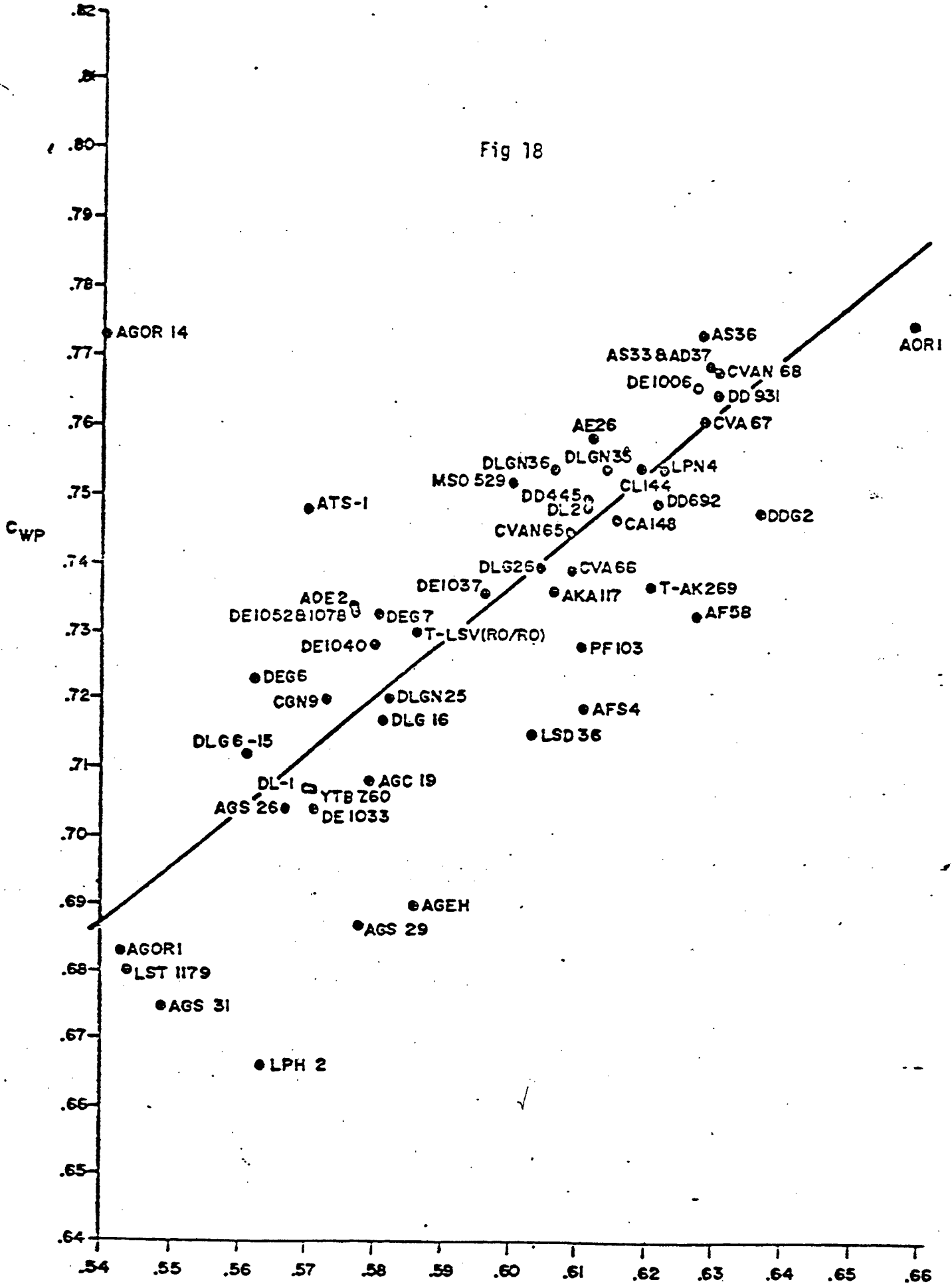


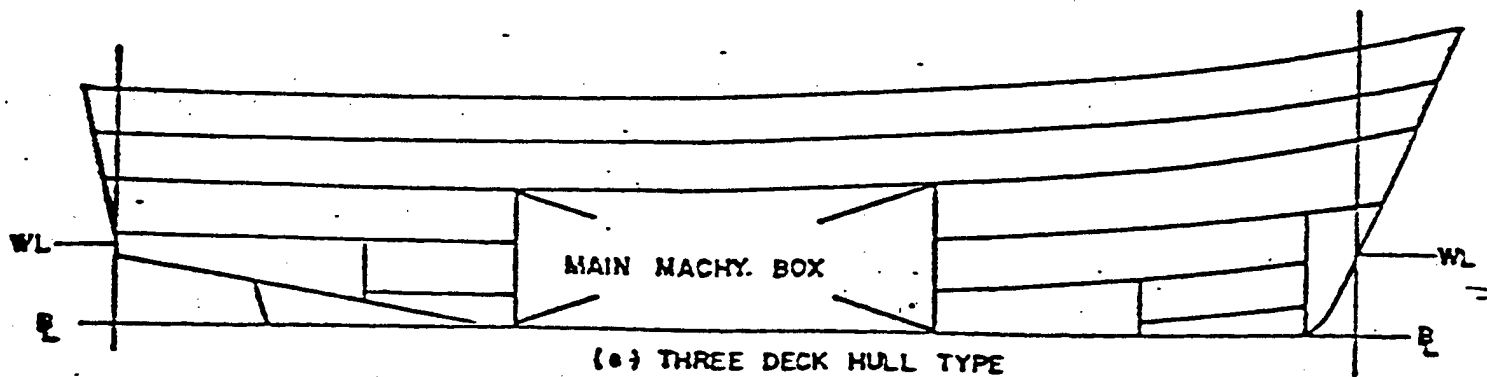
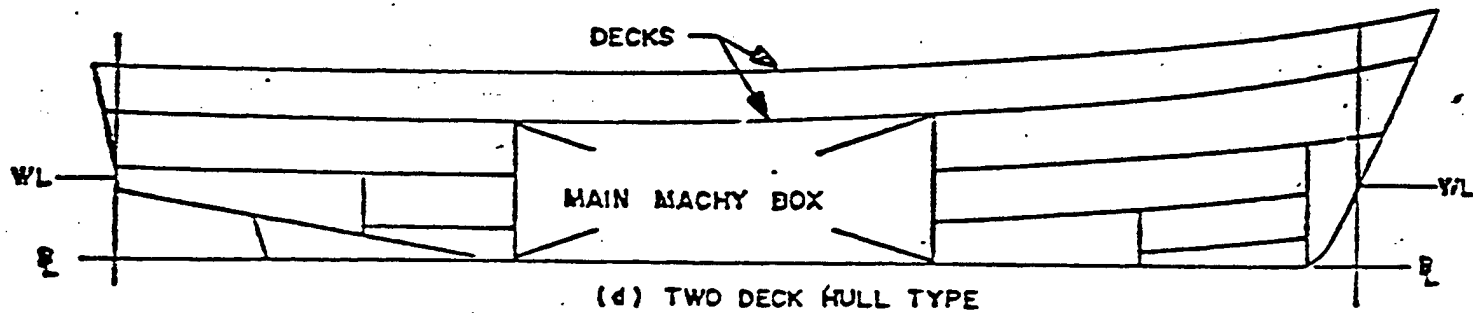
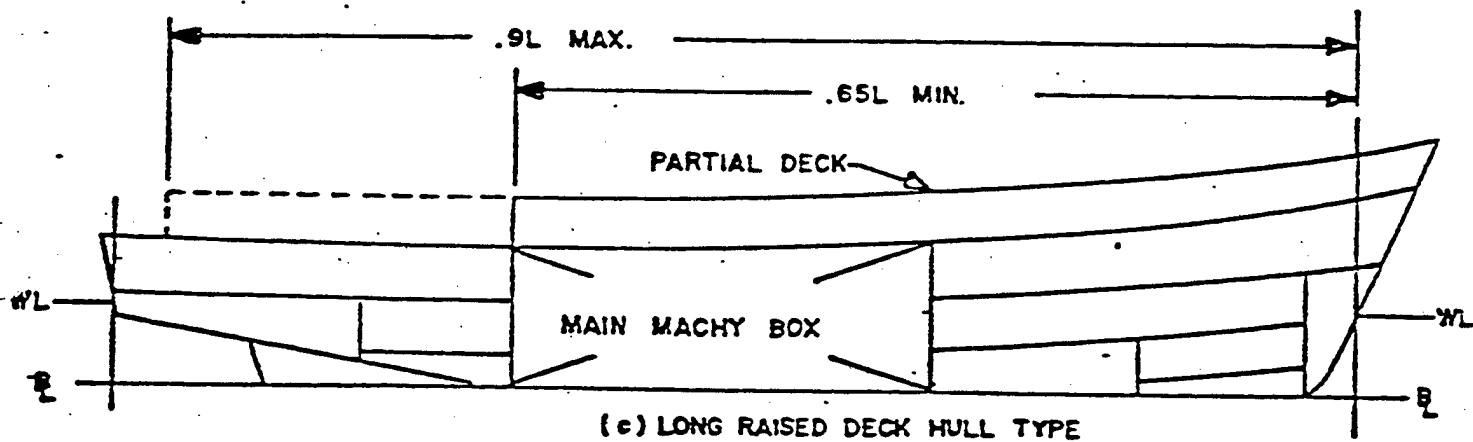
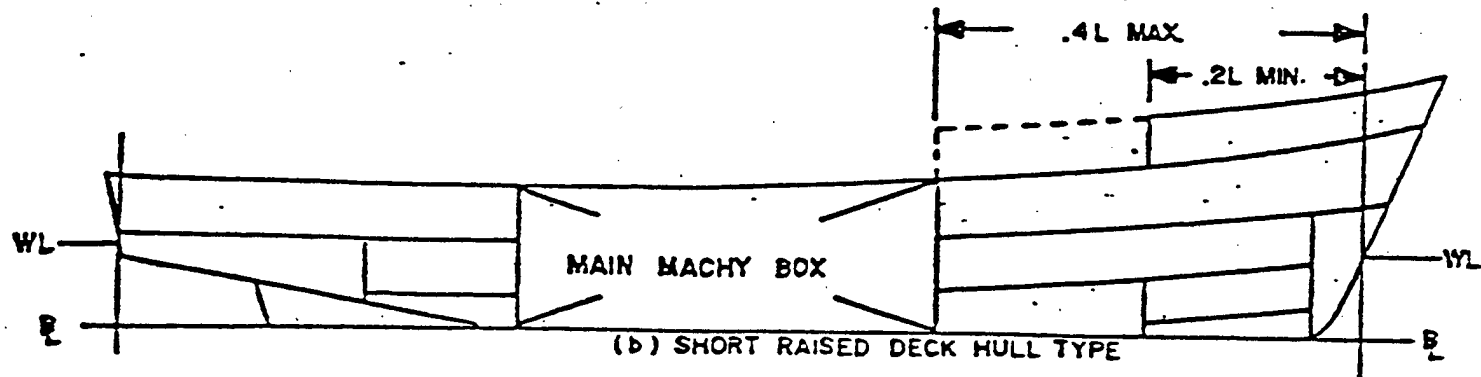
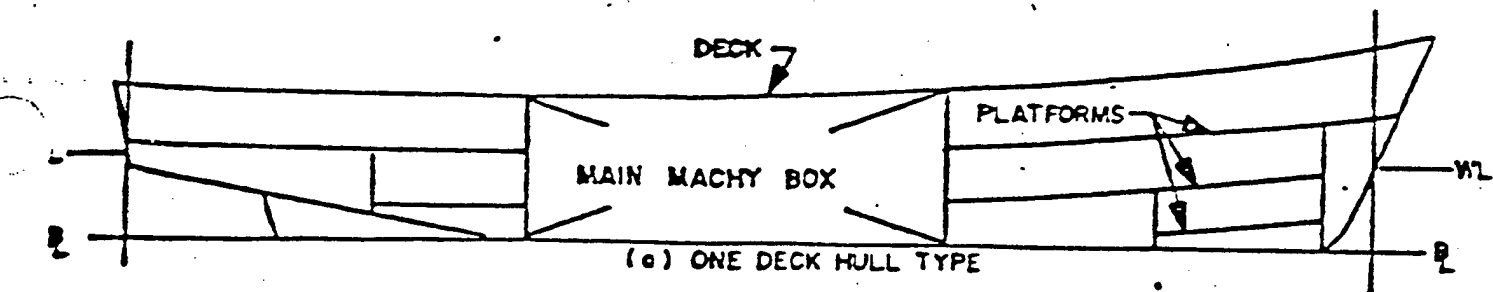
Figure 2. Freeboard Design Practice.

SOURCE:

Fig 17 SEAKEEPING BY DESIGN COMSTOCK/KEANE Naval Engineers Journal, April 1960

Fig 18







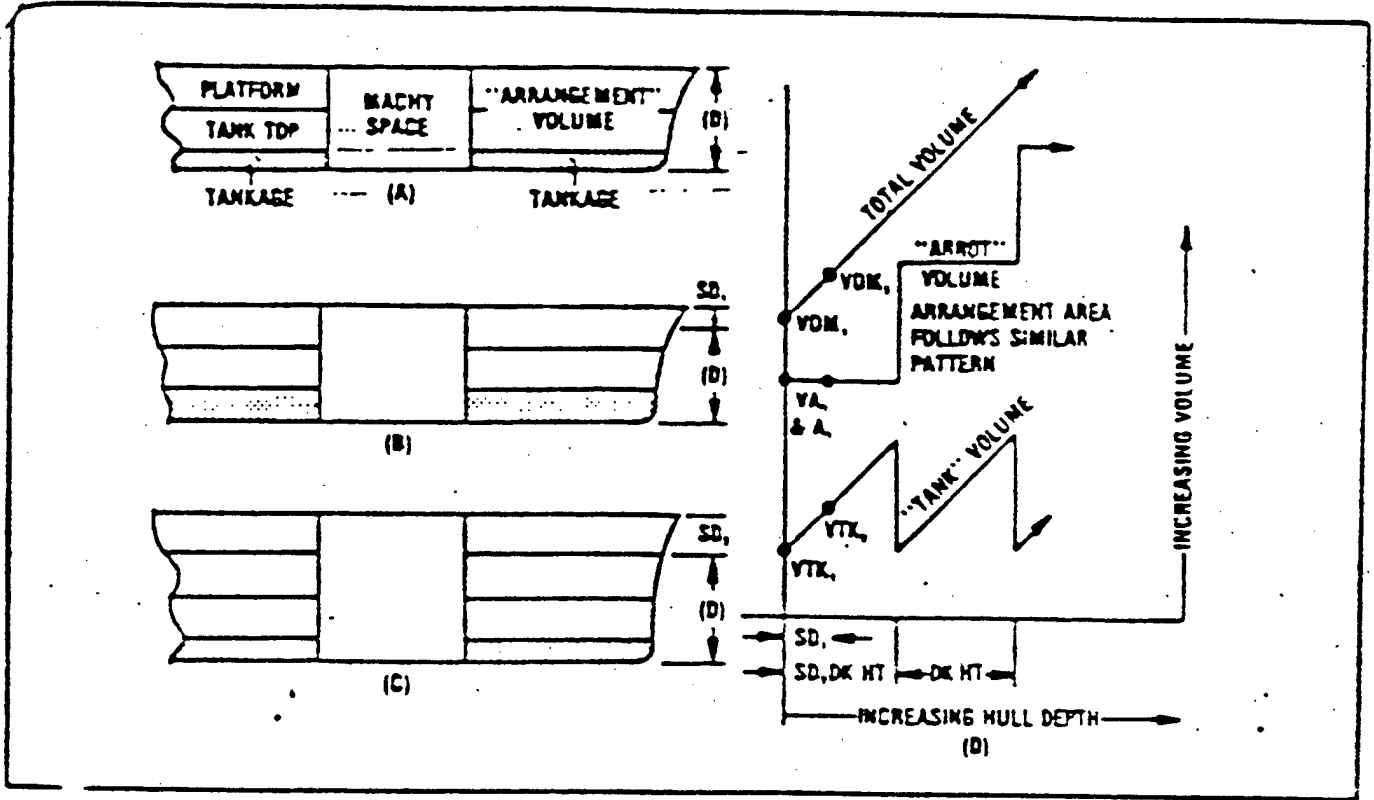


Figure 20 Idealized Area/Depth Relationship

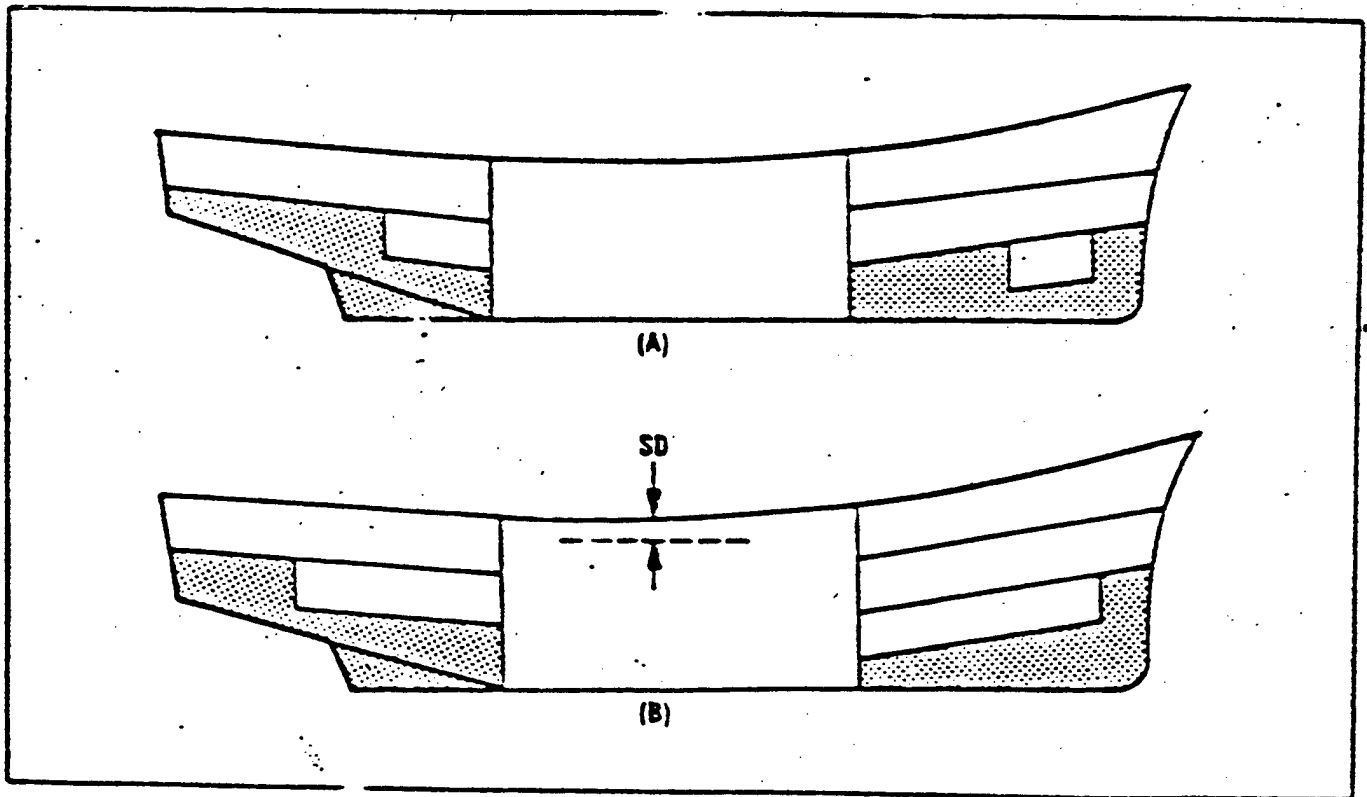


Figure 21 Typical Destroyer Profiles

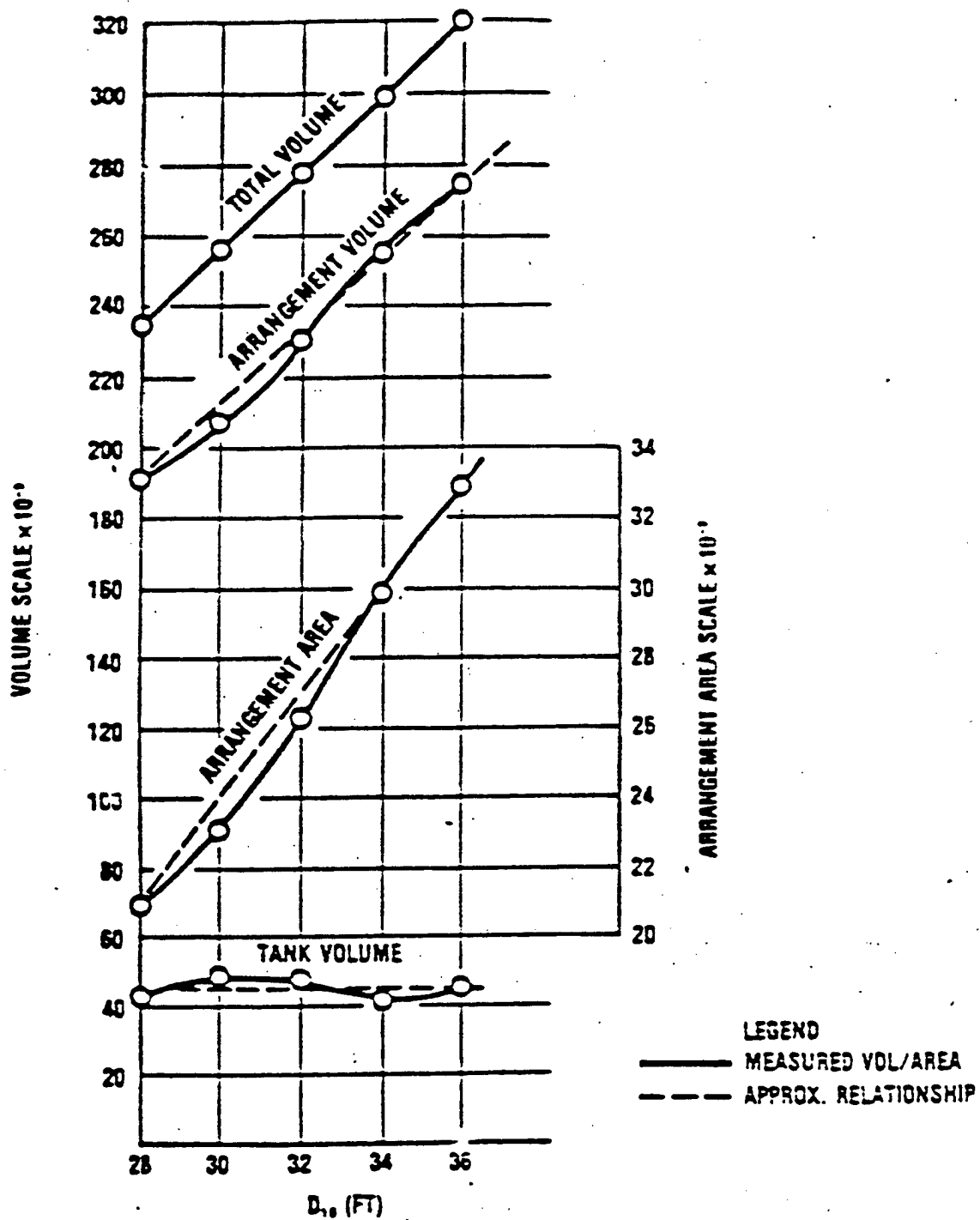
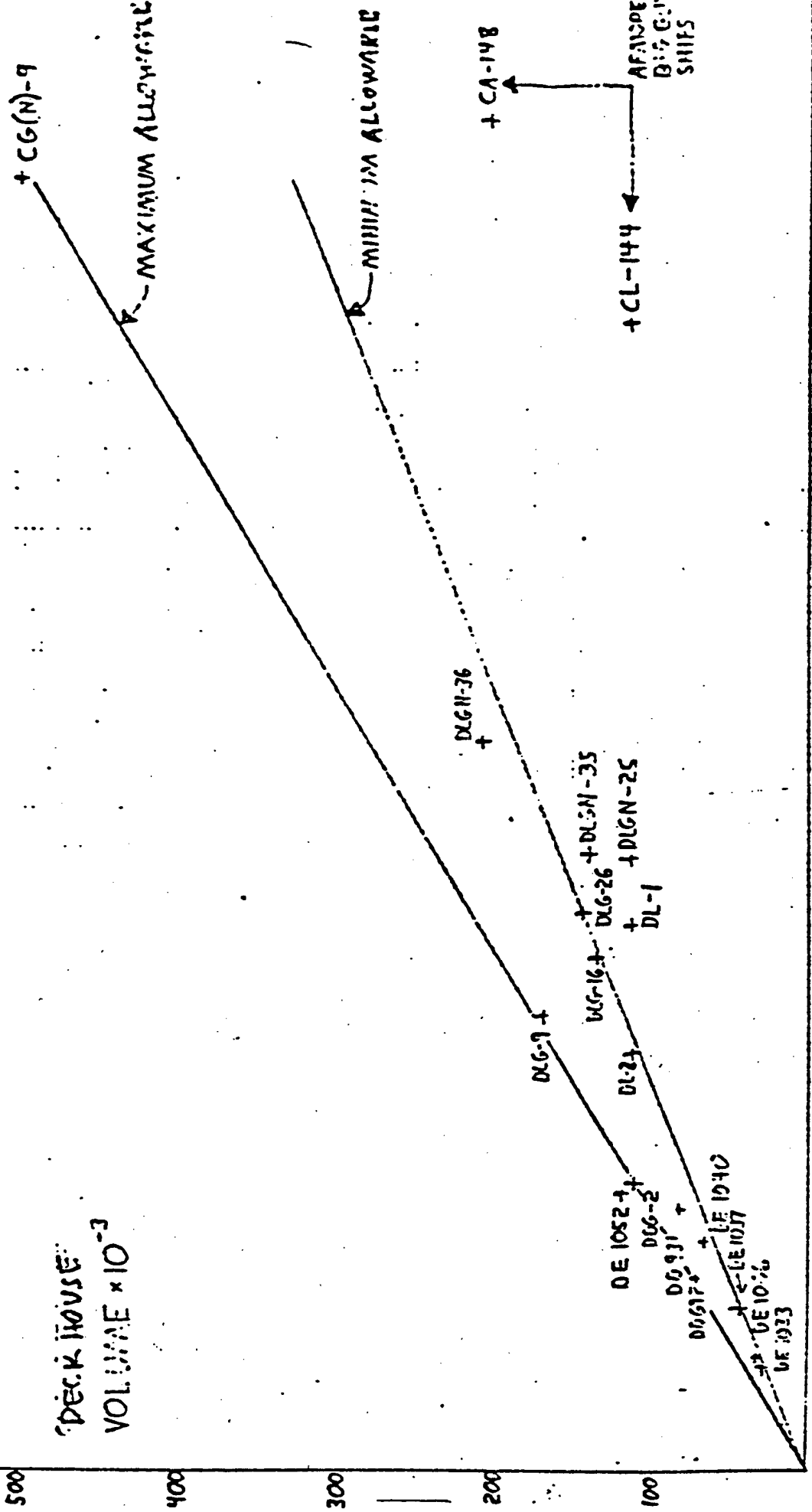


Figure 22 Area/Volume/Depth Relationships



DECK HOUSE  
VOLUME  $\times 10^{-3}$

$(LBP) \times 10^{-6}$

SIMS 6/14/74

Fig 23

Fig 24 FRIGATES - VOLUME

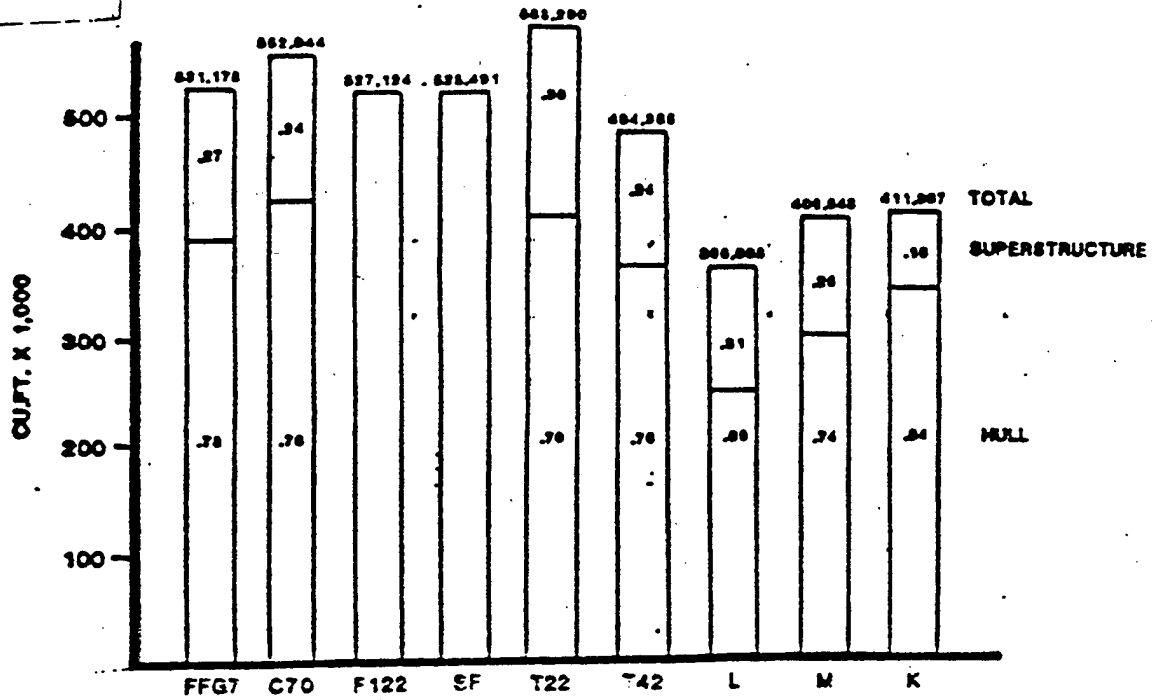
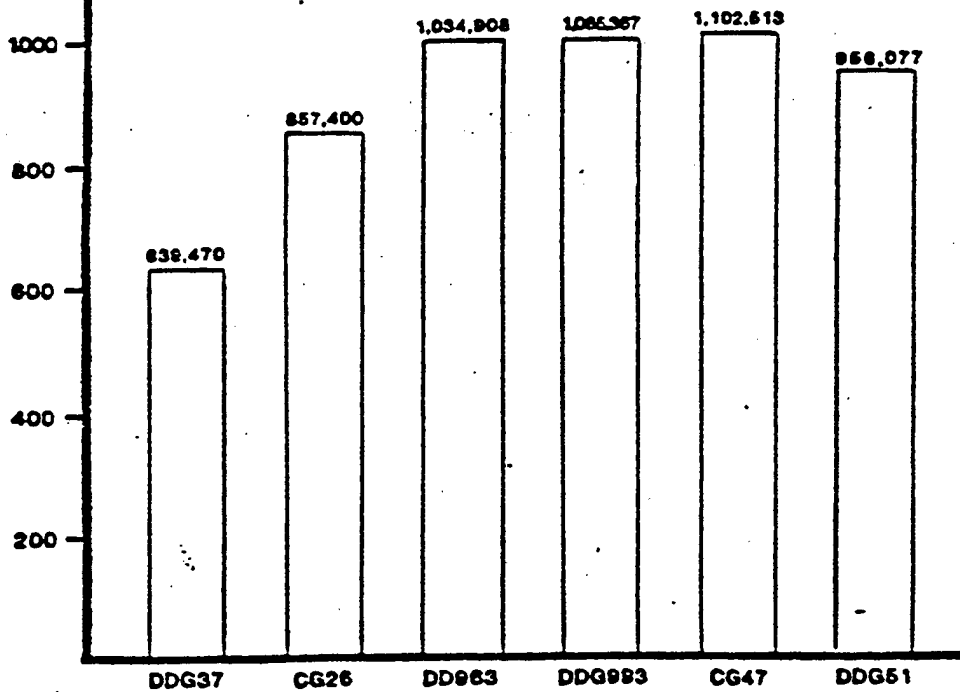


Fig 25 VOLUME - U.S. SHIPS



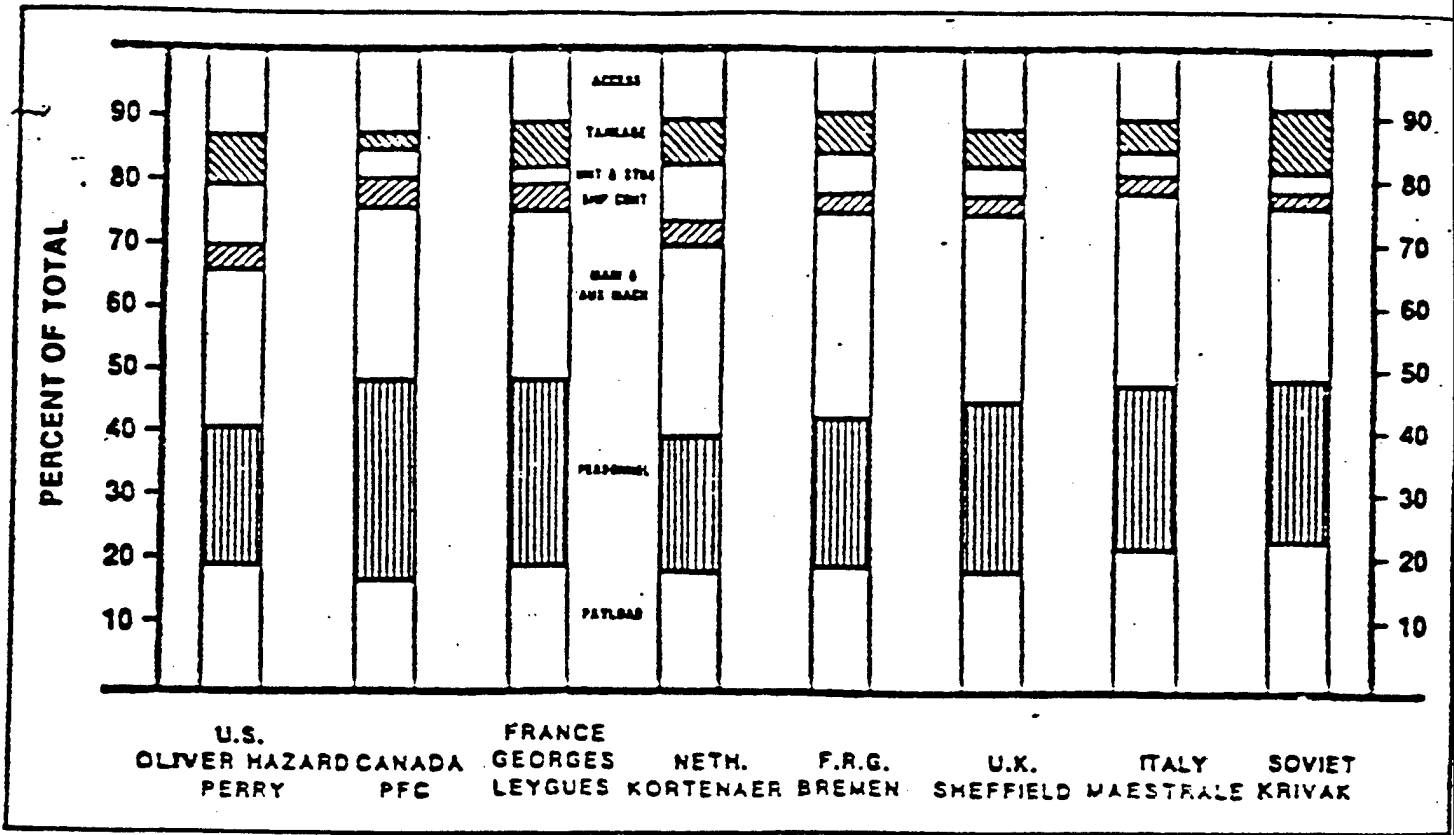
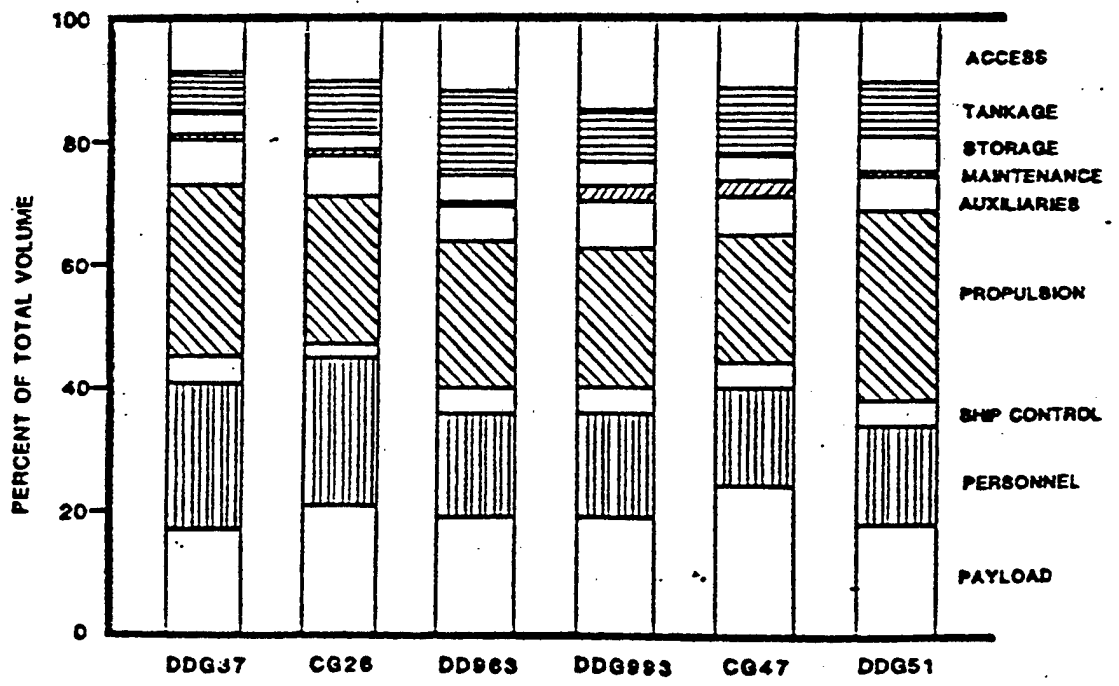


Fig 26 Volume Distributions.

Fig 27 VOLUME DISTRIBUTION - U.S. SHIPS



Micro Flow Diagrams  
(Continued)

V. WEIGHT

Input :  $L, B, T, P_I, N_S, \nabla_D, kW_B, \nabla_T, W_P, N_T, EP, CN, W_{MT}, W_{SD}$

V1.

$$P_I, L, D_P, N_S$$

$$W_{BM} = f(P_I)$$

$$W_{ST} = f(L, D_P, N_S)$$

Propulsion Machinery Weight

$W_2$

V2.

$kW_B$

Electrical Plant Weight

$W_3$

V3.

$W_{PC}, CN$

Communications/Control Weight

$W_4$

V4. and V5.

$\nabla_T, N_T, B, D_{10}$

Auxiliary Systems Weight

$W_5$

Outfit and Furnishing Weight

$W_6$

V6.

$W_{PA}$

Armament Weight

$W_7$

V7.

$CN, \nabla_D, W_{MT}, W_{SD}$   
 $W_{BH}, W_{DH}, W_{FD}$

Hull Structure Weight

$W_1$

Light Ship Weight

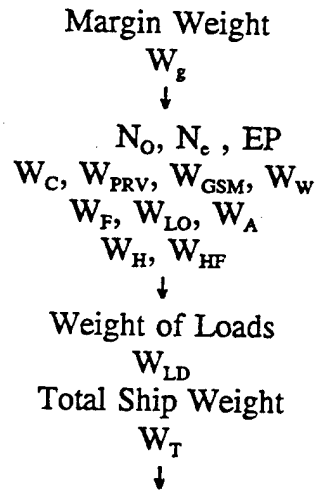
$W_L$

V8.

Margin Policy

Micro Flow Diagrams  
(Continued)

V9.



Useful Output : All Weight Groups, ∇

V. WEIGHT ESTIMATING RELATIONSHIPS

- V1.  $W_{BM} = P_1 \cdot (12.6 + 12.4 \cdot [P_1 \cdot 10^{-5} - 1]^2) / 2240$   
 $W_S = w_s \cdot L \cdot f_1$   
 where  $w_s = 0.356$  tons/ft  
 $f_1 = 0.33$  for single screw ship  
 $W_B = 0.15 \cdot (W_S + W_{PR})$   
 $D_P = (0.6625 \cdot T + 0.0125 \cdot L) \cdot 1.2$   
 $W_{PR} = (0.05575 [D_P]^{(5.497 - 0.0433 D_P)}) \cdot N_S / 2240$   
 $W_{ST} = W_S + W_B + W_{PR}$   
 $W_2 = W_{BM} + W_{ST}$
- V2.  $kW_1 = n \cdot kW_{GEN}$   
 where the following relationship must hold  
 $0.9 \cdot (n - 1) \cdot kW_{GEN} \geq 1.2 \cdot 1.2 \cdot kW_{max\ load}$   
 $kW_1 \geq n \cdot kW_B / (n - 1)$   
 $W_3 = 50 + 0.03214 \cdot kW_1$
- V3.  $W_{PC} = \text{Input}$   
 $W_{CG} = 4.65 \text{ CN}$   
 $W_{CO} = 2.24 \text{ CN}$   
 $W_{CC} = 0.04 (W_{PC} + W_{CG} + W_{CO})$   
 $W_4 = W_{PC} + W_{CG} + W_{CO} + W_{CC} + W_{sw}$
- V4.  $W_5 = 7.72 \times 10^{-8} \cdot \nabla_T^{1.443} + 5.14 \times 10^{-4} \cdot \nabla_T +$   
 $6.19 \times 10^{-4} \cdot \nabla_T^{.7224} + 0.0377 N_T +$   
 $2.74 \times 10^{-4} \cdot P_1 + 113.8 + W_{SS}$
- V5.  $W_{OFH} = 31.4 + 31.87 \times 10^{-5} \cdot \nabla_T$   
 $W_{OFF} = 0.504 \cdot (N_T - 95)$   
 $W_6 = W_{OFH} + W_{OFF}$
- V6.  $W_7 = W_{PA} ; \text{Input}$
- V7.  $W_{BH} = 1.68341 \cdot \text{CN}^2 + 167.1721 \cdot \text{CN} - 23.283$   
 $W_{DH} = f_m \cdot \nabla_D$   
 where  $f_m = \text{deck house material factor which}$   
 for steel is  $1.429 \times 10^{-3}$   
 and for aluminum is  $8.57 \times 10^{-4}$   
 $W_{FD} = 0.0675 \cdot W_{BM} + 0.072 \cdot (W_3 + W_4 + W_5 + W_7)$



Micro Flow Diagrams  
(Continued)

$$W_{MT} = \text{Input}$$

$$W_{SD} = \text{Input}$$

$$W_I = W_{BH} + W_{DH} + W_{FD} + W_{MT} + W_{SD}$$

$$W_L = \sum_{WG=1}^7 W_{WG}$$

V8.  $W_g = W_{\text{margin}} \cdot W_L$

V9.  $W_C = (236 \cdot N_E + 400 \cdot [N_O + 1]) / 2240$

$$W_{PRV} = N_T \cdot (2.8 \cdot EP_{DRY} + 2.2 \cdot EP_{CHL} + 1.3 \cdot EP_{FRZ} + 1.3 \cdot EP_{GSM} + 22.6) / 2240$$

$$W_{GSM} = 9.598 \times 10^{-4} \cdot N_T \cdot EP_{GSM}$$

$$W_W = 0.224 \cdot N_T$$

$W_A, W_H, W_{HF}, W_{LO}$  all input values

$$W_{LD} = W_C + W_{PRV} + W_{GSM} + W_W + W_A + W_H + W_{HF} + W_F + W_{LO}$$

$$W_T = W_L + W_{LD} + W_g$$

# STRUCTURES - HULL GIRDER WEIGHT

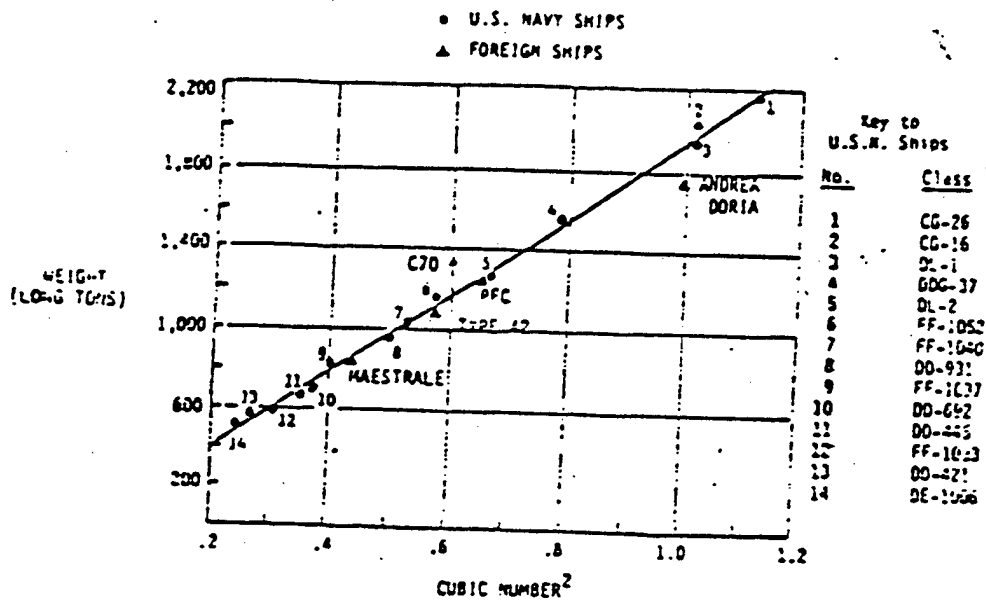
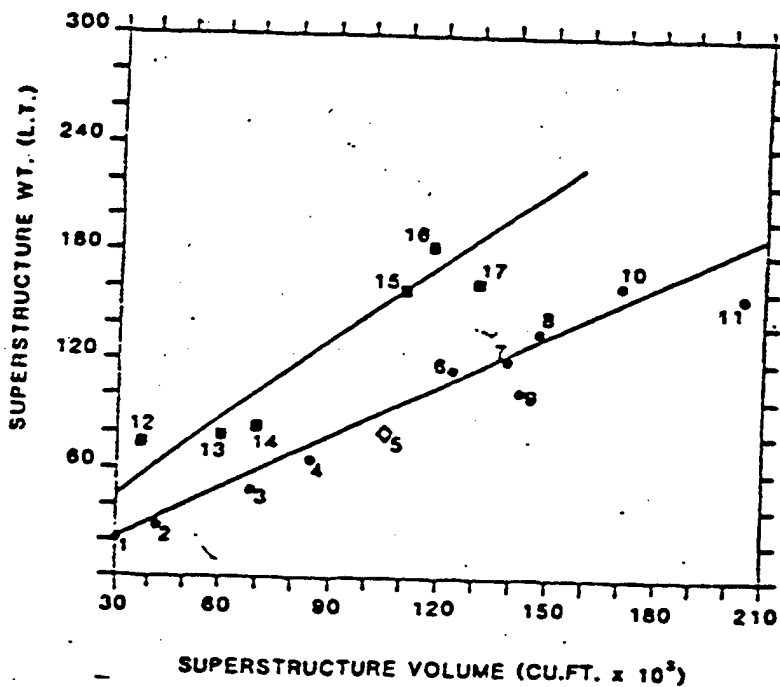


Fig 2 SUPERSTRUCTURE WEIGHT

CLASSIFIED



LEGEND

No.	Ship
1	FF1033
2	FF1037
3	FF1040
4	DD931
5	MAESTRALE
6	DDC2
7	CG(N)35
8	CG26
9	FFG7
10	DDC37
11	CG(N)36
12	FF1006
13	DD445
14	DD692
15	DL2
16	TYPE 42
17	C70

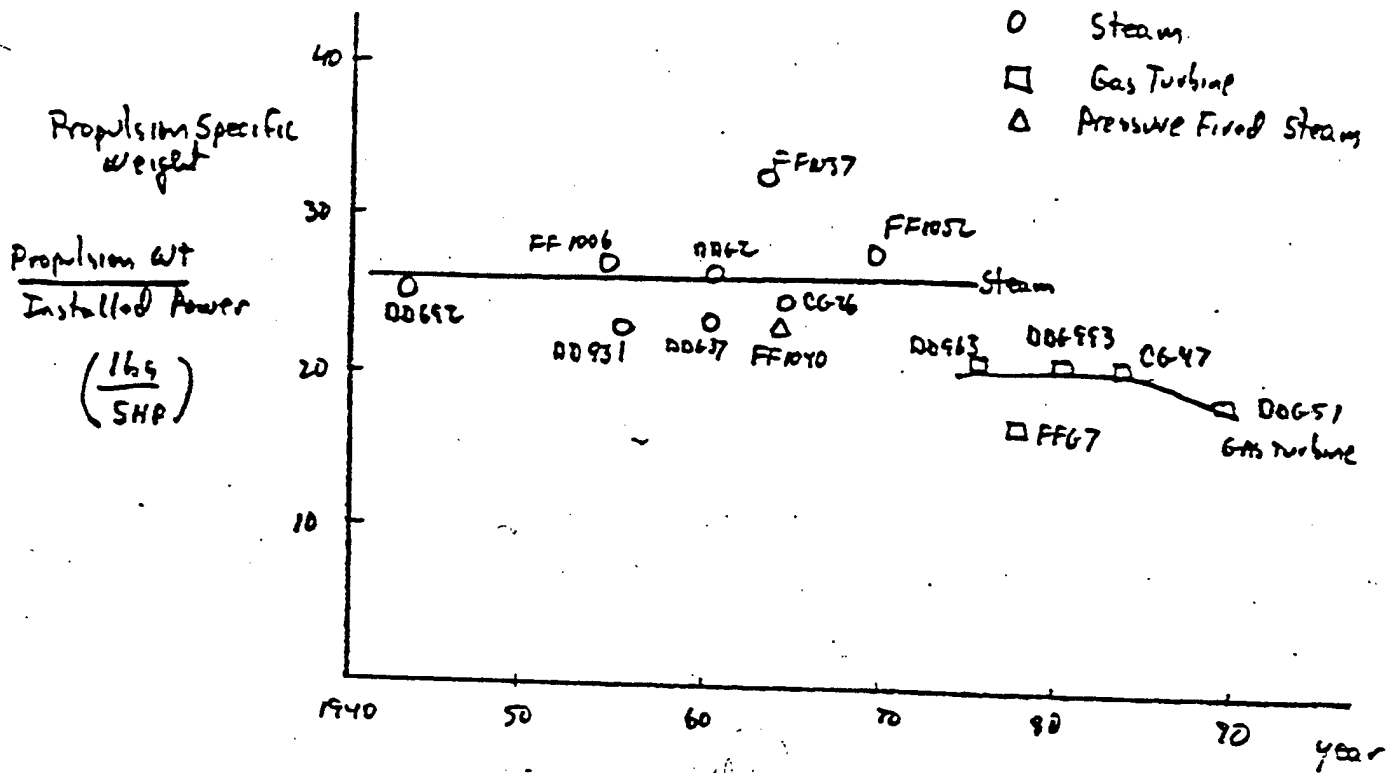


Fig 3.

Fig 4 FRIGATES - PROPULSION WEIGHT

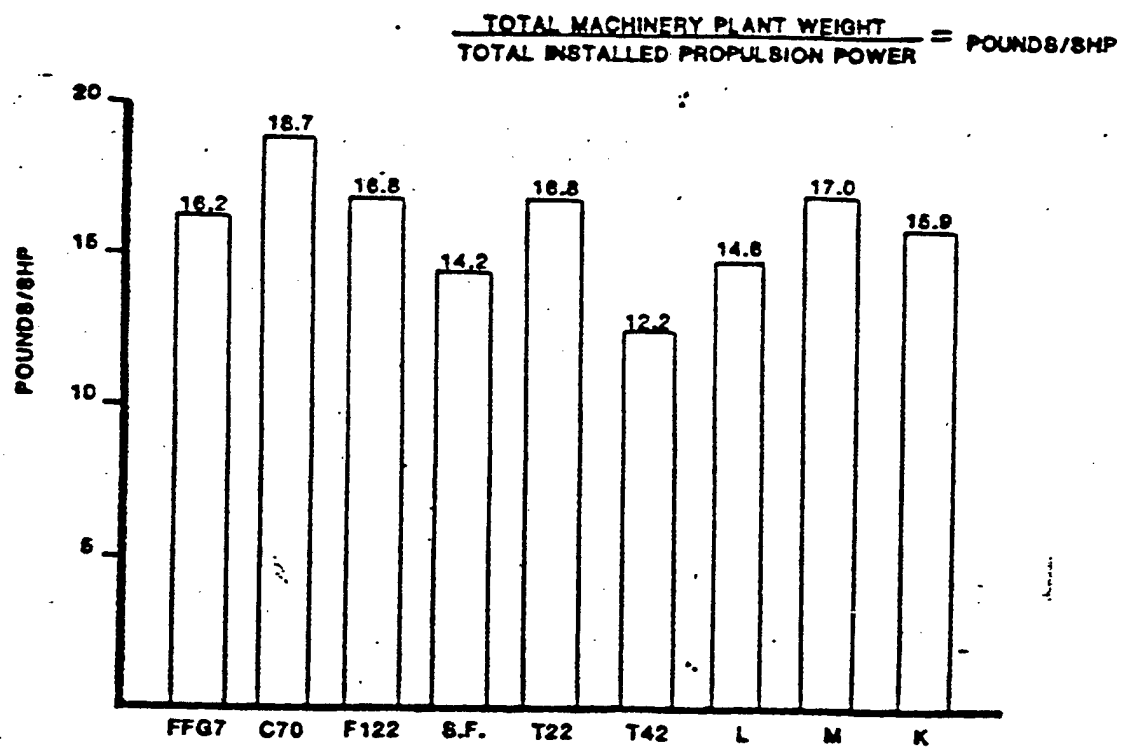


Fig 5

FRIGATES - PAYLOAD WEIGHT DISTRIBUTION

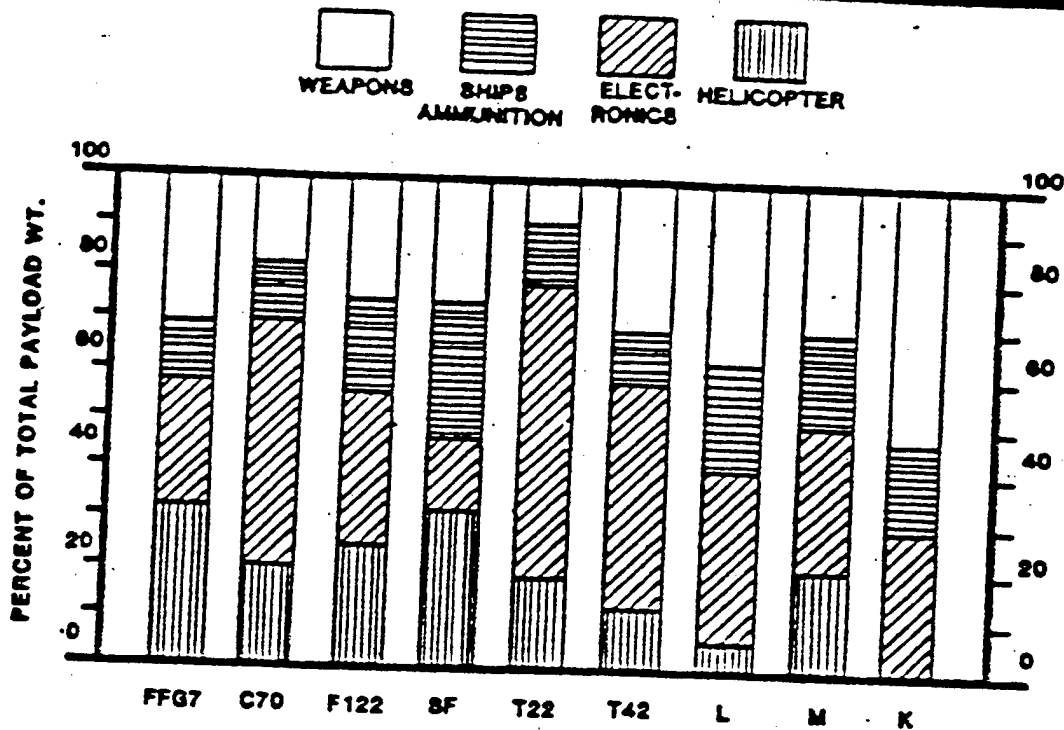


Fig 6 PAYLOAD WEIGHT DISTRIBUTION - U.S. SHIPS

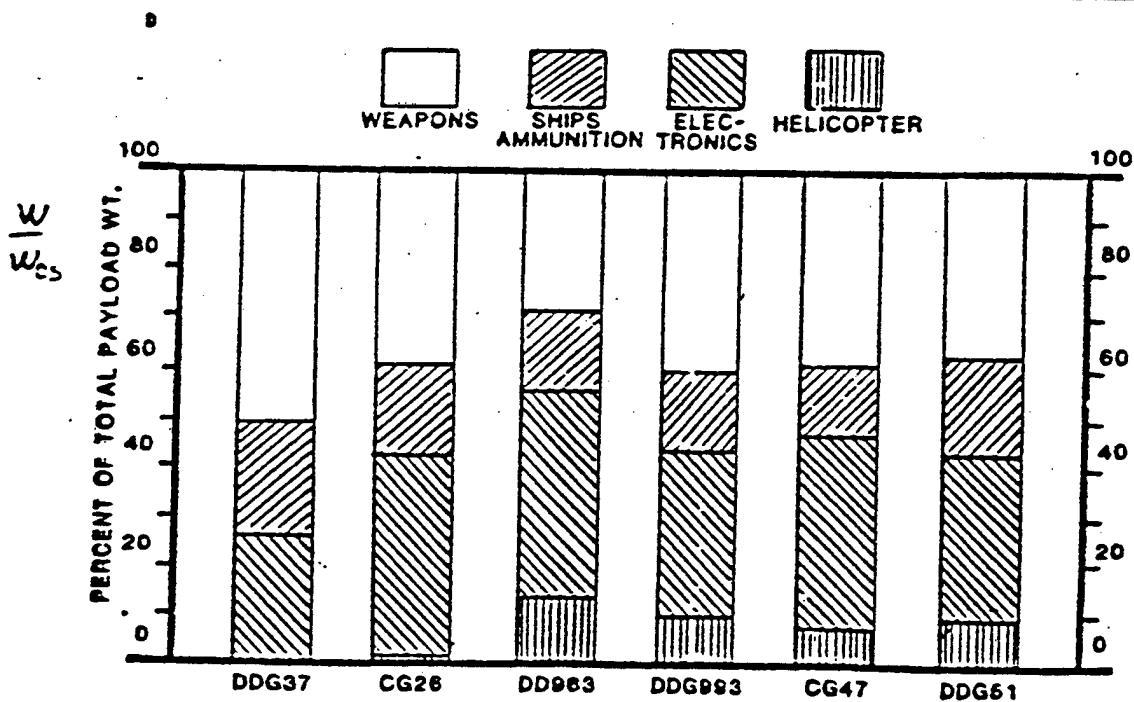


Fig 7

# FRIGATE - SPECIFIC PAYLOAD VOLUME (U)

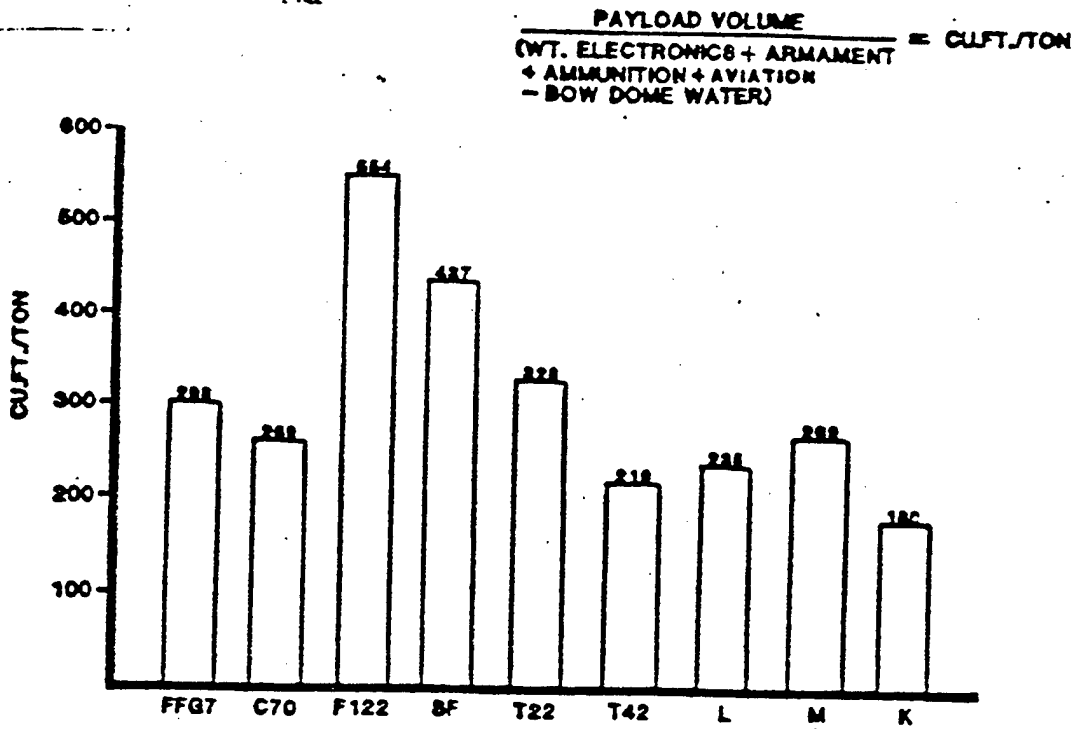
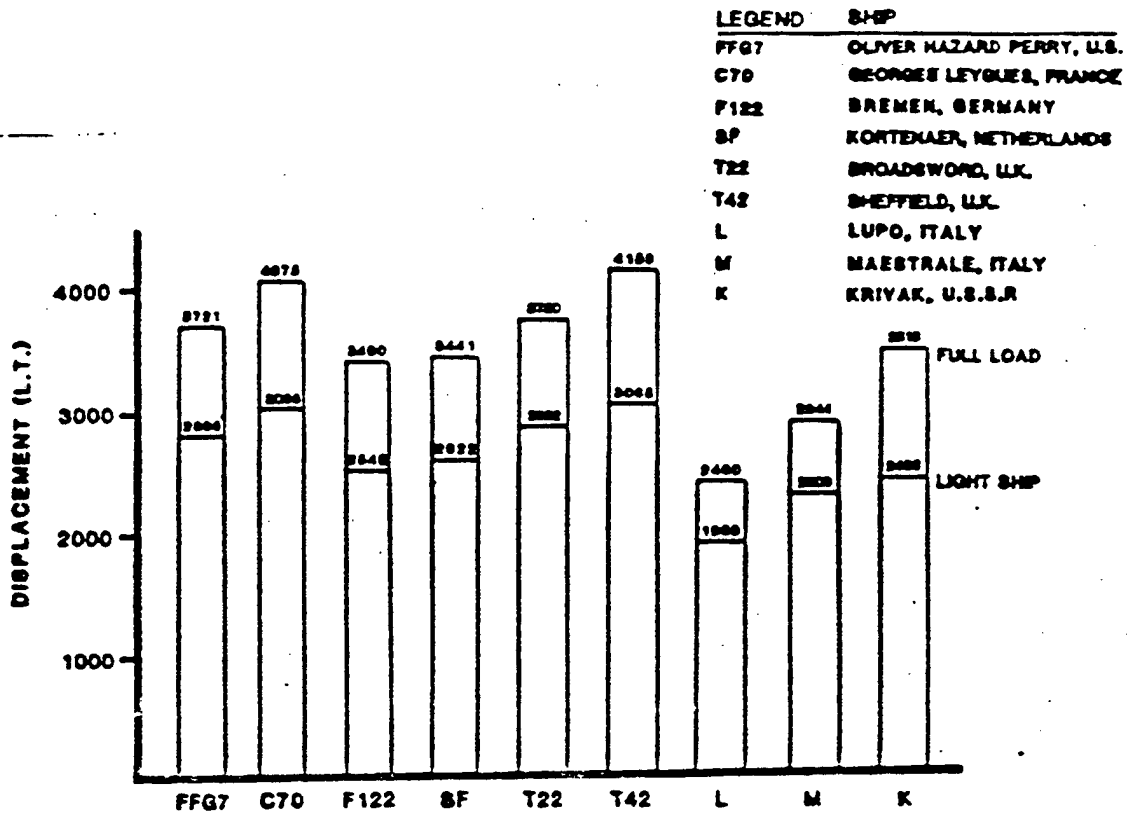


Fig 8 FRIGATES - DISPLACEMENT



4-21

Fig 9 LIGHT SHIP WEIGHT DISTRIBUTION - FRIGATES

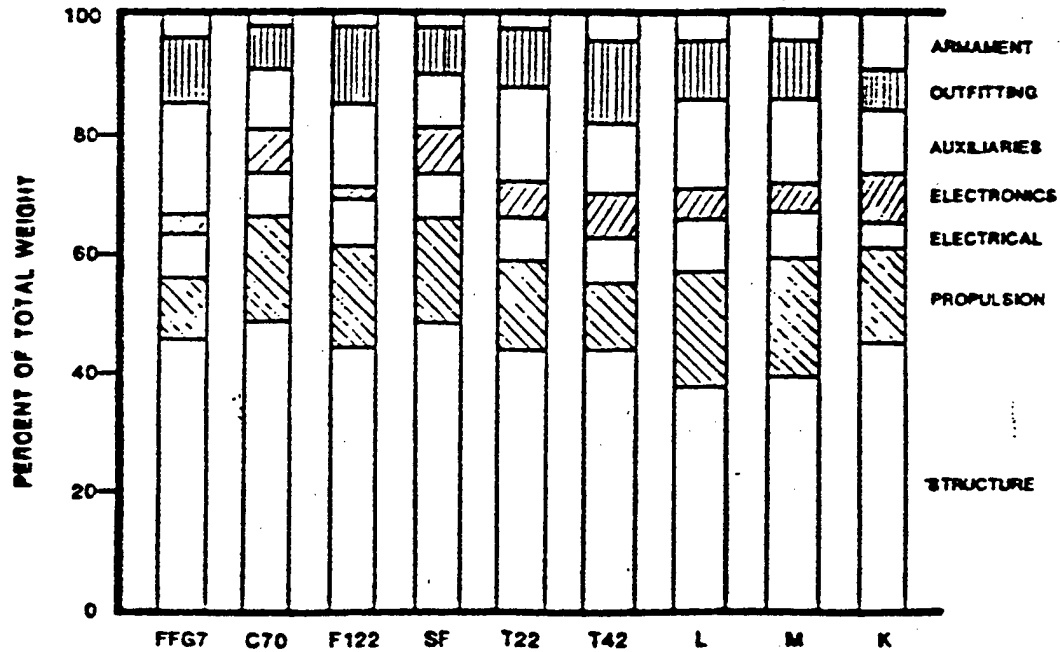


Fig 10 WEIGHT - U.S. SHIPS

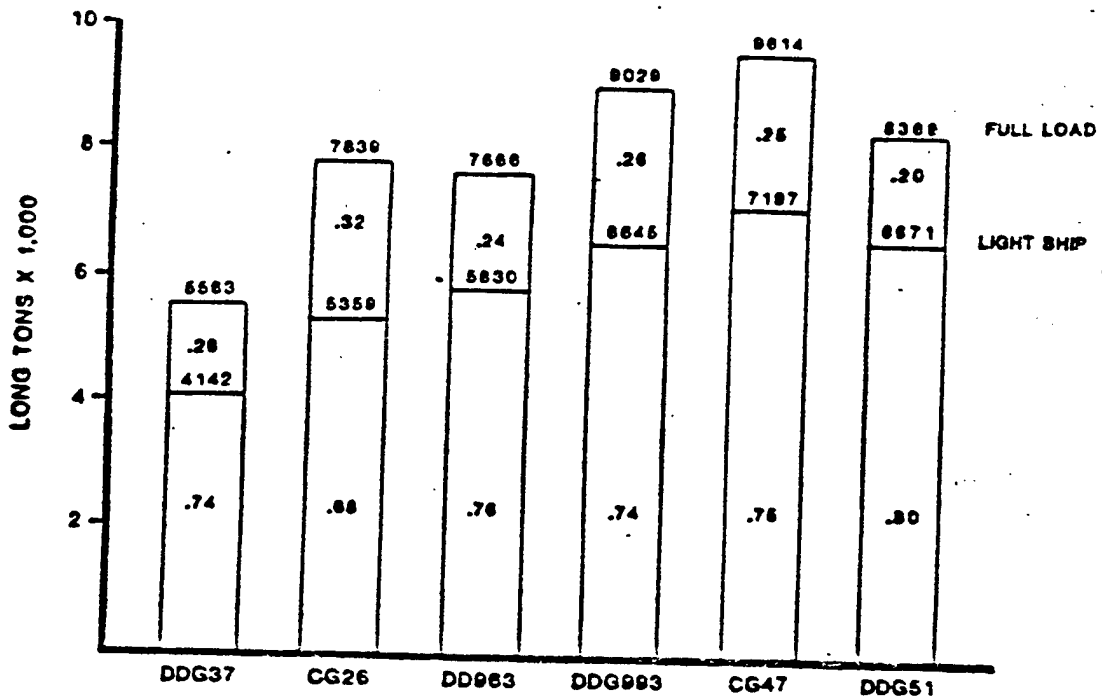
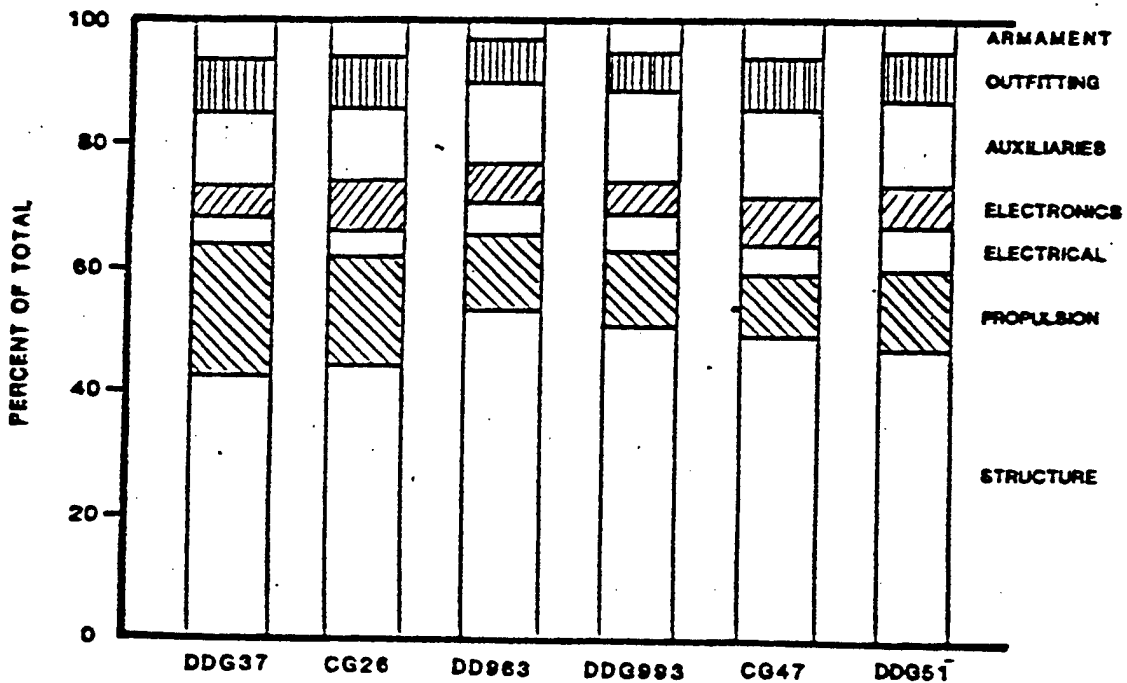


Fig 11 LIGHT SHIP WEIGHT DISTRIBUTION - U.S. SHIPS



Micro Flow Diagrams  
(Continued)

VI. STABILITY

Input :  $D_{AV}$ ,  $\nabla_T$ ,  $\nabla_D$ , L,  $D_{10}$ , T,  $H_{MB}$ , B, Weight Groups

VI1.

Inputs



VCGs of Weight Groups  
VCGs of Loads



VI2.

Moment of Weight Groups  
Weight of Weight groups

$W_{margin}$

$KG_{margin}$



$W_g$

$KG_{Lnm}$

$KG_L$



VI3.

Moment of Loads  
Weight of Loads

$C_P$ ,  $\nabla_T$ , B, L



KG

$C_w$

KB

BM

GM

Useful Output: GM / B



Micro Flow Diagrams  
(Continued)

**VI. STABILITY ESTIMATING RELATIONSHIPS**

**Input Calculations : (all VCGs in feet above baseline)**

<u>SWBS</u>	<u>WEIGHT VARIABLE</u>	<u>VCG FORMULA</u>
1	$W_{BH}$	$VCG_{BH} = 0.527 \cdot D_{AV}$
1	$W_{DH}$	$VCG_{DH} = D_{10} + 2.45 \cdot \nabla_D / (L \cdot B)$
1	$W_{FD}$	$VCG_{FD} = 0.68 \cdot D_{10}$
1	$W_{MT}$	$VCG_{MT} = 2.65 \cdot D_{10}$
1	$W_{SD}$	$VCG_{SD} = -2.5$
2	$W_{BM}$	$VCG_{BM} = 0.55 \cdot D_{10}$
2	$W_{ST}$	$VCG_{ST} = 3.9 + 0.19 \cdot T$
3	$W_3$	$VCG_3 = 0.7 \cdot D_{10}$
4	$W_{SW}$	$VCG_{SW} = -2.5$
4	$W_{PC}$	$VCG_{PC} = \text{Input (Note: use } D_{AV} \text{ to bring to BL)}$
4	$W_{CG}$	$VCG_{CG} = D_{10}$
4	$W_{CO}$	$VCG_{CO} = 5.6 + 0.4625 \cdot D_{10}$
4	$W_{CC}$	$VCG_{CC} = 16$
5	$W_{BA}$	$VCG_{BA} = 1.1 \cdot (D_{10} - 7.4)$
5	$W_{SS}$	$VCG_{SS} = 0.5 \cdot H_{MB}$
6	$W_{OFH}$	$VCG_{OFH} = 0.805 \cdot D_{10}$
6	$W_{OFF}$	$VCG_{OFF} = 8 + 0.71 \cdot D_{10}$
7	$W_7$	$VCG_7 = \text{Input (Note: use } D_{AV} \text{ to bring to BL)}$
L	$W_C$	$VCG_C = 0.746 \cdot D_{10}$
L	$W_{PRV}$	$VCG_{PRV} = 10$

Micro Flow Diagrams  
(Continued)

L	$W_{GSM}$	$VCG_{GSM} = 20$
L	$W_w$	$VCG_w = 7.5$
L	$W_A$	$VCG_A = \text{Input (Note: use } D_{AV} \text{ to bring to BL)}$
L	$W_{LO}$	$VCG_{LO} = 0.728 \cdot D_{10}$
L	$W_F$	$VCG_F = 7.5$
L	$W_{HF}$	$VCG_{HF} = 7.5$
L	$W_g$	$VCG_g = \text{VCG light ship} = M_L / W_L$
L	$W_H$	$VCG_H = \text{Input (Note: use } D_{20} \text{ to bring to BL)}$

VI1.  $M_{WG} = W_{WG} \cdot VCG_{WG}$

VI2.  $M_L = \sum M_{WG}$   
 $W_L = \sum W_{WG}$   
 $VCG_g = \text{VCG light ship} = M_L / W_L$   
 $KG_{Lnm} = VCG_g$   
 $KG_L = KG_{Lnm} \cdot (1 + KG_{margin})$

VI3.  $M_{LD} = \sum M_{\text{individual loads}}$   
 $KG_{LD} = M_{LD} / W_{LD}$   
 $M_T = W_{LD} \cdot KG_{LD} + KG_L \cdot (W_L + W_g)$   
 $KG = M_T / W_T$   
 $C_w = 0.236 + 0.836 \cdot C_p$   
 $C_m = C_x$   
 $KB = (T/3) \cdot (2.5 - C_p \cdot C_m / C_w)$ , Morrish's Formula  
 $C_{IT} = -.497 + 1.44 \cdot C_w$   
 $BM = (L \cdot B^3 \cdot C_{IT}) / (12 \cdot \nabla_{HV})$   
 $GM = KB + BM - KG$

**Final Check : GM/B must be within design range.**

TAYLOR STANDARD SERIES  
MADE EASY

PURPOSE

GIVEN SHIP PARAMETERS, PREDICT  
EFFECTIVE HOUSEPOWER USING  
TAYLOR STANDARD SERIES

REFERENCE

DESIGN DATA SHEET 051-1 OF 15 MAY 1984

THIS DDS USES A REANALYSIS OF TAYLOR'S  
ORIGINAL DATA BY GERTLER, AND ADDS MANY FACETS  
OF ACTUALLY PERFORMING A POWERING CALCULATION.

METHOD

USE THE ATTACHED TABLE TO STEP  
THROUGH THE CALCULATIONS

Taylor Series  
(continued)

CODE	VARIABLE	FORMULA or EXPLANATION of VARIABLE	VALUE
1	L	Length on Waterline (LBP)	
2	B <sub>X</sub>	Beam at maximum section on design waterline	
3	T <sub>X</sub>	Draft to design waterline at maximum section	
4	Δ <sub>FL</sub>	Total displacement at draft T <sub>X</sub>	
5	Δ <sub>APP</sub>	Displacement of appendages	0
6	Δ <sub>BH</sub>	Bare hull displacement (without appendages)	
7	C <sub>X</sub>	Maximum section coefficients	
8	C <sub>P</sub>	Prismatic Coefficient	
9	B <sub>X</sub> /T <sub>X</sub>	Beam to Draft ratio	
10	∇ <sub>BH</sub>	Bare hull displacement volume {6}•{35}	
11	C <sub>V</sub>	Bare hull volumetric coefficient {10}/{1} <sup>3</sup>	
12	D <sub>P</sub>	Propeller diameter, (0.6625•{3} + 0.0125•{1})• 1.2	
13		Number, type of Propellers	
14	A <sub>V</sub>	Frontal area of the ship to predict wind resistance	
15	T <sub>SW</sub>	Temperature of seawater	59 °F
16	ρ <sub>SW</sub>	Density of seawater at given temperature	1.9905 lbf•sec <sup>2</sup> /ft <sup>4</sup>
17	ν <sub>SW</sub>	Kinematic viscosity of seawater at given temperature	1.2817x10 <sup>-5</sup> ft <sup>2</sup> /sec
18	C <sub>A</sub>	Correlation Allowance	0.0005
19	$\frac{C_{S(SHIP)}}{C_{S(TSS)}}$	Ratio of wetted surface coefficients	1.0
20	C <sub>S (TSS)</sub>	Wetted surface coefficient of TSS, Use figure 1 with C <sub>P</sub> and B/T	
21	C <sub>s(ship)</sub>	Wetted Surface coefficient of ship (if known)	unknown

Taylor Series  
(continued)

CODE	VARIABLE	FORMULA or EXPLANATION of VARIABLE	VALUE
22	$CD_{(APP)}$	Drag coefficient of appendages. Use figure 2 or 3 with L	
23	$C_{AA}$	Air drag coefficient	0.0
24	PMF	Power Margin factor - Depends on design stage, usually 10% in early stages	1.10
25	$S_{(TSS)}$	Wetted Surface (SHIP), $\{20\} \cdot \{10\}^{0.5} \cdot \{1\}^{0.5}$	
26	$S_{(SHIP)}$	Wetted Surface (SHIP) $\{25\} \cdot \{19\}$	
a	V	Ship speed (knots), (endurance, threshold, and goal)	1. 2. 3.
b	$V/\sqrt{L}$	Speed to length ratio, $\{a\} / \{1\}^{0.5}$	1. 2. 3.
c and 27	$R_N$	Reynold's Number $1.689 \cdot \{1\} \cdot \{a\} / \{17\}$	1. 2. 3.
d and 28	$C_F$	Frictional resistance Coefficient $0.075 / \{[\log_{10}(\{27\}) - 2]^2\}$	1. 2. 3.
e and 29	$R_F$	Frictional Resistance, $1.4264 \cdot \{16\} \cdot \{26\} \cdot \{a\}^2 \cdot [\{18\} + \{28\}]$	1. 2. 3.
f	$C_{R 2.25}$	Use Taylor Standard Series with $\{8\}$ , $\{11\}$ and $\{b\}$ @ B/T = 2.25	1. 2. 3.
g	$C_{R 3.00}$	Use Taylor Standard Series with $\{8\}$ , $\{11\}$ and $\{b\}$ @ B/T = 3.00	1. 2. 3.

Taylor Series  
(continued)

CODE	VARIABLE	FORMULA or EXPLANATION of VARIABLE	VALUE
h	$C_{R 3.75}$	Use Taylor Standard Series with {8} , {11} and {b} @ B/T = 3.75	1. 2. 3.
31		Form Factor $\frac{4}{3} \left[ \frac{Bx}{Tx} - 3 \right]$	
i		$(\{h\} - \{f\}) / 2$	1. 2. 3.
j		$[ (\{f\} + \{h\}) / 2 ] - \{g\}$	1. 2. 3.
k		$\{31\} \cdot \{i\}$	1. 2. 3.
l		$\{31\}^2 \cdot \{j\}$	1. 2. 3.
m and 30	$C_{R(TSS)}$	Residuary resistance Coefficient, $\{g\} + \{k\} + (\{31\}^2 \times \{j\})$	1. 2. 3.
n and 32	$R_{R(TSS)}$	Residuary Resistance (TSS), $1.4264 \times (\{16\} \cdot \{25\} \cdot \{m\} \cdot \{a\}^2)$	1. 2. 3.
o	WCF	Worm Curve Factor, use figures 4 through 9 with {b}	1. 2. 3.
p	$R_R$	Residuary resistance (ship), $\{n\} \cdot \{o\}$	1. 2. 3.

Taylor Series  
(continued)

CODE	VARIABLE	FORMULA or EXPLANATION of VARIABLE	VALUE
q	$R_T$	Total Resistance, $\{e\} + \{p\}$	1. 2. 3.
r	$P_E$	Effective Horsepower, $\{a\} \cdot \{q\} / 325.6$	1. 2. 3.
s and 33	$P_{E(APP)}$	Appendage Drag, horsepower, $\{1\} \cdot \{12\} \cdot \{a\}^3 \cdot \{22\}$	1. 2. 3.
t and 34	$P_{E(AA)}$	Air Drag, horsepower, $\{14\} \cdot \{23\} \cdot \{a\}^2 / 96,500$	1. 2. 3.
u and 35	$P_{E(MISC)}$	Miscellaneous drag, horsepower,	1. 0.0 2. 0.0 3. 0.0
v	$\sum P_E$	Sum of Effective Horsepowers, $\{r\} + \{s\} + \{t\} + \{u\}$	1. 2. 3.
w	EHP	Total Effective Horsepower, $\{v\} \cdot \{24\}$	1. 2. 3.
x and 36	PC	Propulsive Coefficient, EHP/SHP	0.65
y	$P_e$ $P_{S_{threshold}}$ $P_{S_{goal}}$	Shaft Horsepower, $\{w\} / \{x\}$	1. 2. 3.
	$P_{I_{r_{threshold}}}$ $P_{I_{r_{goal}}}$	Needed Installed Shaft Horsepower $\{y\} \cdot 1.25$	2. 3.
	$P_I$	Total Installed Shaft Horsepower	

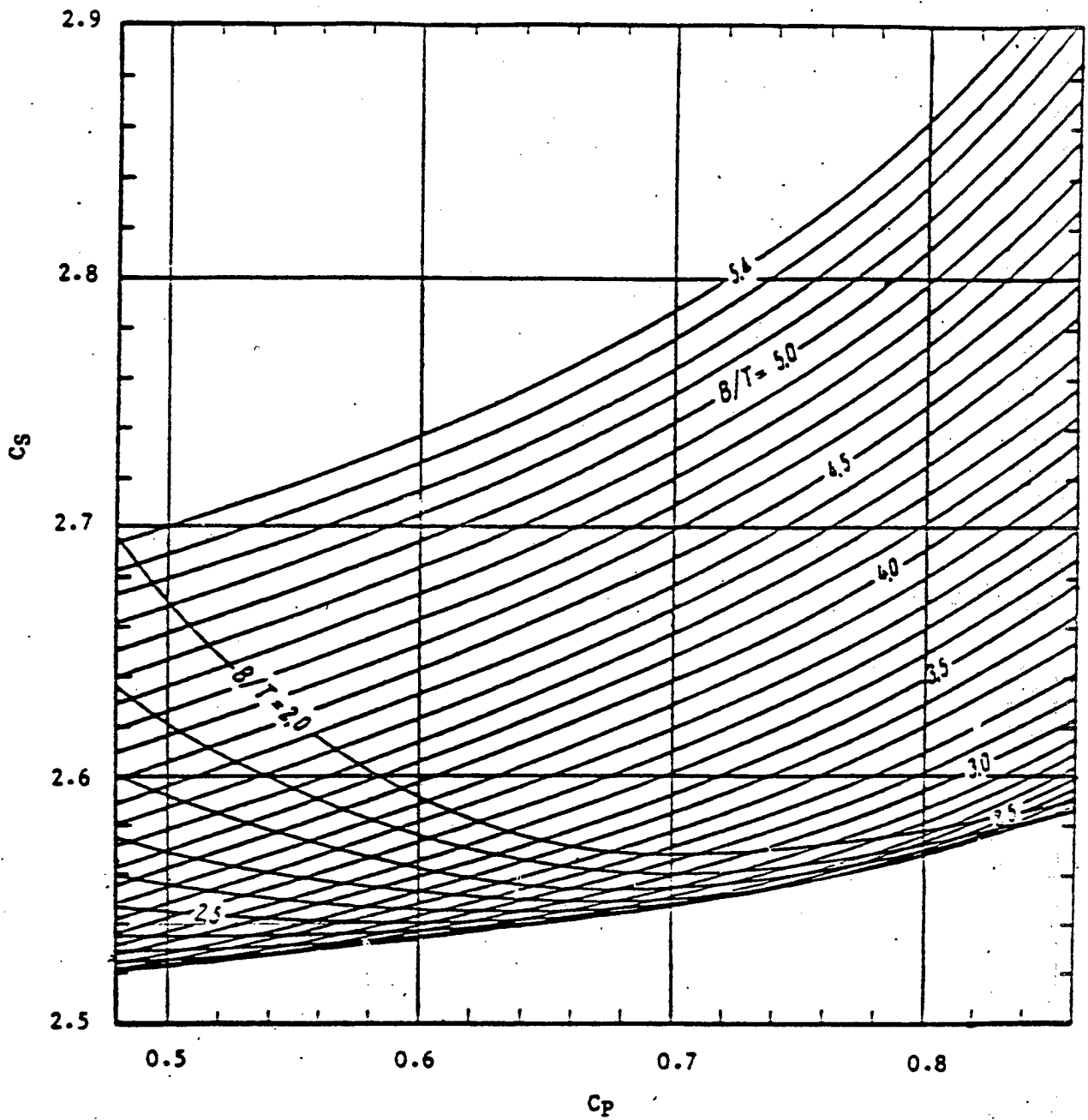
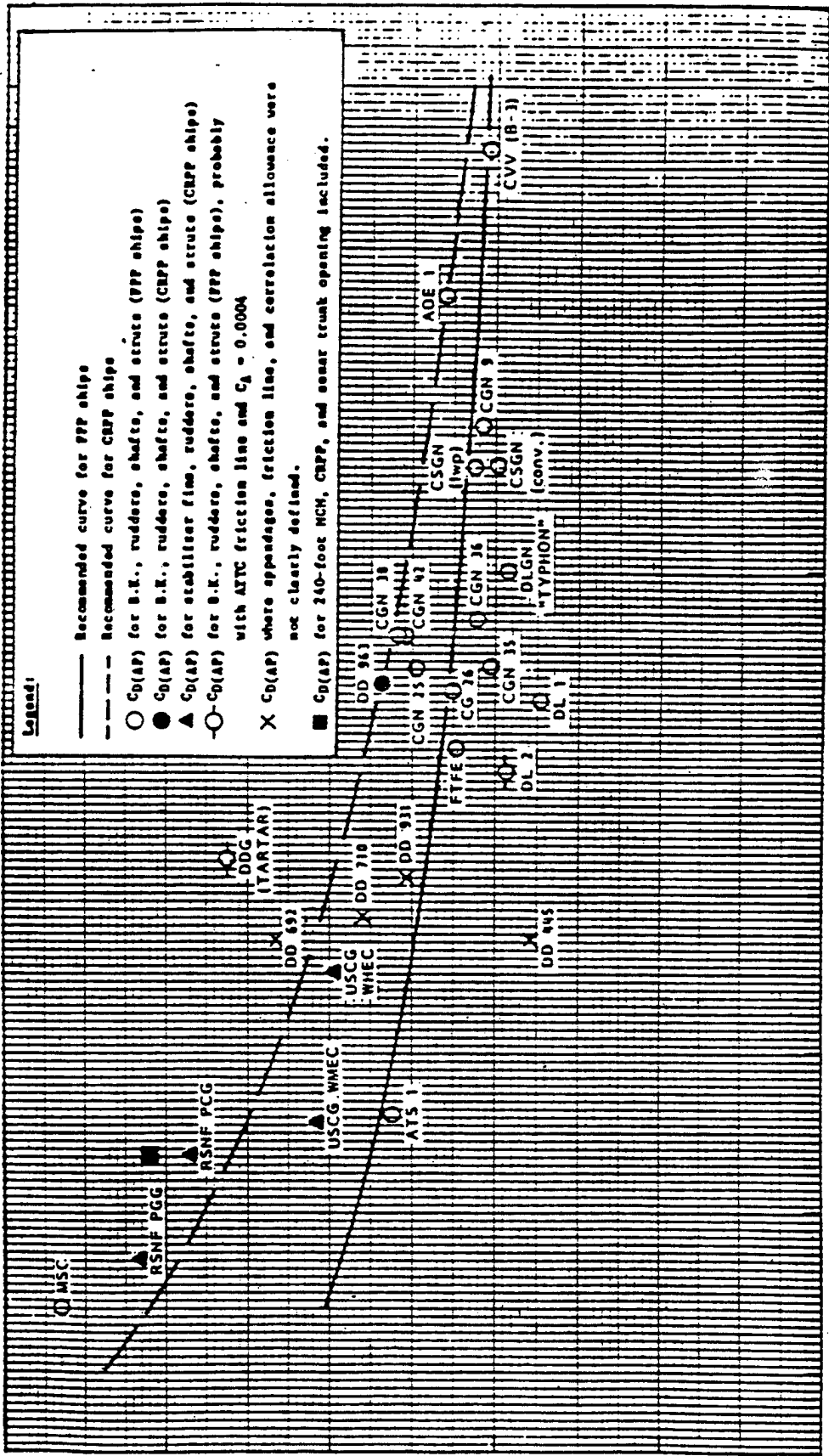


Figure 1 : Surface Coefficients  $C_s = S / (Vol \cdot L_{WL})^{0.5}$  for the Taylor Standard Series





$L/DL \times 10^{-2}$  (feet)

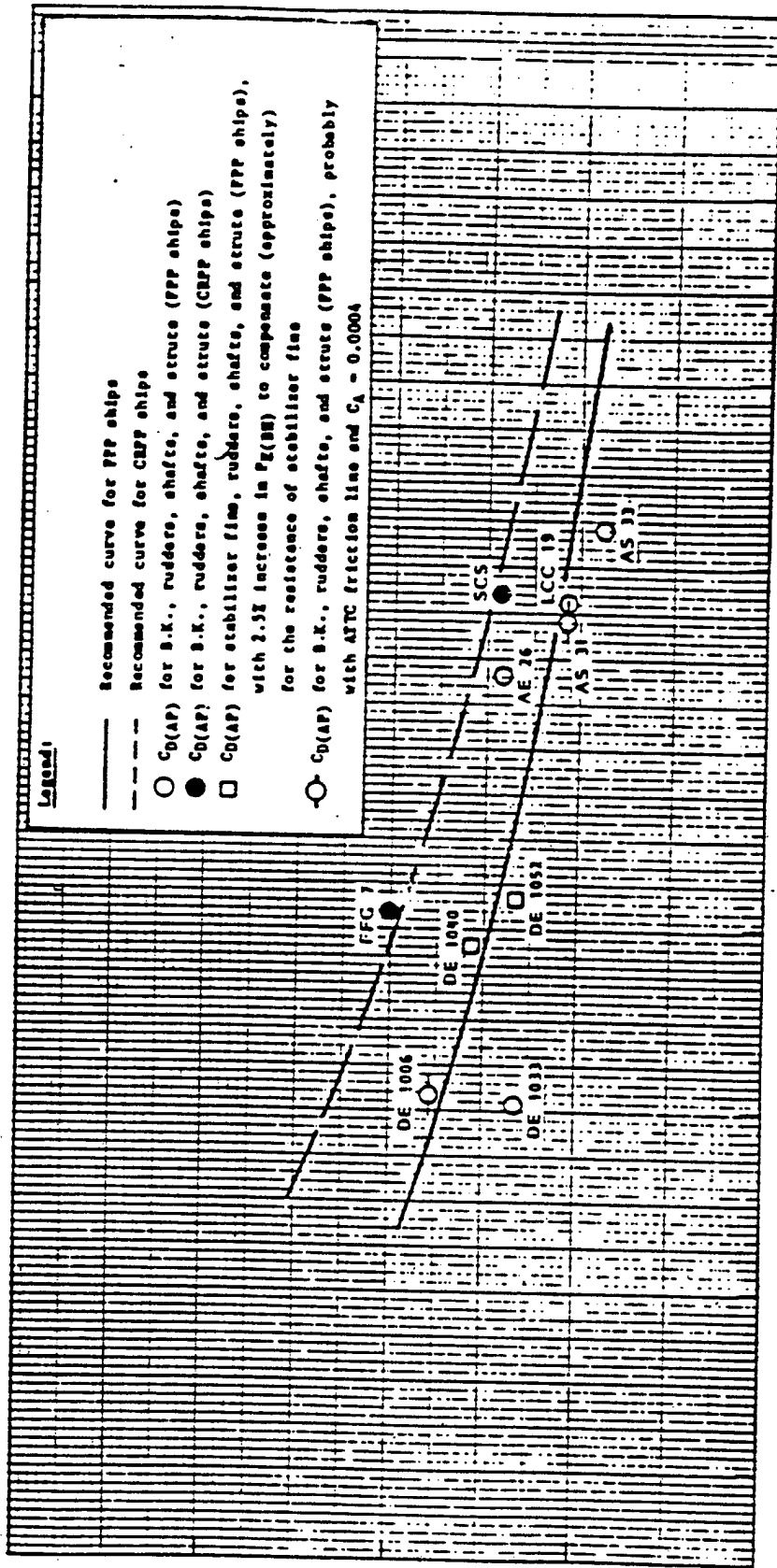
$$C_{DAP} (\times 10^5) = \left( \frac{P_{EAP}}{L_{VL} \cdot T_x \cdot V_S^3} \right) (\times 10^5) / \left( \frac{D_p}{T_x} \right) \left\{ \frac{hp^1}{ft^2 \cdot knots^3} \right\}$$

Figure 2 : Appendage Drag Coefficients For Twin-Screw Naval Ships With Strut-Supported Shafts  
Sheet 1 of 2 : Plot

Notes:

1.  $C_D(AP)$  values based on PE data calculated with ITTC friction line and  $C_A = 0.0005$ , except as noted.
2. When selecting the recommended curves for FPP ships, the "X" points were ignored.
3. When selecting the recommended curve for CRPP ships, the  $C_D(AP)$  values for PGG and PGG were given more "weight" than  $C_D(AP)$  values for WMEC and WMEC.
4. The two CSGN points represent model test data for two difference hull forms.
5. Compared to the typical  $D_p/T_x$  value of ships represented on this plot, the  $D_p/T_x$  value of the AOE 1 is small.

$$C_{DAP} (\times 10^5) = \left( \frac{P_{EAP}}{L_{WL} \cdot T_x \cdot V_s^3} \right) - \left( \frac{D_p}{T_x} \right) \left( \frac{hp^1}{ft^2 \cdot knots^3} \right)$$



1 2 3 4 5 6 7 8

$L_{WL} \times 10^{-2}$  (feet)

Figure 3 : Appendage Drag Coefficients for Single-Screw Naval Ships With Strut-Supported Shafts

Sheet 1 of 2 : Plot

Notes:

1.  $C_{D(AP)}$  values based on  $P_g$  data calculated with ITTC friction line and  $C_A = 0.0005$ , except as noted.
2.  $C_{D(AP)}$  value for the SCS is based on only three  $P_g(AP)$  values at closely spaced speeds.
3.  $C_{D(AP)}$  value for the DE 1006 may include the effect on appendage resistance of two small sound domes.
4.  $C_{D(AP)}$  value for the PFG 7 includes the effect on appendage resistance of a skeg and a small, keel-mounted sound dome.
5. Compared to the typical  $D_p/T_x$  value of ships represented on this plot, the  $D_p/T_x$  value of the AE 26 is small.

Figure 3 : Sheet 2 of 2 : Notes

Taken From:  
 "Residuary Resistance Data for US  
 Navy Destroyer - Type Hull Form 5"  
 UNRSEA Report - 3213-80-27, Sec A80.

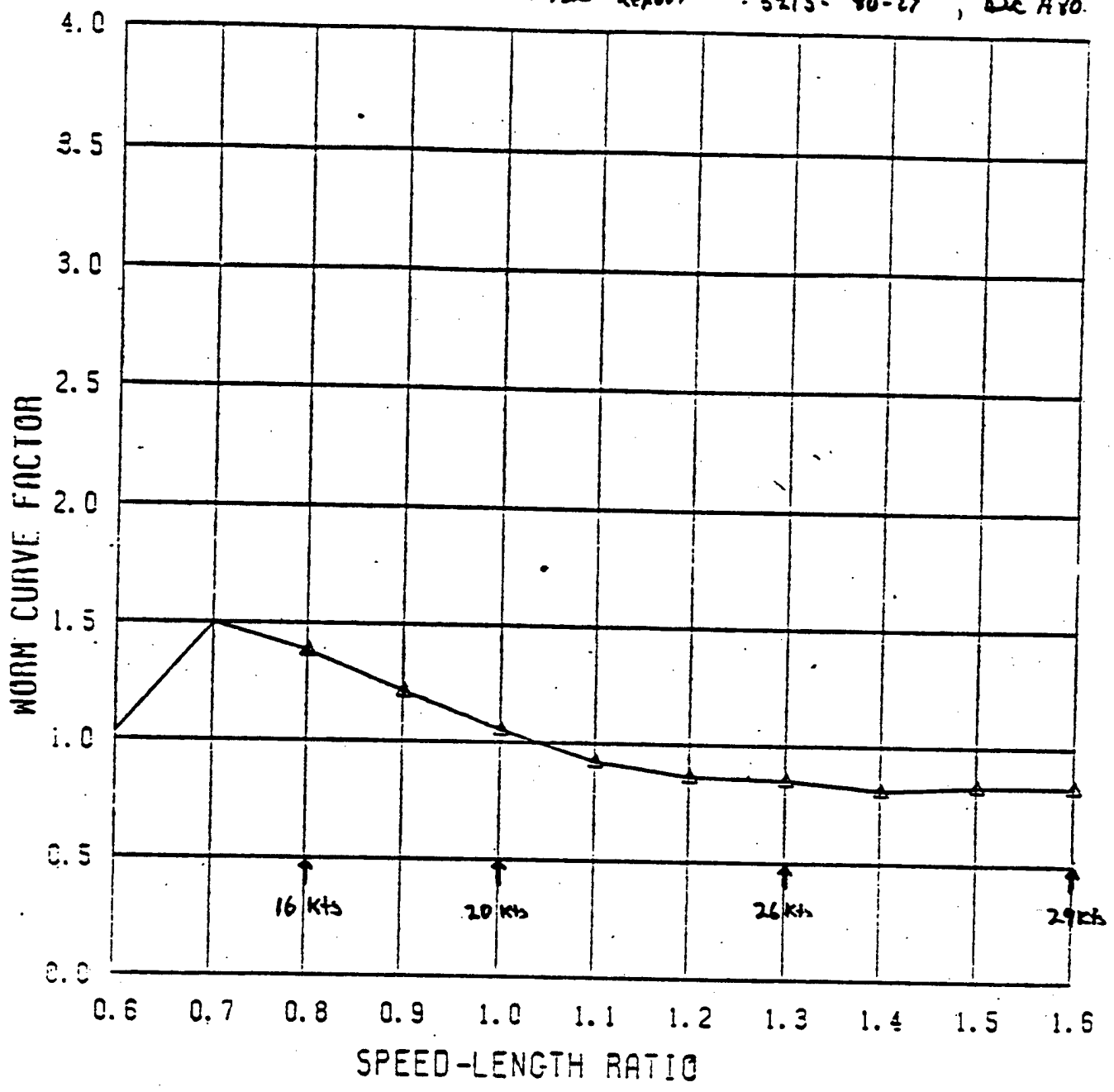


Figure 4 : Worm Curve of FFG-7 Hull Form

—▲— MODEL 5279

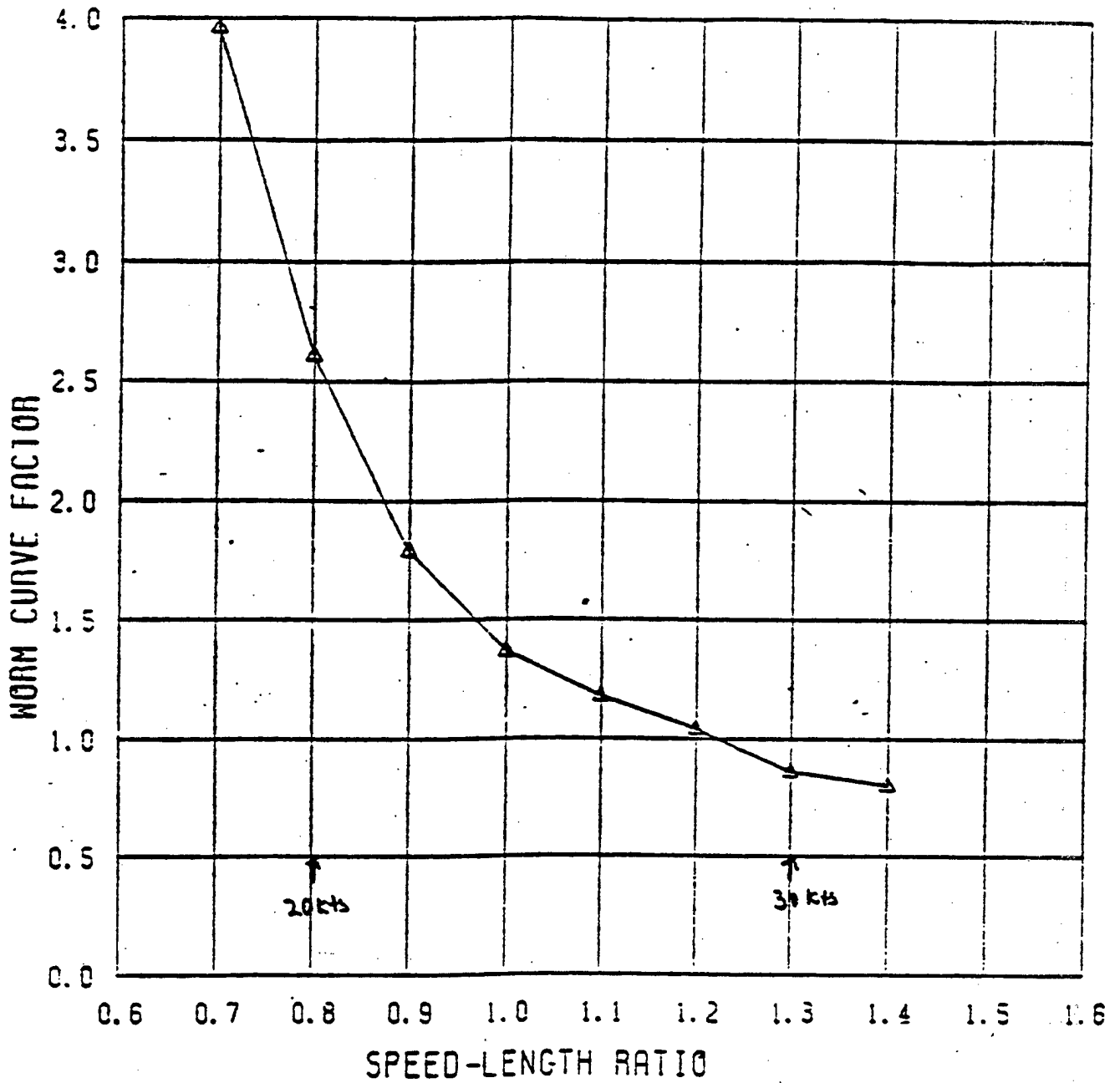


Figure 5 : Worm Curve of DD-963 Hull Form with bow mounted AN/SQS-26 sonar dome

—▲— MODEL 5265-1

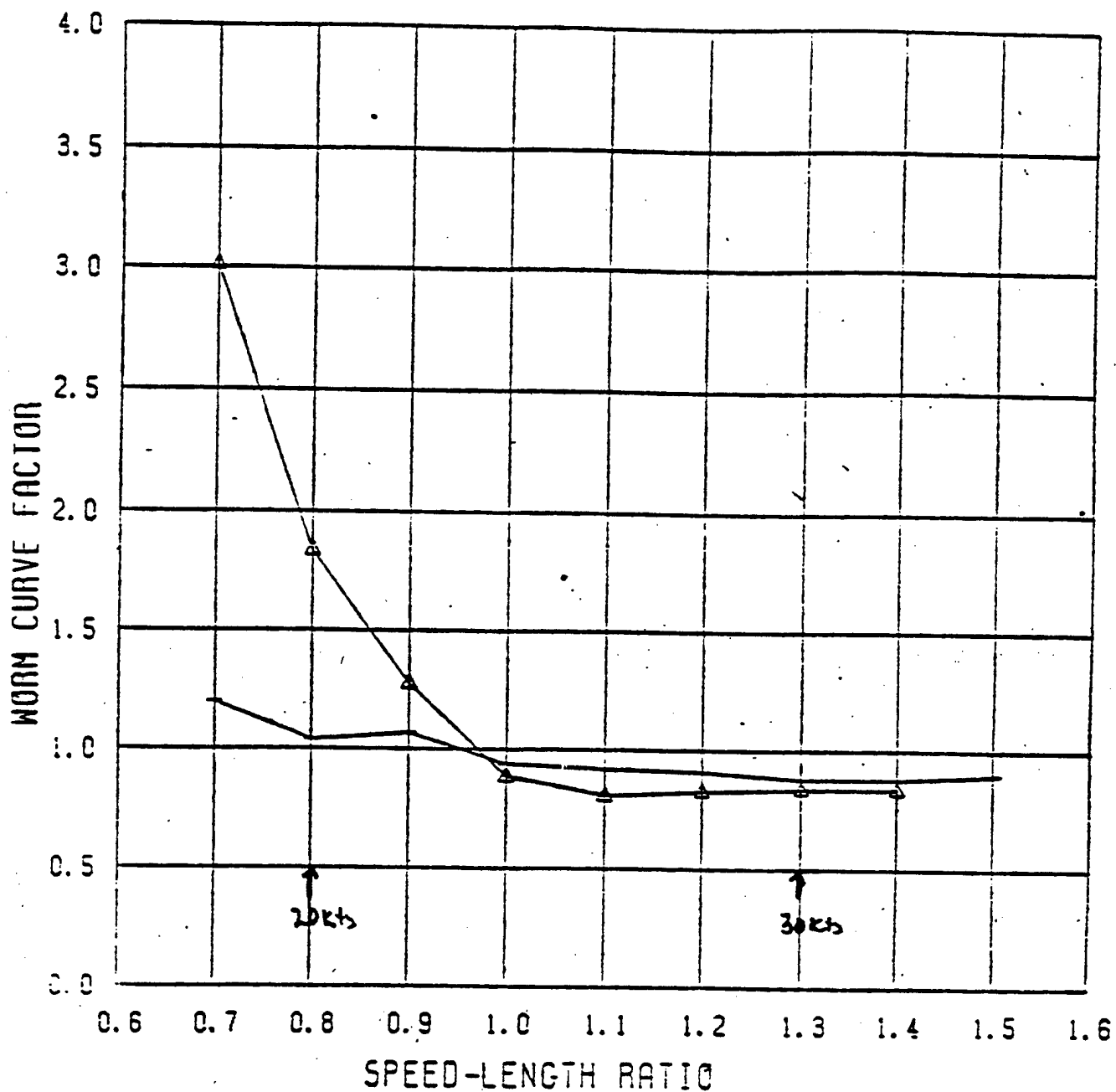


Figure 6 : Worm Curve of CG-26 Hull Form with and without bow mounted AN/SQS-26 sonar dome

—▲— MODEL 4858-1 (WITH DOME)  
 —+— MODEL 4858 (W/O DOME)

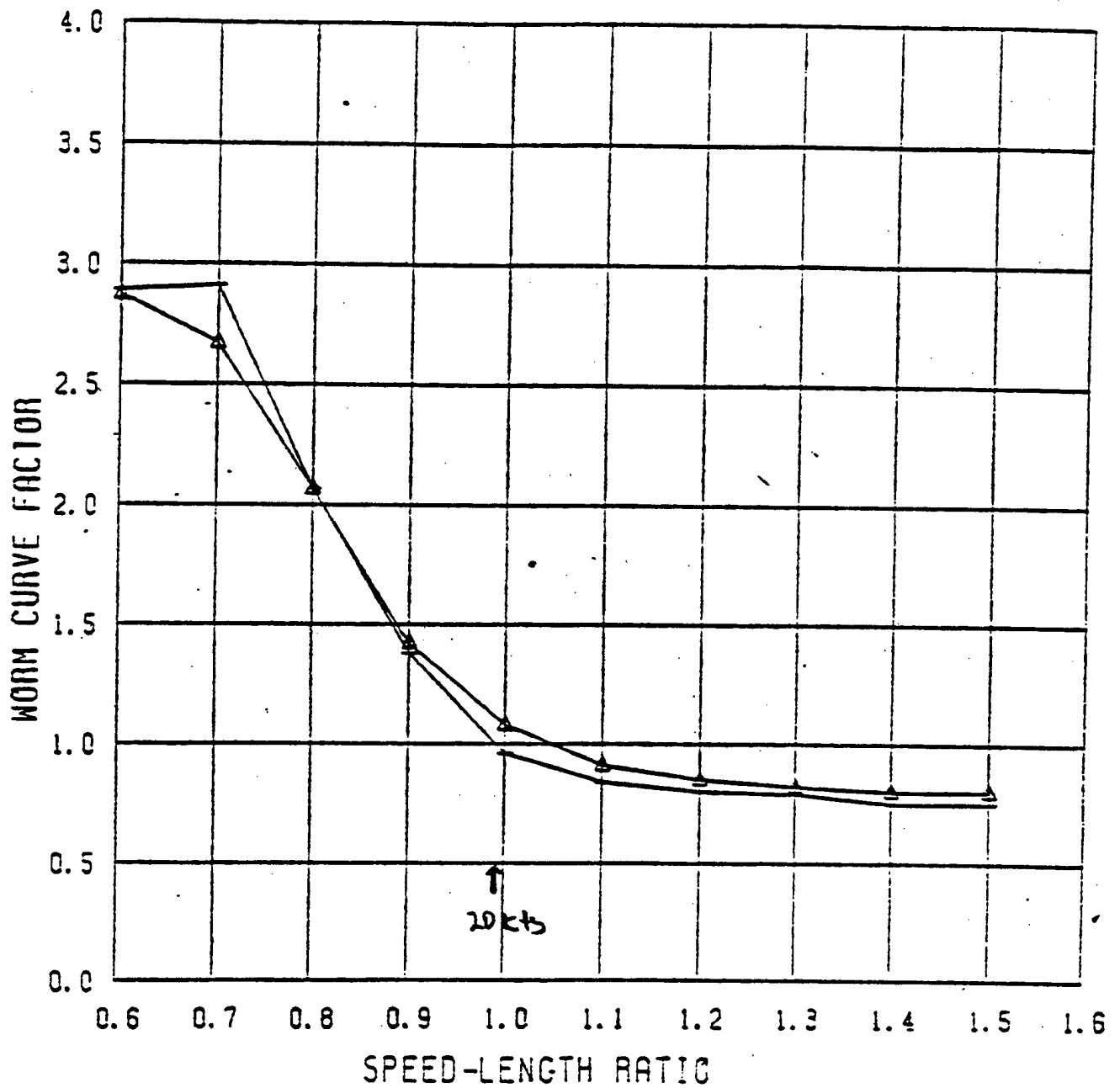


Figure 7 : Worm Curve of DDGX Cruise Variant and Seakeeping Variant Hull Forms both with AN/SQS-26 sonar dome

—▲— MODEL 5403  
 —+— MODEL 5404



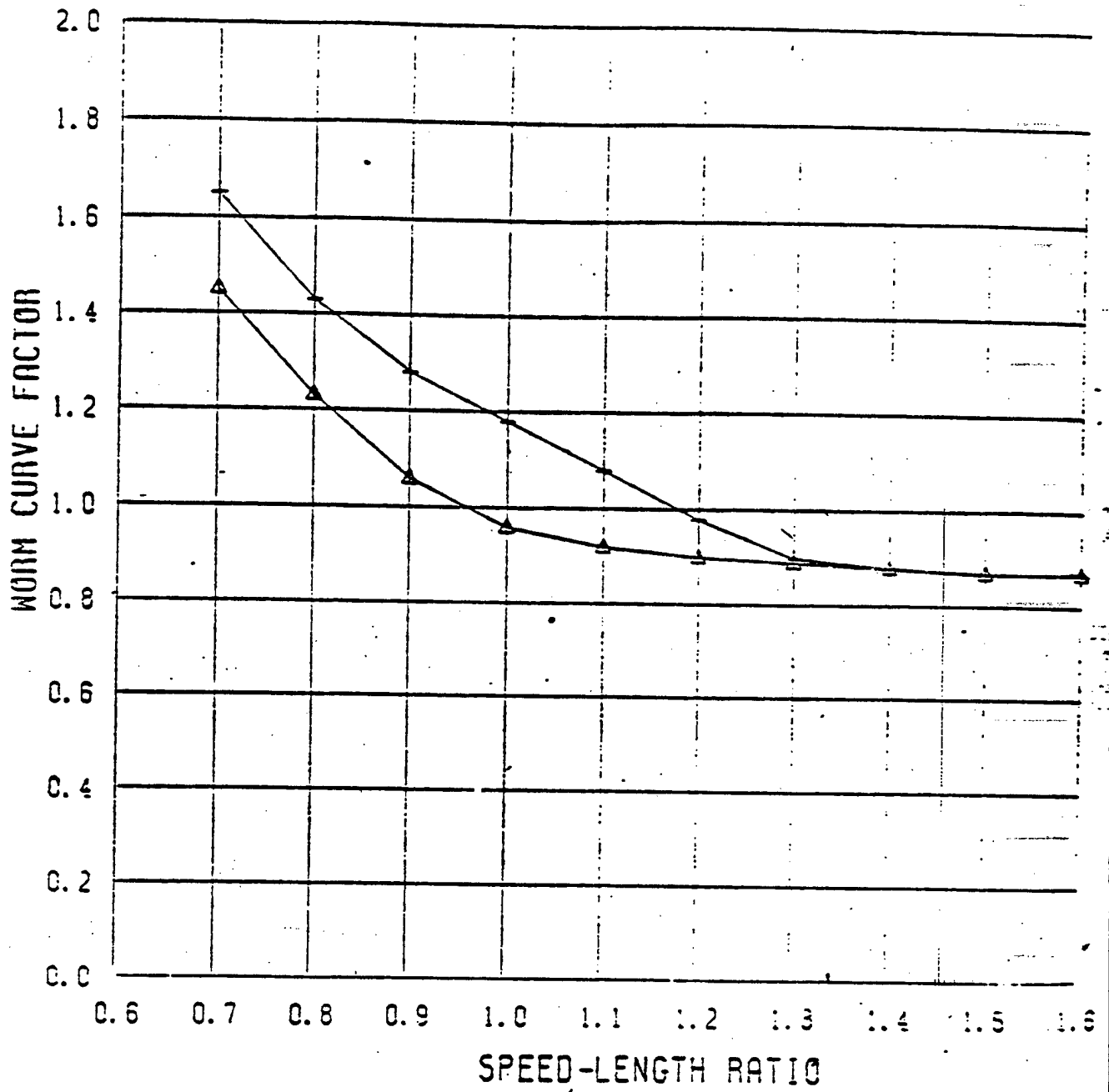


Figure 8 : Recommended Worm Curves for USN Destroyer Type Hull Form without bow dome

—▲— L/B > 9.0  
 —+— L/B < 9.0

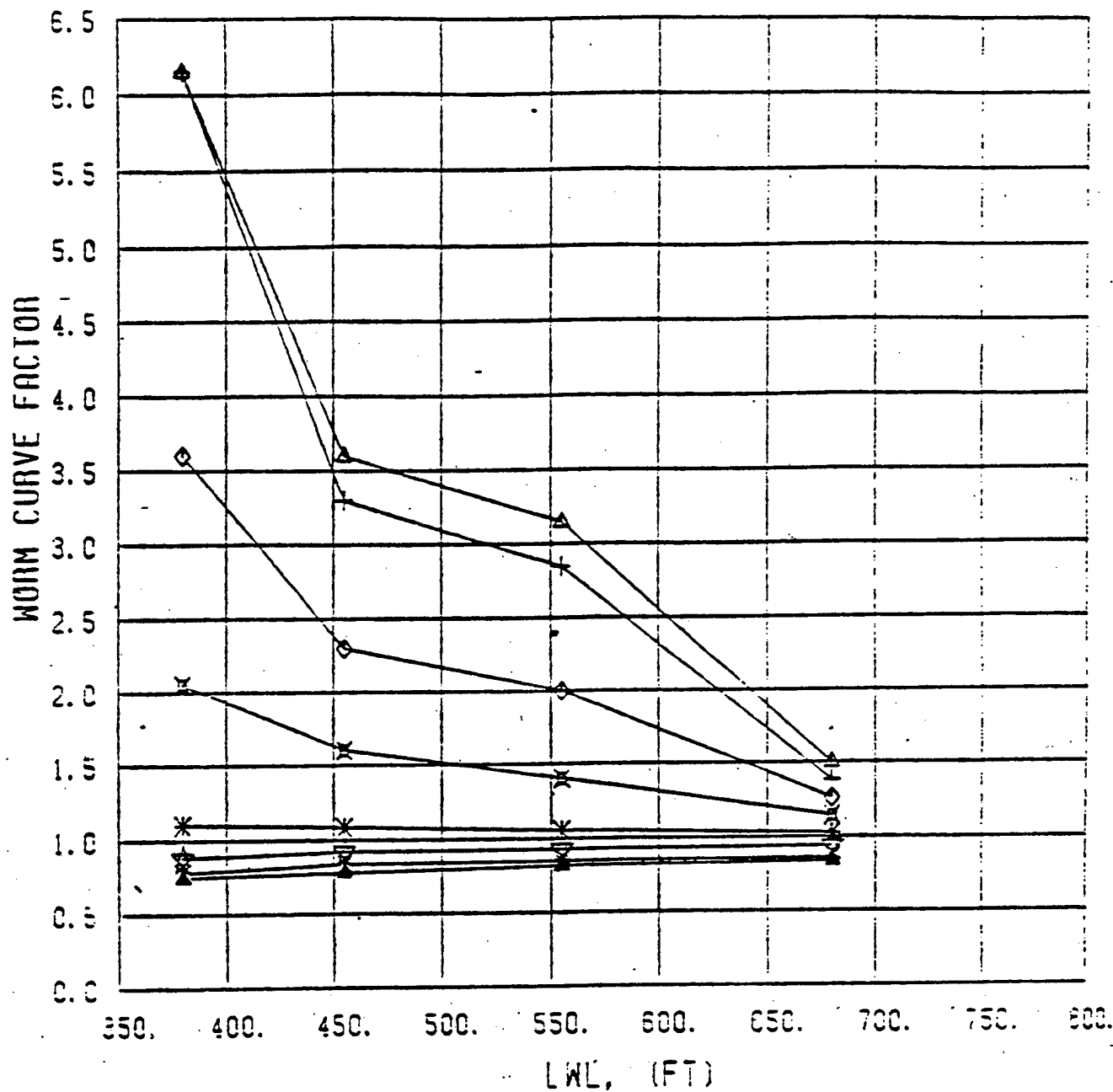


Figure 9 : Contours of recommended Worm Curve factor versus Ship Waterline length. For USN Destroyer Type Hull Forms with bow mounted AN/SQS-26 sonar dome

- |     |     |                    |
|-----|-----|--------------------|
| —▲— | 0.6 | SPEED-LENGTH RATIO |
| —+— | 0.7 | •                  |
| —◇— | 0.8 | •                  |
| —x— | 0.9 | •                  |
| —*— | 1.0 | •                  |
| —x— | 1.1 | •                  |
| —x— | 1.2 | •                  |
| —▲— | 1.4 | •                  |

## ENERGY BALANCE

### VARIABLES USED.

SYMBOLS USED IN ENERGY BALANCE MODULE	
$P_e$	Endurance power, shaft horsepower
$P_{avg}$	Average Endurance power, shaft horsepower
FR	Specific fuel consumption for engine, lb/hp-hr
$F_I$	Power ratio factor
$FR_{SP}$	Specified fuel rate
$P_I$	Installed power, shaft horsepower
$FR_{avg}$	Average Endurance fuel rate
E	Endurance distance, nautical miles
$V_e$	Endurance speed, knots
$W_{BP}$	Burnable propulsion endurance fuel weight
TPA	Tail pipe allowance, propulsion fuel
$W_{FP}$	Propulsion endurance fuel weight
$\gamma$	Specific fuel weight, propulsion
$\nabla_{FP}$	Propulsion fuel tankage volume
$kW_{CL}$	Connected Electrical load
$kW_{MCL}$	Maximum connected load
$kW_{FL}$	Functional load
$kW_{MFL}$	Maximum functional load
$kW_{MFLm}$	Maximum functional load with margin
n	Number of generators
$kW_C$	Electrical power of single generator
$kW_I$	Installed electrical power
$kW_{24}$	Average 24 hour electrical load
$kW_{24avg}$	Average 24 hour electrical load with margin
$FR_e$	Specific fuel consumption for generator, lb/kW-hr
$f_{Ie}$	Power ratio factor, electrical
$FR_{avg e}$	Average electrical fuel rate

## Energy Balance (cont'd)

$W_{Be}$	Burnable electrical endurance fuel weight
$TPA_e$	Tail pipe allowance, electrical fuel
$W_{Fe}$	Electrical endurance fuel weight
$\gamma_e$	Specific fuel weight, electrical
$\nabla_{Fe}$	Electrical fuel tankage volume
$W_F$	Total Fuel Weight
$\nabla_F$	Total propulsion and electrical fuel tankage volume

### Calculations:

#### Propulsion Fuel

##### Average Endurance Power

$$P_{avg} = 1.1 \cdot P_e$$

where the 10% factor is for sea state, hull fouling, machinery degradation, etc.

##### Specified Fuel Rate

$$FR_{SP} = f_1 \cdot FR$$

where  $f_1$  factor is for instrumentation inaccuracies and machinery changes and is given by the following:

$$f_1 = \begin{cases} 1.04 & \text{for } \frac{P_e}{P_I} < \frac{1}{3} \\ 1.03 & \text{for } \frac{P_e}{P_I} < \frac{2}{3} \\ 1.02 & \text{for } \frac{P_e}{P_I} < 1 \end{cases}$$

and FR is the Specified Fuel Consumption for the engine.

##### Average Endurance Fuel Rate

$$FR_{avg} = 1.05 \cdot FR_{SP}$$

where 5% factor is for plant deterioration.

##### Burnable Propulsion Endurance Fuel Weight

Energy Balance (cont'd)

$$W_{B_P} = \frac{E}{V_c} (P_{e_{avg}} \cdot FR_{avg}) \cdot \frac{1}{2240}$$

Tail Pipe Allowance

$$TPA = \left[ \begin{array}{l} 0.95 \text{ for broad, shallow tanks} \\ 0.98 \text{ for narrow, deep tanks} \end{array} \right]$$

Propulsion Endurance Fuel Weight

$$W_{F_P} = \frac{W_{B_P}}{TPA}$$

Tankage Volume for Propulsion Fuel

$$V_{F_P} = 1.02 \cdot 1.05 \cdot \gamma \cdot W_{F_P}$$

where the 5% factor is for fuel expansion and 2% is for the tank structure.

**Electrical Load and Fuel**

Estimate Maximum Functional Load with Margin

- a. Estimate load for four conditions at two temperatures:

FILL IN LOAD kW <sub>CL</sub>	10 °F	
Battle		
Cruise		
Anchor		
In Port		

and the largest of these loads is the maximum connected load, kW<sub>MCL</sub>.

- b. The functional load can be obtained by one of the following methods:

## Energy Balance (cont'd)

$$\text{Functional Load} = kW_{FL} = kW_{CL} \cdot \text{Load Factor (see DDS 9610-2)}$$

or from empirical formulas based on crew size, volume, payload, combat systems, etc. The maximum functional load is designated by  $kW_{MFL}$

c. Maximum functional load with margin:

$$kW_{MFLm} = 1.2 \cdot 1.2 \cdot kW_{MFL}$$

where the 20% factors are for acquisition (design and build) and service life margins.

### Determine Installed Electrical Power

a. Generator size is obtained from the following formula:

$$kW_G \geq \frac{kW_{MFLm}}{(n-1)(0.9)}$$

where the n-1 factor is for one generator out of commission and the 0.9 factor is for generator control

b. Complete generator power installed is gotten from the following:

$$kW_I = n \cdot kW_G$$

### Estimate Average 24 hour Electrical Load

$kW_{24}$  consists of the complete propulsion and steering loads required during cruise operations and 75% of all other cruise loads. Note that this does not contain any margins.

### Average 24 hour Electrical Load with Margin

$$kW_{24avg} = 1.2 \cdot kW_{24}$$

where the 20% factor is an acquisition margin.

## Energy Balance (cont'd)

### Average Electrical Fuel Rate

$$FR_{avg_e} = 1.05 f_{1_e} FR_e$$

where the  $f_{1_e}$  factor is for machinery changes and instrumentation inaccuracies and is given by the following:

$$f_{1_e} = \begin{cases} 1.04 & \text{for } \frac{P_e}{P_I} < \frac{1}{3} \\ 1.03 & \text{for } \frac{P_e}{P_I} < \frac{2}{3} \\ 1.02 & \text{for } \frac{P_e}{P_I} < 1 \end{cases}$$

where  $P_e/P_I$  is defined in the following way for electric power:

$$\frac{P_e}{P_I} = \frac{kW_{24_{avg}}}{(n-1) \cdot kW_G}$$

FR<sub>e</sub> is the specified fuel consumption for a generator and the 5% factor is for plant deterioration.

### Burnable Electrical Endurance Fuel Weight

$$W_{B_e} = \frac{E}{V_e} (kW_{24_{avg}} \cdot FR_{avg_e}) \cdot \frac{1}{2240}$$

### Tail Pipe Allowance, Electrical

$$TPA_e = \begin{cases} 0.95 & \text{for broad, shallow tanks} \\ 0.98 & \text{for narrow, deep tanks} \end{cases}$$

## Energy Balance (cont'd)

### Electrical Endurance Fuel Weight

$$W_{F_e} = \frac{W_{B_e}}{TPA_e}$$

### Tankage Volume for Electrical Fuel

$$V_{F_e} = 1.02 \cdot 1.05 \cdot \gamma \cdot W_{F_e}$$

where the 5% factor is for fuel expansion and the 2% is for tank structure.

### **Total Fuel Values**

### Total Fuel Weight

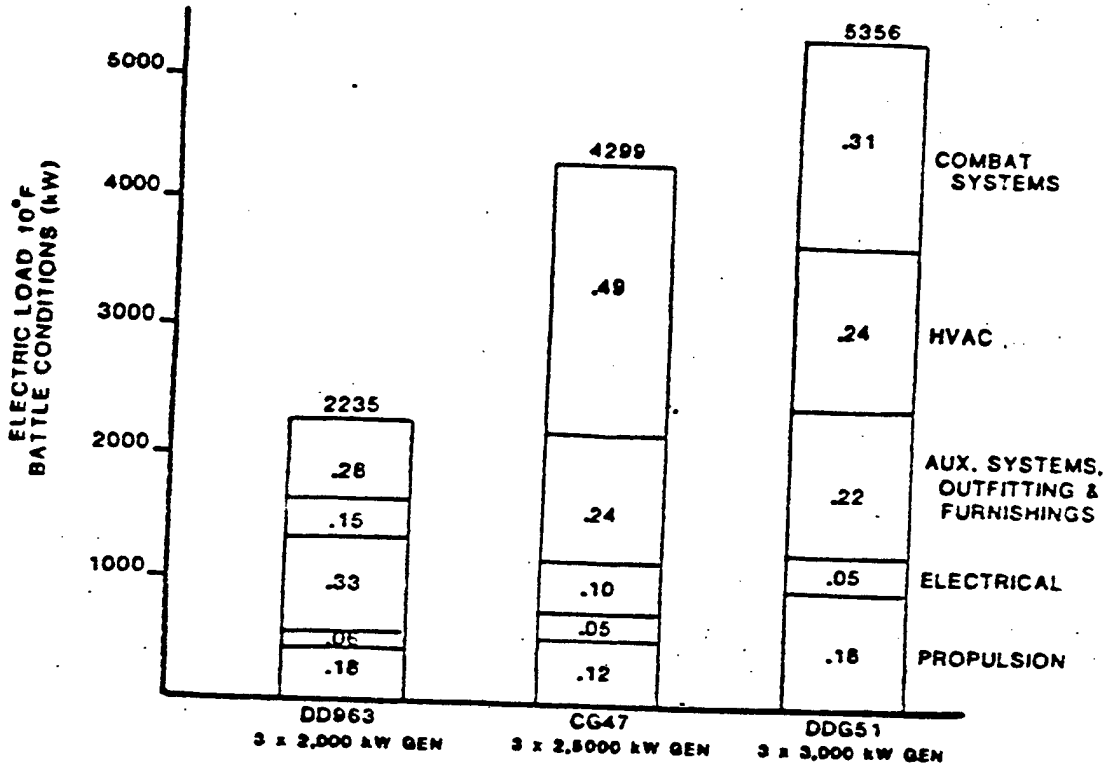
$$W_F = W_{FP} + W_{F_e}$$

### Total Propulsion and Electrical Fuel Tankage

$$V_F = V_{FP} + V_{F_e}$$



Fig 11 U.S. SHIPS - ELECTRICAL LOADS



FRIGATES

Fig 12 INSTALLED POWER

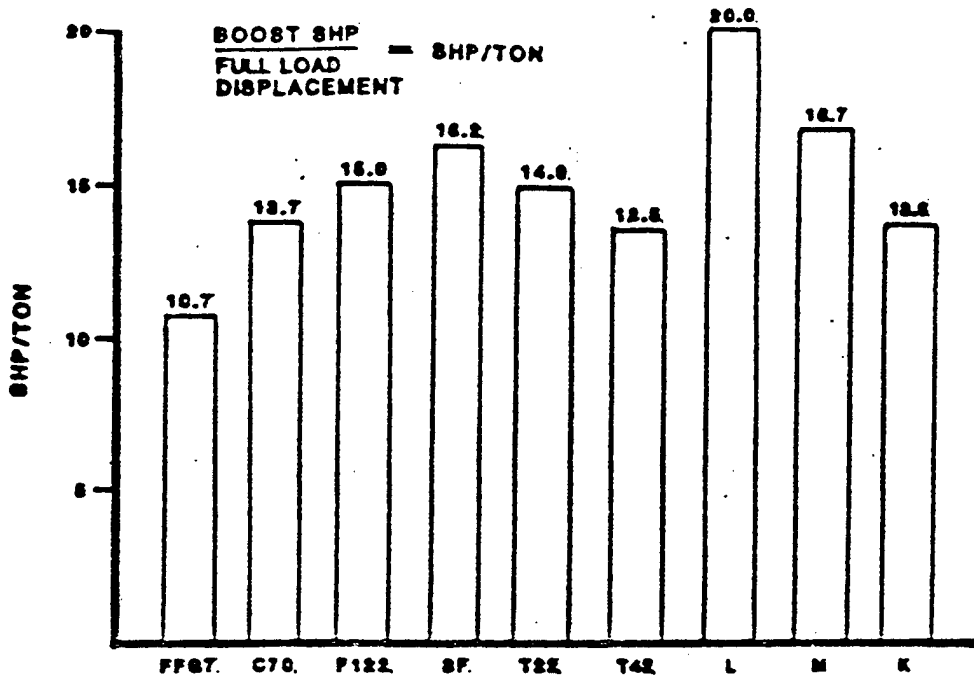
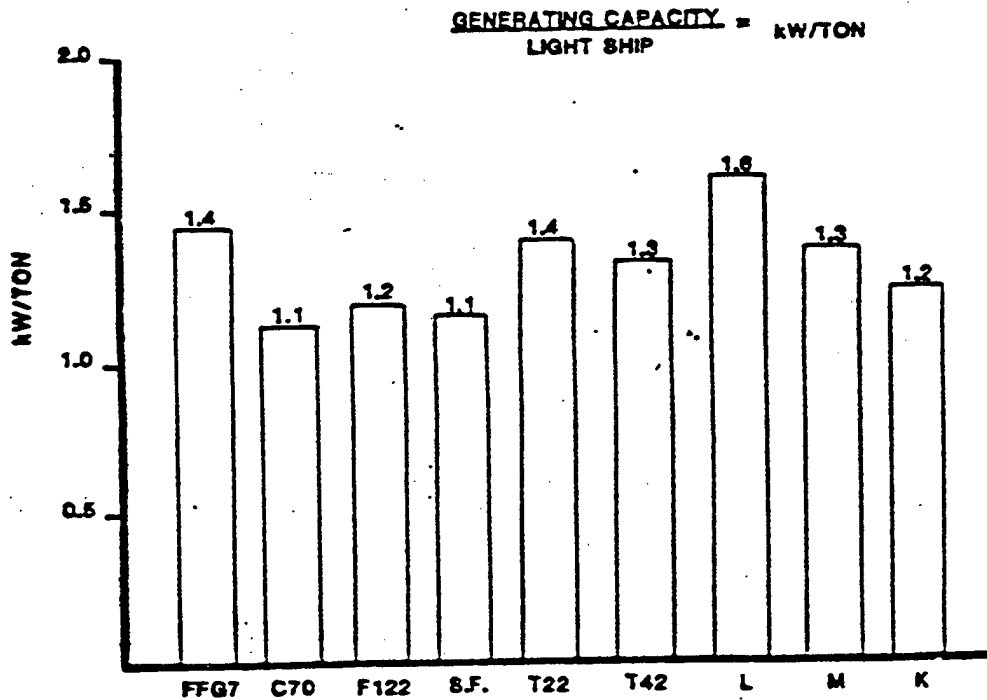


Fig 13 FRIGATES - ELECTRICAL CAPACITY





## APPENDIX D. MATLAB OPTIMIZATION COMPUTER PROGRAM

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This MATLAB program initiates the use of the optimization toolbox for%
% a constrained, non-linear problem. Two input arrays from the Mathcad%
% worksheet (w,z) are used in conjunction with the user defined design %
% space boundaries (vlb,vub) and initial design variable guess (x0). %
% These are passed to the optimizer (constr), which determines the %
% minimum full load displacement and the values of the design variables%
% at that point. %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

w=in0; %Input weight array from Mathcad%

z=in2; % Input values for # of personnel, speed and
% endurance%

options(1)=1; %Toggles on optimizer output summary%

diary outopt % Saves optimizer input/output details to
% MATLAB editor%

x0=[in1(1),in1(2),in1(3),.6,.75] % Initial guess of B,T,LWL,Cp,Cx
% from Mathcad%
%x0=[0,0,0,0,0] %Use different intial guess to check
%if local minimum.

vlb=[20,5,200,.54,.7] %Upper and Lower bounds of design variables%
vub=[90,30,800,.64,.85]

[x,options]=constr('disp3opt',x0,options,vlb,vub,[],w,z)

diary off

optctr=options(10) % Counter for number of optimization
% iterations%

B=x(1)
T=x(2)
LWL=x(3)
cp=x(4)
cx=x(5)

[Wfl,g,Cgmb]=disp3opt(x,w,z);

Cbt=x(1)/x(2);
Clb=x(3)/x(1);
Cdispl=Wfl/((x(3)/100)^3);

out0=[Wfl,x,Cbt]';
out1=[Cbt,Clb,Cgmb,Cdispl,optctr]';

```

```

function [Wf41,Dp]=resist_calc(x,z)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This function calculates the hull resistance, the propulsion power %
% and the electrical service load required to generate the necessary %
% fuel load as part of the full load displacement calculation. The %
% resistance calculation uses Gertler's reanalysis of the Taylor %
% Standard Series. The designer must ensure that the following %
% variables are properly assigned to remain consistent with the %
% Mathcad model; FR %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%RESISTANCE AND PROPULSION POWER CALCULATION%

Cpropd=z(9); %Cpropd=1.2 for one prop, 1.0 for two props%
Dp=(.662*x(2)+.012*x(3))*Cpropd; %Prop diameter%
Aw=x(1)*(3*x(2)); %Frontal Area of Ship%

roair=.0023817; Tsw=59; rosw=1.995; nusw=1.2817e-5; %Physical
hp=33000/60; lton=2240; knt=1.69; %Properties

Ca=.0005; %Correlation allowance%
Cstss=2.53; %Wetted surface coefficient, average value%

volfl=x(1)*x(2)*x(3)*x(4)*x(5); %Underwater volume%

Ss=Cstss*sqrt(volfl)*sqrt(x(3)); %Wetted surface area%

Cdapp=2.85*hp*1e-5/knt^3; %Appendage drag coefficient%
Caa=.7; %Air drag coefficient%
PMF=1.1; %Power Margin Factor%

Ve=z(3)*knt %Endurance speed%
Vs=z(2)*knt %Sustained speed%
E=z(4)*knt %Endurance range%

for i=1:7
    V(i)=i*5*knt;
    V(4)=Ve; %Endurance speed%
    V(6)=Vs; %Sustained speed%

    R(i)=(V(i)/sqrt(x(3)))/knt; %Speed-to-length ratio%
    Rn(i)=x(3)*V(i)/nusw; %Reynolds Number%
    Cf(i)=.075/(log10(Rn(i))-2)^2;
    Rf(i)=.5*(rosw*Ss*(V(i))^2*(Ca+Cf(i))); %ITTC Friction%

    %Taylor Resistance Coefficient for interpolation of Cr%
    Cr225=[.00028 .00028 .00028 .0008 .00150 .00335 .00410];
    Cr300=[.00035 .00035 .00042 .001 .0018 .0035 .0043];
    Cr375=[.00048 .00048 .00048 .00095 .0018 .0036 .0046];

    FF=(4/3)*((x(1)/x(2))-3); %Form Factor%

    Crtss(i)=Cr300(i)+FF*((Cr375(i)-Cr225(i))/2)+FF^2*...
        ((Cr225(i)+Cr375(i))/2-Cr300(i));
    Rrtss(i)=.5*(rosw*Ss*(V(i))^2*Crtss(i)); %TSS Resistance%

    WCF=[3.242 2.124 1.460 1.083 .923 .880 .870]; %Worm Curve Factor%

    Rr(i)=Rrtss(i)*WCF(i);

```

```

Rt(i)=Rf(i)+Rr(i);

Pebh(i)=Rt(i)*V(i)/hp;      %Bare hull effective horsepower%
Csd=.28; Asd=z(5);          %Sonar Dome, SQS-53C=215ft, SQS-56=27ft%
Peapp(i)=(x(3)*Dp*Cdapp+.5*Csd*ros*Asd)*(V(i)^3)/hp; %Appendage HP%
Peaa(i)=.5*Caa*Aw*roair*V(i)^3/hp; %Air resistance horsepower%
Pet(i)=(Pebh(i)+Peapp(i)+Peaa(i));
EHP(i)=PMF*Pet(i);          %Total effective horsepower%

PC=.67;                      %Propulsive Coefficient%
SHP(i)=EHP(i)/PC;          %Shaft horsepower%
end

Pe=SHP(4);                  %Endurance shaft horsepower%
Ps=SHP(6);                  %Sustained speed shaft horsepower%
Pireq=1.25*Ps;              %Required installed horsepower%
Npeng=z(10);                %Number of engines installed%
Pbeng=z(11);                %Engine horsepower%
Pibrake=Npeng*Pbeng;        %Installed BHP%

%PROPULSION FUEL WEIGHT CALCULATION%

Pebavg=(1.1*Pe)/.97;        %Average endurance BHP required, w/fouling%
FR=1.97*Pebavg^(-.15);     %Specific fuel rate, GT. (Diesel=.327, ICR=.347)%
fl=1.04;                    %Margin for instrumentation differences%
FRsp=fl*FR;                 %Specified fuel rate%
FRavg=1.05*FRsp;           %Average fuel due to plant deterioration%
Wbp=(E/Ve)*Pebavg*FRavg/lton;%Burnable propulsion endurance fuel wt%
Wfp=Wbp/.95;                %Tailpipe allowance%
gammaf=43;                  %Fuel specific volume%
Vfp=1.02*1.05*gammaf*Wfp; %Propulsion fuel volume%

%ELECTRICAL LOAD CALCULATION%

Nt=z(1);                    %# of personnel%
kWfins=z(7);                %Stabilizing fin power%

kWp=.00466*Pibrake;         %Propulsion electrical load%
kWs=.00583*x(3)*x(2);       %Steering electrical load%
kWl=.0002053*1.8*x(1)*x(2)*x(3); %Lighting electrical load%
kWm=46.1;                  %Miscellaneous load%
kWh=.0013*1.25*x(1)*x(2)*x(3); %Heating electrical load%
kWcps=.00026*1.8*x(1)*x(2)*x(3); %CPS electrical Load%
kWv=.19*(kWh+kWp)+kWcps;    %Ventilation electrical load%
kWac=.67*(.1*Nt+.0015*.47*1.3*x(1)*x(2)*x(3)+.1*kWp); %A/C load%
kWb=.94*Nt;                 %Aux boiler and FW%
kWf=.0001*1.8*x(1)*x(2)*x(3); %Firemain load%
kWrh=.00002*1.25*x(1)*x(2)*x(3); %Unrep and handling load%
kWa=.22*Nt+kWfins;         %Aux machinery load%
kWserv=.35*Nt;             %Service and work space load%

%Non-payload functional load%
kWnp=kWp+kWs+kWl+kWm+kWh+kWcps+kWv+kWac+kWb+kWf+kWrh+kWa+kWserv;

kWpay=z(6);                 %Payload power%
kWmfl=kWpay+kWnp;          %Maximum functional load%
kWmflm=1.2*1.2*kWmfl;     %With margins%

kW24=.5*(kWmfl-kWp-kWs)+.8*(kWp+kWs); %24 hr electrical load%
kW24avg=1.2*kW24;         %With margins%

```

%ELECTRICAL FUEL RATE%

FRg=.113;	%Specific fuel rate for generators%
FRgsp=f1*FRg;	%With margins%
FRgavg=1.05*FRgsp;	%Plant deterioration%
Wbe=(E/Ve)*(kW24avg*FRgavg)/lton;	%Burnable electric fuel weight%
Wfe=Wbe/.95;	%Tank allowance%
Vfe=1.02*1.05*gammaf*Wfe;	%Electrical Fuel volume%
Wf41=Wfp+Wfe;	%Total ship fuel weight, lton%
Vf=Vfp+Vfe;	%Total ship fuel volume%

```

function [CN,D10,Vd,Vt]=cubicnum_calc(x)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This function calculates the cubic number and the depth of the %
% midships section. The total volume is calculated from the %
% sum of the underwater and deckhouse volumes. The deckhouse volume %
% can be calculated using a range of values to fit the requirement. %
% The designer must ensure that the calculation of Vd is consistent %
% between this M-file and the Final Synthesis Design Mathcad %
% Worksheet. %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%CALCULATE CUBIC NUMBER%

%Sheer Line%

M=[.21*x(1)+x(2), x(3)/15, 22];
D10min=max(M);
D10=D10min+1;
D0=1.0111827*x(2)-(6.36215e-6*x(3)^2)+(2.780649e-2*x(3))+x(2);
D20=.014*x(3)*(2.125+(1.25e-3*x(3)))+x(2);

%Above Water Hull Volume%

F0=D0-x(2);
F10=D10-x(2);
F20=D20-x(2);

Apro=x(3)*(F0+4*F10+F20)/6;
Fav=Apro/x(3);

Dav=Fav+x(2);

CN=x(3)*x(1)*Dav/1e5; %Cubic Number%

Cw=.236+.836*x(4);

ff=.714599+.18098*Dav/x(2)-.018828*(Dav/x(2))^2; %Flare factor%

Mf=[ff 1]; ff=max(Mf);

Vhaw=x(3)*x(1)*Fav*Cw*ff;
Vfl=x(1)*x(2)*x(3)*x(4)*x(5); %Underwater volume%

Vht=Vfl+Vhaw;

Vd=.0025*x(3)^3; %Deckhouse volume, max calc%
%Vd=.0005*x(3)^3; %Deckhouse volume, min calc%

Vt=Vht+Vd; %Total ship volume%

```



```

function [Wdvd,W24,Wls,w]=dvd_weights(x,Dp,CN,Vd,Vt,w,z)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This function calculates the design variable dependent weights and %
% the light ship weight. %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% DESIGN VARIABLE DEPENDENT WEIGHTS %

lton=2240; %Long ton conversion factor%
Nt=z(1); %Number of Personnel%
Npeng=z(10); %Number of propulsion engines%
Pbeng=z(11); %Engine horsepower%
Np=z(12); %Number of propellers%
Pinst=Npeng*Pbeng*.97; %Installed power%
fs=z(13); %1.5 twin screws,.33 single%
W237=w(7); %APU weight%
Wbm=Pinst*(9+12.4*((Pinst*1e-5)-1)^2)/lton;%Propulsion weight%
Ws=.356*x(3)*fs; %Shaft weight%
Wpr=(Np*.05575*Dp^(5.497-.0433*Dp))/lton;%Propeller weight%
Wb=.15*(Ws+Wpr); %Bearing weight%
Wst=Ws+Wpr+Wb; %Total Shafting weight%
W2=Wbm+W237+Wst; %Total propulsion weight%

Waux=(.00072*Vt^1.443+5.14*Vt+6.19*Vt^.7224+377*Nt+2.74*Pinst)*...
1e-4+113.8; %Auxiliary machinery weight
w(13)=Waux;
W598=.000075*Vt; %Auxiliary machinery fluid weight%
W5=Waux+W598;

W6=(31.4+.0003187*Vt); %Wofh, hull fitting weights%
w(15)=W6;

Wic=4.65*CN; %Gyro/Nav/IC%
w(9)=Wic;

Wco=2.24*CN; %Other Group 400%
w(10)=Wco;

Wcc=.04*(w(25)+Wic+Wco); %Cabling Weight%
w(11)=Wcc;

W4=w(25)+Wic+Wco+Wcc+w(12); %Intermediate Weight Group Sum%

Wbh=.93*(1.68341*CN^2+167.1721*CN-103.283); %Bare Hull Weight%
w(1)=Wbh;

rodh=.001429; %Deckhouse density, steel%
Wdh=rodh*Vd; %Deckhouse weight
w(2)=Wdh;

W171=.0688*x(3)-13.75; %Mast Weight%
w(4)=W171;

W180=.0675*Wbm+.072*(w(8)+W4+W5+w(32)); %Foundation Weights%
w(3)=W180;

W1=Wbh+Wdh+W171+W180;

Wvpw=w(24)-w(17)-w(18)-w(19)-w(33); %Subtract out variable payloads%

```

$W_{m24} = 0.1 * (W_{vpw} + W_1 + W_2 + W_4 + W_5 + W_6);$  %10% Weight Margin for Future Growth%

$W_{dvd} = W_1 + W_2 + W_4 + W_5 + W_6 + W_{m24};$  %Design Variable Dependent Weights%

$W_{24} = W_{dvd} - W_{m24} + W_{vpw};$

$W_{ls} = W_{dvd} + W_{vpw}$  %Lightship weight%

```

function GM=stability_calc(x,w,f,D10,Wls,W24)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This function uses the previously calculated full load displacement %
% to generate stability data and return the value of GM for the      %
% constraint requirements.                                          %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% STABILITY CALCULATION %

Vfl=x(1)*x(2)*x(3)*x(4)*x(5);%Underwater volume%

%CALCULATE MOMENTS%

P(1)=w(1)*.527*D10;          %Bare hull weight%
P(2)=w(2)*(D10+1.5*9);      %Deckhouse weight%
P(3)=w(3)*.68*D10;         %Foundation weight%
P(4)=w(4)*2.65*D10;        %Mast weight%
P(5)=w(5)*.5*D10;          %Propusion machinery weight%
P(6)=w(6)*(3.9+.19*x(2));  %Shafting weight%
P(7)=w(7)*w(30);           %APU weight%
P(8)=w(8)*.65*D10;         %Electric generator weight%
P(9)=w(9)*D10;             %Gyro/IC/Nav weight%
P(10)=w(10)*(5.6+.4625*D10);%Misc group 400 weight%
P(11)=w(11)*.5*D10;        %Cabling weight%
P(12)=w(12)*w(31);         %Sonar dome weight%
P(13)=w(13)*.9*(D10-7.4);  %Auxiliary weight%
P(14)=w(14)*.5*D10;        %Aux steam weight%
P(15)=w(15)*.805*D10;      %Hull fitting weight%
P(16)=w(16)*(8+.71*D10);   %Personnel misc%

P(17)=w(17)*.746*D10;      %Crew weight%
P(18)=w(18)*.55*D10;       %Provision weight%
P(19)=w(19)*.65*D10;       %General stores%
P(20)=w(20)*7.5;           %Fuel weight%
P(21)=w(21)*10;            %Helo fuel weight%
P(22)=w(22)*.35*D10;       %Lube oil weight%
P(23)=w(23)*7.5;           %Potable water weight%

ww=w(26)*w(28)-w(27)*w(29);
px=sum(P(1:16));
Pwg=px+ww;

KGls=Pwg/W24;
Pwgl=sum(P(17:23))+w(27)*w(29);
Wl=sum(w(17:23))+w(33);
VCgl=Pwgl/Wl;

KG=((Wls*KGls)+(Wl*VCgl))/f+.5;

Cw=.236+.836*x(4);
Cit=-.497+1.44*Cw;

KB=(x(2)/3)*(2.5-(x(4)*x(5)/Cw));

BM=(x(3)*x(1)^3*Cit)/(12*Vfl);

GM=KB+BM-KG;

```



**APPENDIX E. MATHCONNEX INTEGRATED SHIP DESIGN SYSTEM  
VALIDITY AND ROBUSTNESS CHECKS**

Design Attribute	Initial Run		Expand Side Constraints		High Value Initial Guess	
	Results	vib-vub x0	Results	vib-vub x0	Results	vib-vub x0
Displacement, Wfl (lton)	6123.424		6123.424		6123.424	
Beam, B (ft)	45.50163	40 to 70	45.50163	20 to 90	45.50163	20 to 90
Draft, T (ft)	12.29774	10 to 30	12.29774	5 to 40	12.29774	5 to 40
Waterline Length, LWL (ft)	455.0163	400 to 700	455.0163	200 to 800	455.0163	200 to 800
Prismatic Coefficient, Cp	0.54	.54 to .64	0.54	.54 to .64	0.54	.54 to .64
Max Transverse Section, Cx	0.787983	.70 to .85	0.787983	.70 to .85	0.787983	.70 to .85
Beam-to-Draft, Cbt	3.7		3.7		3.7	
Length-to-Beam, Clb	10		10		10	
GM-to-Beam, Cgmb	0.122		0.122		0.122	
Displacement-to-Length, Cdl	65		65		65	
Number of Iterations	31		31		109	

Design Attribute	Low Value Initial Guess		Constrained Above Optimum		Constrained Below Optimum	
	Results	vib-vub x0	Results	vib-vub x0	Results	vib-vub x0
Displacement, Wfl (lton)	6123.424		7182.628		4729.255	
Beam, B (ft)	45.50163	40 to 70	50	50 to 90	40.22113	20 to 90
Draft, T (ft)	12.29774	10 to 30	15	15 to 40	10.41899	5 to 10
Waterline Length, LWL (ft)	455.0163	400 to 700	500	500 to 800	406.4662	200 to 800
Prismatic Coefficient, Cp	0.54	.54 to .64	0.54	.54 to .64	0.121007	.54 to .64
Max Transverse Section, Cx	0.787983	.70 to .85	0.770449	.70 to .85	0.281007	.70 to .85
Beam-to-Draft, Cbt	3.7		3.333333		3.860366	
Length-to-Beam, Clb	10		10		10.10579	
GM-to-Beam, Cgmb	0.122		0.122		-0.33549	
Displacement-to-Length, Cdl	65		57.46102		70.42378	
Number of Iterations	49		32		37	

Warning:  
No feasible solution found.

Results of Optimizer Validity and Robustness Checks.

**MATLAB OPTIMIZER DETAILED OUTPUT FOR VALIDIDTY AND ROBUSTNESS CHECKS:**

Initial Run Results:

x0 = 55.7451 16.8924 495.3014 0.6000 0.7500  
 vlb = 40.0000 10.0000 400.0000 0.5400 0.7000  
 vub = 70.0000 30.0000 700.0000 0.6400 0.8500

f-COUNT	FUNCTION	MAX{g}	STEP	Procedures
6	7627.82	0.534195	1	
12	6312.8	0.0459915	1	
18	6099.97	0.00388632	1	
24	6123.31	1.92403e-005	1	
30	6123.42	6.04933e-010	1	Hessian modified
31	6123.42	8.88178e-016	1	Hessian modified

Optimization Converged Successfully

Active Constraints:

2  
4  
6  
8

x = 45.5016 12.2977 455.0163 0.5400 0.7880

Expand Side Constraints:

x0 = 55.7451 16.8924 495.3014 0.6000 0.7500  
 vlb = 20.0000 5.0000 200.0000 0.5400 0.7000  
 vub = 90.0000 40.0000 800.0000 0.6400 0.8500

f-COUNT	FUNCTION	MAX{g}	STEP	Procedures
6	7627.82	0.534195	1	
12	6312.8	0.0459915	1	
18	6099.97	0.00388632	1	
24	6123.31	1.92403e-005	1	
30	6123.42	6.04933e-010	1	Hessian modified
31	6123.42	8.88178e-016	1	Hessian modified

Optimization Converged Successfully

Active Constraints:

2  
4  
6  
8

x = 45.5016 12.2977 455.0163 0.5400 0.7880

High Value Initial Guess:

x0 = 100            100            1000            10            10  
v1b = 20.0000      5.0000    200.0000      0.5400      0.7000  
vub = 90.0000      40.0000    800.0000      0.6400      0.8500

f-COUNT	FUNCTION	MAX{g}	STEP	Procedures
6	26700.1	0.244444	1	infeasible
12	23210.4	-0.00381213	1	
19	19983	-0.00179031	0.5	
26	11608.4	-0.03448	0.5	
33	7598.42	-0.0343611	0.5	
40	6651.19	-0.0150468	0.5	
47	6359.78	-0.0075712	0.5	
54	6236.04	-0.00384339	0.5	
61	6178.47	-0.00194103	0.5	
68	6150.64	-0.000975889	0.5	
75	6136.96	-0.000489382	0.5	
82	6130.17	-0.000245074	0.5	
89	6126.79	-0.00012263	0.5	
96	6125.11	-6.13377e-005	0.5	
102	6123.42	6.05291e-008	1	
108	6123.42	1.36113e-013	1	Hessian modified twice
109	6123.42	0	1	Hessian modified twice

Optimization Converged Successfully

Active Constraints:

2  
4  
6  
8

x = 45.5016    12.2977    455.0163    0.5400    0.7880

Low Value Initial Guess:

x0 = 0      0      0      0      0  
v1b = 20.0000      5.0000    200.0000      0.5400      0.7000  
vub = 90.0000      40.0000    800.0000      0.6400      0.8500

f-COUNT	FUNCTION	MAX{g}	STEP	Procedures
6	3317.57	5.37994	1	
12	3686.38	5.72939	1	
18	4293.17	0.774454	1	
24	5199.71	0.23014	1	
30	5911.86	0.0398647	1	
36	6113.23	0.00179708	1	
42	6123.4	4.04898e-006	1	
48	6123.42	1.33333e-011	1	Hessian modified
49	6123.42	3.77476e-015	1	Hessian modified

Optimization Converged Successfully

Active Constraints:

2  
4  
6  
8

x = 45.5016    12.2977    455.0163    0.5400    0.7880



Constrained Above Optimum:

x0 = 55.7451 16.8924 495.3014 0.6000 0.7500  
v1b = 50.0000 15.0000 500.0000 0.5400 0.7000  
vub = 90.0000 40.0000 800.0000 0.6400 0.8500

f-COUNT	FUNCTION	MAX{g}	STEP	Procedures
6	7712.59	0.508232	1	
12	7188.86	0	1	
19	7185.72	0	0.5	
25	7182.61	0.00010248	1	
31	7182.63	2.87194e-009	1	Hessian modified
32	7182.63	1.55431e-015	1	Hessian modified

Optimization Converged Successfully

Active Constraints:

4  
6

x = 50.0000 15.0000 500.0000 0.5400 0.7704

Constrained Below Optimum:

x0 = 55.7451 16.8924 495.3014 0.6000 0.7500  
v1b = 20.0000 5.0000 200.0000 0.5400 0.7000  
vub = 90.0000 10.0000 800.0000 0.6400 0.8500

f-COUNT	FUNCTION	MAX{g}	STEP	Procedures
6	6906.3	1.70751	1	infeasible
12	4987.11	0.801315	1	infeasible
18	4738.86	0.0763757	1	infeasible
24	4729.4	0.083331	1	infeasible
30	4729.26	0.0834429	1	Hessian modified twice;
infeasible				
36	4729.26	0.0834426	1	Hessian modified;
infeasible				
37	4729.26	0.0834427	1	Hessian modified;
infeasible				

Warning: No feasible solution found.

x = 40.2211 10.4190 406.4662 0.1210 0.2810

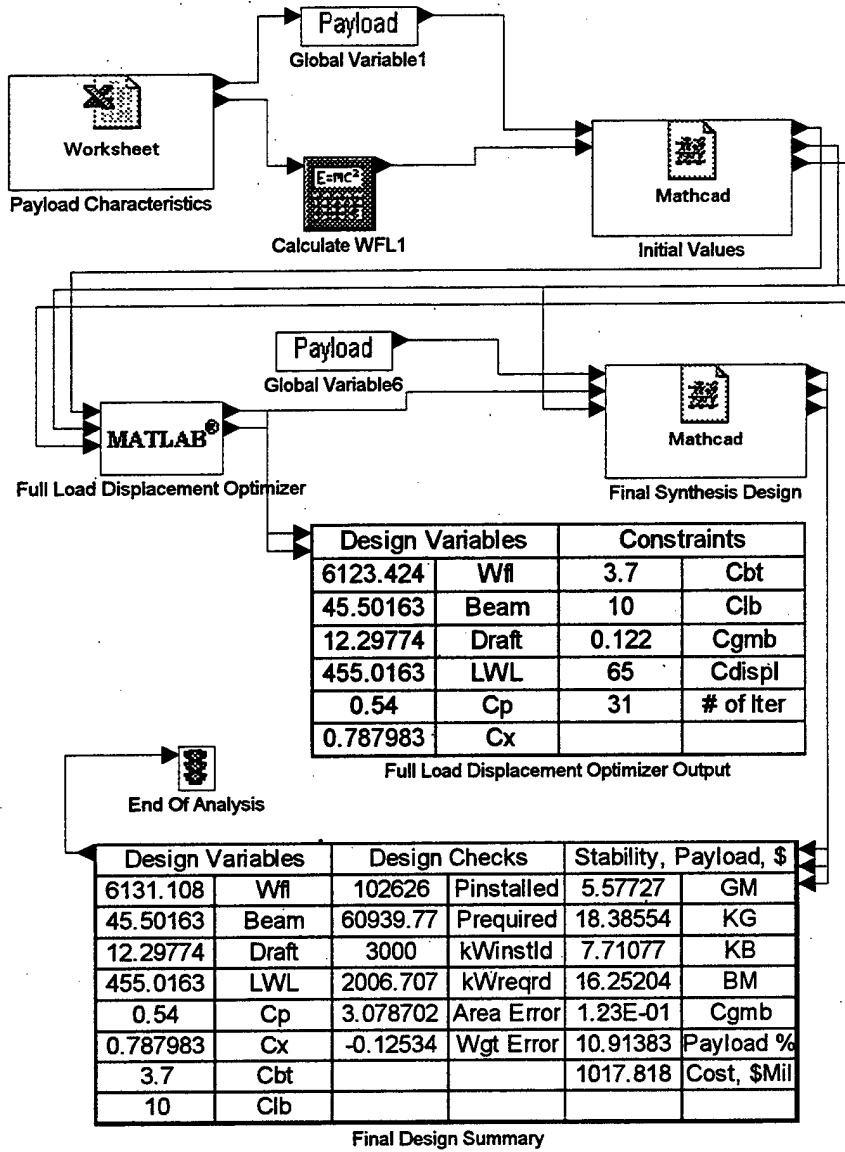


## **APPENDIX F. OPTIMIZED AND NON-OPTIMIZED DESIGN EXAMPLE RESULTS**

This section contains:

- The ISDS MathConnex worksheet
- The Excel spreadsheet of the characteristics for the DD-13A Payload #2
- The Initial Value Mathcad Math Model
- The Matlab Optimizer detailed output
- The Final Design Synthesis Mathcad Math Model
- The Non-Optimized MathConnex worksheet
- The Non-Optimized MIT Math Model

# INTEGRATED SHIP DESIGN SYSTEM



**DD13A  
PAYLOAD #2**

PAYLOAD NAME	WT KEY	WT	VCG	VCG	AREA	HULL	DKHS	CRUISE	BATTLE
			DATUM	FT AD					
STEEL LANDING PAD (ON HULL) - SH-80 CAPABLE	W111	10.7	36.717	0.20	NONE				
128 CELL VLS ARMOR - LEVEL III HY-80									
VGAS HY-80 ARMOR LEVEL II									
SQS-53C 5M BOW SONAR DOME	W165	85.7	0	-1.5	NONE	0	0	0	0
GROUP 100	WP100	96.4				0	0	0	0
CIC W/JYQ-44 & 2X LSD	W410	19.34	0	35.58	A1131	1953	448	45.03	45.03
NAVIGATION SYSTEM	W420	7.29	51	14.00	A1132	0	848.3	55.99	53.5
ADVANCED DIGITAL C-4I (JTIDS/LINK 16/LINK22/TADIXS/TACINTEL)	W440	37.91	51	-48.84	A1110	1230.6	1270.4	35.76	39.87
SPS-67 SURFACE SEARCH RADAR	W451	1.81	51	-10.00	A1121	0	70	8	0
ADVANCED IFF	W455	2.32	51	-5.00	NONE	0	0	3.2	4
SPY-1D MFAIR - SINGLE TRANSMITTER									
X-BAND RADAR AND FOUNDATION, 110 FT ABOVE BL	W456	4.11	0	113.00	NONE	0	0	220.16	220.16
SQS-53C 5M BOW SONAR DOME ELEX	W463	57.7	0	9.3	A1122	1942	0	39	39
LIGHTWEIGHT BROADBAND VARIABLE DEPTH SONAR (LBVDS)									
SSQ-61 BATHYTHERMOGRAPH									
SSQ-28 SONOBUOY PROCESSING SYSTEM	W466	5.26	51	-44.86	NONE	0	0	1.15	1.15
ADVANCED INTEGRATED ELECTRONIC WARFARE SYSTEM (AIEWS)									
AN/SIC-25A NIXIE	W473	0.24	36.717	-6.20	A1142	200	0	3	4.2
MK36 DLS W/6 LAUNCHERS	W474	0.96	33.4	5.39	NONE	0	0	2.4	2.4
MINIHUNTING AUV / REMOTE MINIHUNTING SYSTEM									
AEGIS-BASED VGAS GFCS (UYQ-21 + UYK-44)									
AN/SWG-1 HARPOON CONTROL IN CIC	W482	1.14	38.31575	10.80	NONE	0	0	0	4.9
MK99 GMFCS W/CEC W/3 SPG-62 ILLUM									
VLS WEAPON CONTROL SYSTEM	W482	0.7	38.31575	-7.80	A1220	56	310	13.62	19.89
ADVANCED TACTICAL WEAPON CONTROL SYSTEM (ATWCS)									
ASW CONTROL SYSTEM w/SSTD (ASWCS)									
COMBAT DF	W495	8.28	33.4	21.00	A1141	0	448	15.47	19.34
ELECTRONIC TEST & CHECKOUT	W499	1.11	38.31575	10.80	NONE	0	0	0	0
GROUP 400	WP400	148.14				5381.6	3394.7	442.78	453.04
FWD 64-CELL VLS MAGAZINE DEWATERING SYSTEM	W529	7	35.0585	-0.46	NONE	0	0	0	0
AFT 64-CELL VLS MAGAZINE DEWATERING SYSTEM									
COOLING EQUIPMENT FOR SPY-1D									
COOLING ADJUSTMENT FOR X-BAND RADAR	W532	4.43	0	9.81	A1121	47.85	0	13.64	13.64
LAMPS MKIII AVIATION FUEL SYS	W542	4.86	35.0585	-11.00	A1380	30	0	2	2.9
LAMPS MKIII RAST/RAST CONTROL/HELO CONTROL	W588	31.1	35.0585	-1.60	A1312	219	33	4.4	4.4
GROUP 500	WP500	47.39				296.65	33	20.04	20.94
SQS-53C 5M BOW SONAR DOME HULL DAMPING	W636	6.7	0	-2.5	NONE	0	0	0	0
LAMPS MKIII AVIATION SHOP AND OFFICE	W665	1.04	35.0585	-4.50	A1380	194	75	0	0
GROUP 600	WP600	7.74				194	75	0	0
VGAS 155 MM									
2X HARPOON SSM QUAD CANNISTER LAUNCHERS	W721	4.1	33.4	1.17	A1220	0	0	0	1.8
FWD MK41 VLS 64-CELL	W721	107.72	35.0585	1.14	A1220	128	0	69.65	69.65
AFT MK41 VLS 64-CELL									
2X MK32 SVTT ON DECK	W750	5.55	33.4	2.20	A1244	0	368	2	5
GROUP 700	W7	117.37				128	368	71.65	76.25
VGAS AMMO - 680 RDS									
HARPOON MISSILES - 8 RDS IN CANNISTERS	WF21	3.78	33.4	5.00	NONE	0	0	0	0
AFT MK 41 LAUNCHER MISSILE LOADOUT (ESSM, SM, VLA, TLAM, ATACMS)									
FWD MK 41 LAUNCHER MISSILE LOADOUT (ESSM, SM, VLA, TLAM, ATACMS)	WF21	144	35.0585	0.34	A1220	1420	720	0	0
MK46 LWT ASW TORPEDOES - 6 RDS IN SVTT TUBES	WF21	1.36	33.4	2.50	A1240	368	0	0	0
MK36 DLS SRBOC CANNISTERS - 100 RDS	WF21	2.2	33.4	11.60	NONE	0	0	0	0
SMALL ARMS AMMO - 7.62MM + 50 CAL + PYRO	WF21	4.1	33.4	-6	NONE	0	0	0	0
LAMPS MKIII 18 X MK46 TORP & SONOBUOYS & PYRO	WF22	9.87	35.0585	4.80	A1374	0	588	0	0
LAMPS MKIII 2 X SH-608 HELOS, UAV'S, AND HANGAR (BASED)	WF23	12.73	35.0585	4.50	A1340	0	3408	5.6	5.6
LAMPS MKIII AVIATION SUPPORT AND SPARES	WF26	9.42	35.0585	5.00	A1390	357	0	0	0
BATHYTHERMOGRAPH PROBES									
GROUP WF20	WF20	187.46				2145	4714	5.6	5.6
LAMPS MKIII: AVIATION FUEL (JP-6)	WF42	63.8	0	10.4	A1380	0	0	0	0
VARIABLE MILITARY PAYLOAD (WF20 + WF42)	WVP	251.26							
ARMAMENT (WP500, WP600, W7, WF20)						2763.9	5190		
TOTAL PAYLOAD	WP	668.3				8145.5	8584.7	540.07	555.83
<b>DATUM DEFINITIONS:</b>									
	DEPTH0	47.445		VCG P:	24.78				
	DEPTH3	43.232		VCG VP:	29.61				
	DEPTH6.5	38.316							
	DEPTH10	33.4							
	DEPTH15	35.059							
	DEPTH20	36.717							
	BL	0							
	MAST BAS	51							

**MIT MATH MODEL: INITIAL VALUES**

$$\text{hp} \equiv \frac{33000 \cdot \text{ft} \cdot \text{lb}_f}{\text{min}} \quad \text{knt} \equiv 1.69 \cdot \frac{\text{ft}}{\text{sec}} \quad \text{lton} \equiv 2240 \cdot \text{lb}$$

**I. INPUT:**

Primary Input Variables Are Highlighted in Yellow and Must Be Checked for Consistency Between MATHCAD Elements.

**II. Requirements:**

Payload: (From Excel Payload Spreadsheet )  $W_P := \text{in}0_1 \cdot \text{lton}$       variable:  $W_{VP} := \text{in}0_2 \cdot \text{lton}$

Payload VCG:  $VCG_P := \text{in}0_3 \cdot \text{ft}$       Variable Payload VCG:  $VCG_{VP} := \text{in}0_4 \cdot \text{ft}$

Command and Surveillance Payload:  $W_{P400} := \text{in}0_5 \cdot \text{lton}$   
( $W_{400}$  less 420 and 430)

Armament (all  $W_{700}$ ):  $W_7 := \text{in}0_6 \cdot \text{lton}$       Armor:  $W_{164} := \text{in}0_7 \cdot \text{lton}$

Mission handling/support:  $W_{P500} := \text{in}0_8 \cdot \text{lton}$       Mission outfit:  $W_{P600} := \text{in}0_9 \cdot \text{lton}$

Ordnance:  $W_{F20} := \text{in}0_{10} \cdot \text{lton}$  (incl helo wt,  $WF23$ )      Helo Fuel:  $W_{F42} := \text{in}0_{11} \cdot \text{lton}$

Helo's:  $N_{HELO} := 2$        $W_{F23} := 12.73 \cdot \text{lton}$

Payload Cruise Electric Power Requirement:  $\text{kW}_{PAY} := \text{in}0_{12} \cdot \text{kW}$

**Payload Deck Areas:**

Deckhouse: C&D:  $A_{DPC} := \text{in}0_{13} \cdot \text{ft}^2$       (W400)

Armament:  $A_{DPA} := \text{in}0_{14} \cdot \text{ft}^2$       (W500, W600, W700, WF20)

Hull: C&D:  $A_{HPC} := \text{in}0_{15} \cdot \text{ft}^2$       (W400)

Armament:  $A_{HPA} := \text{in}0_{16} \cdot \text{ft}^2$       (W500, W600, W700, WF20)

**Manning:**

Officers:  $N_O := 15$       Enlisted:  $N_E := 135$       Total:  $N_T := N_E + N_O$        $N_T = 150$

Average deck height:  $H_{DK} := 9 \cdot \text{ft}$

Sustained Speed:  $V_S = 27 \cdot \text{knt}$       (Use Figure 3 as a guide in selecting  $V_S$ )

Endurance Speed:  $V_e = 20 \cdot \text{knt}$       Range:  $E = 7500 \cdot \text{knt} \cdot \text{hr}$

Stores period:  $T_S := 45 \cdot \text{day}$

Sonar Dome/Appendages: SQS-53C; 215ft<sup>2</sup>, 87.9lton, -1.2ft, 85.7lton SQS-56; 27ft<sup>2</sup>, 13.94lton, -3.1ft, 7.43lton

$$A_{SD} := 215 \text{ ft}^2 \quad \text{water: } W_{498} := 87.9 \text{ lton} \quad VCG_{498} := -1.2 \text{ ft} \quad \text{structure: } W_{165} := 85.7 \text{ lton}$$

$$\text{Fin Stabilizers: (for one pair, electric power requirement = 50 kW)} \quad kW_{\text{fins}} := 0 \text{ kW}$$

$$\text{Hull Material: (OS: } C_{HMAT} = 1.0; \text{ HTS: } C_{HMAT} = 0.93) \quad C_{HMAT} := 0.93$$

$$\text{CPS: (} W_{CPS} = 30 \text{ lton): } W_{CPS} := 30 \text{ lton} \quad (\text{ie. no CPS})$$

Machinery:

$$\text{Number of propellers = } N_P := 2 \quad C_{PROPD} := \text{if}(N_P > 1, 1.0, 1.2) \quad C_{PROPD} = 1$$

$$\text{Aux Propulsion (APU): } W_{237} := 0 \text{ lton} \quad VCG_{237} := 0 \text{ ft} \quad (\text{Weight} = 14.2 \text{ lton}, VCG = 3.5 \text{ ft})$$

Propulsion Engines (PE) - standard LM2500's; Generator engines; DDA 501-K34

$$\text{Number and brake horsepower of propulsion engines: } N_{PENG} := 4 \quad P_{BPENG} := 26450 \text{ hp}$$

$$\text{Inlet/exhaust Xsect area for PE: } A_{IE} := 135.2 \text{ ft}^2 \quad A_{PIE} := N_{PENG} \cdot A_{IE} \quad A_{PIE} = 540.8 \text{ ft}^2$$

$$\text{Deckhouse decks impacted by propulsion and generator inlet/exhaust: } N_{DIE} := 1$$

$$\text{Hull decks impacted by propulsion inlet/exhaust: } N_{HPIE} := 0$$

$$\text{Machinery Box: } H_{MBMIN} := 22 \text{ ft} \quad L_{MB} := 40 \text{ ft}$$

$$C_P = 0.59 \quad C_{MB} := \frac{L_{MB}}{LWL} \quad C_{MB} = 0.081 \quad C_{PMB} \text{ from Fig. 10: } C_{PMB} := 0.998$$

$$\text{Ship Service Generators: } N_G := 3 \quad kW_G := 3000 \text{ kW}$$

$$\text{Hull decks impacted by generator inlet/exhaust: } N_{HeIE} := 1$$

$$\text{Specific fuel rate for generator engines: } FR_G := \frac{288 \text{ lb}}{2.54 \text{ kW hr}} \quad FR_G = 0.085 \frac{\text{lb}}{\text{hp hr}}$$

$$\text{Inlet/exhaust X-sect area for gen: } A_{GIE} := 38.4 \text{ ft}^2 \quad A_{eIE} := N_G \cdot A_{GIE} \quad A_{eIE} = 115.2 \text{ ft}^2$$

## II. GROSS CHARACTERISTICS

Hull Principle Characteristics:

$$LWL = 495.301 \text{ ft} \quad B = 55.745 \text{ ft}$$

(see Figures 5 and 6)

$$C_P = 0.59 \quad C_X = 0.85$$

Adjust in  
Summary  
Section at  
end of file

$$\text{deckhouse volume: } V_D = 97715 \text{ ft}^3 \quad C_{DHMAT} := 2$$

(Deckhouse Material: Aluminum -  $C_{DHMAT} = 1$ ; Steel -  $C_{DHMAT} = 2$ )

**III. Complete Principle Characteristics:**

Choose Payload Weight Fraction from Figure 4 and Calculate Full Load Weight (1st Iteration only, set  $W_{FL} = W_{FL1}$  in Summary section at end of file).

$$F_P := .1 \quad W_{FL1} := \frac{W_P}{F_P} \quad W_{FL1} = 6683 \text{ lton}$$

Specify Full Load Weight (subsequent iterations set  $W_{FL} = W_T$  from prior iteration in Summary at end of file):

$$W_{FL} = 6683 \text{ lton}$$

Calculate Full Load Displacement and Volume at LWL:

$$\Delta_{FL} := W_{FL} \quad V_{FL} := \Delta_{FL} \cdot 35 \frac{\text{ft}^3}{\text{lton}} \quad V_{FL} = 233905 \text{ ft}^3$$

Calculate Draft (LWL):

$$T := \frac{V_{FL}}{C_P \cdot C_X \cdot LWL \cdot B} \quad T = 16.892 \text{ ft}$$

**III.2. Calculate Displacement to Length Ratio and Compare to Figure 5:**

$$C_{\Delta L} := \frac{\Delta_{FL}}{\left(\frac{LWL}{100}\right)^3} \quad C_{\Delta L} = 55 \frac{\text{lton}}{\text{ft}^3} \quad (45-65)$$

**III.3. Calculate Speed to Length Ratio and  $C_V$ :**

$$R_{VL} := \frac{V_S}{\sqrt{LWL}} \quad R_{VL} = 1.213 \frac{\text{knt}}{\text{ft}^5} \quad C_V := \frac{V_{FL}}{LWL^3} \quad C_V = 0.001925$$

**III.4. Calculate Beam to Draft Ratio and Compare to Tables 1-4:**

$$C_{BT} := \frac{B}{T} \quad C_{BT} = 3.3 \quad (2.8-3.7)$$

**III.5. Calculate Length to Beam Ratio:**

$$C_{LB} := \frac{LWL}{B} \quad C_{LB} = 8.885 \quad (7.5-10)$$

**III. ENERGY (Uses Taylor Standard Series (TSS))**

References: DDS 051-1 and Taylor Reanalysis by Gertler

**III.1. Calculate TSS Resistance:****III.1.1 Estimate propeller diameter and frontal area of ship:**

$$C_{PROPD} = 1 \quad D_P := (.662 \cdot T + .012 \cdot LWL) \cdot C_{PROPD} \quad D_P = 17.126 \text{ ft}$$

$$\text{Frontal area of ship} = A_W := B \cdot (3 \cdot T) \quad A_W = 2825.012 \text{ ft}^2 \quad \rho_A := .0023817 \frac{\text{slug}}{\text{ft}^3}$$



## III.2 Seawater properties:

$$T_{SW} := 59 \quad \rho_{SW} := 1.9905 \frac{\text{slug}}{\text{ft}^3} \quad v_{SW} := 1.2817 \cdot 10^{-5} \frac{\text{ft}^2}{\text{sec}}$$

## III.3 Resistance calculation parameters:

Correlation Allowance:  $C_A := .0005$

$C_P = 0.59$

Use Figure 7 with  $C_P$  and  $C_{BT}$  for TSS wetted surface coefficient:

$C_{STSS} := 2.536$

$S_{TSS} := C_{STSS} \cdot V_{FL}^5 \cdot LWL^5 \quad S_{TSS} = 27296.301 \text{ ft}^2$

$C_{BT} = 3.3$

Specify or estimate actual ship surface area:

$S_S := S_{TSS}$

Use Figure 8 or 9 with LWL for Appendage Drag Coefficient:

$LWL = 495.301 \text{ ft}$

$C_{DAPP} := 2.85 \frac{\text{hp} \cdot 10^{-5}}{\text{ft}^2 \cdot \text{knt}^3}$

Air Drag Coefficient:  $C_{AA} := .7$

Power Margin Factor (margin for concept design = 10%):

$PMF := 1.05$

III.4 Use range of ship speeds for speed to length ratios ( $R_i$ ), Reynold's numbers ( $R_{N_i}$ ) and ITTC friction ( $R_{F_i}$ ):

$i := 1..7 \quad V_i := i \cdot 5 \cdot \text{knt} \quad \text{Ensure range includes } V_e \text{ and } V_s: \quad V_6 := V_S \quad V_6 = 27 \cdot \text{knt}$

$V_4 := V_e \quad V_4 = 20 \cdot \text{knt}$

$$R_i := \frac{V_i}{\sqrt{LWL}} \quad R_{N_i} := LWL \cdot \frac{V_i}{v_{SW}} \quad C_{F_i} := \frac{.075}{(\log(R_{N_i}) - 2)^2}$$

$$R_{F_i} := .5 \cdot \left[ \rho_{SW} \cdot S_S \cdot (V_i)^2 \cdot (C_A + C_{F_i}) \right]$$

$\frac{V_i}{\text{knt}}$	$R_i \frac{\text{ft}^5}{\text{knt}}$	$R_{N_i}$	$C_{F_i}$	$\frac{R_{F_i}}{\text{lbf}}$
5	0.225	$3.265 \cdot 10^8$	0.002	4398.533
10	0.449	$6.531 \cdot 10^8$	0.002	16409.293
15	0.674	$9.796 \cdot 10^8$	0.002	35518.594
20	0.899	$1.306 \cdot 10^9$	0.001	61486.466
25	1.123	$1.633 \cdot 10^9$	0.001	94155.526
27	1.213	$1.763 \cdot 10^9$	0.001	109072.521
35	1.573	$2.286 \cdot 10^9$	0.001	179157.237

III.5 Use Gertler with  $C_P$ ,  $C_V$ ,  $R_i$  and  $C_{BT}$  to interpolate for  $C_R$  and calculate TSS resistance:

$$C_P = 0.59 \quad C_V = 0.001925$$

$R_i \frac{\text{ft}^5}{\text{knt}}$	$C_{BT}=2.25$	$C_{BT}=3.00$	$C_{BT}=3.75$
0.225	.00028	.00035	.00048
0.449	.00028	.00035	.00048
0.674	.00028	.00042	.00048
0.899	$C_{R2.25} := .00080$	$C_{R3.00} := .00100$	$C_{R3.75} := .00095$
1.123	.00150	.00180	.00180
1.213	.00335	.00350	.00360
1.573	.00410	.00430	.00460

Form Factor:  $FF := \frac{4}{3} \cdot (C_{BT} - 3) \quad FF = 0.4$

$$C_{RTSS_i} := C_{R3.00_i} + FF \cdot \left( \frac{C_{R3.75_i} - C_{R2.25_i}}{2} \right) + FF^2 \cdot \left( \frac{C_{R2.25_i} + C_{R3.75_i}}{2} - C_{R3.00_i} \right)$$

$$C_{RTSS} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.001 \\ 0.002 \\ 0.004 \\ 0.004 \end{bmatrix} \quad R_{RTSS_i} := .5 \cdot [\rho_{SW} \cdot S_S \cdot (V_i)^2 \cdot C_{RTSS_i}] \quad R_{RTSS} = \begin{bmatrix} 765.82 \\ 3063.279 \\ 7918.902 \\ 31346.623 \\ 89035.271 \\ 200574.47 \\ 418973.994 \end{bmatrix} \text{ lbf}$$

III2 Calculate Bare Hull Ship Resistance - Worm Curve data from ASSET:

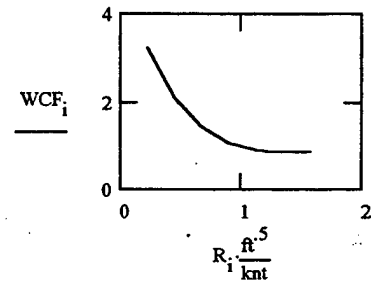
WCFA :=	.2	3.5
	.3	2.95
	.4	2.5
	.5	2.1
	.6	1.8
	.7	1.55
	.8	1.33
	.9	1.17
	1.0	1.07
	1.1	1
	1.2	.94
	1.3	.89
	1.4	.88
	1.5	.87
	1.6	.87

iw := 1.. 15

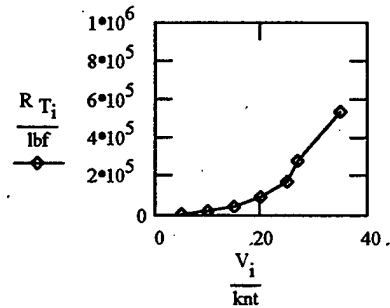
$$R = \begin{bmatrix} 0.225 \\ 0.449 \\ 0.674 \\ 0.899 \\ 1.123 \\ 1.213 \\ 1.573 \end{bmatrix} \frac{\text{knt}}{\text{ft}^5} \quad \text{WCF} := \begin{bmatrix} 3.242 \\ 2.124 \\ 1.460 \\ 1.083 \\ .923 \\ .880 \\ .870 \end{bmatrix}$$

$R_{R_i} := R_{RTSS_i} \cdot WCF_i$

$R_{T_i} := R_{F_i} + R_{R_i}$



$$R_R = \begin{bmatrix} 2482.788 \\ 6506.404 \\ 11561.597 \\ 33948.392 \\ 82179.556 \\ 176505.533 \\ 364507.375 \end{bmatrix} \text{ lbf} \quad R_T = \begin{bmatrix} 6881.321 \\ 22915.697 \\ 47080.19 \\ 95434.858 \\ 176335.081 \\ 285578.054 \\ 543664.612 \end{bmatrix} \text{ lbf}$$



III3. Total Ship Effective Horsepower:

hull:

$P_{EBH_i} := R_{T_i} \cdot V_i$

$\frac{P_{EBH}}{\text{hp}} =$

$C_{SD} := .28$

105.722
704.137
2169.969
5864.906
13545.74
23692.594
58468.658

appendage:  $P_{EAPP_i} := (LWL \cdot D P \cdot C_{DAPP} + .5 \cdot C_{SD} \cdot \rho_{SW} \cdot A_{SD}) \cdot (V_i)^3$

95.946
767.565
2590.531
6140.518
11993.199
15107.977
32909.338

air:  $P_{EAA_i} := .5 \cdot C_{AA} \cdot A_{WA} \cdot \rho_A \cdot (V_i)^3$

2.583
20.667
69.75
165.334
322.918
406.784
886.088

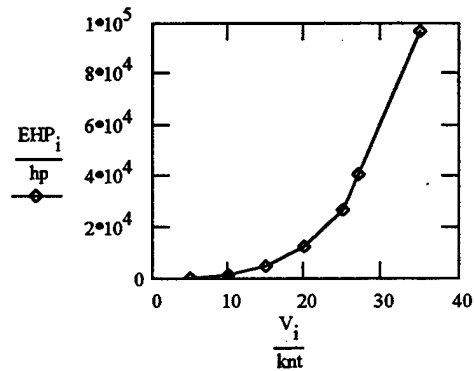
$P_{ET_i} := P_{EBH_i} + P_{EAPP_i} + P_{EAA_i}$

204.251
1492.368
4830.25
12170.758
25861.858
39207.355
92264.084

$EHP_i := PMF \cdot P_{ET_i}$

$V_i$	
knt	
5	214.464
10	1566.987
15	5071.763
20	12779.296
25	27154.951
27	41167.722
35	96877.288

EHP = hp



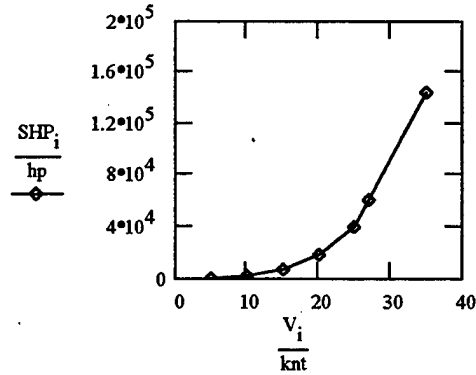
III.4. Shaft Horsepower:

Approximate Propulsive Coefficient (PC):

PC := .67

$$SHP_i := \frac{EHP_i}{PC}$$

$$SHP = \begin{bmatrix} 320.095 \\ 2338.786 \\ 7569.795 \\ 19073.576 \\ 40529.777 \\ 61444.362 \\ 144592.967 \end{bmatrix} \text{ hp}$$



Endurance Shaft Horsepower:

$P_e := SHP_4$

$P_e = 19073.576 \text{ hp}$

Sustained Speed Installed Shaft Horsepower Required (Allows for fouling and sea state):

$P_S := SHP_6$

$P_S = 61444.362 \text{ hp}$

$P_{IREQ} := 1.25 \cdot P_S$

$P_{IREQ} = 76805.452 \text{ hp}$

Actual installed SHP must be greater than  $P_{IREQ}$

$P_{IBRAKE} := N_{PENG} \cdot P_{BPENG}$

$P_{IBRAKE} = 105800 \text{ hp}$

$\eta := .97$

$P_I := \eta \cdot P_{IBRAKE}$

$P_I = 102626 \text{ hp}$

( $P_I$  must be  $> P_{IREQ}$ )

$P_{IREQ} = 76805.452 \text{ hp}$

$$ERR_{POWER} := \frac{P_I - P_{IREQ}}{P_{IREQ}}$$

$ERR_{POWER} = 0.336$

III.5. Estimate Propulsion Fuel Required:

Reference: DDS 200-1 "Calculate of Surface Ship Endurance Fuel"

Average Endurance Brake SHP Required (Allows for fouling and sea state):

$$P_{eBAVG} := 1.1 \cdot \frac{P_e}{\eta}$$

$P_{eBAVG} = 21629.828 \text{ hp}$

Specific fuel rate for propulsion engines:  
(GT; FR for diesel = .327)

$$FR := 1.97 \cdot \frac{\text{lb}}{\text{hp}^{.85} \cdot \text{hr}} \cdot P_{eBAVG}^{-.15}$$

$$FR = 0.441 \cdot \frac{\text{lb}}{\text{hp} \cdot \text{hr}}$$

(for ICR: FR=.347 lb/hphr)

Margin for instrumentation and machinery differences,  $f(P/P_p)$ :

$f_1 := 1.04$

Specified fuel rate:  $FR_{SP} := f_1 \cdot FR$

Average fuel rate allowing for plant deterioration:

$$FR_{AVG} := 1.05 \cdot FR_{SP} \quad FR_{AVG} = 0.481 \cdot \frac{\text{lb}}{\text{hp} \cdot \text{hr}}$$

Burnable propulsion endurance fuel weight:

$$W_{BP} := \frac{E}{V_e} \cdot (P_{eBAVG} \cdot FR_{AVG})$$

$W_{BP} = 1742.879 \text{ ton}$

Tailpipe allowance and propulsion endurance fuel:

TPA := .95  
(shallow tanks)

$$W_{FP} := \frac{W_{BP}}{TPA} \quad W_{FP} = 1834.609 \text{ ton}$$

Allow for expansion and tank structure in required propulsion tank volume:

$$\gamma_F := 43 \frac{\text{ft}^3}{\text{ton}} \quad V_{FP} := 1.02 \cdot 1.05 \cdot \gamma_F \cdot W_{FP} \quad V_{FP} = 84489.268 \text{ ft}^3$$

## III6. Estimate electric load.

Reference: DDS 310-1

Estimate Maximum Functional Load based on parametrics for WINTER cruise condition:

Propulsion:  $kW_P := .00466 \cdot \frac{\text{kW}}{\text{hp}} \cdot P_{IBRAKE} \quad kW_P = 493.028 \text{ kW}$

Steering:  $kW_S := .00583 \cdot \frac{\text{kW}}{\text{ft}^2} \cdot LWL \cdot T \quad kW_S = 48.779 \text{ kW}$

Lighting:  $kW_L := .0002053 \cdot \frac{\text{kW}}{\text{ft}^3} \cdot 1.8 \cdot LWL \cdot T \cdot B \quad kW_L = 172.357 \text{ kW}$

Miscellaneous:  $kW_M := 46.1 \text{ kW}$

Heating:  $kW_H := .0013 \cdot \frac{\text{kW}}{\text{ft}^3} \cdot 1.25 \cdot LWL \cdot T \cdot B \quad kW_H = 757.917 \text{ kW}$

Ventilation:  $kW_{CPS} := .00026 \cdot \frac{\text{kW}}{\text{ft}^3} \cdot 1.8 \cdot LWL \cdot T \cdot B \quad kW_{CPS} = 218.28 \text{ kW}$   
(zero if no CPS)

$$kW_V := .19 \cdot (kW_H + kW_P) + kW_{CPS} \quad kW_V = 455.96 \text{ kW}$$

Air Conditioning:  $kW_{AC} := .67 \cdot \left( .1 \cdot kW \cdot N_T + .0015 \cdot \frac{\text{kW}}{\text{ft}^3} \cdot .47 \cdot 1.3 \cdot LWL \cdot T \cdot B + .1 \cdot kW_P \right)$   
 $kW_{AC} = 329.485 \text{ kW}$

Aux Boiler and FW:  
(electric boiler)  $kW_B := .94 \cdot N_T \cdot kW \quad kW_B = 141 \text{ kW}$

Firemain:  $kW_F := .0001 \cdot \frac{\text{kW}}{\text{ft}^3} \cdot 1.8 \cdot LWL \cdot T \cdot B \quad kW_F = 83.954 \text{ kW}$

Unrep and handling:  $kW_{RH} := .00002 \cdot \frac{\text{kW}}{\text{ft}^3} \cdot 1.25 \cdot LWL \cdot T \cdot B \quad kW_{RH} = 11.66 \text{ kW}$

**Aux Machinery:**  $kW_A := .22 \cdot N_T \cdot kW + kW_{fins}$   $kW_A = 33 \cdot kW$

**Services and Work Spaces:**  $kW_{SERV} := .35 \cdot N_T \cdot kW$   $kW_{SERV} = 52.5 \cdot kW$

**Non-Payload Functional Load:**

$$kW_{NP} := kW_P + kW_S + kW_L + kW_M + kW_H + kW_V + kW_{AC} + kW_B + kW_F + kW_{RH} + kW_A + kW_{SER}$$

**Maximum Functional Load:**

$$kW_{MFL} := kW_{PAY} + kW_{NP} \quad kW_{MFL} = 3165.811 \cdot kW$$

**MFL with margins: (design, growth):**

$$kW_{MFLM} := 1.2 \cdot 1.2 \cdot kW_{MFL} \quad kW_{MFLM} = 4558.767 \cdot kW$$

**Installed Electrical Power Required:**

**Power available per generator:**  $kW_G = 3000 \cdot kW$

**Power required per generator:**  $kW_{GREQ} := \frac{kW_{MFLM}}{(N_G - 1) \cdot .9}$   $kW_{GREQ} = 2532.648 \cdot kW$

**24 hour electrical load:**

$$kW_{24} := .5 \cdot (kW_{MFL} - kW_P - kW_S) + .8 \cdot (kW_P + kW_S) \quad kW_{24} = 1745.447 \cdot kW$$

$$ERR_{KW} := \frac{kW_G - kW_{GREQ}}{kW_{GREQ}}$$

**with margin (design):**  $kW_{24AVG} := 1.2 \cdot kW_{24}$   $kW_{24AVG} = 2094.537 \cdot kW$

$$ERR_{KW} = 0.185$$

**III7. Estimate Electric Fuel Rate:**

$$FR_G = 0.113 \cdot \frac{lb}{kW \cdot hr}$$

**Margin for instrumentation and machinery differences, f(P, P):**  $f_{le} := 1.04$

**Specified fuel rate:**  $FR_{GSP} := f_{le} \cdot FR_G$

**Average fuel rate allowing for plant deterioration:**

$$FR_{GAVG} := 1.05 \cdot FR_{GSP} \quad FR_{GAVG} = 0.124 \cdot \frac{lb}{kW \cdot hr} \quad FR_{GAVG} = 0.092 \cdot \frac{lb}{hp \cdot hr}$$

**III8. Estimate Electrical and Total fuel Required****Burnable electrical endurance fuel weight:**

$$W_{Be} := \frac{E}{V_e} \cdot (kW_{24AVG} \cdot FR_{GAVG}) \quad W_{Be} = 43.416 \cdot \text{tton}$$

**Tailpipe allowance and electrical endurance fuel:**

$$W_{Fe} := \frac{W_{Be}}{TPA} \quad W_{Fe} = 45.701 \text{ tton} \quad TPA := .95$$

(shallow tanks)

**Allow for expansion and tank structure in required electrical fuel tank volume:**

$$V_{Fe} := 1.02 \cdot 1.05 \cdot \gamma_F \cdot W_{Fe} \quad V_{Fe} = 2104.684 \text{ ft}^3$$

**Total ship fuel: (DFM)**

$$W_{F41} := W_{FP} + W_{Fe} \quad W_{F41} = 1880.311 \text{ tton}$$

$$V_F := V_{FP} + V_{Fe} \quad V_F = 86593.952 \text{ ft}^3$$

**IV. Space Estimate****IVA. Available Space****IVA1. Underwater Hull Volume Available**

$$V_{HUW} := V_{FL} \quad V_{HUW} = 233905 \text{ ft}^3$$

**IVA2. Sheer Line. (3 criteria)**

1) Keep deck edge above water at 25 degree heel

2) Longitudinal strength

3) Contain machinery box height:

$$H_{MBMIN} = 22 \text{ ft}$$

$$M := \begin{bmatrix} .21 \cdot B + T \\ \frac{LWL}{15} \\ H_{MBMIN} \end{bmatrix} \quad M = \begin{bmatrix} 28.599 \\ 33.02 \\ 22 \end{bmatrix} \text{ ft}$$

$$D_{10MIN} := \max(M) \quad D_{10MIN} = 33.02 \text{ ft}$$

$$D_{10} := D_{10MIN} + 1 \text{ ft} \quad D_{10} = 34.02 \text{ ft}$$

$$D_{0MIN} := 1.011827 \cdot T - 6.36215 \cdot \frac{10^{-6}}{\text{ft}} \cdot LWL^2 + 2.780649 \cdot 10^{-2} \cdot LWL + T \quad D_{0MIN} = 46.196 \text{ ft} \quad D_0 := D_{0MIN}$$

$$D_{20MIN} := .014 \cdot LWL \cdot \left( 2.125 + 1.25 \cdot \frac{10^{-3}}{\text{ft}} \cdot LWL \right) + T \quad D_{20MIN} = 35.921 \text{ ft} \quad D_{20} := D_{20MIN}$$

**IVA3. Above-Water Hull Volume**

$$F_0 := D_0 - T \quad F_{10} := D_{10} - T \quad F_{20} := D_{20} - T$$

$$A_{PRO} := LWL \cdot \frac{F_0 + 4 \cdot F_{10} + F_{20}}{6} \quad F_{AV} := \frac{A_{PRO}}{LWL} \quad F_{AV} = 19.474 \text{ ft}$$

$$D_{AV} := F_{AV} + T \quad D_{AV} = 36.366 \text{ ft} \quad \text{cubic \#}: CN := \frac{LWL \cdot B \cdot D_{AV}}{10^5 \cdot \text{ft}^3} \quad CN = 10.041$$

$$C_W := .236 + .836 \cdot C_P \quad C_W = 0.729$$



$$\text{flare factor: } f_f := .714599 + .18098 \cdot \frac{D_{AV}}{T} - .018828 \cdot \left( \frac{D_{AV}}{T} \right)^2 \quad M_f := \begin{bmatrix} f_f \\ 1 \end{bmatrix} \quad f_f := \max(M_f) \\ f_f = 1.017$$

$$V_{HAW} := LWL \cdot B \cdot F_{AV} \cdot C_W \cdot f_f \quad V_{HAW} = 398749.111 \text{ ft}^3$$

**IVA4. Total Hull Volume.**

$$V_{HT} := V_{HUW} + V_{HAW} \quad V_{HT} = 632654.111 \text{ ft}^3$$

**IVA5. Size Deck House:**

$$V_{D_{MAX}} := .0025 \cdot LWL^3 \quad V_{D_{MAX}} = 303772.727 \text{ ft}^3$$

$$V_{D_{MIN}} := .0005 \cdot LWL^3 \quad V_{D_{MIN}} = 60754.545 \text{ ft}^3 \quad V_D = 97715 \text{ ft}^3$$

**IVA6. Calculate Total Ship Volume**

$$V_T := V_{HT} + V_D \quad V_T = 730369.111 \text{ ft}^3$$

**IVB. Space Requirement****IVB1. Machinery Box**

(assumed near midships)

$$B_{MB} := B \quad B_{MB} = 55.745 \text{ ft}$$

$$H_{MB} := D_{10} \quad L_{MB} = 40 \text{ ft} \quad A_{MB} := B \cdot T \cdot C_X + B \cdot (H_{MB} - T) \quad A_{MB} = 1755.202 \text{ ft}^2$$

Calculate Machinery Box Volume:

$$V_{MB} := L_{MB} \cdot A_{MB} \cdot C_{PMB} \quad V_{MB} = 70067.665 \text{ ft}^3 \quad V_{AUX} := 1.2 \cdot V_{MB} \quad V_{AUX} = 84081.198 \text{ ft}^3$$

**IVB2. Tankage****Helo:**

$$\text{Helo fuel weight from Payload Spreadsheet: } W_{F42} = 63.8 \text{ tton}$$

Allow for tank structure and expansion:

$$\gamma_{HF} := 43 \cdot \frac{\text{ft}^3}{\text{tton}}$$

$$V_{HF} := 1.02 \cdot 1.05 \cdot W_{F42} \cdot \gamma_{HF} \quad V_{HF} = 2938.181 \text{ ft}^3$$

**Lube Oil:**

$$\text{LO weight: } W_{F46} := 7.2 \text{ tton}$$

Allow for tank structure and expansion:

$$\gamma_{LO} := 39 \cdot \frac{\text{ft}^3}{\text{tton}}$$

$$V_{LO} := 1.02 \cdot 1.05 \cdot W_{F46} \cdot \gamma_{LO} \quad V_{LO} = 300.737 \text{ ft}^3$$

**Potable Water:**

$$\text{Water weight: } W_{F52} := N_T \cdot 15 \text{ tton} \quad W_{F52} = 22.5 \text{ tton}$$

Allow for tank structure:

$$\gamma_W := 36 \cdot \frac{\text{ft}^3}{\text{tton}}$$

$$V_W := 1.02 \cdot W_{F52} \cdot \gamma_W \quad V_W = 826.2 \text{ ft}^3$$

$$\text{Sewage: } V_{\text{SEW}} := N_T \cdot 2 \cdot \text{ft}^3 \quad V_{\text{SEW}} = 300 \text{ ft}^3$$

$$\text{Waste Oil: } V_{\text{WASTE}} := .005 \cdot V_{\text{FL}} \quad V_{\text{WASTE}} = 1169.525 \text{ ft}^3$$

$$\text{Clean Balast: } V_{\text{BAL}} := .032 \cdot V_{\text{FL}} \quad V_{\text{BAL}} := 0 \text{ ft}^3 \quad V_{\text{BAL}} = 0 \text{ ft}^3$$

**Total:**

(for compensated system)

$$V_{\text{TK}} := V_{\text{F}} + V_{\text{HF}} + V_{\text{LO}} + V_{\text{W}} + V_{\text{SEW}} + V_{\text{WASTE}} + V_{\text{BAL}} \quad V_{\text{TK}} = 92128.595 \text{ ft}^3$$

### IVB3. Payload Deck Areas

$$\text{Deckhouse payload area: } A_{\text{DPR}} := 1.15 \cdot A_{\text{DPA}} + 1.23 \cdot A_{\text{DPC}} \quad A_{\text{DPR}} = 10143.981 \text{ ft}^2$$

(including access)

$$\text{Hull payload area: } A_{\text{HPR}} := 1.15 \cdot A_{\text{HPA}} + 1.23 \cdot A_{\text{HPC}} \quad A_{\text{HPR}} = 9797.796 \text{ ft}^2$$

(including access)

### IVB4. Living Deck Area

$$\text{Deckhouse: } A_{\text{COXO}} := 225 \text{ ft}^2 \quad A_{\text{DO}} := 75 \cdot N_O \text{ ft}^2 \quad A_{\text{DO}} = 1125 \text{ ft}^2$$

$$A_{\text{DL}} := A_{\text{COXO}} + A_{\text{DO}} \quad A_{\text{DL}} = 1350 \text{ ft}^2$$

$$\text{Hull: } A_{\text{HAB}} := 50 \text{ ft}^2 \quad A_{\text{HL}} := \left( A_{\text{HAB}} + \frac{\text{LWL}}{100} \cdot \text{ft} \right) \cdot N_T - A_{\text{DL}}$$

$$A_{\text{HL}} = 6892.952 \text{ ft}^2$$

### IVB5. Hull Stores

$$A_{\text{HS}} := 300 \text{ ft}^2 + .0158 \cdot \frac{\text{ft}^2}{\text{lb}} \cdot N_T \cdot 9 \cdot \frac{\text{lb}}{\text{day}} \cdot T_S \quad A_{\text{HS}} = 1259.85 \text{ ft}^2$$

### IVB6. Other Ship Functions

**Deckhouse:**

**Maintenance:**

$$A_{\text{DM}} := .05 \cdot (A_{\text{DPR}} + A_{\text{DL}}) \quad A_{\text{DM}} = 574.699 \text{ ft}^2$$

**Bridge and Chartroom:**

$$A_{\text{DB}} := 16 \text{ ft} \cdot (B - 18 \text{ ft}) \quad A_{\text{DB}} = 603.921 \text{ ft}^2$$

**Engine Inlet/Exhaust:**

$$A_{\text{DIE}} := 1.4 \cdot N_{\text{DIE}} \cdot (A_{\text{PIE}} + A_{\text{eIE}}) \quad A_{\text{DIE}} = 918.4 \text{ ft}^2$$

**Hull:**

**Ship Functions:**

$$A_{\text{HSF}} := 2500 \text{ ft}^2 \cdot \text{CN} \quad A_{\text{HSF}} = 25102.384 \text{ ft}^2$$

**Engine Inlet/Exhaust:**

$$A_{HIE} := 1.4 \cdot (N_{HPIE} \cdot A_{PIE} + N_{HeIE} \cdot A_{eIE}) \quad A_{HIE} = 161.28 \text{ ft}^2$$

**IVB7. Total Required Area and Volume****Hull:**

$$A_{HR} := A_{HPR} + A_{HL} + A_{HS} + A_{HSF} + A_{HIE} \quad A_{HR} = 43214.262 \text{ ft}^2$$

$$V_{HR} := H_{DK} \cdot A_{HR} \quad V_{HR} = 388928.354 \text{ ft}^3$$

**Deckhouse:**

$$A_{DR} := A_{DPR} + A_{DL} + A_{DM} + A_{DB} + A_{DIE} \quad A_{DR} = 13591.001 \text{ ft}^2$$

$$V_{DR} := H_{DK} \cdot A_{DR} \quad V_{DR} = 122319.01 \text{ ft}^3$$

**Total:**

$$A_{TR} := A_{HR} + A_{DR} \quad A_{TR} = 56805.263 \text{ ft}^2$$

$$V_{TR} := H_{DK} \cdot A_{TR} \quad V_{TR} = 511247.364 \text{ ft}^3$$

**IVC. Space Balance**

$$V_D = 97715 \text{ ft}^3$$

$$V_{DR} = 122319.01 \text{ ft}^3$$

$$V_{HA} := V_{HT} - V_{MB} - V_{AUX} - V_{TK} \quad V_{HA} = 386376.654 \text{ ft}^3$$

$$V_{HR} = 388928.354 \text{ ft}^3$$

$$V_{TA} := V_{HA} + V_D$$

$$V_{TA} = 484091.654 \text{ ft}^3 >$$

$$V_{TR} = 511247.364 \text{ ft}^3$$

$$A_{HA} := \frac{V_{HA}}{H_{DK}}$$

$$A_{HA} = 42930.739 \text{ ft}^2$$

$$A_{HR} = 43214.262 \text{ ft}^2$$

$$A_{DA} := \frac{V_D}{H_{DK}}$$

$$A_{DA} = 10857.222 \text{ ft}^2$$

$$A_{DR} = 13591.001 \text{ ft}^2$$

$$A_{TA} := A_{DA} + A_{HA}$$

$$A_{TA} = 53787.962 \text{ ft}^2 >$$

$$A_{TR} = 56805.263 \text{ ft}^2$$

$$ERR_{VOL} := \frac{V_{TA} - V_{TR}}{V_{TR}} \quad ERR_{VOL} = -0.053117$$

$$ERR_{AREA} := \frac{A_{TA} - A_{TR}}{A_{TR}} \quad ERR_{AREA} = -0.053117$$

**V. Weight****V1. Propulsion (200)**

$$\text{Basic Machinery: } W_{BM} := P_I \frac{\text{lb}}{\text{hp}} \left[ 9.0 + 12.4 \cdot \left( P_I \frac{10^{-5}}{\text{hp}} - 1 \right)^2 \right] \quad W_{BM} = 412.728 \text{ ton}$$

(230+241/242+  
250-290)

$$\text{Shafting: (243)} \quad W_S := .356 \cdot \frac{\text{lton}}{\text{ft}} \cdot \text{LWL} \cdot f_S \quad W_S = 88.164 \text{ lton}$$

( $f_S=0.5$  for twin screws, 0.33 for single screw)

$$\text{Props: (245)} \quad W_{PR} := .05575 \cdot \text{lb} \cdot \left( \frac{D_P}{\text{ft}} \right)^{5.497 - \frac{.0433}{\text{ft}} \cdot D_P} \cdot N_P \quad W_{PR} = 36.613 \text{ lton}$$

$$\text{Bearings: (244)} \quad W_B := .15 \cdot (W_S + W_{PR}) \quad W_B = 18.717 \text{ lton}$$

$$\text{Total Shafting:} \quad W_{ST} := W_S + W_B + W_{PR} \quad W_{ST} = 143.493 \text{ lton}$$

$$\text{Total Propulsion:} \quad W_2 := W_{BM} + W_{ST} + W_{237} \quad W_2 = 556.222 \text{ lton}$$

#### V2. Electrical Plant (300)

$$W_3 := 50 \cdot \text{lton} + .03214 \cdot \frac{\text{lton}}{\text{kW}} \cdot N_G \cdot \text{kW}_G \quad W_3 = 339.26 \text{ lton}$$

#### V3. Command/Control/Surveillance (400)

$$\text{Gyro/IC/Navigation (420, 430):} \quad W_{IC} := 4.65 \cdot \text{CN} \cdot \text{lton} \quad W_{IC} = 46.69 \text{ lton}$$

$$\text{Other/Misc Group 400:} \quad W_{CO} := 2.24 \cdot \text{CN} \cdot \text{lton} \quad W_{CO} = 22.492 \text{ lton}$$

$$\text{Cabling:} \quad W_{CC} := .04 \cdot (W_{P400} + W_{IC} + W_{CO}) \quad W_{CC} = 8.693 \text{ lton}$$

$$W_4 := W_{P400} + W_{IC} + W_{CO} + W_{CC} + W_{498} \quad W_4 = 313.915 \text{ lton}$$

#### V4. Auxiliary Systems (500)

$$\text{aux steam (electric aux boiler):} \quad \text{hotel steam:} \quad Q_{HS} := 15 \cdot N_T \quad \text{distiller:} \quad Q_{DS} := 6.5 \cdot N_T + 250$$

$$W_{517} := .0013 \cdot (Q_{HS} + Q_{DS}) \cdot \text{lton} \quad W_{517} = 4.518 \text{ lton} \quad \text{aux sys operating fluids:} \quad W_{598} := .000075 \cdot V_T \cdot \frac{\text{lton}}{\text{ft}^3}$$

$$W_{598} = 54.778 \text{ lton}$$

$$W_{AUX} := \left[ .000772 \cdot \left( \frac{V_T}{\text{ft}^3} \right)^{1.443} + 5.14 \cdot \frac{V_T}{\text{ft}^3} + 6.19 \cdot \left( \frac{V_T}{\text{ft}^3} \right)^{.7224} + 377 \cdot N_T + 2.74 \cdot \frac{P_I}{\text{hp}} \right] \cdot 10^{-4} \cdot \text{lton} + 113.8 \cdot \text{lton}$$

$$\text{environmental support:} \quad W_{593} := 10 \cdot \text{lton} \quad W_5 := W_{P500} + W_{517} + W_{593} + W_{CPS} \quad W_5 = 91.907 \text{ lton}$$

## V5. Outfit &amp; Furnishings (600)

$$\text{Hull Fittings: } W_{\text{OFH}} := \left( 31.4 + \frac{.0003187}{\text{ft}^3} \cdot V_T \right) \cdot \text{ton} \quad W_{\text{OFH}} = 264.169 \text{ ton}$$

$$\text{Personnel-related: } W_{\text{OFP}} := .8 \cdot (N_T - 9.5) \cdot \text{ton} \quad W_{\text{OFP}} = 112.4 \text{ ton}$$

$$W_6 := W_{\text{OFP}} + W_{\text{P600}} \quad W_6 = 120.14 \text{ ton}$$

## V6. Structure (100)

$$\text{Hull (110-140, 160, 190): } W_{\text{BH}} := C_{\text{HMAT}} \cdot (1.68341 \cdot \text{CN}^2 + 167.1721 \cdot \text{CN} - 103.283) \cdot \text{ton} \quad W_{\text{BH}} = 1622.856 \text{ ton}$$

$$\rho_{\text{DH}} := \text{if}(C_{\text{DHMAT}} = 1, .0007, .001429) \quad \rho_{\text{DH}} = 0.001$$

$$\text{Deckhouse (150): } W_{\text{DH}} := \rho_{\text{DH}} \cdot \frac{\text{ton}}{\text{ft}^3} \cdot V_D \quad W_{\text{DH}} = 139.635 \text{ ton}$$

$$\text{Masts: } W_{171} := .0688 \cdot \frac{\text{ton}}{\text{ft}} \cdot \text{LWL} - 13.75 \cdot \text{ton} \quad W_{171} = 20.327 \text{ ton}$$

$$\text{Foundations: } W_{180} := .0675 \cdot W_{\text{BM}} + .072 \cdot (W_3 + W_4 + W_5 + W_7) \quad W_{180} = 89.956 \text{ ton}$$

$$W_1 := W_{\text{BH}} + W_{\text{DH}} + W_{171} + W_{180} + W_{165} + W_{164} \quad W_1 = 1958.474 \text{ ton}$$

## V7. Single Digit Weight Summary &amp; Weight Balance:

$$i1 := 1, 2, \dots, 7$$

$$\text{Weight margin: } W_{\text{M24}} := .1 \cdot \left( \sum_{i1} W_{i1} \right) \quad W_{\text{M24}} = 349.729 \text{ ton}$$

(Future Growth)

## Lightship:

$$W_{\text{LS}} := \sum_{i1} W_{i1} + W_{\text{M24}} \quad W_{\text{LS}} = 3847.017 \text{ ton}$$

## Additional Loads:

$$\text{Provisions: } W_{\text{F31}} := N_T \cdot 9 \cdot \frac{\text{lb}}{\text{day}} \cdot T_S \quad W_{\text{F31}} = 27.121 \text{ ton}$$

$$\text{General stores: } W_{\text{F32}} := .0009598 \cdot \frac{\text{ton}}{\text{day}} \cdot T_S \cdot N_T \quad W_{\text{F32}} = 6.479 \text{ ton}$$

$$\text{Crew: } W_{\text{F10}} := 236 \cdot \text{lb} \cdot N_E + 400 \cdot \text{lb} \cdot (N_O + 1) \quad W_{\text{F10}} = 17.08 \text{ ton}$$

$$W_T := W_{\text{LS}} + W_{\text{F41}} + W_{\text{F42}} + W_{\text{F20}} + W_{\text{F46}} + W_{\text{F52}} + W_{\text{F31}} + W_{\text{F32}} + W_{\text{F10}}$$

$$W_T = 6058.967 \text{ ton}$$

$$\text{Weight Balance: } \text{ERR\_WEIGHT} := \frac{\Delta_{\text{FL}} - W_T}{W_T} \quad \text{ERR\_WEIGHT} = 0.102993$$

**Weights Independent of the Design Variables:**

$$W_{IND} := W_{237} + W_3 + W_5 + W_6 + W_7 + W_{165} + W_{164} + W_{F31} + W_{F32} + W_{F10} + W_{F20}$$

$$W_{IND} = 992.517 \text{ tton}$$

**VL Stability****VII. Calculate Light Ship Weight Group Moments:**

<u>Weight</u>	<u>VCG</u>	<u>Product</u>
$W_{BH} = 1622.856 \text{ tton}$	$VCG_1 := .527 \cdot D_{10}$	$VCG_1 = 17.929 \text{ ft}$ $P_1 := W_{BH} \cdot VCG_1$
$W_{DH} = 139.635 \text{ tton}$	$VCG_2 := D_{10} + 1.5 \cdot H_{DK}$	$VCG_2 = 47.52 \text{ ft}$ $P_2 := W_{DH} \cdot VCG_2$
$W_{180} = 89.956 \text{ tton}$	$VCG_3 := .68 \cdot D_{10}$	$VCG_3 = 23.134 \text{ ft}$ $P_3 := W_{180} \cdot VCG_3$
$W_{171} = 20.327 \text{ tton}$	$VCG_4 := 2.65 \cdot D_{10}$	$VCG_4 = 90.153 \text{ ft}$ $P_4 := W_{171} \cdot VCG_4$
$P_{100} := P_1 + P_2 + P_3 + P_4$		$VCG_{100} := \frac{P_{100}}{W_1}$ $VCG_{100} = 20.243 \text{ ft}$
$W_{BM} = 412.728 \text{ tton}$	$VCG_5 := .5 \cdot D_{10}$	$VCG_5 = 17.01 \text{ ft}$ $P_5 := W_{BM} \cdot VCG_5$
$W_{ST} = 143.493 \text{ tton}$	$VCG_6 := 3.9 \cdot \text{ft} + .19 \cdot T$	$VCG_6 = 7.11 \text{ ft}$ $P_6 := W_{ST} \cdot VCG_6$
$W_{237} = 0 \text{ tton}$	$VCG_7 := VCG_{237}$	$VCG_7 = 0 \text{ ft}$ $P_7 := W_{237} \cdot VCG_7$
$P_{200} := P_5 + P_6 + P_7$		$VCG_{200} := \frac{P_{200}}{W_2}$ $VCG_{200} = 14.456 \text{ ft}$
$W_3 = 339.26 \text{ tton}$	$VCG_8 := .65 \cdot D_{10}$	$VCG_8 = 22.113 \text{ ft}$ $P_8 := W_3 \cdot VCG_8$
$W_{IC} = 46.69 \text{ tton}$	$VCG_9 := D_{10}$	$VCG_9 = 34.02 \text{ ft}$ $P_9 := W_{IC} \cdot VCG_9$
$W_{CO} = 22.492 \text{ tton}$	$VCG_{10} := 5.6 \cdot \text{ft} + .4625 \cdot D_{10}$	$VCG_{10} = 21.334 \text{ ft}$ $P_{10} := W_{CO} \cdot VCG_{10}$
$W_{CC} = 8.693 \text{ tton}$	$VCG_{11} := .5 \cdot D_{10}$	$VCG_{11} = 17.01 \text{ ft}$ $P_{11} := W_{CC} \cdot VCG_{11}$
$W_{498} = 87.9 \text{ tton}$	$VCG_{12} := VCG_{498}$	$VCG_{12} = -1.2 \text{ ft}$ $P_{12} := W_{498} \cdot VCG_{12}$
$W_{AUX} = 555.959 \text{ tton}$	$VCG_{13} := .9 \cdot (D_{10} - 7.4 \cdot \text{ft})$	$VCG_{13} = 23.958 \text{ ft}$ $P_{13} := W_{AUX} \cdot VCG_{13}$
$W_{517} = 4.518 \text{ tton}$	$VCG_{14} := .5 \cdot H_{MB}$	$VCG_{14} = 17.01 \text{ ft}$ $P_{14} := W_{517} \cdot VCG_{14}$
$W_{OFH} = 264.169 \text{ tton}$	$VCG_{15} := .805 \cdot D_{10}$	$VCG_{15} = 27.386 \text{ ft}$ $P_{15} := W_{OFH} \cdot VCG_{15}$
$W_{OFF} = 112.4 \text{ tton}$	$VCG_{16} := 8 \cdot \text{ft} + .71 \cdot D_{10}$	$VCG_{16} = 32.154 \text{ ft}$ $P_{16} := W_{OFF} \cdot VCG_{16}$

$$ip := 1..16$$

$$P_{WG} := \sum_{ip} P_{ip} + W_P \cdot VCG_P - W_{VP} \cdot VCG_{VP} \quad P_{WG} = 90665.675 \text{ ton}\cdot\text{ft}$$

### VI2. Light Ship KG

$$VCG_{LS} := \frac{P_{WG}}{\sum_{il} W_{il}} \quad VCG_{LS} = 25.925 \text{ ft} \quad KG_{LS} := VCG_{LS} \quad KG_{LS} = 25.925 \text{ ft}$$

### VI3. Calculate Variable Load Weight Group Moments:

<u>Weight</u>	<u>VCG</u>	<u>Product</u>
$W_{F10} = 17.08 \text{ ton}$	$VCG_{17} := .746 \cdot D_{10}$	$VCG_{17} = 25.379 \text{ ft} \quad P_{17} := W_{F10} \cdot VCG_{17}$
$W_{F31} = 27.121 \text{ ton}$	$VCG_{18} := .55 \cdot D_{10}$	$VCG_{18} = 18.711 \text{ ft} \quad P_{18} := W_{F31} \cdot VCG_{18}$
$W_{F32} = 6.479 \text{ ton}$	$VCG_{19} := .65 \cdot D_{10}$	$VCG_{19} = 22.113 \text{ ft} \quad P_{19} := W_{F32} \cdot VCG_{19}$
$W_{F41} = 1880.311 \text{ ton}$	$VCG_{20} := 7.5 \text{ ft}$	$VCG_{20} = 7.5 \text{ ft} \quad P_{20} := W_{F41} \cdot VCG_{20}$
$W_{F42} = 63.8 \text{ ton}$	$VCG_{21} := 10 \text{ ft}$	$VCG_{21} = 10 \text{ ft} \quad P_{21} := W_{F42} \cdot VCG_{21}$
$W_{F46} = 7.2 \text{ ton}$	$VCG_{22} := .35 \cdot D_{10}$	$VCG_{22} = 11.907 \text{ ft} \quad P_{22} := W_{F46} \cdot VCG_{22}$
$W_{F52} = 22.5 \text{ ton}$	$VCG_{23} := 7.5 \text{ ft}$	$VCG_{23} = 7.5 \text{ ft} \quad P_{23} := W_{F52} \cdot VCG_{23}$

$$il := 17..23 \quad P_{WGL} := \sum_{il} P_{il} + W_{VP} \cdot VCG_{VP} \quad P_{WGL} = 23519.564 \text{ ton}\cdot\text{ft}$$

$$W_L := W_{F41} + W_{F42} + W_{F20} + W_{F46} + W_{F52} + W_{F31} + W_{F32} + W_{F10} \quad W_L = 2211.95 \text{ ton}$$

$$VCG_L := \frac{P_{WGL}}{W_L} \quad VCG_L = 10.633 \text{ ft}$$

### VI4. Calculate Ship Stability Characteristics:

$$KG_{MARG} := .5 \text{ ft} \quad KG := \frac{W_{LS} \cdot KG_{LS} + W_L \cdot VCG_L}{W_T} + KG_{MARG} \quad C_{IT} := -.497 + 1.44 \cdot C_W \quad C_{IT} = 0.553$$

$$KB := \frac{T}{3} \cdot \left( 2.5 - \frac{C_P \cdot C_X}{C_W} \right) \quad BM := \frac{LWL \cdot B^3 \cdot C_{IT}}{12 \cdot V_{FL}} \quad GM := KB + BM - KG \quad C_{GMB} := \frac{GM}{B}$$

$$KG = 20.842 \text{ ft} \quad KB = 10.205 \text{ ft} \quad BM = 16.907 \text{ ft} \quad GM = 6.27 \text{ ft} \quad C_{GMB} = 0.112$$

**VII. VERY SIMPLIFIED COST MODEL (Lead-Ship End Cost only)**

Mdol := coul

$$\text{Kdol} := \frac{\text{Mdol}}{1000}$$

Bdol := 1000·Mdol

$$\text{dol} := \frac{\text{Kdol}}{1000}$$

**VII.1. Additional characteristics:**Ship Service Life:  $L_S := 30$ Initial Operational Capability:  $Y_{IOC} := 1998$ Total Ship Acquisition:  $N_S := 25$ Production Rate (per year):  $R_P := 3$ **Inflation:**Base Year:  $Y_B := 1998$   $iy := 1.. Y_B - 1981$ Average Inflation Rate (%):  $R_I := 5$   
(from 1981)

$$F_I := \prod_{iy} \left( 1 + \frac{R_I}{100} \right)$$

 $F_I = 2.292$ **a. Lead Ship Cost - Shipbuilder Portion:**SWBS costs: (See Table 5 for  $K_N$  factors)

Structure	$K_{N1} := \frac{.55 \cdot \text{Mdol}}{\text{lton}^{.772}}$	$C_{L1} := .03395 \cdot F_I \cdot K_{N1} \cdot (W_1)^{.772}$	$C_{L1} = 14.886 \cdot \text{Mdol}$
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+ Propulsion	$K_{N2} := \frac{1.2 \cdot \text{Mdol}}{\text{hp}^{.808}}$	$C_{L2} := .00186 \cdot F_I \cdot K_{N2} \cdot P_{IBRAKE}^{.808}$	$C_{L2} = 58.708 \cdot \text{Mdol}$
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+ Electric	$K_{N3} := \frac{1.0 \cdot \text{Mdol}}{\text{lton}^{.91}}$	$C_{L3} := .07505 \cdot F_I \cdot K_{N3} \cdot (W_3)^{.91}$	$C_{L3} = 34.542 \cdot \text{Mdol}$
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**+ Command, Control, Surveillance**

	$K_{N4} := \frac{2.0 \cdot \text{Mdol}}{\text{lton}^{.617}}$	$C_{L4} := .10857 \cdot F_I \cdot K_{N4} \cdot (W_4)^{.617}$	$C_{L4} = 17.278 \cdot \text{Mdol}$
--	--	--	-------------------------------------

(less payload GFM cost)

+ Auxiliary	$K_{N5} := \frac{1.5 \cdot \text{Mdol}}{\text{lton}^{.782}}$	$C_{L5} := .09487 \cdot F_I \cdot K_{N5} \cdot (W_5)^{.782}$	$C_{L5} = 11.189 \cdot \text{Mdol}$
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+ Outfit	$K_{N6} := \frac{1.0 \cdot \text{Mdol}}{\text{lton}^{.784}}$	$C_{L6} := .09859 \cdot F_I \cdot K_{N6} \cdot (W_6)^{.784}$	$C_{L6} = 9.65 \cdot \text{Mdol}$
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+ Armament	$K_{N7} := \frac{1.0 \cdot \text{Mdol}}{\text{lton}^{.987}}$	$C_{L7} := .00838 \cdot F_I \cdot K_{N7} \cdot (W_7)^{.987}$	$C_{L7} = 2.119 \cdot \text{Mdol}$
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(Less payload GFM cost)



+ Margin Cost:

$$C_{LM} := \frac{W_{M24}}{(W_{LS} - W_{M24})} \cdot \left( \sum_{i1} C_{L_{i1}} \right) \quad C_{LM} = 14.837 \cdot \text{Mdol}$$

+ Integration/Engineering: (Lead ship includes detail design engineering for class)

$$K_{N8} := \frac{10.0 \cdot \text{Mdol}}{\text{Mdol}^{1.099}} \quad C_{L_8} := .034 \cdot K_{N8} \cdot \left( \sum_{i1} C_{L_{i1}} + C_{LM} \right)^{1.099} \quad C_{L_8} = 91.894 \cdot \text{Mdol}$$

+ Ship Assembly and Support: (Lead ship includes all tooling, jigs, special facilities for class)

$$K_{N9} := \frac{2.0 \cdot \text{Mdol}}{(\text{Mdol})^{.839}} \quad C_{L_9} := .135 \cdot K_{N9} \cdot \left( \sum_{i1} C_{L_{i1}} + C_{LM} \right)^{.839} \quad C_{L_9} = 19.402 \cdot \text{Mdol}$$

= Total Lead Ship Construction Cost: (BCC) :

$$C_{LCC} := \sum_{i1} C_{L_{i1}} + C_{L_8} + C_{L_9} + C_{LM} \quad C_{LCC} = 274.505 \cdot \text{Mdol}$$

+ Profit:

$$F_{\text{PROFIT}} := .10 \quad C_{LP} := F_{\text{PROFIT}} \cdot C_{LCC} \quad C_{LP} = 27.451 \cdot \text{Mdol}$$

= Lead Ship Price :

$$P_L := C_{LCC} + C_{LP} \quad P_L = 301.956 \cdot \text{Mdol}$$

+ Change Orders:

$$C_{LCORD} := .12 \cdot P_L \quad C_{LCORD} = 36.235 \cdot \text{Mdol}$$

= Total Shipbuilder Portion:

$$C_{SB} := P_L + C_{LCORD} \quad C_{SB} = 338.19 \cdot \text{Mdol}$$

*b. Lead Ship Cost - Government Portion*

Other support:

$$C_{LOTH} := .025 \cdot P_L \quad C_{LOTH} = 7.549 \cdot \text{Mdol}$$

+ Program Manager's Growth:

$$C_{LPMG} := .1 \cdot P_L \quad C_{LPMG} = 30.196 \cdot \text{Mdol}$$

Costed Military Payload:

$$W_{MP} := W_4 + W_7 + W_{F20} - W_{IC} - W_{F23} \quad W_{MP} = 559.325 \cdot \text{ton}$$

+ Ordnance and Electrical GFE:  
(Military Payload GFE)

$$C_{LMPG} := \left( .319 \cdot \frac{\text{Mdol}}{\text{ton}} \cdot W_{MP} + N_{\text{HELO}} \cdot 18.71 \cdot \text{Mdol} \right) \cdot F_I$$

$$C_{LMPG} = 494.72 \cdot \text{Mdol}$$

$$+ \text{HM\&E GFE (boats, IC):} \quad C_{\text{LHMEG}} := .02 \cdot P_L \quad C_{\text{LHMEG}} = 6.039 \cdot \text{Mdol}$$

$$+ \text{Outfitting Cost:} \quad C_{\text{LOUT}} := .04 \cdot P_L \quad C_{\text{LOUT}} = 12.078 \cdot \text{Mdol}$$

= Total Government Cost:

$$C_{\text{LGOV}} := C_{\text{LOTH}} + C_{\text{LPMG}} + C_{\text{LMPG}} + C_{\text{LHMEG}} + C_{\text{LOUT}} \quad C_{\text{LGOV}} = 550.581 \cdot \text{Mdol}$$

c. Total End Cost: (Must always be less than SCN appropriation)

\* Total End Cost:

$$C_{\text{LEND}} := C_{\text{SB}} + C_{\text{LGOV}} \quad C_{\text{LEND}} = 888.772 \cdot \text{Mdol}$$

**SUMMARY: INITIAL VALUES**

ITERATION WEIGHT:  $W_{FL} \equiv \text{inl} \cdot \text{ton}$       ERR WEIGHT = 0.102993       $V_{FL} \equiv W_{FL} \cdot 35 \cdot \frac{\text{ft}^3}{\text{ton}}$   
 $W_{FL1} = 6683 \cdot \text{ton}$        $W_T = 6058.967 \cdot \text{ton}$

**GROSS CHARACTERISTICS:**

$C_P \equiv .59$  (54 - .64)       $C_{\Delta L} \equiv 55 \cdot \frac{\text{ton}}{\text{ft}^3}$  (45 - 65)       $LWL \equiv 100 \cdot \left( \frac{W_{FL}}{C_{\Delta L}} \right)^{\frac{1}{3}}$        $LWL = 495.301 \cdot \text{ft}$

$C_X \equiv .85$  (7 - .85)       $C_V := \frac{V_{FL}}{LWL^3}$        $C_V = 1.925 \cdot 10^{-3}$

$C_{BT} \equiv 3.3$  (2.8 - 3.7)       $B \equiv \sqrt{\frac{C_{BT} \cdot V_{FL}}{C_P \cdot C_X \cdot LWL}}$        $B = 55.745 \cdot \text{ft}$        $T = 16.892 \cdot \text{ft}$        $C_{LB} = 8.885$  (7.5 - 10)

**ENERGY BALANCE:**

$V_S = 27 \cdot \text{knt}$        $P_I = 102626 \cdot \text{hp}$        $P_{IREQ} = 76805.452 \cdot \text{hp}$       ERR POWER = 0.336

$V_e = 20 \cdot \text{knt}$        $\text{kW}_G = 3000 \cdot \text{kW}$        $\text{kW}_{GREQ} = 2532.648 \cdot \text{kW}$       ERR KW = 0.185

$E = 7500 \cdot \text{knt} \cdot \text{hr}$

**AREA/VOLUME BALANCE:**

$V_D = 97715 \cdot \text{ft}^3$        $V_T = 730369.111 \cdot \text{ft}^3$        $V_{MB} = 70067.665 \cdot \text{ft}^3$        $V_{TR} = 511247.364 \cdot \text{ft}^3$   
 $V_{DMIN} = 60754.545 \cdot \text{ft}^3$        $V_{HT} = 632654.111 \cdot \text{ft}^3$        $V_{AUX} = 84081.198 \cdot \text{ft}^3$        $V_{TA} = 484091.654 \cdot \text{ft}^3$   
 $V_{DMAX} = 303772.727 \cdot \text{ft}^3$        $V_{TK} = 92128.595 \cdot \text{ft}^3$       ERR AREA = -0.053117

$D_{10} = 34.02 \cdot \text{ft}$  (Must be >  $D_{10MIN}$ )

$D_{10MIN} = 33.02 \cdot \text{ft}$        $A_{TR} = 56805.263 \cdot \text{ft}^2$        $A_{HR} = 43214.262 \cdot \text{ft}^2$        $A_{DR} = 13591.001 \cdot \text{ft}^2$   
 $A_{TA} = 53787.962 \cdot \text{ft}^2$        $A_{HA} = 42930.739 \cdot \text{ft}^2$        $A_{DA} = 10857.222 \cdot \text{ft}^2$

**WEIGHT BALANCE:**

$W_{FL} = 6683 \cdot \text{ton}$        $W_T = 6058.967 \cdot \text{ton}$       ERR WEIGHT = 0.102993

$W_1 = 1958.474 \cdot \text{ton}$        $W_5 = 91.907 \cdot \text{ton}$        $W_{LS} = 3847.017 \cdot \text{ton}$

$W_2 = 556.222 \cdot \text{ton}$        $W_6 = 120.14 \cdot \text{ton}$        $W_P = 668.3 \cdot \text{ton}$

$W_3 = 339.26 \cdot \text{ton}$        $W_7 = 117.37 \cdot \text{ton}$        $W_{F41} = 1880.311 \cdot \text{ton}$

$W_4 = 313.915 \cdot \text{ton}$

STABILITY/PAYLOAD:  $C_{GMB} = 0.112$  (.09 - .122)       $F_P := \frac{W_P}{W_{FL}}$        $F_P = 0.1$

MATLAB OPTIMIZER OUTPUT FOR OPTIMIZED DESIGN EXAMPLE:

x0 =

55.7451 16.8924 495.3014 0.6000 0.7500

vlb =

20.0000 5.0000 200.0000 0.5400 0.7000

vub =

90.0000 30.0000 800.0000 0.6400 0.8500

f-COUNT	FUNCTION	MAX{g}	STEP	Procedures
6	7627.82	0.534195	1	
12	6312.8	0.0459915	1	
18	6099.97	0.00388632	1	
24	6123.31	1.92403e-005	1	
30	6123.42	6.04933e-010	1	Hessian modified
31	6123.42	8.88178e-016	1	Hessian modified

Optimization Converged Successfully

Active Constraints:

- 2
- 4
- 6
- 8

x =

45.5016 12.2977 455.0163 0.5400 0.7880

options =

1.0e+003 \*

Columns 1 through 7

0.0010 0.0000 0.0000 0.0000 0 0 0

Columns 8 through 14

6.1234 0 0.0310 0.0060 0.0060 0 0.5000

Columns 15 through 18

0 0.0000 0.0001 0.0010

**MIT MATH MODEL: FINAL SYNTHESIS DESIGN**

$$\text{hp} = \frac{33000 \cdot \text{ft} \cdot \text{lbf}}{\text{min}} \quad \text{knt} = 1.69 \cdot \frac{\text{ft}}{\text{sec}} \quad \text{lton} = 2240 \cdot \text{lb}$$

**I INPUT:**

Primary Input Variables Are Highlighted in Yellow and Must Be Checked for Consistency Between MATHCAD Elements.

**II. Requirements:**

**Payload:** (From CS2MP.XLS, Fig 1&2)  $W_P := \text{in0}_1 \cdot \text{lton}$       **variable:**  $W_{VP} := \text{in0}_2 \cdot \text{lton}$

**Payload VCG:**  $VCG_P := \text{in0}_3 \cdot \text{ft}$       **Variable Payload VCG:**  $VCG_{VP} := \text{in0}_4 \cdot \text{ft}$

**Command and Surveillance Payload:** ( $W_{400}$  less 420 and 430)  $W_{P400} := \text{in0}_5 \cdot \text{lton}$        $\frac{W_{P400}}{\text{lton}} = 148.14$

**Armament (all  $W_{700}$ ):**  $W_7 := \text{in0}_6 \cdot \text{lton}$       **Armor:**  $W_{164} := \text{in0}_7 \cdot \text{lton}$

**Mission handling/support:**  $W_{P500} := \text{in0}_8 \cdot \text{lton}$       **Mission outfit:**  $W_{P600} := \text{in0}_9 \cdot \text{lton}$

**Ordnance:**  $W_{F20} := \text{in0}_{10} \cdot \text{lton}$  (incl helo wt, WF23)      **Helo Fuel:**  $W_{F42} := \text{in0}_{11} \cdot \text{lton}$

**Helo's:**  $N_{HELO} := 2$        $W_{F23} := 12.73 \cdot \text{lton}$

**Payload Cruise Electric Power Requirement:**  $\text{kW}_{PAY} := \text{in0}_{12} \cdot \text{kW}$

**Payload Deck Areas:**

**Deckhouse:** **C&D:**  $A_{DPC} := \text{in0}_{13} \cdot \text{ft}^2$       (W400)

**Armament:**  $A_{DPA} := \text{in0}_{14} \cdot \text{ft}^2$       (W500, W600, W700, WF20)

**Hull:** **C&D:**  $A_{HPC} := \text{in0}_{15} \cdot \text{ft}^2$       (W400)

**Armament:**  $A_{HPA} := \text{in0}_{16} \cdot \text{ft}^2$       (W500, W600, W700, WF20)

**Manning:**

**Officers:**  $N_O := 15$       **Enlisted:**  $N_E := 135$       **Total:**  $N_T := N_E + N_O$        $N_T = 150$

**Average deck height:**  $H_{DK} := 9 \cdot \text{ft}$

**Sustained Speed:**  $V_S = 27 \cdot \text{knt}$       (Use Figure 3 as a guide in selecting  $V_S$ )

**Endurance Speed:**  $V_e = 20 \cdot \text{knt}$       **Range:**  $E = 7500 \cdot \text{knt} \cdot \text{hr}$

**Stores period:**  $T_S := 45 \cdot \text{day}$

Sonar Dome/Appendages: SQS-53C; 215ft<sup>2</sup>, 87.91ton, -1.2ft, 85.71ton SQS-56; 27ft<sup>2</sup>, 13.941ton, -3.1ft, 7.431ton

$A_{SD} := \text{in}_{2,5} \text{ft}^2$  water:  $W_{498} := 87.9 \text{ ton}$   $VCG_{498} := -1.2 \text{ ft}$  structure:  $W_{165} := 85.7 \text{ ton}$

Fin Stabilizers: (for one pair, electric power requirement = 50 kW)  $\text{kW}_{\text{fins}} := \text{in}_{2,7} \text{ kW}$

Hull Material: (OS:  $C_{\text{HMAT}}=1.0$ ; HTS:  $C_{\text{HMAT}}=0.93$ )  $C_{\text{HMAT}} := 93$

CPS: ( $W_{\text{CPS}}=30 \text{ ton}$ ):  $W_{\text{CPS}} := 30 \text{ ton}$  (ie. No CPS=0)

**Machinery:**

Number of propellers =  $N_P := \text{in}_{12} C_{\text{PROPD}} := \text{if}(N_P > 1, 1.0, 1.2)$   $C_{\text{PROPD}} = 1$

Aux Propulsion (APU):  $W_{237} := 0 \text{ ton}$   $VCG_{237} := 0 \text{ ft}$  (Weight=14.21ton, VCG=3.5ft)

Propulsion Engines (PE) - standard LM2500's; Generator engines DDA149TI  $N_P = 2$

Number and brake horsepower of propulsion engines:  $N_{\text{PENG}} := \text{in}_{10} P_{\text{BPENG}} := \text{in}_{11} \text{ hp}$

Inlet/exhaust Xsect area for PE:  $A_{\text{IE}} := 135.2 \text{ ft}^2$   $A_{\text{PIE}} := N_{\text{PENG}} \cdot A_{\text{IE}}$   $A_{\text{PIE}} = 540.8 \text{ ft}^2$

Deckhouse decks impacted by propulsion and generator inlet/exhaust:  $N_{\text{DIE}} := 1$

Hull decks impacted by propulsion inlet/exhaust:  $N_{\text{HPIE}} := 0$

Machinery Box:  $H_{\text{MBMIN}} := 22 \text{ ft}$   $L_{\text{MB}} := 40 \text{ ft}$   $N_{\text{PENG}} = 4$

$C_P = 0.54$   $C_{\text{MB}} := \frac{L_{\text{MB}}}{\text{LWL}}$   $C_{\text{MB}} = 0.088$   $C_{\text{PMB}}$  from Fig. 10:  $C_{\text{PMB}} := .998$

Ship Service Generators:  $N_G := 3$   $\text{kW}_G := 3000 \text{ kW}$

Hull decks impacted by generator inlet/exhaust:  $N_{\text{HeIE}} := 1$

Specific fuel rate for generator engines:  $FR_G := \frac{288 \text{ lb}}{2.54 \text{ kW}\cdot\text{hr}}$   $FR_G = 0.085 \frac{\text{lb}}{\text{hp}\cdot\text{hr}}$

Inlet/exhaust X-sect area for gen:  $A_{\text{GIE}} := 38.4 \text{ ft}^2$   $A_{\text{eIE}} := N_G \cdot A_{\text{GIE}}$   $A_{\text{eIE}} = 115.2 \text{ ft}^2$

**II. GROSS CHARACTERISTICS**

**Hull Principle Characteristics:**

$\text{LWL} = 455.016 \text{ ft}$   $B = 45.502 \text{ ft}$

(see Figures 5 and 6)

$C_P = 0.54$   $C_X = 0.788$

Adjust in  
Summary  
Section at  
end of file

deckhouse volume:  $V_D = 235516.369 \text{ ft}^3$   $C_{\text{DHMAT}} := 2$

(Deckhouse Material: Aluminum -  $C_{\text{DHMAT}}=1$ ; Steel -  $C_{\text{DHMAT}}=2$ )

III.2 Seawater properties:

$$T_{SW} := 59 \quad \rho_{SW} := 1.9905 \frac{\text{slug}}{\text{ft}^3} \quad v_{SW} := 1.2817 \cdot 10^{-5} \frac{\text{ft}^2}{\text{sec}}$$

III.3 Resistance calculation parameters:

Correlation Allowance:  $C_A := .0005$   $C_P = 0.54$   
 Use Figure 7 with  $C_P$  and  $C_{BT}$  for TSS wetted surface coefficient:  $C_{STSS} := 2.536$

$$S_{TSS} := C_{STSS} \cdot \sqrt{(V_{FL}) \cdot LWL} \quad S_{TSS} = 17805.64 \cdot \text{ft}^2 \quad C_{BT} = 3.7$$

$$\text{Specify or estimate actual ship surface area:} \quad S_S := S_{TSS} \quad V_{FL} = 108340.212 \cdot \text{ft}^3$$

Use Figure 8 or 9 with LWL for Appendage Drag Coefficient:  $LWL = 455.016 \cdot \text{ft}$

Air Drag Coefficient:  $C_{AA} := .7$   $C_{DAPP} := 2.85 \cdot \frac{\text{hp} \cdot 10^{-5}}{\text{ft}^2 \cdot \text{knt}^3}$

Power Margin Factor (margin for concept design = 10%):  $PMF := 1.1$

III.4 Use range of ship speeds for speed to length ratios ( $R_{N_i}$ ), Reynold's numbers ( $R_{N_i}$ ) and ITTC friction ( $R_{F_i}$ ):

$i := 1..7$   $V_i := i \cdot 5 \cdot \text{knt}$  Ensure range includes  $V_e$  and  $V_s$ :  $V_6 := V_S \quad V_6 = 27 \cdot \text{knt}$   
 $V_4 := V_e \quad V_4 = 20 \cdot \text{knt}$

$$R_i := \frac{V_i}{\sqrt{LWL}} \quad R_{N_i} := LWL \cdot \frac{V_i}{v_{SW}} \quad C_{F_i} := \frac{.075}{(\log(R_{N_i}) - 2)^2}$$

$V_i$ knt	$R_i$ $\frac{\text{ft}^5}{\text{knt}}$	$R_{N_i}$	$C_{F_i}$	$R_{F_i}$ lbf
5	0.234	$3 \cdot 10^8$	0.002	2894.721
10	0.469	$6 \cdot 10^8$	0.002	10793.033
15	0.703	$9 \cdot 10^8$	0.002	23354.773
20	0.938	$1.2 \cdot 10^9$	0.001	40421.138
25	1.172	$1.5 \cdot 10^9$	0.001	61888.007
27	1.266	$1.62 \cdot 10^9$	0.001	71689.062
35	1.641	$2.1 \cdot 10^9$	0.001	117732.25

$$R_{F_i} := .5 \left[ \rho_{SW} \cdot S_S \cdot (V_i)^2 \cdot (C_A + C_{F_i}) \right]$$

III.1.5 Use Gertler with  $C_p$ ,  $C_v$ ,  $R_i$  and  $C_{BT}$  to interpolate for  $C_R$  and calculate TSS resistance:

$C_p = 0.54$      $C_v = 0.00115$

$R_i \frac{ft^5}{knt}$	$C_{BT}=2.25$	$C_{BT}=3.00$	$C_{BT}=3.75$
0.234	$C_{R2.25} := \begin{bmatrix} .00028 \\ .00028 \\ .00028 \\ .00080 \\ .00150 \\ .00335 \\ .00410 \end{bmatrix}$	$C_{R3.00} := \begin{bmatrix} .00035 \\ .00035 \\ .00042 \\ .00100 \\ .00180 \\ .00350 \\ .00430 \end{bmatrix}$	$C_{R3.75} := \begin{bmatrix} .00048 \\ .00048 \\ .00048 \\ .00095 \\ .00180 \\ .00360 \\ .00460 \end{bmatrix}$
0.469			
0.703			
0.938			
1.172			
1.266			
1.641			

Form Factor:  $FF := \frac{4}{3} \cdot (C_{BT} - 3)$      $FF = 0.933$

$$C_{RTSS_i} := C_{R3.00_i} + FF \cdot \left( \frac{C_{R3.75_i} - C_{R2.25_i}}{2} \right) + FF^2 \cdot \left( \frac{C_{R2.25_i} + C_{R3.75_i}}{2} - C_{R3.00_i} \right)$$

$$C_{RTSS} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.001 \\ 0.002 \\ 0.004 \\ 0.005 \end{bmatrix}$$

$$R_{RTSS_i} := .5 \cdot \left[ \rho_{SW} \cdot S \cdot (V_i)^2 \cdot C_{RTSS_i} \right]$$

$$R_{RTSS} = \begin{bmatrix} 594.029 \\ 2376.118 \\ 5449.009 \\ 19457.936 \\ 57235.012 \\ 132640.508 \\ 283772.062 \end{bmatrix} \text{ lbf}$$



III2 Calculate Bare Hull Ship Resistance - Worm Curve data from ASSET:

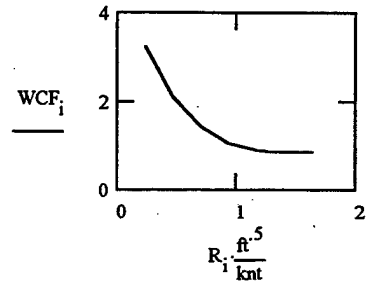
WCFA :=	.2	3.5
	.3	2.95
	.4	2.5
	.5	2.1
	.6	1.8
	.7	1.55
	.8	1.33
	.9	1.17
	1.0	1.07
	1.1	1
	1.2	.94
	1.3	.89
	1.4	.88
	1.5	.87
	1.6	.87

iw := 1..15

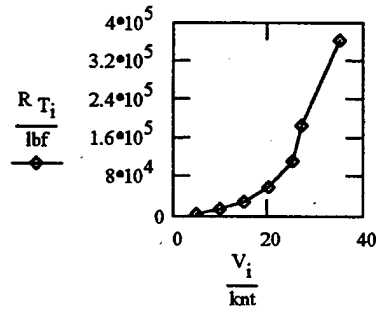
$$R = \begin{bmatrix} 0.234 \\ 0.469 \\ 0.703 \\ 0.938 \\ 1.172 \\ 1.266 \\ 1.641 \end{bmatrix} \frac{\text{knt}}{\text{ft}^5} \quad \text{WCF} := \begin{bmatrix} 3.242 \\ 2.124 \\ 1.460 \\ 1.083 \\ .923 \\ .880 \\ .870 \end{bmatrix}$$

$$R_{R_i} := R_{RTSS_i} \cdot \text{WCF}_i$$

$$R_{T_i} := R_{F_i} + R_{R_i}$$



$$R_R = \begin{bmatrix} 1925.843 \\ 5046.874 \\ 7955.554 \\ 21072.945 \\ 52827.916 \\ 116723.647 \\ 246881.694 \end{bmatrix} \text{ lbf} \quad R_T = \begin{bmatrix} 4820.565 \\ 15839.907 \\ 31310.327 \\ 61494.083 \\ 114715.923 \\ 188412.709 \\ 364613.944 \end{bmatrix} \text{ lbf}$$



III3. Total Ship Effective Horsepower:

hull:  $P_{EBH_i} := R_{T_i} \cdot V_i$

$$\frac{P_{EBH_1}}{\text{hp}} = 74.061 \quad C_{SD} := .28$$

$$\frac{P_{EBH}}{\text{hp}} = \begin{bmatrix} 74.061 \\ 486.717 \\ 1443.121 \\ 3779.091 \\ 8812.269 \\ 15631.404 \\ 39212.572 \end{bmatrix}$$

appendage:  $P_{EAPP_i} := (LWL \cdot D_P \cdot C_{DAPP} + .5 \cdot C_{SD} \cdot \rho \cdot SW \cdot A_{SD}) \cdot (V_i)^3$

$\frac{P_{EAPP}}{hp}$	87.773
	702.188
	2369.884
	5617.503
	10971.685
	13821.164
	30106.304

air:  $P_{EAA_i} := .5 \cdot C_{AA} \cdot A_{WP} \cdot \rho \cdot A \cdot (V_i)^3$

$\frac{P_{EAA}}{hp}$	1.535
	12.281
	41.448
	98.246
	191.887
	241.723
	526.539

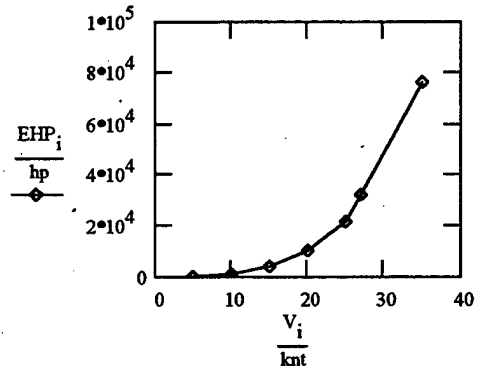
$P_{ET_i} := P_{EBH_i} + P_{EAPP_i} + P_{EAA_i}$

$\frac{P_{ET}}{hp}$	163.37
	1201.186
	3854.453
	9494.84
	19975.841
	29694.29
	69845.415

$EHP_i := PMF \cdot P_{ET_i}$

$\frac{V_i}{knt}$	
5	179.707
10	1321.304
15	4239.898
20	10444.324
25	21973.425
27	32663.719
35	76829.957

EHP =  $\phi$ hp



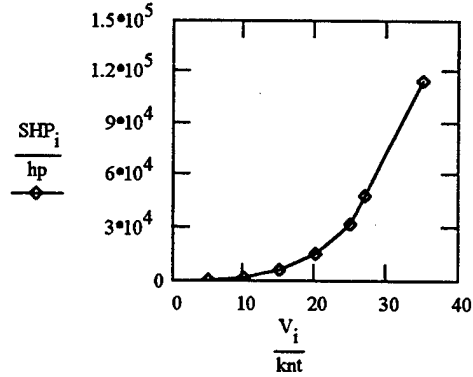
**III4. Shaft Horsepower:**

Approximate Propulsive Coefficient (PC):

$PC := .67$

$SHP_i := \frac{EHP_i}{PC}$

$$SHP = \begin{bmatrix} 268.219 \\ 1972.096 \\ 6328.207 \\ 15588.543 \\ 32796.157 \\ 48751.819 \\ 114671.577 \end{bmatrix} \text{ hp}$$



Endurance Shaft Horsepower:

$P_e := SHP_4$

$P_e = 15588.543 \text{ hp}$

Sustained Speed Installed Shaft Horsepower Required (Allows for fouling and sea state):

$P_S := SHP_6$

$P_S = 48751.819 \text{ hp}$

$P_{IREQ} := 1.25 \cdot P_S$

$P_{IREQ} = 60939.774 \text{ hp}$

Actual installed SHP must be greater than  $P_{IREQ}$

$P_{IBRAKE} := N_{PENG} \cdot P_{BPENG}$

$P_{IBRAKE} = 105800 \text{ hp}$

$P_I := \eta \cdot P_{IBRAKE}$

$P_I = 102626 \text{ hp}$

( $P_I$  must be  $> P_{IREQ}$ )

$P_{IREQ} = 60939.774 \text{ hp}$

$ERR_{POWER} := \frac{P_I - P_{IREQ}}{P_{IREQ}}$

$ERR_{POWER} = 0.684$

**III5. Estimate Propulsion Fuel Required:**

Reference: DDS 200-1 "Calculate of Surface Ship Endurance Fuel"

Average Endurance Brake SHP Required (Allows for fouling and sea state):

$P_{eBAVG} := 1.1 \cdot \frac{P_e}{\eta}$

$P_{eBAVG} = 17677.73 \text{ hp}$

Specific fuel rate for propulsion engines:  
(GT; FR for diesel = .327)

$FR := 1.97 \cdot \frac{\text{lb}}{\text{hp}^{.85} \cdot \text{hr}} \cdot P_{eBAVG}^{-.15}$

$FR = 0.454 \cdot \frac{\text{lb}}{\text{hp} \cdot \text{hr}}$

(for ICR: FR=.347 lb/hphr)

Margin for instrumentation and machinery differences,  $f(P_{I/P})$ :

$f_1 := 1.04$

Specified fuel rate:  $FR_{SP} := f_1 \cdot FR$

Average fuel rate allowing for plant deterioration:

$FR_{AVG} := 1.05 \cdot FR_{SP}$

$FR_{AVG} = 0.496 \cdot \frac{\text{lb}}{\text{hp} \cdot \text{hr}}$

Burnable propulsion endurance fuel weight:

$W_{BP} := \frac{E}{V_e} \cdot (P_{eBAVG} \cdot FR_{AVG})$

$W_{BP} = 1468.198 \text{ ton}$

Tailpipe allowance and propulsion endurance fuel:

$$\text{TPA} := .95$$

(shallow tanks)

$$W_{FP} := \frac{W_{BP}}{\text{TPA}} \quad W_{FP} = 1545.472 \text{ ton}$$

Allow for expansion and tank structure in required propulsion tank volume:

$$\gamma_F := 43 \frac{\text{ft}^3}{\text{ton}} \quad V_{FP} := 1.02 \cdot 1.05 \cdot \gamma_F \cdot W_{FP} \quad V_{FP} = 71173.602 \text{ ft}^3$$

## III.6. Estimate electric load.

Reference: DDS 310-1

Estimate Maximum Functional Load based on parametrics for WINTER cruise condition:

**Propulsion:**  $\text{kW}_P := .00466 \frac{\text{kW}}{\text{hp}} \cdot P_{\text{IBRAKE}} \quad \text{kW}_P = 493.028 \text{ kW}$

**Steering:**  $\text{kW}_S := .00583 \frac{\text{kW}}{\text{ft}^2} \cdot \text{LWL} \cdot T \quad \text{kW}_S = 32.623 \text{ kW}$

**Lighting:**  $\text{kW}_L := .0002053 \frac{\text{kW}}{\text{ft}^3} \cdot 1.8 \cdot \text{LWL} \cdot T \cdot B \quad \text{kW}_L = 94.089 \text{ kW}$

**Miscellaneous:**  $\text{kW}_M := 46.1 \text{ kW}$

**Heating:**  $\text{kW}_H := .0013 \frac{\text{kW}}{\text{ft}^3} \cdot 1.25 \cdot \text{LWL} \cdot T \cdot B \quad \text{kW}_H = 413.745 \text{ kW}$

**Ventilation:**  $\text{kW}_{\text{CPS}} := .00026 \frac{\text{kW}}{\text{ft}^3} \cdot 1.8 \cdot \text{LWL} \cdot T \cdot B \quad \text{kW}_{\text{CPS}} = 119.159 \text{ kW}$   
(zero if no CPS)

$$\text{kW}_V := .19 \cdot (\text{kW}_H + \text{kW}_P) + \text{kW}_{\text{CPS}} \quad \text{kW}_V = 291.445 \text{ kW}$$

**Air Conditioning:**  $\text{kW}_{\text{AC}} := .67 \cdot \left( .1 \cdot \text{kW} \cdot N_T + .0015 \frac{\text{kW}}{\text{ft}^3} \cdot .47 \cdot 1.3 \cdot \text{LWL} \cdot T \cdot B + .1 \cdot \text{kW}_P \right)$   
 $\text{kW}_{\text{AC}} = 199.429 \text{ kW}$

**Aux Boiler and FW:**  $\text{kW}_B := .94 \cdot N_T \cdot \text{kW} \quad \text{kW}_B = 141 \text{ kW}$   
(electric boiler)

**Firemain:**  $\text{kW}_F := .0001 \frac{\text{kW}}{\text{ft}^3} \cdot 1.8 \cdot \text{LWL} \cdot T \cdot B \quad \text{kW}_F = 45.83 \text{ kW}$

**Unrep and handling:**  $\text{kW}_{\text{RH}} := .00002 \frac{\text{kW}}{\text{ft}^3} \cdot 1.25 \cdot \text{LWL} \cdot T \cdot B \quad \text{kW}_{\text{RH}} = 6.365 \text{ kW}$

$$\begin{aligned} \text{Aux Machinery:} \quad kW_A &:= .22 \cdot N_T \cdot kW + kW_{\text{fins}} & kW_A &= 33 \text{ kW} \\ \text{Services and Work Spaces:} \quad kW_{\text{SERV}} &:= .35 \cdot N_T \cdot kW & kW_{\text{SERV}} &= 52.5 \text{ kW} \end{aligned}$$

**Non-Payload Functional Load:**

$$kW_{\text{NP}} := kW_P + kW_S + kW_L + kW_M + kW_H + kW_{\text{CPS}} + kW_V + kW_{\text{AC}} + kW_B + kW_F + kW_{\text{RH}} + kW_A + kW_S$$

**Maximum Functional Load:**

$$kW_{\text{MFL}} := kW_{\text{PAY}} + kW_{\text{NP}} \quad kW_{\text{MFL}} = 2508.383 \text{ kW} \quad \frac{kW_{\text{NP}}}{kW} = 1968.313$$

**MFL with margins: (design, growth):**

$$kW_{\text{MFLM}} := 1.2 \cdot 1.2 \cdot kW_{\text{MFL}} \quad kW_{\text{MFLM}} = 3612.072 \text{ kW}$$

**Installed Electrical Power Required:**

$$\text{Power available per generator:} \quad kW_G = 3000 \text{ kW}$$

$$\text{Power required per generator:} \quad kW_{\text{GREQ}} := \frac{kW_{\text{MFLM}}}{(N_G - 1) \cdot .9} \quad kW_{\text{GREQ}} = 2006.707 \text{ kW}$$

**24 hour electrical load:**

$$kW_{24} := .5 \cdot (kW_{\text{MFL}} - kW_P - kW_S) + .8 \cdot (kW_P + kW_S) \quad kW_{24} = 1411.887 \text{ kW}$$

$$ERR_{\text{KW}} := \frac{kW_G - kW_{\text{GREQ}}}{kW_{\text{GREQ}}} \quad ERR_{\text{KW}} = 0.495$$

$$\text{with margin (design):} \quad kW_{24\text{AVG}} := 1.2 \cdot kW_{24} \quad kW_{24\text{AVG}} = 1694.264 \text{ kW}$$

$$\text{III7. Estimate Electric Fuel Rate:} \quad FR_G = 0.113 \frac{\text{lb}}{\text{kW} \cdot \text{hr}}$$

$$\text{Margin for instrumentation and machinery differences, } f(P_{\text{I}}): \quad f_{\text{Ie}} := 1.04$$

$$\text{Specified fuel rate:} \quad FR_{\text{GSP}} := f_{\text{Ie}} \cdot FR_G$$

**Average fuel rate allowing for plant deterioration:**

$$FR_{\text{GAVG}} := 1.05 \cdot FR_{\text{GSP}} \quad FR_{\text{GAVG}} = 0.124 \frac{\text{lb}}{\text{kW} \cdot \text{hr}} \quad FR_{\text{GAVG}} = 0.092 \frac{\text{lb}}{\text{hp} \cdot \text{hr}}$$

**III8. Estimate Electrical and Total fuel Required****Burnable electrical endurance fuel weight:**

$$W_{\text{Be}} := \frac{E}{V_e} \cdot (kW_{24\text{AVG}} \cdot FR_{\text{GAVG}}) \quad W_{\text{Be}} = 35.119 \text{ ton}$$

**Tailpipe allowance and electrical endurance fuel:**

$$W_{\text{Fe}} := \frac{W_{\text{Be}}}{\text{TPA}} \quad W_{\text{Fe}} = 36.968 \text{ ton}$$

TPA := .95  
(shallow tanks)

Allow for expansion and tank structure in required electrical fuel tank volume:

$$V_{Fe} := 1.02 \cdot 1.05 \cdot \gamma_F \cdot W_{Fe} \quad V_{Fe} = 1702.473 \text{ ft}^3$$

Total ship fuel: (DFM)

$$W_{F41} := W_{FP} + W_{Fe} \quad W_{F41} = 1582.439 \text{ ton}$$

$$V_F := V_{FP} + V_{Fe} \quad V_F = 72876.075 \text{ ft}^3$$

#### IV. Space Estimate

##### IVA. Available Space

###### IVA1. Underwater Hull Volume Available

$$V_{HUW} := V_{FL} \quad V_{HUW} = 108340.212 \text{ ft}^3$$

###### IVA2. Sheer Line. (3 criteria)

1) Keep deck edge above water at 25 degree heel

2) Longitudinal strength

3) Contain machinery box height:

$$H_{MBMIN} = 22 \text{ ft}$$

$$M := \begin{bmatrix} .21 \cdot B + T \\ \frac{LWL}{15} \\ H_{MBMIN} \end{bmatrix} \quad M = \begin{bmatrix} 21.853 \\ 30.334 \\ 22 \end{bmatrix} \text{ ft} \quad D_{10MIN} := \max(M) \quad D_{10MIN} = 30.334 \text{ ft}$$

$$D_{10} := (D_{10MIN} + 1 \text{ ft})$$

$$D_{0MIN} := 1.011827 \cdot T - 6.36215 \cdot \frac{10^{-6}}{\text{ft}} \cdot LWL^2 + 2.780649 \cdot 10^{-2} \cdot LWL + T \quad D_{0MIN} = 36.076 \text{ ft} \quad D_0 := D_{0MIN}$$

$$D_{20MIN} := .014 \cdot LWL \cdot \left( 2.125 + 1.25 \cdot \frac{10^{-3}}{\text{ft}} \cdot LWL \right) + T \quad D_{20MIN} = 29.458 \text{ ft} \quad D_{20} := D_{20MIN}$$

###### IVA3. Above-Water Hull Volume

$$F_0 := D_0 - T \quad F_{10} := D_{10} - T \quad F_{20} := D_{20} - T$$

$$A_{PRO} := LWL \cdot \frac{F_0 + 4 \cdot F_{10} + F_{20}}{6} \quad F_{AV} := \frac{A_{PRO}}{LWL} \quad F_{AV} = 19.514 \text{ ft}$$

$$D_{AV} := F_{AV} + T \quad D_{AV} = 31.812 \text{ ft} \quad \text{cubic \#} : CN := \frac{LWL \cdot B \cdot D_{AV}}{10^5 \cdot \text{ft}^3} \quad CN = 6.586$$

$$C_W := .236 + .836 \cdot C_P \quad C_W = 0.687$$

$$\text{flare factor: } f_f := .714599 + .18098 \cdot \frac{D_{AV}}{T} - .018828 \cdot \left( \frac{D_{AV}}{T} \right)^2 \quad M_f := \begin{bmatrix} f_f \\ 1 \end{bmatrix} \quad f_f := \max(M_f) \\ f_f = 1.057$$

$$V_{HAW} := LWL \cdot B \cdot F_{AV} \cdot C_W \cdot f_f \quad V_{HAW} = 293507.825 \text{ ft}^3$$

**IVA4. Total Hull Volume.**

$$V_{HT} := V_{HUW} + V_{HAW} \quad V_{HT} = 401848.037 \text{ ft}^3$$

**IVA5. Size Deck House:**

$$V_{D_{MAX}} := .0025 \cdot LWL^3 \quad V_{D_{MAX}} = 235516.298 \text{ ft}^3$$

$$V_{D_{MIN}} := .0005 \cdot LWL^3 \quad V_{D_{MIN}} = 47103.26 \text{ ft}^3 \quad V_D = 235516.298 \text{ ft}^3$$

**IVA6. Calculate Total Ship Volume**

$$V_T := V_{HT} + V_D \quad V_T = 637364.335 \text{ ft}^3$$

**IVB. Space Requirement****IVB1. Machinery Box**

(assumed near midships)

$$B_{MB} := B \quad B_{MB} = 45.502 \text{ ft}$$

$$H_{MB} := D_{10} \quad L_{MB} = 40 \text{ ft} \quad A_{MB} := B \cdot T \cdot C_X + B \cdot (H_{MB} - T) \quad A_{MB} = 1307.129 \text{ ft}^2$$

Calculate Machinery Box Volume:

$$V_{MB} := L_{MB} \cdot A_{MB} \cdot C_{PMB} \quad V_{MB} = 52180.608 \text{ ft}^3 \quad V_{AUX} := 1.2 \cdot V_{MB} \quad V_{AUX} = 62616.73 \text{ ft}^3$$

**IVB2. Tankage****Helo:**

$$\text{Helo fuel weight from Payload Spreadsheet:} \quad W_{F42} = 63.8 \text{ tton}$$

Allow for tank structure and expansion:

$$\gamma_{HF} := 43 \cdot \frac{\text{ft}^3}{\text{tton}}$$

$$V_{HF} := 1.02 \cdot 1.05 \cdot W_{F42} \cdot \gamma_{HF} \quad V_{HF} = 2938.181 \text{ ft}^3$$

**Lube Oil:**

$$\text{LO weight:} \quad W_{F46} := 7.2 \cdot \text{tton}$$

Allow for tank structure and expansion:

$$\gamma_{LO} := 39 \cdot \frac{\text{ft}^3}{\text{tton}}$$

$$V_{LO} := 1.02 \cdot 1.05 \cdot W_{F46} \cdot \gamma_{LO} \quad V_{LO} = 300.737 \text{ ft}^3$$

**Potable Water:**

$$\text{Water weight:} \quad W_{F52} := N_T \cdot 15 \cdot \text{tton} \quad W_{F52} = 22.5 \text{ tton}$$

Allow for tank structure:

$$\gamma_W := 36 \cdot \frac{\text{ft}^3}{\text{tton}}$$

$$V_W := 1.02 \cdot W_{F52} \cdot \gamma_W \quad V_W = 826.2 \text{ ft}^3$$

**Sewage:**

$$V_{SEW} := N_T \cdot 2 \cdot \text{ft}^3 \quad V_{SEW} = 300 \text{ ft}^3$$

**Waste Oil:**

$$V_{WASTE} := .005 \cdot V_{FL} \quad V_{WASTE} = 541.701 \text{ ft}^3$$

**Clean Ballast:**

$$V_{BAL} := .032 \cdot V_{FL} \quad V_{BAL} := 0 \cdot \text{ft}^3 \quad V_{BAL} = 0 \text{ ft}^3$$

**Total:**

(for compensated system)

$$V_{TK} := V_F + V_{HF} + V_{LO} + V_W + V_{SEW} + V_{WASTE} + V_{BAL} \quad V_{TK} = 77782.894 \text{ ft}^3$$

## IVB3. Payload Deck Areas

$$\text{Deckhouse payload area: } A_{DPR} := 1.15 \cdot A_{DPA} + 1.23 \cdot A_{DPC} \quad A_{DPR} = 10143.981 \text{ ft}^2$$

(including access)

$$\text{Hull payload area: } A_{HPR} := 1.15 \cdot A_{HPA} + 1.23 \cdot A_{HPC} \quad A_{HPR} = 9797.796 \text{ ft}^2$$

(including access)

## IVB4. Living Deck Area

$$\text{Deckhouse: } A_{COXO} := 225 \cdot \text{ft}^2 \quad A_{DO} := 75 \cdot N_O \cdot \text{ft}^2 \quad A_{DO} = 1125 \text{ ft}^2$$

$$A_{DL} := A_{COXO} + A_{DO} \quad A_{DL} = 1350 \text{ ft}^2$$

$$\text{Hull: } A_{HAB} := 50 \cdot \text{ft}^2 \quad A_{HL} := \left( A_{HAB} + \frac{LWL}{100} \cdot \text{ft} \right) \cdot N_T - A_{DL}$$

$$A_{HL} = 6832.524 \text{ ft}^2$$

## IVB5. Hull Stores

$$A_{HS} := 300 \cdot \text{ft}^2 + .0158 \cdot \frac{\text{ft}^2}{\text{lb}} \cdot N_T \cdot 9 \cdot \frac{\text{lb}}{\text{day}} \cdot T_S \quad A_{HS} = 1259.85 \text{ ft}^2$$

## IVB6. Other Ship Functions

## Deckhouse:

## Maintenance:

$$A_{DM} := .05 \cdot (A_{DPR} + A_{DL}) \quad A_{DM} = 574.699 \text{ ft}^2$$

## Bridge and Chartroom:

$$A_{DB} := 16 \cdot \text{ft} \cdot (B - 18 \cdot \text{ft}) \quad A_{DB} = 440.026 \text{ ft}^2$$

## Engine Inlet/Exhaust:

$$A_{DIE} := 1.4 \cdot N_{DIE} \cdot (A_{PIE} + A_{eIE}) \quad A_{DIE} = 918.4 \text{ ft}^2$$

## Hull:

## Ship Functions:

$$A_{HSF} := 2500 \cdot \text{ft}^2 \cdot CN \quad A_{HSF} = 16465.835 \text{ ft}^2$$

## Engine Inlet/Exhaust:

$$A_{HIE} := 1.4 \cdot (N_{HPIE} \cdot A_{PIE} + N_{HeIE} \cdot A_{eIE}) \quad A_{HIE} = 161.28 \text{ ft}^2$$

## IVB7. Total Required Area and Volume

## Hull:

$$A_{HR} := A_{HPR} + A_{HL} + A_{HS} + A_{HSF} + A_{HIE} \quad A_{HR} = 34517.285 \text{ ft}^2$$

$$V_{HR} := H_{DK} \cdot A_{HR} \quad V_{HR} = 310655.563 \text{ ft}^3$$



**Deckhouse:**

$$A_{DR} := A_{DPR} + A_{DL} + A_{DM} + A_{DB} + A_{DIE} \quad A_{DR} = 13427.106 \text{ ft}^2$$

$$V_{DR} := H_{DK} \cdot A_{DR} \quad V_{DR} = 120843.956 \text{ ft}^3$$

**Total:**

$$A_{TR} := A_{HR} + A_{DR} \quad A_{TR} = 47944.391 \text{ ft}^2$$

$$V_{TR} := H_{DK} \cdot A_{TR} \quad V_{TR} = 431499.519 \text{ ft}^3$$

**IVC. Space Balance**

$$V_D = 235516.298 \text{ ft}^3 \quad V_{DR} = 120843.956 \text{ ft}^3$$

$$V_{HA} := V_{HT} - V_{MB} - V_{AUX} - V_{TK} \quad V_{HA} = 209267.805 \text{ ft}^3 \quad V_{HR} = 310655.563 \text{ ft}^3$$

$$V_{TA} := V_{HA} + V_D \quad V_{TA} = 444784.103 \text{ ft}^3 > V_{TR} = 431499.519 \text{ ft}^3$$

$$A_{HA} := \frac{V_{HA}}{H_{DK}} \quad A_{HA} = 23251.978 \text{ ft}^2 \quad A_{HR} = 34517.285 \text{ ft}^2$$

$$A_{DA} := \frac{V_D}{H_{DK}} \quad A_{DA} = 26168.478 \text{ ft}^2 \quad A_{DR} = 13427.106 \text{ ft}^2$$

$$A_{TA} := A_{DA} + A_{HA} \quad A_{TA} = 49420.456 \text{ ft}^2 > A_{TR} = 47944.391 \text{ ft}^2$$

$$ERR_{VOL} := \frac{V_{TA} - V_{TR}}{V_{TR}} \quad ERR_{VOL} = 3.078702 \%$$

$$ERR_{AREA} := \frac{A_{TA} - A_{TR}}{A_{TR}} \%$$

**V. Weight**

**V1. Propulsion (200)**

**Basic Machinery:** (230+241/242+250-290)  $W_{BM} := P_I \frac{\text{lb}}{\text{hp}} \left[ 9.0 + 12.4 \left( P_I \frac{10^{-5}}{\text{hp}} - 1 \right)^2 \right]$   $W_{BM} = 412.728 \text{ tton}$

**Shafting:** (243)  $f_s := .5$   $W_S := .356 \frac{\text{tton}}{\text{ft}} \cdot LWL \cdot f_s$   $W_S = 80.993 \text{ tton}$   
 ( $f_s=0.5$  for twin screws,  $0.33$  for single screw)

**Props:** (245)  $W_{PR} := .05575 \cdot \text{lb} \cdot \left( \frac{D_P}{\text{ft}} \right)^{5.497 - \frac{.0433}{\text{ft}} \cdot D_P} \cdot N_P$   $W_{PR} = 18.227 \text{ tton}$

**Bearings:** (244)  $W_B := .15 \cdot (W_S + W_{PR})$   $W_B = 14.883 \text{ tton}$

**Total Shafting:**  $W_{ST} := W_S + W_B + W_{PR}$   $W_{ST} = 114.103 \text{ tton}$

**Total Propulsion:**  $W_2 := W_{BM} + W_{ST} + W_{237}$   $W_2 = 526.831 \text{ tton}$

**V2. Electrical Plant (300)**

$$W_3 := 50 \cdot \text{tton} + .03214 \cdot \frac{\text{tton}}{\text{kW}} \cdot N_G \cdot kW_G \quad W_3 = 339.26 \cdot \text{tton}$$

**V3. Command/Control/Surveillance (400)**

$$\text{Gyro/IC/Navigation (420, 430):} \quad W_{IC} := 4.65 \cdot CN \cdot \text{tton} \quad W_{IC} = 30.626 \cdot \text{tton}$$

$$\text{Other/Misc Group 400:} \quad W_{CO} := 2.24 \cdot CN \cdot \text{tton} \quad W_{CO} = 14.753 \cdot \text{tton}$$

$$\text{Cabling:} \quad W_{CC} := .04 \cdot (W_{P400} + W_{IC} + W_{CO}) \quad W_{CC} = 7.741 \cdot \text{tton}$$

$$W_4 := W_{P400} + W_{IC} + W_{CO} + W_{CC} + W_{498} \quad W_4 = 289.161 \cdot \text{tton}$$

**V4. Auxiliary Systems (500)**

$$\text{aux steam (electric aux boiler):} \quad \text{hotel steam:} \quad Q_{HS} := 15 \cdot N_T \quad \text{distiller:} \quad Q_{DS} := 6.5 \cdot N_T + 250$$

$$W_{517} := .0013 \cdot (Q_{HS} + Q_{DS}) \cdot \text{tton} \quad W_{517} = 4.518 \cdot \text{tton} \quad \text{aux sys operating fluids:} \quad W_{598} := .000075 \cdot V_T \cdot \frac{\text{tton}}{\text{ft}^3}$$

$$W_{598} = 47.802 \cdot \text{tton}$$

$$W_{AUX} := \left[ .000772 \cdot \left( \frac{V_T}{\text{ft}^3} \right)^{1.443} + 5.14 \cdot \frac{V_T}{\text{ft}^3} + 6.19 \cdot \left( \frac{V_T}{\text{ft}^3} \right)^{.7224} + 377 \cdot N_T + 2.74 \cdot \frac{P_I}{\text{hp}} \right] \cdot 10^{-4} \cdot \text{tton} + 113.8 \cdot \text{tton}$$

$$W_{AUX} = 503.173 \cdot \text{tton}$$

$$\text{environmental support:} \quad W_{593} := 10 \cdot \text{tton} \quad W_5 := W_{AUX} + W_{P500} + W_{517} + W_{593} + W_{598} + W_{CPS}$$

**V5. Outfit & Furnishings (600)**

$$W_5 = 642.883 \cdot \text{tton}$$

$$\text{Hull Fittings:} \quad W_{OFH} := \left( 31.4 + \frac{.0003187}{\text{ft}^3} \cdot V_T \right) \cdot \text{tton} \quad W_{OFH} = 234.528 \cdot \text{tton}$$

$$\text{Personnel-related:} \quad W_{OFP} := .8 \cdot (N_T - 9.5) \cdot \text{tton} \quad W_{OFP} = 112.4 \cdot \text{tton}$$

$$W_6 := W_{OFH} + W_{OFP} + W_{P600} \quad W_6 = 354.668 \cdot \text{tton}$$

**V6. Structure (100)**

$$\text{Hull (110-140, 160, 190):} \quad W_{BH} := C_{HMAT} \cdot (1.68341 \cdot CN^2 + 167.1721 \cdot CN - 103.283) \cdot \text{tton} \quad W_{BH} = 995.839 \cdot \text{tton}$$

$$\rho_{DH} := \text{if}(C_{DHMAT} = 1, .0007, .001429) \quad \rho_{DH} = 0.001$$

$$\text{Deckhouse (150):} \quad W_{DH} := \rho_{DH} \cdot \frac{\text{tton}}{\text{ft}^3} \cdot V_D \quad W_{DH} = 336.553 \cdot \text{tton}$$

**Masts:**  $W_{171} := .0688 \cdot \frac{\text{tton}}{\text{ft}} \cdot \text{LWL} - 13.75 \cdot \text{tton}$   $W_{171} = 17.555 \cdot \text{tton}$

**Foundations:**  $W_{180} := .0675 \cdot W_{BM} + .072 \cdot (W_3 + W_4 + W_5 + W_7)$   $W_{180} = 127.844 \cdot \text{tton}$

$W_1 := W_{BH} + W_{DH} + W_{171} + W_{180} + W_{165} + W_{164}$   $W_1 = 1563.49 \cdot \text{tton}$

**V7. Single Digit Weight Summary & Weight Balance:**

il := 1, 2.. 7

**Weight margin:**  $W_{M24} := .1 \cdot \left( \sum_{il} W_{il} \right)$   $W_{M24} = 383.366 \cdot \text{tton}$   
**(Future Growth)**

**Lightship:**

$W_{LS} := \sum_{il} W_{il} + W_{M24}$   $W_{LS} = 4217.029 \cdot \text{tton}$

**Additional Loads:**

**Provisions:**  $W_{F31} := N_T \cdot 9 \cdot \frac{\text{lb}}{\text{day}} \cdot T_S$   $W_{F31} = 27.121 \cdot \text{tton}$

**General stores:**  $W_{F32} := .0009598 \cdot \frac{\text{tton}}{\text{day}} \cdot T_S \cdot N_T$   $W_{F32} = 6.479 \cdot \text{tton}$

**Crew:**  $W_{F10} := 236 \cdot \text{lb} \cdot N_E + 400 \cdot \text{lb} \cdot (N_O + 1)$   $W_{F10} = 17.08 \cdot \text{tton}$

$W_T := W_{LS} + W_{F41} + W_{F42} + W_{F20} + W_{F46} + W_{F52} + W_{F31} + W_{F32} + W_{F10}$

$W_T = 6131.108 \cdot \text{tton}$

**Weight Balance:**  $\text{ERR WEIGHT} := \frac{\Delta FL - W_T}{W_T}$   $\text{ERR WEIGHT} = -0.125335 \%$

**Weights Independent of the Design Variables:**

$W_{IND} := W_{BM} + W_B + W_{237} + W_3 + W_{P400} + W_{498} + W_5 + W_6 + W_7 \dots$   
 $+ W_{DH} + W_{180} + W_{165} + W_{F31} + W_{F32} + W_{F10}$

$W_{IND} = 2718.608 \cdot \text{tton}$

**VL Stability**

**VII. Calculate Light Ship Weight Group Moments:**

<u>Weight</u>	<u>VCG</u>		<u>Product</u>
$W_{BH} = 995.839 \text{ tton}$	$VCG_1 := .527 \cdot D_{10}$	$VCG_1 = 16.513 \text{ ft}$	$P_1 := W_{BH} \cdot VCG_1$
$W_{DH} = 336.553 \text{ tton}$	$VCG_2 := D_{10} + 1.5 \cdot H_{DK}$	$VCG_2 = 44.834 \text{ ft}$	$P_2 := W_{DH} \cdot VCG_2$
$W_{180} = 127.844 \text{ tton}$	$VCG_3 := .68 \cdot D_{10}$	$VCG_3 = 21.307 \text{ ft}$	$P_3 := W_{180} \cdot VCG_3$
$W_{171} = 17.555 \text{ tton}$	$VCG_4 := 2.65 \cdot D_{10}$	$VCG_4 = 83.036 \text{ ft}$	$P_4 := W_{171} \cdot VCG_4$
$P_{100} := P_1 + P_2 + P_3 + P_4$		$VCG_{100} := \frac{P_{100}}{W_1}$	$VCG_{100} = 22.843 \text{ ft}$
$W_{BM} = 412.728 \text{ tton}$	$VCG_5 := .5 \cdot D_{10}$	$VCG_5 = 15.667 \text{ ft}$	$P_5 := W_{BM} \cdot VCG_5$
$W_{ST} = 114.103 \text{ tton}$	$VCG_6 := 3.9 \cdot \text{ft} + .19 \cdot T$	$VCG_6 = 6.237 \text{ ft}$	$P_6 := W_{ST} \cdot VCG_6$
$W_{237} = 0 \text{ tton}$	$VCG_7 := VCG_{237}$	$VCG_7 = 0 \text{ ft}$	$P_7 := W_{237} \cdot VCG_7$
$P_{200} := P_5 + P_6 + P_7$		$VCG_{200} := \frac{P_{200}}{W_2}$	$VCG_{200} = 13.625 \text{ ft}$
$W_3 = 339.26 \text{ tton}$	$VCG_8 := .65 \cdot D_{10}$	$VCG_8 = 20.367 \text{ ft}$	$P_8 := W_3 \cdot VCG_8$
$W_{IC} = 30.626 \text{ tton}$	$VCG_9 := D_{10}$	$VCG_9 = 31.334 \text{ ft}$	$P_9 := W_{IC} \cdot VCG_9$
$W_{CO} = 14.753 \text{ tton}$	$VCG_{10} := 5.6 \cdot \text{ft} + .4625 \cdot D_{10}$	$VCG_{10} = 20.092 \text{ ft}$	$P_{10} := W_{CO} \cdot VCG_{10}$
$W_{CC} = 7.741 \text{ tton}$	$VCG_{11} := .5 \cdot D_{10}$	$VCG_{11} = 15.667 \text{ ft}$	$P_{11} := W_{CC} \cdot VCG_{11}$
$W_{498} = 87.9 \text{ tton}$	$VCG_{12} := VCG_{498}$	$VCG_{12} = -1.2 \text{ ft}$	$P_{12} := W_{498} \cdot VCG_{12}$
$W_{AUX} = 503.173 \text{ tton}$	$VCG_{13} := .9 \cdot (D_{10} - 7.4 \cdot \text{ft})$	$VCG_{13} = 21.541 \text{ ft}$	$P_{13} := W_{AUX} \cdot VCG_{13}$
$W_{517} = 4.518 \text{ tton}$	$VCG_{14} := .5 \cdot H_{MB}$	$VCG_{14} = 15.667 \text{ ft}$	$P_{14} := W_{517} \cdot VCG_{14}$
$W_{OFH} = 234.528 \text{ tton}$	$VCG_{15} := .805 \cdot D_{10}$	$VCG_{15} = 25.224 \text{ ft}$	$P_{15} := W_{OFH} \cdot VCG_{15}$
$W_{OFF} = 112.4 \text{ tton}$	$VCG_{16} := 8 \cdot \text{ft} + .71 \cdot D_{10}$	$VCG_{16} = 30.247 \text{ ft}$	$P_{16} := W_{OFF} \cdot VCG_{16}$

$ip := 1..16$

$P_{WG} := \sum_{ip} P_{ip} + W_P \cdot VCG_P - W_{VP} \cdot VCG_{VP} \quad P_{WG} = 80422.723 \text{ tton} \cdot \text{ft}$

**VI2. Light Ship KG**

$$VCG_{LS} := \frac{\sum_{i1} P_{WG}}{\sum_{i1} W_{i1}} \quad VCG_{LS} = 20.978 \text{ ft} \quad KG_{LS} := VCG_{LS} \quad KG_{LS} = 20.978 \text{ ft}$$

**VI3. Calculate Variable Load Weight Group Moments:**

<u>Weight</u>	<u>VCG</u>	<u>Product</u>
$W_{F10} = 17.08 \text{ ton}$	$VCG_{17} := .746 \cdot D_{10}$	$VCG_{17} = 23.375 \text{ ft} \quad P_{17} := W_{F10} \cdot VCG_{17}$
$W_{F31} = 27.121 \text{ ton}$	$VCG_{18} := .55 \cdot D_{10}$	$VCG_{18} = 17.234 \text{ ft} \quad P_{18} := W_{F31} \cdot VCG_{18}$
$W_{F32} = 6.479 \text{ ton}$	$VCG_{19} := .65 \cdot D_{10}$	$VCG_{19} = 20.367 \text{ ft} \quad P_{19} := W_{F32} \cdot VCG_{19}$
$W_{F41} = 1582.439 \text{ ton}$	$VCG_{20} := 7.5 \text{ ft}$	$VCG_{20} = 7.5 \text{ ft} \quad P_{20} := W_{F41} \cdot VCG_{20}$
$W_{F42} = 63.8 \text{ ton}$	$VCG_{21} := 10 \text{ ft}$	$VCG_{21} = 10 \text{ ft} \quad P_{21} := W_{F42} \cdot VCG_{21}$
$W_{F46} = 7.2 \text{ ton}$	$VCG_{22} := .35 \cdot D_{10}$	$VCG_{22} = 10.967 \text{ ft} \quad P_{22} := W_{F46} \cdot VCG_{22}$
$W_{F52} = 22.5 \text{ ton}$	$VCG_{23} := 7.5 \text{ ft}$	$VCG_{23} = 7.5 \text{ ft} \quad P_{23} := W_{F52} \cdot VCG_{23}$

$$iL := 17..23 \quad P_{WGL} := \sum_{iL} P_{iL} + W_{VP} \cdot VCG_{VP} \quad P_{WGL} = 21193.169 \text{ ton-ft}$$

$$W_L := W_{F41} + W_{F42} + W_{F20} + W_{F46} + W_{F52} + W_{F31} + W_{F32} + W_{F10} \quad W_L = 1914.079 \text{ ton}$$

$$VCG_L := \frac{P_{WGL}}{W_L} \quad VCG_L = 11.072 \text{ ft}$$

**VI4. Calculate Ship Stability Characteristics:**

$$KG_{MARG} := .5 \text{ ft} \quad KG := \frac{W_{LS} \cdot KG_{LS} + W_L \cdot VCG_L}{W_T} + KG_{MARG} \quad C_{IT} := -.497 + 1.44 \cdot C_W \quad C_{IT} = 0.493$$

$$KB := \frac{T}{3} \cdot \left( 2.5 - \frac{C_P \cdot C_X}{C_W} \right) \quad BM := \frac{LWL \cdot B^3 \cdot C_{IT}}{12 \cdot V_{FL}} \quad GM := KB + BM - KG \quad C_{GMB} := \frac{GM}{B}$$

$$KG = 18.386 \text{ ft} \quad KB = 7.711 \text{ ft} \quad BM = 16.252 \text{ ft} \quad GM = 5.577 \text{ ft} \quad C_{GMB} = 0.123$$

**VII VERY SIMPLIFIED COST MODEL (Lead-Ship End Cost only)**

Mdol := coul

Kdol :=  $\frac{\text{Mdol}}{1000}$

Bdol := 1000 · Mdol

dol :=  $\frac{\text{Kdol}}{1000}$

**VIII. Additional characteristics:**

Ship Service Life:  $L_S := 30$

Initial Operational Capability:  $Y_{IOC} := 1998$

Total Ship Acquisition:  $N_S := 25$

Production Rate (per year):  $R_P := 3$

**Inflation:**

Base Year:  $Y_B := 1998$   $iy := 1.. Y_B - 1981$

Average Inflation Rate (%):  $R_I := 5$   
(from 1981)

$$F_I := \prod_{iy} \left( 1 + \frac{R_I}{100} \right) \quad F_I = 2.292$$

**a. Lead Ship Cost - Shipbuilder Portion:**

SWBS costs: (See Table 5 for  $K_N$  factors)

Structure  $K_{N1} := \frac{.55 \cdot \text{Mdol}}{\text{tton}^{.772}} \quad C_{L1} := .03395 \cdot F_I \cdot K_{N1} \cdot (W_1)^{.772} \quad C_{L1} = 12.51 \cdot \text{Mdol}$

+ Propulsion  $K_{N2} := \frac{1.2 \cdot \text{Mdol}}{\text{hp}^{.808}} \quad C_{L2} := .00186 \cdot F_I \cdot K_{N2} \cdot P_{IBRAKE}^{.808} \quad C_{L2} = 58.708 \cdot \text{Mdol}$

+ Electric  $K_{N3} := \frac{1.0 \cdot \text{Mdol}}{\text{tton}^{.91}} \quad C_{L3} := .07505 \cdot F_I \cdot K_{N3} \cdot (W_3)^{.91} \quad C_{L3} = 34.542 \cdot \text{Mdol}$

**+ Command, Control, Surveillance**

$K_{N4} := \frac{2.0 \cdot \text{Mdol}}{\text{tton}^{.617}} \quad C_{L4} := .10857 \cdot F_I \cdot K_{N4} \cdot (W_4)^{.617} \quad C_{L4} = 16.424 \cdot \text{Mdol}$   
(less payload GFM cost)

+ Auxiliary  $K_{N5} := \frac{1.5 \cdot \text{Mdol}}{\text{tton}^{.782}} \quad C_{L5} := .09487 \cdot F_I \cdot K_{N5} \cdot (W_5)^{.782} \quad C_{L5} = 51.215 \cdot \text{Mdol}$

+ Outfit  $K_{N6} := \frac{1.0 \cdot \text{Mdol}}{\text{tton}^{.784}} \quad C_{L6} := .09859 \cdot F_I \cdot K_{N6} \cdot (W_6)^{.784} \quad C_{L6} = 22.548 \cdot \text{Mdol}$

+ Armament  $K_{N7} := \frac{1.0 \cdot \text{Mdol}}{\text{Iton}^{.987}}$   $C_{L7} := .00838 \cdot F_I \cdot K_{N7} \cdot (W_7)^{.987}$   $C_{L7} = 2.119 \cdot \text{Mdol}$   
 (Less payload GFM cost)

+ Margin Cost:

$$C_{LM} := \frac{W_{M24}}{(W_{LS} - W_{M24})} \cdot \left( \sum_{i1} C_{L_{i1}} \right) \quad C_{LM} = 19.807 \cdot \text{Mdol}$$

+ Integration/Engineering: (Lead ship includes detail design engineering for class)

$$K_{N8} := \frac{10.0 \cdot \text{Mdol}}{\text{Mdol}^{1.099}} \quad C_{L8} := .034 \cdot K_{N8} \cdot \left( \sum_{i1} C_{L_{i1}} + C_{LM} \right)^{1.099} \quad C_{L8} = 126.231 \cdot \text{Mdol}$$

+ Ship Assembly and Support: (Lead ship includes all tooling, jigs, special facilities for class)

$$K_{N9} := \frac{2.0 \cdot \text{Mdol}}{(\text{Mdol})^{.839}} \quad C_{L9} := .135 \cdot K_{N9} \cdot \left( \sum_{i1} C_{L_{i1}} + C_{LM} \right)^{.839} \quad C_{L9} = 24.724 \cdot \text{Mdol}$$

= Total Lead Ship Construction Cost: (BCC) :

$$C_{LCC} := \sum_{i1} C_{L_{i1}} + C_{L8} + C_{L9} + C_{LM} \quad C_{LCC} = 368.828 \cdot \text{Mdol}$$

+ Profit:

$$F_{\text{PROFIT}} := .10 \quad C_{LP} := F_{\text{PROFIT}} \cdot C_{LCC} \quad C_{LP} = 36.883 \cdot \text{Mdol}$$

= Lead Ship Price :

$$P_L := C_{LCC} + C_{LP} \quad P_L = 405.711 \cdot \text{Mdol}$$

+ Change Orders:

$$C_{LCORD} := .12 \cdot P_L \quad C_{LCORD} = 48.685 \cdot \text{Mdol}$$

= Total Shipbuilder Portion:

$$C_{SB} := P_L + C_{LCORD} \quad C_{SB} = 454.396 \cdot \text{Mdol}$$

*b. Lead Ship Cost - Government Portion*

Other support:

$$C_{LOTH} := .025 \cdot P_L \quad C_{LOTH} = 10.143 \cdot \text{Mdol}$$

+ Program Manager's Growth:

$$C_{LPMG} := .1 \cdot P_L \quad C_{LPMG} = 40.571 \cdot \text{Mdol}$$

Costed Military Payload:

$$W_{MP} := W_4 + W_7 + W_{F20} - W_{IC} - W_{F23} \quad W_{MP} = 550.634 \cdot \text{ton}$$

+ Ordnance and Electrical GFE:  
(Military Payload GFE)

$$C_{LMPG} := \left( .319 \cdot \frac{\text{Mdol}}{\text{ton}} \cdot W_{MP} + N_{HELO} \cdot 18.71 \cdot \text{Mdol} \right) \cdot F_I$$

$$C_{LMPG} = 488.366 \cdot \text{Mdol}$$

+ HM&E GFE (boats, IC):

$$C_{LHMEG} := .02 \cdot P_L \quad C_{LHMEG} = 8.114 \cdot \text{Mdol}$$

+ Outfitting Cost :

$$C_{LOUT} := .04 \cdot P_L \quad C_{LOUT} = 16.228 \cdot \text{Mdol}$$

= Total Government Cost:

$$C_{LGOV} := C_{LOTH} + C_{LPMG} + C_{LMPG} + C_{LHMEG} + C_{LOUT} \quad C_{LGOV} = 563.422 \cdot \text{Mdol}$$

c. Total End Cost: (Must always be less than SCN appropriation)

\* Total End Cost:

$$C_{LEND} := C_{SB} + C_{LGOV} \quad C_{LEND} = 1017.818 \cdot \text{Mdol}$$



**SUMMARY: FINAL SYSTHESIS DESIGN****ITERATION WEIGHT:**

$$W_{FL1} = 6683 \text{ tton} \quad W_{FL} \equiv \text{inl}_1 \cdot \text{tton} \quad W_{FL} = 6123.424 \text{ tton} \quad W_T = 6131.108 \text{ tton} \quad \text{ERR WEIGHT} = -0.125335 \%$$

**GROSS CHARACTERISTICS:**

$$C_P \equiv \text{inl}_5 \text{ (.54 - .64)} \quad C_{\Delta L} \equiv 55 \frac{\text{lton}}{\text{ft}^3} \text{ (45 - 65)} \quad \text{LWL} \equiv \text{inl}_4 \text{ ft} \quad \text{LWL} = 455.016 \text{ ft}$$

$$C_X \equiv \text{inl}_6 \text{ (.7 - .85)} \quad C_V := \frac{V_{FL}}{\text{LWL}^3} \quad C_V = 1.15 \cdot 10^{-3} \quad V_{FL} = 108340.212 \cdot \text{ft}^3$$

$$C_{BT} \equiv \text{inl}_7 \text{ (2.8 - 3.7)} \quad B \equiv \text{inl}_2 \text{ ft} \quad B = 45.502 \cdot \text{ft} \quad T = 12.298 \text{ ft} \quad C_{LB} = 10 \text{ (7.5 - 10)}$$

**ENERGY BALANCE:**

$$V_{FL} \equiv B \cdot T \cdot \text{LWL} \cdot C_X \cdot C_P \quad V_{FL} = 108340.212 \cdot \text{ft}^3$$

$$V_S \equiv \text{inl}_2 \cdot \text{knt} \quad P_I = 102626 \text{ hp} \quad P_{IREQ} = 60939.774 \text{ hp} \quad \text{ERR POWER} = 68.406 \%$$

$$V_e \equiv \text{inl}_3 \cdot \text{knt} \quad \text{kW}_G = 3000 \text{ kW} \quad \text{kW}_{GREQ} = 2006.707 \text{ kW} \quad \text{ERR KW} = 49.499 \%$$

$$E \equiv \text{inl}_4 \cdot \text{knt} \cdot \text{hr}$$

**AREA/VOLUME BALANCE:**

$$V_D \equiv .0025 \cdot \text{LWL}^3 \quad V_T = 637364.335 \cdot \text{ft}^3 \quad V_{MB} = 52180.608 \cdot \text{ft}^3 \quad V_{TR} = 431499.519 \cdot \text{ft}^3$$

$$V_{DMIN} = 47103.26 \cdot \text{ft}^3 \quad V_{HT} = 401848.037 \cdot \text{ft}^3 \quad V_{AUX} = 62616.73 \cdot \text{ft}^3 \quad V_{TA} = 444784.103 \cdot \text{ft}^3$$

$$V_{DMAX} = 235516.298 \cdot \text{ft}^3 \quad V_{TK} = 77782.894 \cdot \text{ft}^3 \quad \text{ERR AREA} = 0.030787 \%$$

$$D_{10} = 31.334 \cdot \text{ft} \text{ (Must be } > D_{10MIN})$$

$$D_{10MIN} = 30.334 \cdot \text{ft} \quad A_{TR} = 47944.391 \cdot \text{ft}^2 \quad A_{HR} = 34517.285 \cdot \text{ft}^2 \quad A_{DR} = 13427.106 \cdot \text{ft}^2$$

$$A_{TA} = 49420.456 \cdot \text{ft}^2 \quad A_{HA} = 23251.978 \cdot \text{ft}^2 \quad A_{DA} = 26168.478 \cdot \text{ft}^2$$

**WEIGHT BALANCE:**

$$W_{FL} = 6123.424 \text{ tton} \quad W_T = 6131.108 \text{ tton} \quad \text{ERR WEIGHT} = -0.125335 \%$$

$$W_1 = 1563.49 \text{ tton} \quad W_5 = 642.883 \text{ tton} \quad W_{LS} = 4217.029 \text{ tton}$$

$$W_2 = 526.831 \text{ tton} \quad W_6 = 354.668 \text{ tton} \quad W_P = 668.3 \text{ tton}$$

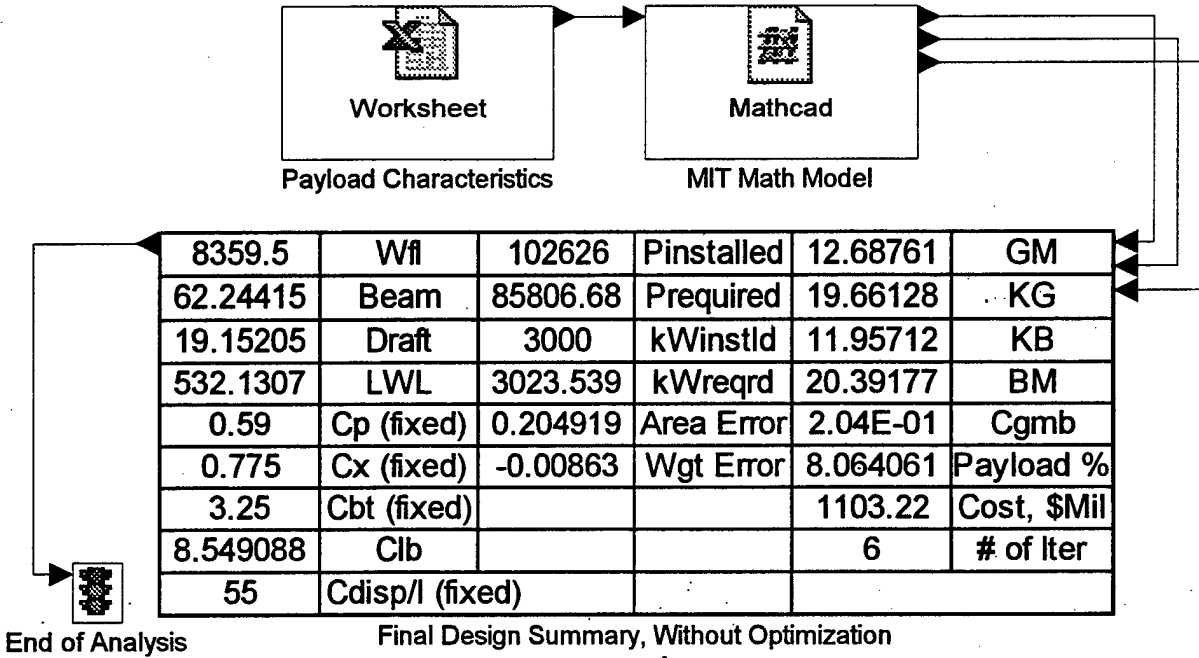
$$W_3 = 339.26 \text{ tton} \quad W_7 = 117.37 \text{ tton} \quad W_{F41} = 1582.439 \text{ tton}$$

$$W_4 = 289.161 \text{ tton}$$

**STABILITY/PAYLOAD:**

$$C_{GMB} = 0.123 \text{ (.09 - .122)} \quad F_P := \frac{W_P}{W_{FL}} \cdot 100 \quad F_P = 10.9138$$

# NON-OPTIMIZED MATH MODEL



**MIT MATH MODEL: NO OPTIMIZATION**

$$\text{hp} \equiv \frac{33000 \cdot \text{ft} \cdot \text{lbf}}{\text{min}} \quad \text{knt} \equiv 1.69 \cdot \frac{\text{ft}}{\text{sec}} \quad \text{lton} \equiv 2240 \cdot \text{lb}$$

**I INPUT**

# = Primary Input Variables

## = Check after every iteration

**II. Requirements:**Payload: (From CS2MP.XLS, Fig 1&2)  $W_P := \text{in}0_1 \cdot \text{lton}$  variable:  $W_{VP} := \text{in}0_2 \cdot \text{lton}$ Payload VCG:  $VCG_P := \text{in}0_3 \cdot \text{ft}$  Variable Payload VCG:  $VCG_{VP} := \text{in}0_4 \cdot \text{ft}$ Command and Surveillance Payload:  
( $W_{400}$  less 420 and 430)  $W_{P400} := \text{in}0_5 \cdot \text{lton}$ Armament (all  $W_{700}$ ):  $W_7 := \text{in}0_6 \cdot \text{lton}$  Armor:  $W_{164} := \text{in}0_7 \cdot \text{lton}$ Mission handling/support:  $W_{P500} := \text{in}0_8 \cdot \text{lton}$  Mission outfit:  $W_{P600} := \text{in}0_9 \cdot \text{lton}$ Ordnance:  $W_{F20} := \text{in}0_{10} \cdot \text{lton}$  (incl helo wt,  $WF23$ ) Helo Fuel:  $W_{F42} := \text{in}0_{11} \cdot \text{lton}$ Helo's:  $N_{HELO} := 2$   $W_{F23} := 12.73 \cdot \text{lton}$ Payload Cruise Electric Power Requirement:  $\text{kW}_{PAY} := \text{in}0_{12} \cdot \text{kW}$ **Payload Deck Areas:**Deckhouse: C&D:  $A_{DPC} := \text{in}0_{13} \cdot \text{ft}^2$  (W400)Armament:  $A_{DPA} := \text{in}0_{14} \cdot \text{ft}^2$  (W500, W600, W700, WF20)Hull: C&D:  $A_{HPC} := \text{in}0_{15} \cdot \text{ft}^2$  (W400)Armament:  $A_{HPA} := \text{in}0_{16} \cdot \text{ft}^2$  (W500, W600, W700, WF20)**Manning:**Officers:  $N_O := 15$  Enlisted:  $N_E := 135$  Total:  $N_T := N_E + N_O$   $N_T = 150$ Average deck height:  $H_{DK} := 9 \cdot \text{ft}$ Sustained Speed:  $V_S = 27 \cdot \text{knt}$  (Use Figure 3 as a guide in selecting  $V_S$ )Endurance Speed:  $V_e = 20 \cdot \text{knt}$  Range:  $E = 7500 \cdot \text{knt} \cdot \text{hr}$ Stores period:  $T_S := 45 \cdot \text{day}$

Sonar Dome/Appendages: SQS-56 Sonar:  $A_{SD} := 215 \cdot \text{ft}^2$  (SQS-56: 27ft<sup>2</sup>; SQS-53C: 215ft<sup>2</sup>)

water:  $W_{498} := 87.9 \cdot \text{ton}$  VCG<sub>498</sub> := -1.2-ft structure:  $W_{165} := 85.7 \cdot \text{ton}$

Fin Stabilizers: (for one pair, electric power requirement = 50 kW)  $\text{kW}_{\text{fins}} := 0 \cdot \text{kW}$

Hull Material: (OS:  $C_{\text{HMAT}}=1.0$ ; HTS:  $C_{\text{HMAT}}=0.93$ )  $C_{\text{HMAT}} := .93$

CPS: ( $W_{\text{CPS}}=30\text{ton}$ ):  $W_{\text{CPS}} := 30 \cdot \text{ton}$  (ie. no CPS)

**Machinery:**

Number of propellers =  $N_P := 2$   $C_{\text{PROPD}} := \text{if}(N_P > 1, 1.0, 1.2)$   $C_{\text{PROPD}} = 1$

Aux Propulsion (APU):  $W_{237} := 0 \cdot \text{ton}$  VCG<sub>237</sub> := 0-ft

Propulsion Engines (PE) - standard LM2500's; Generator engines DDA149TI

Number and brake horsepower of propulsion engines:  $N_{\text{PENG}} := 4$   $P_{\text{BPENG}} := 26450 \cdot \text{hp}$

Inlet/exhaust Xsect area for PE:  $A_{\text{IE}} := 135.2 \cdot \text{ft}^2$   $A_{\text{PIE}} := N_{\text{PENG}} \cdot A_{\text{IE}}$   $A_{\text{PIE}} = 540.8 \cdot \text{ft}^2$

Deckhouse decks impacted by propulsion and generator inlet/exhaust:  $N_{\text{DIE}} := 1$

Hull decks impacted by propulsion inlet/exhaust:  $N_{\text{HPIE}} := 0$

Machinery Box:  $H_{\text{MBMIN}} := 22 \cdot \text{ft}$   $L_{\text{MB}} := 40 \cdot \text{ft}$

$C_P = 0.59$   $C_{\text{MB}} := \frac{L_{\text{MB}}}{\text{LWL}}$   $C_{\text{MB}} = 0.075$   $C_{\text{PMB}}$  from Fig. 10:  $C_{\text{PMB}} := .998$  #

Ship Service Generators:  $N_G := 3$   $\text{kW}_G := 3000 \cdot \text{kW}$

Hull decks impacted by generator inlet/exhaust:  $N_{\text{HeIE}} := 1$

Specific fuel rate for generator engines:  $\text{FR}_G := \frac{.288 \cdot \text{lb}}{2.54 \cdot \text{kW} \cdot \text{hr}}$   $\text{FR}_G = 0.085 \cdot \frac{\text{lb}}{\text{hp} \cdot \text{hr}}$

Inlet/exhaust X-sect area for gen:  $A_{\text{GIE}} := 38.4 \cdot \text{ft}^2$   $A_{\text{eIE}} := N_G \cdot A_{\text{GIE}}$   $A_{\text{eIE}} = 115.2 \cdot \text{ft}^2$

**II. GROSS CHARACTERISTICS**

Hull Principle Characteristics:

(see Figures 5 and 6)

Adjust in  
Summary  
Section at  
end of file

LWL = 532.131 ft B = 62.244 ft

$C_P = 0.59$   $C_X = 0.775$

deckhouse volume:  $V_D = 190000 \cdot \text{ft}^3$   $C_{\text{DHMAT}} := 2$

(Deckhouse Material: Aluminum -  $C_{\text{DHMAT}}=1$ ; Steel -  $C_{\text{DHMAT}}=2$ )

**III. Complete Principle Characteristics:**

Choose Payload Weight Fraction from Figure 4 and Calculate Full Load Weight (1st Iteration only, set  $W_{FL} = W_{FL1}$  in Summary section at end of file).

$$F_P := .1 \quad W_{FL1} := \frac{W_P}{F_P} \quad W_{FL1} = 6683 \text{ tton}$$

Specify Full Load Weight (subsequent iterations set  $W_{FL} = W_T$  from prior iteration in Summary at end of file):

$$W_{FL} = 8287.388 \text{ tton} \quad V_{FL} := B \cdot T \cdot LWL \cdot C_P \cdot C_X \quad ##$$

Calculate Full Load Displacement and Volume at LWL:

$$\Delta_{FL} := W_{FL} \quad V_{FL} := \Delta_{FL} \cdot 35 \cdot \frac{\text{ft}^3}{\text{tton}} \quad V_{FL} = 290058.58 \text{ ft}^3$$

Calculate Draft (LWL):

$$T := \frac{V_{FL}}{C_P \cdot C_X \cdot LWL \cdot B} \quad T = 19.152 \text{ ft}$$

**II2. Calculate Displacement to Length Ratio and Compare to Figure 5:**

$$C_{\Delta L} := \frac{\Delta_{FL}}{\left(\frac{LWL}{100}\right)^3} \quad C_{\Delta L} = 55 \cdot \frac{\text{tton}}{\text{ft}^3} \quad (45-65)$$

**II3. Calculate Speed to Length Ratio and  $C_V$ :**

$$R_{VL} := \frac{V_S}{\sqrt{LWL}} \quad R_{VL} = 1.17 \cdot \frac{\text{knt}}{\text{ft}^5} \quad C_V := \frac{V_{FL}}{LWL^3} \quad C_V = 0.001925$$

**II4. Calculate Beam to Draft Ratio and Compare to Tables 1-4:**

$$C_{BT} := \frac{B}{T} \quad C_{BT} = 3.25 \quad (2.8-3.7)$$

**II5. Calculate Length to Beam Ratio:**

$$C_{LB} := \frac{LWL}{B} \quad C_{LB} = 8.549 \quad (7.5-10)$$

**III. ENERGY (Uses Taylor Standard Series (TSS))**

References: DDS 051-1 and Taylor Reanalysis by Gertler

**III1. Calculate TSS Resistance:****III1.1 Estimate propeller diameter and frontal area of ship:**

$$C_{PROP} = 1 \quad D_P := (.662 \cdot T + .012 \cdot LWL) \cdot C_{PROP} \quad D_P = 19.064 \text{ ft}$$

$$\text{Frontal area of ship} = A_W := B \cdot (3 \cdot T) \quad A_W = 3576.308 \text{ ft}^2 \quad \rho_A := .0023817 \cdot \frac{\text{slug}}{\text{ft}^3}$$

III.2 Seawater properties:

$$T_{SW} := 59 \quad \rho_{SW} := 1.9905 \frac{\text{slug}}{\text{ft}^3} \quad v_{SW} := 1.2817 \cdot 10^{-5} \frac{\text{ft}^2}{\text{sec}}$$

III.3 Resistance calculation parameters:

Correlation Allowance:  $C_A := .0005$

$C_P = 0.59$

Use Figure 7 with  $C_P$  and  $C_{BT}$  for TSS wetted surface coefficient:

$C_{STSS} := 2.536$  ##

$C_{BT} = 3.25$

$$S_{TSS} := C_{STSS} \cdot V_{FL}^{.5} \cdot LWL^{.5} \quad S_{TSS} = 31506.581 \text{ ft}^2$$

Specify or estimate actual ship surface area:  $S_S := S_{TSS}$  #

Use Figure 8 or 9 with LWL for Appendage Drag Coefficient:

$LWL = 532.131 \text{ ft}$

$C_{DAPP} := 2.85 \frac{\text{hp} \cdot 10^{-5}}{\text{ft}^2 \cdot \text{knt}^3}$  ##

Air Drag Coefficient:  $C_{AA} := .7$

Power Margin Factor (margin for concept design = 10%):

$PMF := 1.05$

III.4 Use range of ship speeds for speed to length ratios ( $R_{N_i}$ ), Reynold's numbers ( $R_{N_i}$ ) and ITTC friction ( $R_{F_i}$ ):

$i := 1..7 \quad V_i := i \cdot 5 \cdot \text{knt} \quad \text{Ensure range includes } V_e \text{ and } V_s: \quad V_6 := V_S \quad V_6 = 27 \text{ knt}$

$V_4 := V_e \quad V_4 = 20 \text{ knt}$  ##

$$R_i := \frac{V_i}{\sqrt{LWL}} \quad R_{N_i} := LWL \cdot \frac{V_i}{v_{SW}} \quad C_{F_i} := \frac{.075}{(\log(R_{N_i}) - 2)^2}$$

$$R_{F_i} := .5 \cdot \left[ \rho_{SW} \cdot S_S \cdot (V_i)^2 \cdot (C_A + C_{F_i}) \right]$$

$\frac{V_i}{\text{knt}}$	$R_i \frac{\text{ft}^{.5}}{\text{knt}}$	$R_{N_i}$	$C_{F_i}$	$\frac{R_{F_i}}{\text{lbf}}$
5	0.217	$3.508 \cdot 10^8$	0.002	5039.4
10	0.434	$7.016 \cdot 10^8$	0.002	18809.018
15	0.65	$1.052 \cdot 10^9$	0.002	40723.396
20	0.867	$1.403 \cdot 10^9$	0.001	70508.886
25	1.084	$1.754 \cdot 10^9$	0.001	107985.975
27	1.17	$1.894 \cdot 10^9$	0.001	125099.7
35	1.517	$2.456 \cdot 10^9$	0.001	205513.005

III.5 Use Gertler with  $C_P$ ,  $C_V$ ,  $R_i$  and  $C_{BT}$  to interpolate for  $C_R$  and calculate TSS resistance:

$C_P = 0.59$      $C_V = 0.001925$

$R_i \frac{ft^5}{knt}$	$C_{BT}=2.25$	$C_{BT}=3.00$	$C_{BT}=3.75$
0.217	.00028	.00035	.00048
0.434	.00028	.00035	.00048
0.65	.00028	.00042	.00048
0.867	$C_{R2.25} :=$ .00080	$C_{R3.00} :=$ .00100	$C_{R3.75} :=$ .00095
1.084	.00150	.00180	.00180
1.17	.00335	.00350	.00360
1.517	.00410	.00430	.00460

##

Form Factor:  $FF := \frac{4}{3} \cdot (C_{BT} - 3)$      $FF = 0.333$

$$C_{RTSS_i} := C_{R3.00_i} + FF \cdot \left( \frac{C_{R3.75_i} - C_{R2.25_i}}{2} \right) + FF^2 \cdot \left( \frac{C_{R2.25_i} + C_{R3.75_i}}{2} - C_{R3.00_i} \right)$$

$$C_{RTSS} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.001 \\ 0.002 \\ 0.004 \\ 0.004 \end{bmatrix}$$

$$R_{RTSS_i} := .5 \cdot [\rho_{SW} \cdot S_S \cdot (V_i)^2 \cdot C_{RTSS_i}]$$

$$R_{RTSS} = \begin{bmatrix} 865.732 \\ 3462.929 \\ 9045.41 \\ 36221.442 \\ 102619.128 \\ 231047.526 \\ 481501.386 \end{bmatrix} \text{ lbf}$$

III2 Calculate Bare Hull Ship Resistance - Worm Curve data from ASSET:

WCFA :=	.2	3.5
	.3	2.95
	.4	2.5
	.5	2.1
	.6	1.8
	.7	1.55
	.8	1.33
	.9	1.17
	1.0	1.07
	1.1	1.
	1.2	.94
	1.3	.89
	1.4	.88
	1.5	.87
	1.6	.87

iw := 1.. 15

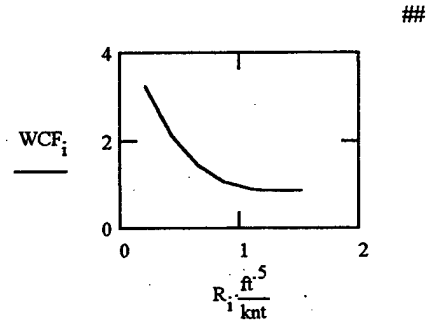
R =	0.217
	0.434
	0.65
	0.867
	1.084
	1.17
	1.517

$\frac{\text{knt}}{\text{ft}^5}$

WCF :=	3.242
	2.124
	1.460
	1.083
	.923
	.880
	.870

$R_{R_i} := R_{RTSS_i} \cdot WCF_i$

$R_{T_i} := R_{F_i} + R_{R_i}$

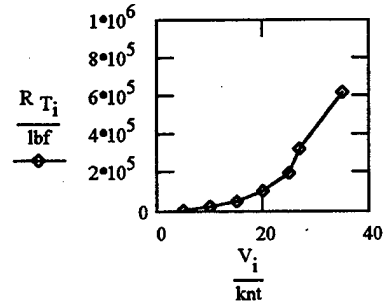


R <sub>R</sub> =	2806.704
	7355.261
	13206.298
	39227.822
	94717.455
	203321.823
	418906.206

•lbf

R <sub>T</sub> =	7846.104
	26164.279
	53929.694
	109736.708
	202703.429
	328421.523
	624419.211

•lbf





III. Total Ship Effective Horsepower:

hull:  $P_{EBH_i} := R_{T_i} \cdot V_i$   $\frac{P_{EBH}}{hp} =$   $\begin{bmatrix} 120.545 \\ 803.957 \\ 2485.669 \\ 6743.82 \\ 15571.309 \\ 27247.044 \\ 67153.448 \end{bmatrix}$

$C_{SD} := .28$

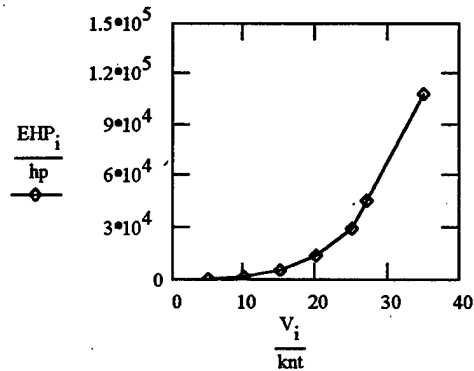
appendage:  $P_{EAPP_i} := (LWL \cdot D_P \cdot C_{DAPP} + .5 \cdot C_{SD} \cdot \rho \cdot SW \cdot A_{SD}) \cdot (V_i)^3$   $\frac{P_{EAPP}}{hp} =$   $\begin{bmatrix} 101.866 \\ 814.929 \\ 2750.387 \\ 6519.436 \\ 12733.273 \\ 16040.256 \\ 34940.1 \end{bmatrix}$

air:  $P_{EAA_i} := .5 \cdot C_{AA} \cdot A_{WP} \cdot \rho \cdot A \cdot (V_i)^3$   $\frac{P_{EAA}}{hp} =$   $\begin{bmatrix} 3.27 \\ 26.163 \\ 88.3 \\ 209.304 \\ 408.797 \\ 514.966 \\ 1121.738 \end{bmatrix}$

$P_{ET_i} := P_{EBH_i} + P_{EAPP_i} + P_{EAA_i}$   $\frac{P_{ET}}{hp} =$   $\begin{bmatrix} 225.681 \\ 1645.049 \\ 5324.356 \\ 13472.559 \\ 28713.378 \\ 43802.266 \\ 103215.286 \end{bmatrix}$

$EHP_i := PMF \cdot P_{ET_i}$

$\frac{V_i}{knt}$	EHP =	hp
5	236.965	
10	1727.302	
15	5590.573	
20	14146.187	
25	30149.047	
27	45992.38	
35	108376.051	



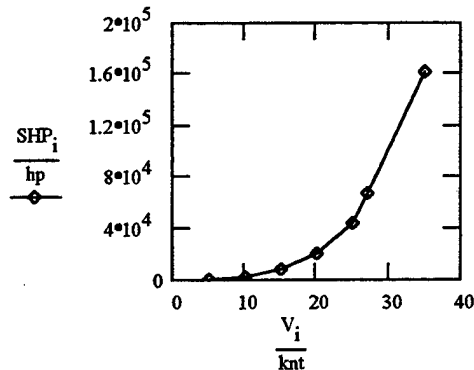
III.4. Shaft Horsepower:

Approximate Propulsive Coefficient (PC):

PC := .67

$$SHP_i := \frac{EHP_i}{PC}$$

$$SHP = \begin{bmatrix} 353.68 \\ 2578.062 \\ 8344.139 \\ 21113.712 \\ 44998.578 \\ 68645.343 \\ 161755.299 \end{bmatrix} \text{ hp}$$



Endurance Shaft Horsepower:

P<sub>e</sub> := SHP<sub>4</sub>

P<sub>e</sub> = 21113.712 hp

Sustained Speed Installed Shaft Horsepower Required (Allows for fouling and sea state):

P<sub>S</sub> := SHP<sub>6</sub>

P<sub>S</sub> = 68645.343 hp

P<sub>IREQ</sub> := 1.25 · P<sub>S</sub>

P<sub>IREQ</sub> = 85806.678 hp

Actual installed SHP must be greater than P<sub>IREQ</sub>

P<sub>IBRAKE</sub> := N<sub>PENG</sub> · P<sub>BPENG</sub>

P<sub>IBRAKE</sub> = 105800 hp

η := .97

P<sub>I</sub> := η · P<sub>IBRAKE</sub>

P<sub>I</sub> = 102626

(P<sub>I</sub> must be > P<sub>IREQ</sub>)

P<sub>IREQ</sub> = 85806.678 hp

$$ERR_{POWER} := \frac{P_I - P_{IREQ}}{P_{IREQ}}$$

ERR<sub>POWER</sub> = 0.196

##ck

III.5. Estimate Propulsion Fuel Required:

Reference: DDS 200-1 "Calculate of Surface Ship Endurance Fuel"

Average Endurance Brake SHP Required (Allows for fouling and sea state):

$$P_{eBAVG} := 1.1 \cdot \frac{P_e}{\eta}$$

P<sub>eBAVG</sub> = 23943.385 hp

Specific fuel rate for propulsion engines:  
(GT; FR for diesel = .327)

$$FR := 1.97 \cdot \frac{\text{lb}}{\text{hp}^{.85} \cdot \text{hr}} \cdot P_{eBAVG}^{-.15}$$

FR = 0.434  $\frac{\text{lb}}{\text{hp} \cdot \text{hr}}$  #

(for ICR: FR=.347 lb/hphr)

Margin for instrumentation and machinery differences, f(P<sub>I</sub>):

f<sub>1</sub> := 1.04

Specified fuel rate: FR<sub>SP</sub> := f<sub>1</sub> · FR

Average fuel rate allowing for plant deterioration:

$$FR_{AVG} := 1.05 \cdot FR_{SP}$$

FR<sub>AVG</sub> = 0.474  $\frac{\text{lb}}{\text{hp} \cdot \text{hr}}$

Burnable propulsion endurance fuel weight:

$$W_{BP} := \frac{E}{V_e} \cdot (P_{eBAVG} \cdot FR_{AVG})$$

W<sub>BP</sub> = 1900.115 tton

Tailpipe allowance and propulsion endurance fuel:

TPA := .95  
(shallow tanks)

$$W_{FP} := \frac{W_{BP}}{TPA} \quad W_{FP} = 2000.121 \text{ tton}$$

Allow for expansion and tank structure in required propulsion tank volume:

$$\gamma_F := 43 \cdot \frac{\text{ft}^3}{\text{lton}} \quad V_{FP} := 1.02 \cdot 1.05 \cdot \gamma_F \cdot W_{FP} \quad V_{FP} = 92111.562 \text{ ft}^3$$

## III6. Estimate electric load.

Reference: DDS 310-1

Estimate Maximum Functional Load based on parametrics for WINTER cruise condition:

Propulsion:  $kW_P := .00466 \cdot \frac{\text{kW}}{\text{hp}} \cdot P_{IBRAKE} \quad kW_P = 493.028 \text{ kW}$

Steering:  $kW_S := .00583 \cdot \frac{\text{kW}}{\text{ft}^2} \cdot LWL \cdot T \quad kW_S = 59.416 \text{ kW}$

Lighting:  $kW_L := .0002053 \cdot \frac{\text{kW}}{\text{ft}^3} \cdot 1.8 \cdot LWL \cdot T \cdot B \quad kW_L = 234.419 \text{ kW}$

Miscellaneous:  $kW_M := 46.1 \cdot \text{kW}$

Heating:  $kW_H := .0013 \cdot \frac{\text{kW}}{\text{ft}^3} \cdot 1.25 \cdot LWL \cdot T \cdot B \quad kW_H = 1030.826 \text{ kW}$

Ventilation:  $kW_{CPS} := .00026 \cdot \frac{\text{kW}}{\text{ft}^3} \cdot 1.8 \cdot LWL \cdot T \cdot B \quad kW_{CPS} = 296.878 \text{ kW}$   
(zero if no CPS)

$$kW_V := .19 \cdot (kW_H + kW_P) + kW_{CPS} \quad kW_V = 586.41 \text{ kW}$$

Air Conditioning:  $kW_{AC} := .67 \cdot \left( .1 \cdot kW \cdot N_T + .0015 \cdot \frac{\text{kW}}{\text{ft}^3} \cdot .47 \cdot 1.3 \cdot LWL \cdot T \cdot B + .1 \cdot kW_P \right)$   
 $kW_{AC} = 432.611 \text{ kW}$

Aux Boiler and FW:  
(electric boiler)  $kW_B := .94 \cdot N_T \cdot \text{kW} \quad kW_B = 141 \text{ kW}$

Firemain:  $kW_F := .0001 \cdot \frac{\text{kW}}{\text{ft}^3} \cdot 1.8 \cdot LWL \cdot T \cdot B \quad kW_F = 114.184 \text{ kW}$

Unrep and handling:  $kW_{RH} := .00002 \cdot \frac{\text{kW}}{\text{ft}^3} \cdot 1.25 \cdot LWL \cdot T \cdot B \quad kW_{RH} = 15.859 \text{ kW}$

$$\begin{aligned} \text{Aux Machinery:} \quad kW_A &:= .22 \cdot N_T \cdot kW + kW_{\text{fins}} & kW_A &= 33 \text{ kW} \\ \text{Services and Work Spaces:} \quad kW_{\text{SERV}} &:= .35 \cdot N_T \cdot kW & kW_{\text{SERV}} &= 52.5 \text{ kW} \end{aligned}$$

**Non-Payload Functional Load:**

$$kW_{\text{NP}} := kW_P + kW_S + kW_L + kW_M + kW_H + kW_V + kW_{\text{AC}} + kW_B + kW_F + kW_{\text{RH}} + kW_A + kW_{\text{SERV}}$$

**Maximum Functional Load:**

$$kW_{\text{MFL}} := kW_{\text{PAY}} + kW_{\text{NP}} \quad kW_{\text{MFL}} = 3779.423 \text{ kW}$$

**MFL with margins: (design, growth):**

$$kW_{\text{MFLM}} := 1.2 \cdot 1.2 \cdot kW_{\text{MFL}} \quad kW_{\text{MFLM}} = 5442.37 \text{ kW}$$

**Installed Electrical Power Required:**

$$\text{Power available per generator:} \quad kW_G = 3000 \text{ kW}$$

$$\text{Power required per generator:} \quad kW_{\text{GREQ}} := \frac{kW_{\text{MFLM}}}{(N_G - 1) \cdot 9} \quad kW_{\text{GREQ}} = 3023.539 \text{ kW} \quad \#ck$$

**24 hour electrical load:**

$$kW_{24} := .5 \cdot (kW_{\text{MFL}} - kW_P - kW_S) + .8 \cdot (kW_P + kW_S) \quad kW_{24} = 2055.445 \text{ kW}$$

$$ERR_{\text{KW}} := \frac{kW_G - kW_{\text{GREQ}}}{kW_{\text{GREQ}}}$$

$$\text{with margin (design):} \quad kW_{24\text{AVG}} := 1.2 \cdot kW_{24} \quad kW_{24\text{AVG}} = 2466.534 \text{ kW}$$

$$ERR_{\text{KW}} = -0.008$$

$$\text{III7. Estimate Electric Fuel Rate:} \quad FR_G = 0.113 \frac{\text{lb}}{\text{kW} \cdot \text{hr}}$$

$$\text{Margin for instrumentation and machinery differences, } f_{1e} \text{ } (P/P): \quad f_{1e} = 1.04$$

$$\text{Specified fuel rate:} \quad FR_{\text{GSP}} := f_{1e} \cdot FR_G$$

**Average fuel rate allowing for plant deterioration:**

$$FR_{\text{GAVG}} := 1.05 \cdot FR_{\text{GSP}} \quad FR_{\text{GAVG}} = 0.124 \frac{\text{lb}}{\text{kW} \cdot \text{hr}} \quad FR_{\text{GAVG}} = 0.092 \frac{\text{lb}}{\text{hp} \cdot \text{hr}}$$

**III8. Estimate Electrical and Total fuel Required****Burnable electrical endurance fuel weight:**

$$W_{\text{Be}} := \frac{E}{V_e} \cdot (kW_{24\text{AVG}} \cdot FR_{\text{GAVG}}) \quad W_{\text{Be}} = 51.127 \text{ ton}$$

**Tailpipe allowance and electrical endurance fuel:**

$$\text{TPA} := .95 \\ \text{(shallow tanks)}$$

$$W_{\text{Fe}} := \frac{W_{\text{Be}}}{\text{TPA}} \quad W_{\text{Fe}} = 53.818 \text{ ton}$$

Allow for expansion and tank structure in required electrical fuel tank volume:

$$V_{Fe} := 1.02 \cdot 1.05 \cdot \gamma_F \cdot W_{Fe} \quad V_{Fe} = 2478.484 \text{ ft}^3$$

Total ship fuel: (DFM)

$$W_{F41} := W_{FP} + W_{Fe} \quad W_{F41} = 2053.939 \text{ ton}$$

$$V_F := V_{FP} + V_{Fe} \quad V_F = 94590.046 \text{ ft}^3$$

#### IV. Space Estimate

##### IVA. Available Space

###### IVA1. Underwater Hull Volume Available

$$V_{HUW} := V_{FL} \quad V_{HUW} = 290058.58 \text{ ft}^3$$

###### IVA2. Sheer Line. (3 criteria)

1) Keep deck edge above water at 25 degree heel

2) Longitudinal strength

3) Contain machinery box height:

$$H_{MBMIN} = 22 \text{ ft}$$

$$M := \begin{bmatrix} .21 \cdot B + T \\ \frac{LWL}{15} \\ H_{MBMIN} \end{bmatrix} \quad M = \begin{bmatrix} 32.223 \\ 35.475 \\ 22 \end{bmatrix} \text{ ft} \quad D_{10MIN} := \max(M) \quad D_{10MIN} = 35.475 \text{ ft} \quad \#ck$$

$$D_{10} := D_{10MIN} + 1 \text{ ft}$$

$$D_{0MIN} := 1.011827 \cdot T - 6.36215 \cdot \frac{10^{-6}}{\text{ft}} \cdot LWL^2 + 2.780649 \cdot 10^{-2} \cdot LWL + T \quad D_{0MIN} = 51.526 \text{ ft} \quad D_0 := D_{0MIN}$$

$$D_{20MIN} := .014 \cdot LWL \cdot \left( 2.125 + 1.25 \cdot \frac{10^{-3}}{\text{ft}} \cdot LWL \right) + T \quad D_{20MIN} = 39.938 \text{ ft} \quad D_{20} := D_{20MIN}$$

###### IVA3. Above-Water Hull Volume

$$F_0 := D_0 - T \quad F_{10} := D_{10} - T \quad F_{20} := D_{20} - T$$

$$A_{PRO} := LWL \cdot \frac{F_0 + 4 \cdot F_{10} + F_{20}}{6} \quad F_{AV} := \frac{A_{PRO}}{LWL} \quad F_{AV} = 20.409 \text{ ft}$$

$$D_{AV} := F_{AV} + T \quad D_{AV} = 39.561 \text{ ft} \quad \text{cubic \#}: CN := \frac{LWL \cdot B \cdot D_{AV}}{10^5 \cdot \text{ft}^3} \quad CN = 13.103$$

$$C_W := .236 + .836 \cdot C_P \quad C_W = 0.729$$

$$\text{flare factor: } f_f := .714599 + .18098 \cdot \frac{D_{AV}}{T} - .018828 \cdot \left( \frac{D_{AV}}{T} \right)^2 \quad M_f := \begin{bmatrix} f_f \\ 1 \end{bmatrix} \quad f_f := \max(M_f) \quad f_f = 1.008$$

$$V_{HAW} := LWL \cdot B \cdot F_{AV} \cdot C_W \cdot f_f \quad V_{HAW} = 496947.294 \text{ ft}^3$$

## IVA4. Total Hull Volume.

$$V_{HT} := V_{HUW} + V_{HAW} \quad V_{HT} = 787005.874 \text{ ft}^3$$

## IVA5. Size Deck House:

$$V_{D_{MAX}} := .0025 \cdot LWL^3 \quad V_{D_{MAX}} = 376699.455 \text{ ft}^3$$

$$V_{D_{MIN}} := .0005 \cdot LWL^3 \quad V_{D_{MIN}} = 75339.891 \text{ ft}^3 \quad V_D = 190000 \text{ ft}^3$$

#ck

## IVA6. Calculate Total Ship Volume

$$V_T := V_{HT} + V_D \quad V_T = 977005.874 \text{ ft}^3$$

## IVB. Space Requirement

IVB1. Machinery Box (assumed near midships)  $B_{MB} := B \quad B_{MB} = 62.244 \text{ ft}$

$$H_{MB} := D_{10} \quad L_{MB} = 40 \text{ ft} \quad A_{MB} := B \cdot T \cdot C_X + B \cdot (H_{MB} - T) \quad A_{MB} = 2002.156 \text{ ft}^2$$

Calculate Machinery Box Volume:

$$V_{MB} := L_{MB} \cdot A_{MB} \cdot C_{PMB} \quad V_{MB} = 79926.062 \text{ ft}^3 \quad V_{AUX} := 1.2 \cdot V_{MB} \quad V_{AUX} = 95911.274 \text{ ft}^3$$

## IVB2. Tankage

Helo:

Helo fuel weight from Payload Spreadsheet:  $W_{F42} = 63.8 \text{ tton}$

Allow for tank structure and expansion:  $\gamma_{HF} := 43 \cdot \frac{\text{ft}^3}{\text{tton}}$

$$V_{HF} := 1.02 \cdot 1.05 \cdot W_{F42} \cdot \gamma_{HF} \quad V_{HF} = 2938.181 \text{ ft}^3$$

Lube Oil:

LO weight:  $W_{F46} := 7.2 \text{ tton}$

Allow for tank structure and expansion:  $\gamma_{LO} := 39 \cdot \frac{\text{ft}^3}{\text{tton}}$

$$V_{LO} := 1.02 \cdot 1.05 \cdot W_{F46} \cdot \gamma_{LO} \quad V_{LO} = 300.737 \text{ ft}^3$$

Potable Water:

Water weight:  $W_{F52} := N_T \cdot 15 \text{ tton} \quad W_{F52} = 22.5 \text{ tton}$

Allow for tank structure:  $\gamma_W := 36 \cdot \frac{\text{ft}^3}{\text{tton}}$

$$V_W := 1.02 \cdot W_{F52} \cdot \gamma_W \quad V_W = 826.2 \text{ ft}^3$$

Sewage:  $V_{SEW} := N_T \cdot 2 \text{ ft}^3 \quad V_{SEW} = 300 \text{ ft}^3$

Waste Oil:  $V_{WASTE} := .005 \cdot V_{FL} \quad V_{WASTE} = 1450.293 \text{ ft}^3$

Clean Ballast:  $V_{BAL} := .032 \cdot V_{FL} \quad V_{BAL} := 0 \text{ ft}^3 \quad V_{BAL} = 0 \text{ ft}^3$

(for compensated system)

Total:

$$V_{TK} := V_F + V_{HF} + V_{LO} + V_W + V_{SEW} + V_{WASTE} + V_{BAL} \quad V_{TK} = 100405.457 \text{ ft}^3$$

## IVB3. Payload Deck Areas

$$\text{Deckhouse payload area: (including access)} \quad A_{DPR} := 1.15 \cdot A_{DPA} + 1.23 \cdot A_{DPC} \quad A_{DPR} = 10143.981 \text{ ft}^2$$

$$\text{Hull payload area: (including access)} \quad A_{HPR} := 1.15 \cdot A_{HPA} + 1.23 \cdot A_{HPC} \quad A_{HPR} = 9797.796 \text{ ft}^2$$

## IVB4. Living Deck Area

$$\text{Deckhouse:} \quad A_{COXO} := 225 \text{ ft}^2 \quad A_{DO} := 75 \cdot N_O \cdot \text{ft}^2 \quad A_{DO} = 1125 \text{ ft}^2$$

$$A_{DL} := A_{COXO} + A_{DO} \quad A_{DL} = 1350 \text{ ft}^2$$

$$\text{Hull:} \quad A_{HAB} := 50 \text{ ft}^2 \quad A_{HL} := \left( A_{HAB} + \frac{LWL}{100} \cdot \text{ft} \right) \cdot N_T - A_{DL}$$

$$A_{HL} = 6948.196 \text{ ft}^2$$

## IVB5. Hull Stores

$$A_{HS} := 300 \text{ ft}^2 + .0158 \cdot \frac{\text{ft}^2}{\text{lb}} \cdot N_T \cdot 9 \cdot \frac{\text{lb}}{\text{day}} \cdot T_S \quad A_{HS} = 1259.85 \text{ ft}^2$$

## IVB6. Other Ship Functions

## Deckhouse:

## Maintenance:

$$A_{DM} := .05 \cdot (A_{DPR} + A_{DL}) \quad A_{DM} = 574.699 \text{ ft}^2$$

## Bridge and Chartroom:

$$A_{DB} := 16 \text{ ft} \cdot (B - 18 \text{ ft}) \quad A_{DB} = 707.906 \text{ ft}^2$$

## Engine Inlet/Exhaust:

$$A_{DIE} := 1.4 \cdot N_{DIE} \cdot (A_{PIE} + A_{eIE}) \quad A_{DIE} = 918.4 \text{ ft}^2$$

## Hull:

## Ship Functions:

$$A_{HSF} := 2500 \text{ ft}^2 \cdot CN \quad A_{HSF} = 32758.449 \text{ ft}^2$$

## Engine Inlet/Exhaust:

$$A_{HIE} := 1.4 \cdot (N_{HPIE} \cdot A_{PIE} + N_{HeIE} \cdot A_{eIE}) \quad A_{HIE} = 161.28 \text{ ft}^2$$

## IVB7. Total Required Area and Volume

## Hull:

$$A_{HR} := A_{HPR} + A_{HL} + A_{HS} + A_{HSF} + A_{HIE} \quad A_{HR} = 50925.571 \text{ ft}^2$$

$$V_{HR} := H_{DK} \cdot A_{HR} \quad V_{HR} = 458330.139 \text{ ft}^3$$

## Deckhouse:

$$A_{DR} := A_{DPR} + A_{DL} + A_{DM} + A_{DB} + A_{DIE} \quad A_{DR} = 13694.986 \text{ ft}^2$$

$$V_{DR} := H_{DK} \cdot A_{DR} \quad V_{DR} = 123254.878 \text{ ft}^3$$

**Total:**

$$A_{TR} := A_{HR} + A_{DR} \quad A_{TR} = 64620.557 \text{ ft}^2$$

$$V_{TR} := H_{DK} \cdot A_{TR} \quad V_{TR} = 581585.017 \text{ ft}^3$$

**IVC. Space Balance**

$$V_D = 190000 \text{ ft}^3 \quad V_{DR} = 123254.878 \text{ ft}^3$$

$$V_{HA} := V_{HT} - V_{MB} - V_{AUX} - V_{TK} \quad V_{HA} = 510763.081 \text{ ft}^3 \quad V_{HR} = 458330.139 \text{ ft}^3$$

$$V_{TA} := V_{HA} + V_D \quad V_{TA} = 700763.081 \text{ ft}^3 > V_{TR} = 581585.017 \text{ ft}^3 \quad \#ck$$

$$A_{HA} := \frac{V_{HA}}{H_{DK}} \quad A_{HA} = 56751.453 \text{ ft}^2 \quad A_{HR} = 50925.571 \text{ ft}^2$$

$$A_{DA} := \frac{V_D}{H_{DK}} \quad A_{DA} = 21111.111 \text{ ft}^2 \quad A_{DR} = 13694.986 \text{ ft}^2$$

$$A_{TA} := A_{DA} + A_{HA} \quad A_{TA} = 77862.565 \text{ ft}^2 > A_{TR} = 64620.557 \text{ ft}^2 \quad \#ck$$

$$ERR_{VOL} := \frac{V_{TA} - V_{TR}}{V_{TR}} \quad ERR_{VOL} = 0.204919 \quad ERR_{AREA} := \frac{A_{TA} - A_{TR}}{A_{TR}} \quad ERR_{AREA} = 0.204919$$

**V. Weight**

**V1. Propulsion (200)**

**Basic Machinery:**  
(230+241/242+250-290)

$$W_{BM} := P_I \frac{\text{lb}}{\text{hp}} \left[ 9.0 + 12.4 \cdot \left( P_I \frac{10^{-5}}{\text{hp}} - 1 \right)^2 \right] \quad W_{BM} = 412.728 \text{ tton}$$

**Shafting:**  
(243)

$$f_S := .5 \quad W_S := 356 \frac{\text{tton}}{\text{ft}} \cdot \text{LWL} \cdot f_S \quad W_S = 94.719 \text{ tton}$$

( $f_S = .5$  for twin screws)

**Props:**  
(245)

$$W_{PR} := .05575 \cdot \text{lb} \cdot \left( \frac{D_P}{\text{ft}} \right)^{5.497 - \frac{.0433}{\text{ft}} \cdot D_P} \cdot N_P \quad W_{PR} = 47.599 \text{ tton}$$

**Bearings:**  
(244)

$$W_B := .15 \cdot (W_S + W_{PR}) \quad W_B = 21.348 \text{ tton}$$

**Total Shafting:**

$$W_{ST} := W_S + W_B + W_{PR} \quad W_{ST} = 163.666 \text{ tton}$$

**Total Propulsion:**

$$W_2 := W_{BM} + W_{ST} + W_{237} \quad W_2 = 576.394 \text{ tton}$$

**V2. Electrical Plant (300)**

$$W_3 := 50 \cdot \text{tton} + .03214 \cdot \frac{\text{tton}}{\text{kW}} \cdot N_G \cdot \text{kW}_G \quad W_3 = 339.26 \text{ tton}$$



**V3. Command/Control/Surveillance (400)**

$$\begin{aligned} \text{Gyro/IC/Navigation (420, 430):} \quad W_{IC} &:= 4.65 \cdot \text{CN} \cdot \text{tton} & W_{IC} &= 60.931 \cdot \text{tton} \\ \text{Other/Misc Group 400:} \quad W_{CO} &:= 2.24 \cdot \text{CN} \cdot \text{tton} & W_{CO} &= 29.352 \cdot \text{tton} \\ \text{Cabling:} \quad W_{CC} &:= .04 \cdot (W_{P400} + W_{IC} + W_{CO}) & W_{CC} &= 9.537 \cdot \text{tton} \\ W_4 &:= W_{P400} + W_{IC} + W_{CO} + W_{CC} + W_{498} & W_4 &= 335.859 \cdot \text{tton} \end{aligned}$$

**V4. Auxiliary Systems (500)**

$$\begin{aligned} \text{aux steam (electric aux boiler):} \quad \text{hotel steam:} \quad Q_{HS} &:= 15 \cdot N_T & \text{distiller:} \quad Q_{DS} &:= 6.5 \cdot N_T + 250 \\ W_{517} &:= .0013 \cdot (Q_{HS} + Q_{DS}) \cdot \text{tton} & W_{517} &= 4.518 \cdot \text{tton} & \text{aux sys operating fluids:} & W_{598} &:= .000075 \cdot V_T \cdot \frac{\text{tton}}{\text{ft}^3} \\ & & & & & & W_{598} &= 73.275 \cdot \text{tton} \end{aligned}$$

$$W_{AUX} := \left[ .000772 \cdot \left( \frac{V_T}{\text{ft}^3} \right)^{1.443} + 5.14 \cdot \frac{V_T}{\text{ft}^3} + 6.19 \cdot \left( \frac{V_T}{\text{ft}^3} \right)^{.7224} + 377 \cdot N_T + 2.74 \cdot \frac{P_I}{\text{hp}} \right] \cdot 10^{-4} \cdot \text{tton} + 113.8 \cdot \text{tton}$$

$$\text{environmental support:} \quad W_{593} := 10 \cdot \text{tton} \quad W_5 := W_{AUX} + W_{P500} + W_{517} + W_{593} + W_{598} + W_{CPS}$$

**V5. Outfit & Furnishings (600)**

$$W_5 = 862.05 \cdot \text{tton}$$

$$\text{Hull Fittings:} \quad W_{OFH} := \left( 31.4 + \frac{.0003187}{\text{ft}^3} \cdot V_T \right) \cdot \text{tton} \quad W_{OFH} = 342.772 \cdot \text{tton}$$

$$\text{Personnel-related:} \quad W_{OFP} := .8 \cdot (N_T - 9.5) \cdot \text{tton} \quad W_{OFP} = 112.4 \cdot \text{tton}$$

$$W_6 := W_{OFP} + W_{OFH} + W_{P600} \quad W_6 = 462.912 \cdot \text{tton}$$

**V6. Structure (100)**

$$\text{Hull (110-140, 160, 190):} \quad W_{BH} := C_{HMAT} \cdot (1.68341 \cdot \text{CN}^2 + 167.1721 \cdot \text{CN} - 103.283) \cdot \text{tton} \quad W_{BH} = 2209.936 \cdot \text{tton}$$

$$\rho_{DH} := \text{if}(C_{DHMAT} = 1, .0007, .001429) \quad \rho_{DH} = 0.001$$

$$\text{Deckhouse (150):} \quad W_{DH} := \rho_{DH} \cdot \frac{\text{tton}}{\text{ft}^3} \cdot V_D \quad W_{DH} = 271.51 \cdot \text{tton}$$

$$\text{Masts:} \quad W_{171} := .0688 \cdot \frac{\text{tton}}{\text{ft}} \cdot \text{LWL} - 13.75 \cdot \text{tton} \quad W_{171} = 22.861 \cdot \text{tton}$$

$$\text{Foundations:} \quad W_{180} := .0675 \cdot W_{BM} + .072 \cdot (W_3 + W_4 + W_5 + W_7) \quad W_{180} = 146.986 \cdot \text{tton}$$

$$W_1 := W_{BH} + W_{DH} + W_{171} + W_{180} + W_{165} + W_{164} \quad W_1 = 2736.993 \cdot \text{tton}$$

## V7. Single Digit Weight Summary &amp; Weight Balance:

il := 1, 2.. 7

**Weight margin:**  
(Future Growth)  $W_{M24} := .1 \cdot \left( \sum_{il} W_{il} \right)$   $W_{M24} = 543.084 \text{ tton}$

**Lightship:**

$$W_{LS} := \sum_{il} W_{il} + W_{M24} \quad W_{LS} = 5973.922 \text{ tton}$$

**Additional Loads:**

**Provisions:**  $W_{F31} := N_T \cdot 9 \cdot \frac{\text{lb}}{\text{day}} \cdot T_S$   $W_{F31} = 27.121 \text{ tton}$

**General stores:**  $W_{F32} := .0009598 \cdot \frac{\text{tton}}{\text{day}} \cdot T_S \cdot N_T$   $W_{F32} = 6.479 \text{ tton}$

**Crew:**  $W_{F10} := 236 \cdot \text{lb} \cdot N_E + 400 \cdot \text{lb} \cdot (N_O + 1)$   $W_{F10} = 17.08 \text{ tton}$

$$W_T := W_{LS} + W_{F41} + W_{F42} + W_{F20} + W_{F46} + W_{F52} + W_{F31} + W_{F32} + W_{F10}$$

$$W_T = 8359.5 \text{ tton}$$

**Weight Balance:**  $\text{ERR\_WEIGHT} := \frac{\Delta_{FL} - W_T}{W_T}$

$$\text{ERR\_WEIGHT} = -0.008626$$

#ck

**VI. Stability**

**VII. Calculate Light Ship Weight Group Moments:**

<u>Weight</u>	<u>VCG</u>	<u>Product</u>
$W_{BH} = 2209.936 \text{ tton}$	$VCG_1 := .527 \cdot D_{10}$	$VCG_1 = 19.223 \text{ ft} \quad P_1 := W_{BH} \cdot VCG_1$
$W_{DH} = 271.51 \text{ tton}$	$VCG_2 := D_{10} + 1.5 \cdot H_{DK}$	$VCG_2 = 49.975 \text{ ft} \quad P_2 := W_{DH} \cdot VCG_2$
$W_{180} = 146.986 \text{ tton}$	$VCG_3 := .68 \cdot D_{10}$	$VCG_3 = 24.803 \text{ ft} \quad P_3 := W_{180} \cdot VCG_3$
$W_{171} = 22.861 \text{ tton}$	$VCG_4 := 2.65 \cdot D_{10}$	$VCG_4 = 96.66 \text{ ft} \quad P_4 := W_{171} \cdot VCG_4$
$P_{100} := P_1 + P_2 + P_3 + P_4$		$VCG_{100} := \frac{P_{100}}{W_1} \quad VCG_{100} = 22.618 \text{ ft}$
$W_{BM} = 412.728 \text{ tton}$	$VCG_5 := .5 \cdot D_{10}$	$VCG_5 = 18.238 \text{ ft} \quad P_5 := W_{BM} \cdot VCG_5$
$W_{ST} = 163.666 \text{ tton}$	$VCG_6 := 3.9 \cdot \text{ft} + .19 \cdot T$	$VCG_6 = 7.539 \text{ ft} \quad P_6 := W_{ST} \cdot VCG_6$
$W_{237} = 0 \text{ tton}$	$VCG_7 := VCG_{237}$	$VCG_7 = 0 \text{ ft} \quad P_7 := W_{237} \cdot VCG_7$
$P_{200} := P_5 + P_6 + P_7$		$VCG_{200} := \frac{P_{200}}{W_2} \quad VCG_{200} = 15.2 \text{ ft}$
$W_3 = 339.26 \text{ tton}$	$VCG_8 := .65 \cdot D_{10}$	$VCG_8 = 23.709 \text{ ft} \quad P_8 := W_3 \cdot VCG_8$
$W_{IC} = 60.931 \text{ tton}$	$VCG_9 := D_{10}$	$VCG_9 = 36.475 \text{ ft} \quad P_9 := W_{IC} \cdot VCG_9$
$W_{CO} = 29.352 \text{ tton}$	$VCG_{10} := 5.6 \cdot \text{ft} + .4625 \cdot D_{10}$	$VCG_{10} = 22.47 \text{ ft} \quad P_{10} := W_{CO} \cdot VCG_{10}$
$W_{CC} = 9.537 \text{ tton}$	$VCG_{11} := .5 \cdot D_{10}$	$VCG_{11} = 18.238 \text{ ft} \quad P_{11} := W_{CC} \cdot VCG_{11}$
$W_{498} = 87.9 \text{ tton}$	$VCG_{12} := VCG_{498}$	$VCG_{12} = -1.2 \text{ ft} \quad P_{12} := W_{498} \cdot VCG_{12}$
$W_{AUX} = 696.867 \text{ tton}$	$VCG_{13} := .9 \cdot (D_{10} - 7.4 \cdot \text{ft})$	$VCG_{13} = 26.168 \text{ ft} \quad P_{13} := W_{AUX} \cdot VCG_{13}$
$W_{517} = 4.518 \text{ tton}$	$VCG_{14} := .5 \cdot H_{MB}$	$VCG_{14} = 18.238 \text{ ft} \quad P_{14} := W_{517} \cdot VCG_{14}$
$W_{OFH} = 342.772 \text{ tton}$	$VCG_{15} := .805 \cdot D_{10}$	$VCG_{15} = 29.363 \text{ ft} \quad P_{15} := W_{OFH} \cdot VCG_{15}$
$W_{OFF} = 112.4 \text{ tton}$	$VCG_{16} := 8 \cdot \text{ft} + .71 \cdot D_{10}$	$VCG_{16} = 33.898 \text{ ft} \quad P_{16} := W_{OFF} \cdot VCG_{16}$

$ip := 1..16$

$$P_{WG} := \sum_{ip} P_{ip} + W_P \cdot VCG_P - W_{VP} \cdot VCG_{VP} \quad P_{WG} = 122974.982 \text{ tton} \cdot \text{ft}$$

## VI2. Light Ship KG

$$VCG_{LS} := \frac{\sum_{iL} W_{iL} \cdot VCG_{iL}}{\sum_{iL} W_{iL}} \quad VCG_{LS} = 22.644 \text{ ft} \quad KG_{LS} := VCG_{LS} \quad KG_{LS} = 22.644 \text{ ft}$$

## VI3. Calculate Variable Load Weight Group Moments:

<u>Weight</u>	<u>VCG</u>	<u>Product</u>
$W_{F10} = 17.08 \text{ tton}$	$VCG_{17} := .746 \cdot D_{10}$	$VCG_{17} = 27.211 \text{ ft} \quad P_{17} := W_{F10} \cdot VCG_{17}$
$W_{F31} = 27.121 \text{ tton}$	$VCG_{18} := .55 \cdot D_{10}$	$VCG_{18} = 20.061 \text{ ft} \quad P_{18} := W_{F31} \cdot VCG_{18}$
$W_{F32} = 6.479 \text{ tton}$	$VCG_{19} := .65 \cdot D_{10}$	$VCG_{19} = 23.709 \text{ ft} \quad P_{19} := W_{F32} \cdot VCG_{19}$
$W_{F41} = 2053.939 \text{ tton}$	$VCG_{20} := 7.5 \text{ ft}$	$VCG_{20} = 7.5 \text{ ft} \quad P_{20} := W_{F41} \cdot VCG_{20}$
$W_{F42} = 63.8 \text{ tton}$	$VCG_{21} := 10 \text{ ft}$	$VCG_{21} = 10 \text{ ft} \quad P_{21} := W_{F42} \cdot VCG_{21}$
$W_{F46} = 7.2 \text{ tton}$	$VCG_{22} := .35 \cdot D_{10}$	$VCG_{22} = 12.766 \text{ ft} \quad P_{22} := W_{F46} \cdot VCG_{22}$
$W_{F52} = 22.5 \text{ tton}$	$VCG_{23} := 7.5 \text{ ft}$	$VCG_{23} = 7.5 \text{ ft} \quad P_{23} := W_{F52} \cdot VCG_{23}$

$$iL := 17..23 \quad P_{WGL} := \sum_{iL} P_{iL} + W_{VP} \cdot VCG_{VP} \quad P_{WGL} = 24906.211 \text{ tton} \cdot \text{ft}$$

$$W_L := W_{F41} + W_{F42} + W_{F20} + W_{F46} + W_{F52} + W_{F31} + W_{F32} + W_{F10} \quad W_L = 2385.578 \text{ tton}$$

$$VCG_L := \frac{P_{WGL}}{W_L} \quad VCG_L = 10.44 \text{ ft}$$

## VI4. Calculate Ship Stability Characteristics:

$$KG_{MARG} := .5 \text{ ft} \quad KG := \frac{W_{LS} \cdot KG_{LS} + W_L \cdot VCG_L}{W_T} + KG_{MARG} \quad C_{IT} := -.497 + 1.44 \cdot C_W \quad C_{IT} = 0.553$$

$$KB := \frac{T}{3} \left( 2.5 - \frac{C_P \cdot C_X}{C_W} \right) \quad BM := \frac{LWL \cdot B^3 \cdot C_{IT}}{12 \cdot V_{FL}} \quad GM := KB + BM - KG \quad C_{GMB} := \frac{GM}{B}$$

$$KG = 19.661 \text{ ft} \quad KB = 11.957 \text{ ft} \quad BM = 20.392 \text{ ft} \quad GM = 12.688 \text{ ft} \quad C_{GMB} = 0.204$$

#ck

**VII VERY SIMPLIFIED COST MODEL (Lead-Ship End Cost only)**

$$\begin{aligned} \text{Mdol} &:= \text{coul} & \text{Kdol} &:= \frac{\text{Mdol}}{1000} \\ \text{Bdol} &:= 1000 \cdot \text{Mdol} & \text{dol} &:= \frac{\text{Kdol}}{1000} \end{aligned}$$

**V!!1. Additional characteristics:**

<b>Ship Service Life:</b>	$L_S := 30$	<b>Initial Operational Capability:</b>	$Y_{IOC} := 1998$	#
<b>Total Ship Acquisition:</b>	$N_S := 25$	<b>Production Rate (per year):</b>	$R_P := 3$	#

**Inflation:**

**Base Year:**  $Y_B := 1998$       $iy := 1.. Y_B - 1981$

**Average Inflation Rate (%):**  $R_I := 5$   
(from 1981)

$$F_I := \prod_{iy} \left( 1 + \frac{R_I}{100} \right) \quad F_I = 2.292$$

**a. Lead Ship Cost - Shipbuilder Portion:**

SWBS costs: (See Table 5 for  $K_N$  factors)

<b>Structure</b>	$K_{N1} := \frac{.55 \cdot \text{Mdol}}{\text{tton}^{.772}}$	$C_{L1} := .03395 \cdot F_I \cdot K_{N1} \cdot (W_1)^{.772}$	$C_{L1} = 19.275 \cdot \text{Mdol}$
------------------	--	--	-------------------------------------

<b>+ Propulsion</b>	$K_{N2} := \frac{1.2 \cdot \text{Mdol}}{\text{hp}^{.808}}$	$C_{L2} := .00186 \cdot F_I \cdot K_{N2} \cdot P_{IBRAKE}^{.808}$	$C_{L2} = 58.708 \cdot \text{Mdol}$
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<b>+ Electric</b>	$K_{N3} := \frac{1.0 \cdot \text{Mdol}}{\text{tton}^{.91}}$	$C_{L3} := .07505 \cdot F_I \cdot K_{N3} \cdot (W_3)^{.91}$	$C_{L3} = 34.542 \cdot \text{Mdol}$
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**+ Command, Control, Surveillance**

	$K_{N4} := \frac{2.0 \cdot \text{Mdol}}{\text{tton}^{.617}}$	$C_{L4} := .10857 \cdot F_I \cdot K_{N4} \cdot (W_4)^{.617}$	$C_{L4} = 18.013 \cdot \text{Mdol}$
		(less payload GFM cost)	

<b>+ Auxiliary</b>	$K_{N5} := \frac{1.5 \cdot \text{Mdol}}{\text{tton}^{.782}}$	$C_{L5} := .09487 \cdot F_I \cdot K_{N5} \cdot (W_5)^{.782}$	$C_{L5} = 64.421 \cdot \text{Mdol}$
--------------------	--	--	-------------------------------------

<b>+ Outfit</b>	$K_{N6} := \frac{1.0 \cdot \text{Mdol}}{\text{tton}^{.784}}$	$C_{L6} := .09859 \cdot F_I \cdot K_{N6} \cdot (W_6)^{.784}$	$C_{L6} = 27.784 \cdot \text{Mdol}$
-----------------	--	--	-------------------------------------

<b>+ Armament</b>	$K_{N7} := \frac{1.0 \cdot \text{Mdol}}{\text{tton}^{.987}}$	$C_{L7} := .00838 \cdot F_I \cdot K_{N7} \cdot (W_7)^{.987}$	$C_{L7} = 2.119 \cdot \text{Mdol}$
		(Less payload GFM cost)	

+ **Margin Cost:**

$$C_{LM} := \frac{W_{M24}}{(W_{LS} - W_{M24})} \left( \sum_{i1} C_{L_{i1}} \right) \quad C_{LM} = 22.486 \cdot \text{Mdol}$$

+ **Integration/Engineering: (Lead ship includes detail design engineering for class)**

$$K_{N8} := \frac{10.0 \cdot \text{Mdol}}{\text{Mdol}^{1.099}} \quad C_{L_8} := .034 \cdot K_{N8} \left( \sum_{i1} C_{L_{i1}} + C_{LM} \right)^{1.099} \quad C_{L_8} = 145.12 \cdot \text{Mdol}$$

+ **Ship Assembly and Support: (Lead ship includes all tooling, jigs, special facilities for class)**

$$K_{N9} := \frac{2.0 \cdot \text{Mdol}}{(\text{Mdol})^{.839}} \quad C_{L_9} := .135 \cdot K_{N9} \left( \sum_{i1} C_{L_{i1}} + C_{LM} \right)^{.839} \quad C_{L_9} = 27.501 \cdot \text{Mdol}$$

= **Total Lead Ship Construction Cost: (BCC) :**

$$C_{LCC} := \sum_{i1} C_{L_{i1}} + C_{L_8} + C_{L_9} + C_{LM} \quad C_{LCC} = 419.97 \cdot \text{Mdol}$$

+ **Profit:**

$$F_{\text{PROFIT}} := .10 \quad C_{LP} := F_{\text{PROFIT}} \cdot C_{LCC} \quad C_{LP} = 41.997 \cdot \text{Mdol}$$

= **Lead Ship Price :**

$$P_L := C_{LCC} + C_{LP} \quad P_L = 461.967 \cdot \text{Mdol}$$

+ **Change Orders:**

$$C_{LCORD} := .12 \cdot P_L \quad C_{LCORD} = 55.436 \cdot \text{Mdol}$$

= **Total Shipbuilder Portion:**

$$C_{SB} := P_L + C_{LCORD} \quad C_{SB} = 517.403 \cdot \text{Mdol}$$

*b. Lead Ship Cost - Government Portion*

**Other support:**

$$C_{LOTH} := .025 \cdot P_L \quad C_{LOTH} = 11.549 \cdot \text{Mdol}$$

+ **Program Manager's Growth:**

$$C_{LPMG} := .1 \cdot P_L \quad C_{LPMG} = 46.197 \cdot \text{Mdol}$$

**Costed Military Payload:**

$$W_{MP} := W_4 + W_7 + W_{F20} - W_{IC} - W_{F23} \quad W_{MP} = 567.028 \cdot \text{ton}$$

+ **Ordnance and Electrical GFE:  
(Military Payload GFE)**

$$C_{LMPG} := \left( .319 \cdot \frac{\text{Mdol}}{\text{ton}} \cdot W_{MP} + N_{HELO} \cdot 18.71 \cdot \text{Mdol} \right) \cdot F_I$$

$$C_{LMPG} = 500.352 \cdot \text{Mdol}$$

+ HM&E GFE (boats, IC):  $C_{LHMEG} := .02 \cdot P_L$   $C_{LHMEG} = 9.239 \cdot \text{Mdol}$

+ Outfitting Cost :  $C_{LOUT} := .04 \cdot P_L$   $C_{LOUT} = 18.479 \cdot \text{Mdol}$

= Total Government Cost:

$C_{LGOV} := C_{LOTH} + C_{LPMG} + C_{LMPG} + C_{LHMEG} + C_{LOUT}$   $C_{LGOV} = 585.816 \cdot \text{Mdol}$

c. Total End Cost: (Must always be less than SCN appropriation)

\* Total End Cost:

$C_{LEND} := C_{SB} + C_{LGOV}$   $C_{LEND} = 1103.22 \cdot \text{Mdol}$

**SUMMARY: WITHOUT OPTIMIZATION**

**ITERATION WEIGHT:**  $W_{FL} \equiv 8287.388 \cdot \text{tton}$      $ERR_{WEIGHT} = -0.008626$      $V_{FL} \equiv W_{FL} \cdot 35 \cdot \frac{\text{ft}^3}{\text{tton}}$   
 $W_{FL1} = 6683 \cdot \text{tton}$      $W_T = 8359.5 \cdot \text{tton}$

**GROSS CHARACTERISTICS:**

$C_P \equiv .59$  (.54 - .64)     $C_{\Delta L} \equiv 55 \cdot \frac{\text{tton}}{\text{ft}^3}$  (45 - 65)     $LWL \equiv 100 \cdot \left( \frac{W_{FL}}{C_{\Delta L}} \right)^{\frac{1}{3}}$      $LWL = 532.131 \cdot \text{ft}$   
 $C_X \equiv .775$  (.7 - .85)     $C_V := \frac{V_{FL}}{LWL^3}$      $C_V = 1.925 \cdot 10^{-3}$      $V_{FL} = 290058.58 \cdot \text{ft}^3$

$C_{BT} \equiv 3.25$  (2.8 - 3.7)     $B \equiv \sqrt{\frac{C_{BT} \cdot V_{FL}}{C_P \cdot C_X \cdot LWL}}$      $B = 62.244 \cdot \text{ft}$      $T = 19.152 \cdot \text{ft}$      $C_{LB} = 8.549$  (7.5 - 10)

**ENERGY BALANCE:**

$V_S \equiv 27 \cdot \text{knt}$      $P_I = 102626 \cdot \text{hp}$      $P_{IREQ} = 85806.678 \cdot \text{hp}$      $ERR_{POWER} = 0.196$   
 $V_e \equiv 20 \cdot \text{knt}$      $kW_G = 3000 \cdot \text{kW}$      $kW_{GREQ} = 3023.539 \cdot \text{kW}$      $ERR_{KW} = -0.008$   
 $E \equiv 7500 \cdot \text{knt} \cdot \text{hr}$

**AREA/VOLUME BALANCE:**

$V_D \equiv 190000 \cdot \text{ft}^3$      $V_T = 977005.874 \cdot \text{ft}^3$      $V_{MB} = 79926.062 \cdot \text{ft}^3$      $V_{TR} = 581585.017 \cdot \text{ft}^3$   
 $V_{DMIN} = 75339.891 \cdot \text{ft}^3$      $V_{HT} = 787005.874 \cdot \text{ft}^3$      $V_{AUX} = 95911.274 \cdot \text{ft}^3$      $V_{TA} = 700763.081 \cdot \text{ft}^3$   
 $V_{DMAX} = 376699.455 \cdot \text{ft}^3$      $V_{TK} = 100405.457 \cdot \text{ft}^3$      $ERR_{AREA} = 0.204919$   
 $D_{10} = 36.475 \cdot \text{ft}$  (Must be  $> D_{10MIN}$ )  
 $D_{10MIN} = 35.475 \cdot \text{ft}$      $A_{TR} = 64620.557 \cdot \text{ft}^2$      $A_{HR} = 50925.571 \cdot \text{ft}^2$      $A_{DR} = 13694.986 \cdot \text{ft}^2$   
 $A_{TA} = 77862.565 \cdot \text{ft}^2$      $A_{HA} = 56751.453 \cdot \text{ft}^2$      $A_{DA} = 21111.111 \cdot \text{ft}^2$

**WEIGHT BALANCE:**

$W_{FL} = 8287.388 \cdot \text{tton}$      $W_T = 8359.5 \cdot \text{tton}$      $ERR_{WEIGHT} = -0.008626$   
 $W_1 = 2736.993 \cdot \text{tton}$      $W_5 = 862.05 \cdot \text{tton}$      $W_{LS} = 5973.922 \cdot \text{tton}$   
 $W_2 = 576.394 \cdot \text{tton}$      $W_6 = 462.912 \cdot \text{tton}$      $W_P = 668.3 \cdot \text{tton}$   
 $W_3 = 339.26 \cdot \text{tton}$      $W_7 = 117.37 \cdot \text{tton}$      $W_{F41} = 2053.939 \cdot \text{tton}$   
 $W_4 = 335.859 \cdot \text{tton}$

**STABILITY/PAYLOAD:**

$C_{GMB} = 0.204$  (.09 - .122)     $F_P := \frac{W_P}{W_{FL}} \cdot 100$      $F_P = 8.0641$





**APPENDIX G. INTEGRATED SHIP DESIGN SYSTEM USER'S GUIDE**

## INTEGRATED SHIP DESIGN SYSTEM USER'S GUIDE

### 1. Computer System Requirements.

The ISDS was developed using the following software products;

- Microsoft Excel, Version 7.0 for Windows 95 for the Payload Spreadsheet.
- Mathcad 7 Professional for Windows 95 for the MIT Math Model and the MathConnex working environment.
- Matlab 5 with the Optimization Toolbox for the Numerical Optimizer.

### 2. Getting Started.

First and foremost it is strongly encouraged that the user become familiar with the mechanics of the application programs and the supporting documentation for the MIT Math Model prior to using ISDS.

- 2.1. Open ISDS in MathConnex. The worksheet will display the block and wire diagram of the ISDS, and by following the arrows you can step through the program logic path that connects the different application modules. The two view boxes display the intermediate results from the optimizer and the final design summary.
- 2.2. Open the file "outopt" in the Matlab editor/debugger. This file contains the diary output of the optimizer that is normally displayed in the Matlab command screen. When using MathConnex, the Matlab command screen is not viewed, so this permits the optimization details to be stored for later viewing and reviewing.
- 2.3. Each time the ISDS is run, "outopt" is updated and its contents should be viewed by the user to ensure the optimizer is producing feasible results.
- 2.4. To de-clutter the file after each session, "outopt" can be cleared by selecting all in the edit menu and then deleting.

### 3. Modify Payload Spreadsheet.

- 3.1 Double-click on the Excel icon to activate the Payload spreadsheet for editing.
- 3.2 Delete the contents of the cells of the combat systems that will NOT be installed in the design. Remember only to delete the cells with numerical values, not the system name, so that the data can be reloaded for different designs later on.
- 3.3 A complete Payload spreadsheet is included in the ISDS program files under the heading "mit\_payload". By using the cut and paste command, data can be easily reloaded into the MathConnex Excel spreadsheet from "mit\_payload".
- 3.4 Selected payload values are then loaded into the global variable "Payload" for

transfer to the Initial Values and Final Design Synthesis Mathcad worksheets.

4. Modify the Initial Values Mathcad Worksheet.

- 4.1 Double-click on the Initial Values Mathcad icon to open the Mathcad worksheet.
- 4.2 Inspect and modify, as required, the yellow highlighted sections. Cross-check highlighted values between Initial Values and Final Design Synthesis modules to ensure consistency between the two.
- 4.3 Three arrays are output from this module;
  - The design variable independent weights and center of gravity data are output as "out0". This has a change variable name in Matlab to "w".
  - The first guess at the design variable values for beam, draft and waterline length are output as "out1".
  - Additional design specifics that need to be passed to the Matlab optimizer and The Final Design Synthesis Mathcad module are output as "out2". This has a change of variable name in Matlab to "z".

5. Modify the Matlab Optimizer Worksheet.

- 5.1 Double-click on the Matlab icon to activate the Matlab worksheet.
- 5.2 This Matlab worksheet contains the variables that control the optimization process. There are two choices for assigning the initial guess of the design variables, "x0". The first uses the guess generated by the Initial Values Mathcad worksheet, and the second can be manually input by the designer. To switch between the two, place a "%" in front of the line you want to inactivate and delete the "%" on the line you want to activate. Make sure you click the "check" button on the toolbar to save the change to the Matlab worksheet.
- 5.3 The side constraints of the design variables, vlb and vub, can be modified to ensure a global vice local minimum is being sought. Only the first three bounds should be modified, as the last two are constrained to keep the Math Model valid when using the Taylor Standard Series. Make sure you click the "check" button on the toolbar to save the change to the Matlab worksheet.

6. Cross-Check the Final Design Synthesis Mathcad Worksheet.

- 6.1 Make sure all the yellow highlighted sections match between the Initial Values and the Final Design Synthesis worksheets.

7. Interpreting Results.

- 7.1 Results are displayed in two view boxes within the ISDS MathConnex

worksheet. The first view box contains the output from the Matlab optimizer. Additional optimization details are contained in the "outopt" file in the Matlab editor/debugger.

- 7.2 The second view box contains a summary of the Final Synthesis Design Mathcad worksheet. The Design Checks column should be scrutinized by the designer to ensure that the installed power plant is sufficient and that the area weight errors are reasonable.
- 7.3 If the area error is excessive, it can be adjusted by the designer to bring it into compliance. The deckhouse volume ( $V_D$ ) is the variable that is modified to adjust this error. In the Area/Volume Balance section of the Summary page in the Final Design Synthesis Mathcad worksheet there is a range for the value of  $V_D$ . The model can be set up so that the value is calculated using the equation for  $V_{DMIN}$  or  $V_{DMAX}$  or any numerical value can be chosen between  $V_{DMIN}$  and  $V_{DMAX}$  and assigned as the value of  $V_D$  in the worksheet. The Matlab function M-file "cubicnum\_calc" must also be modified so that the value of  $V_D$  is consistently calculated. Change the value and run the ISDS again and check the area error, if it is still unreasonable, adjust  $V_D$  up or down within the range until it reaches a reasonable error.
- 7.4 The entire detailed design can be reviewed by double-clicking on the Final Design Synthesis Mathcad icon.

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Naval Surface Warfare Center  
9500 MacArthur Blvd.  
West Bethesda, MD 20817-5700
10. Mr. Al Bauer..... 1  
C/O Naval Sea Systems Command  
Code 03D  
2531 Jefferson Davis Highway  
Arlington, VA 22242-5160