

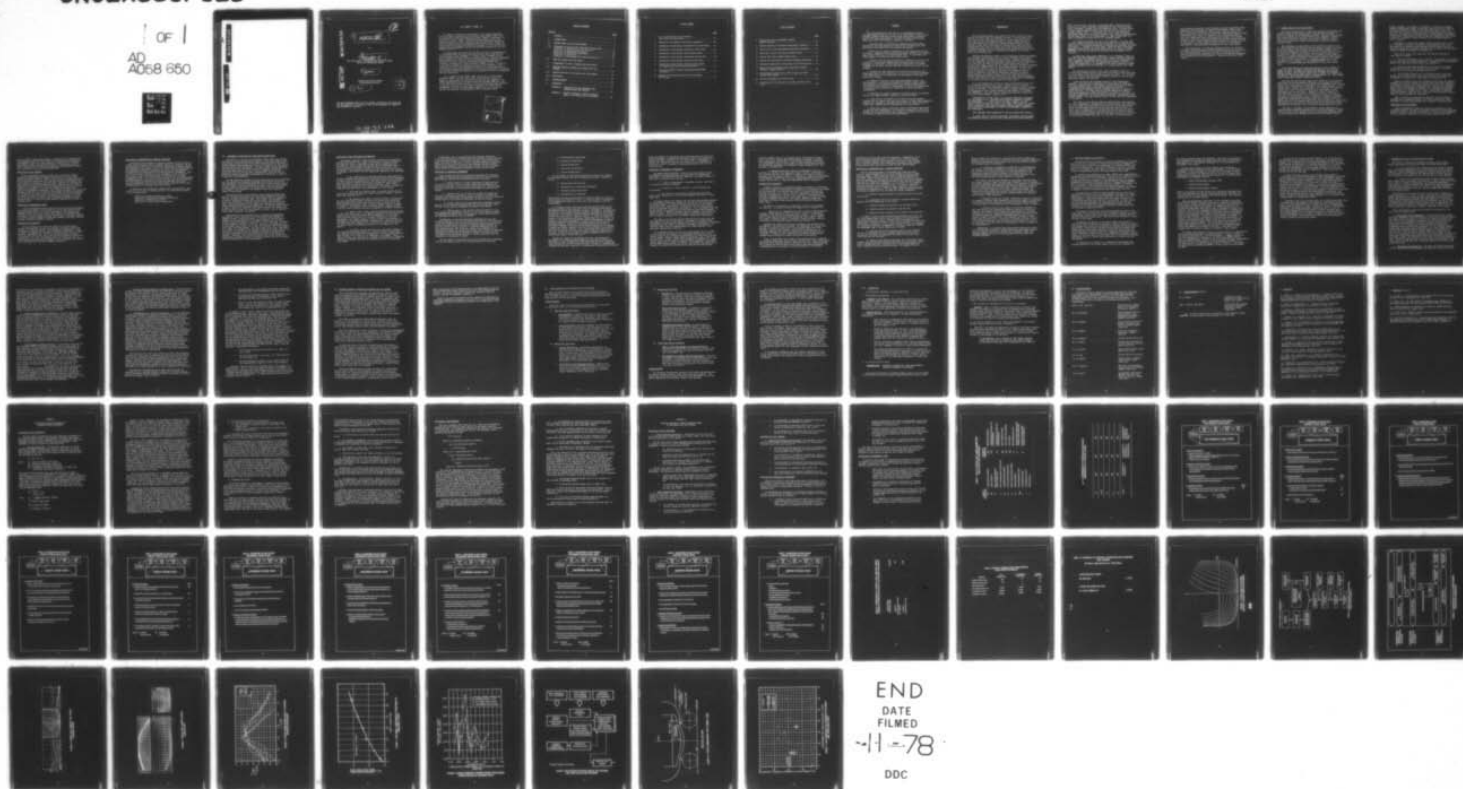
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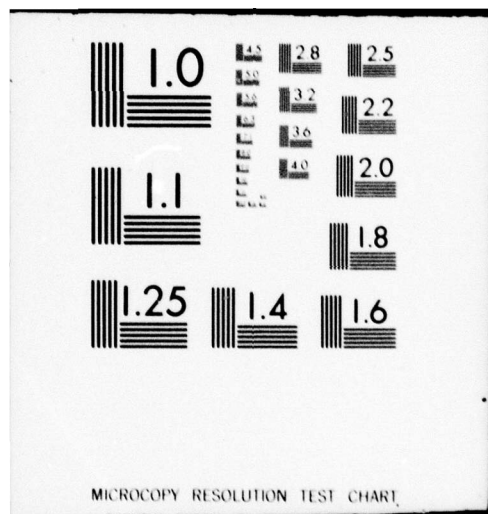
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THE STEPCHILD OF R AND D - THE DISPLACEMENT MONOHULL, (U)  
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⑥ THE STEPCHILD OF <sup>and</sup> R&D  
THE DISPLACEMENT MONOHULL,

BY

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⑪ MARCH 1978

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He is a member of ASE, SNAME, ASNE, and Society of Allied Weight Engineers (SAWE). Active in all, he has been President of the D.C. Council of Engineering and Architectural Societies; is a member of the SNAME Seakeeping Panel; has served on many ASE and ASNE committees; and is presently the Secretary of ASE. He is also listed with those appearing in the 1977-78 edition of "WHO'S WHO IN THE EAST" and "WHO'S WHO IN ENGINEERING", and has received numerous awards for his technical and society contributions, including ASE's John C. Niedermair Award.

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## TABLE OF CONTENTS

<u>SECTION</u>	<u>PAGE</u>
ABSTRACT . . . . .	v
I. INTRODUCTION . . . . .	1
II. GENERAL NEEDS OF HULL FORM DESIGNER. . . . .	4
III. ASSESSMENT OF EXISTING HULL FORM DESIGN CAPABILITIES . . . . .	8
Prediction of Ship Resistance and Powering . . . . .	9
Prediction of Seakeeping Performance . . . . .	10
Prediction of Maneuvering Performance. . . . .	12
Prediction of Cavitation . . . . .	13
Prediction of Hydrodynamically-Induced Vibrations. . . . .	14
IV. NEED FOR SURFACE SHIP R&D EFFORT . . . . .	16
V. CONSEQUENCES OF LACK OF SURFACE SHIP R&D EFFORT. . . . .	19
VI. PROPOSED TECHNICAL APPROACH FOR SURFACE SHIP R&D PROGRAM . . . . .	23
VII. BENEFITS/PAYOFFS OF NEW SURFACE SHIP R&D PROGRAM . . . . .	25
VIII. CONCLUSIONS . . . . .	28
IX. ACKNOWLEDGEMENTS . . . . .	30
X. REFERENCES . . . . .	32
APPENDIX A - DESCRIPTION OF SHIP RESISTANCE AND POWERING PREDICTION METHODS . . . . .	34
APPENDIX B - SPECIFIC APPROACH TO CERTAIN TECHNICAL AREAS OF THE SURFACE SHIP R&D PROGRAM . . . . .	40

## LIST OF TABLES

	<u>Page</u>
1. List of Typical Hull Form Parameters That Affect Ship Resistance . . . . .	43
2. Comparison of Propulsive Coefficient Components . . . . .	44
3. Seakeeping in Ship Design, Pre-Feasibility Study Phase. . .	45
4. Seakeeping in Ship Design, Feasibility Study Phase. . . . .	46
5. Seakeeping in Ship Design, Concept Design Phase . . . . .	47
6. Seakeeping in Ship Design, Preliminary Design Phase . . . . .	50
7. Seakeeping in Ship Design, Contract Design Phase. . . . .	54
8. Comparison of Vertical Hull Surface Forces Caused by Propeller-Excited Fluctuating Pressures. . . . .	56
9. Potential Economic Payoff from Improved Speed/Power Performance . . . . .	57
10. Examples of Potential Acquisition and Operating Cost Savings . . . . .	58



## LIST OF FIGURES

	<u>Page</u>
1. Typical Body Plan from NAVSEC's HULGEN Computer Program . . . . .	59
2. General Approach to Calm Water Speed/Power Estimates . . . .	60
3. Subdivision of Ship Hydrodynamic Resistance Components . . .	61
4. Parent Hull Form of the Taylor Standard Series . . . . .	62
5. Typical Hull Form of Naval Surface Ship. . . . .	63
6. Typical Worm Curve Used to Estimate Residuary Resistance . .	64
7. Ship-Model Comparison of Resistance of Twin Shaft Struts . .	65
8. Rudder Vibratory Loading Versus Longitudinal Rudder- Propeller Clearance Ratio . . . . .	66
9. Relationships Between Surface SHIP Program and Other Related R&D Programs . . . . .	67
10. Typical Arrangement with Tunnel Stern . . . . .	68
11. Hull-Propeller Tip Clearance for Single and Twin Screw Ships . . . . .	69

## ABSTRACT

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This paper demonstrates the need for a comprehensive Advanced Development RDT&E Program in the area of the hydrodynamic design of displacement monohulls for naval surface ships, and outlines a proposed Surface SHIP (Ship Hydrodynamics - Improved Performance) R&D Program which will fulfill this need. In particular, the paper:

- o Describes some of the existing hydrodynamics-related design deficiencies and gives examples of some specific problems which these deficiencies have caused in recent surface ship designs;
- o Shows that the general consequences of such design deficiencies are either: failure to meet potential performance capabilities; excessive cost required to attain a given performance level; or unnecessary and costly delay in the design of naval surface ships;
- o Explains that the present approach of attempting to correct this situation in a piece-meal fashion under individual ship acquisition programs or existing but limited Exploratory Development (6.2) RDT&E programs will not work, and that this fact reflects no discredit on such programs;
- o Analyzes the underlying cause of the above deficiencies, and shows that these are just symptoms of the lack of an Advanced Development (6.3) RDT&E effort for the application of hydrodynamics technology to surface ship design;
- o Proposes a solution to the underlying problem, namely, the establishment of an Advanced Development (6.3) RDT&E program, aimed at the development of performance-oriented hydrodynamic design methods which effect either significant improvements in surface ship performance, or acquisition and operating cost reductions for given performance requirements;
- o Describes the proposed program in sufficient detail to establish that it will indeed provide a remedy for the basic problem;
- o Lists some of the benefits to be derived from the proposed program, such as reduced ship acquisition costs, increased speed capability, reduced fuel consumption, improved crew performance, reduced propulsion system size, improved tactical maneuvering, etc., and finally;
- o Shows that, given an achievable level of performance improvement in just one area (speed/power), the financial investment involved in the program can be recovered many times through cost savings to be realized as a result of improved surface ship performance.



## I. INTRODUCTION

The displacement monohull has served as the hull envelope for most merchant and naval ships for thousands of years. It has proven to be a very versatile hull which has been used for a wide range of different ship types varying from mammoth tankers to small fishing vessels; a very cost-effective hull which has transported many different cargos/payloads at much lower ship acquisition and operating costs per ton of cargo/payload than other hull types; and a very durable hull which has survived the severe storms of the North Atlantic Ocean and North Sea and maintained reasonable levels of performance throughout 30 (or more) years of service-life use.

Today the displacement monohull is the predominant platform throughout the U.S. Navy's Surface Fleet, and is used for virtually every type of naval surface ship, including aircraft carriers, frigates, destroyers, cruisers, amphibious and auxiliary ships, tugs, patrol craft, minesweepers, etc. Even with the advent of advanced surface ship types, such as surface effect ships, hydrofoils, air cushion vehicles, and Small Waterplane Area Twin Hull (SWATH) ships, the displacement monohull continues to be the primary platform for the U.S. Navy's Surface Fleet. In fact, at a recent conference on "Problems of Sea Power as We Approach the 21st Century", sponsored by the America Enterprise Institute for Public Policy Research, Dr. Reuven Leopold, who is the Technical Director of NAVSEC's Ship Design Division, stated that "its other natural advantages for most applications will make the displacement type hull still dominant in our Navy of the early 21st century as it does today."

It is the capabilities of the U.S. Navy's future Surface Fleet that is the important subject of this paper. However, there is serious concern in the naval ship engineering community about the future viability of our Surface Fleet. This serious concern is strongly presented by the following excerpt from a recent address by Rear Admiral J. W. Lisanby, USN, COMNAVSEC, to the 18th American Towing Tank Conference (ATTC) held at the U.S. Naval Academy in August 1977:

"THROUGHOUT MY 27-YEAR CAREER I HAVE BECOME INCREASINGLY IMPRESSED WITH THE NECESSITY FOR A MORE EQUITABLY ORGANIZED APPROACH TO RESEARCH AND DEVELOPMENT..... I DON'T WISH TO BE OVERLY DRAMATIC, BUT THE FUTURE VIABILITY OF OUR NAVAL FLEET IS AT STAKE. THAT VIABILITY, HOWEVER, MAY BE IN QUESTION TODAY WITH THE APPARENT FUNDING DISPARITY AFFORDED NAVAL SURFACE SHIP DEVELOPMENT IN LIGHT OF THE BURGEONING TECHNOLOGY IN ALL OTHER AREAS.

LET'S CONSIDER THESE DISPARITIES OF THE R&D PROCESS MORE CLOSELY....

IN FISCAL YEAR 1976 VEHICLE EXPLORATORY DEVELOPMENT (LESS MACHINERY AND PROPULSION SYSTEMS) FOR AIR FORCE, ARMY AND NAVY AIRCRAFT RECEIVED A



TOTAL OF \$75 MILLION. THE NAVY, ON THE OTHER HAND, RECEIVED ONLY \$20 MILLION FOR ALL SHIP EXPLORATORY DEVELOPMENT AND THAT INCLUDES SURFACE SHIPS, SUBMARINES, ADVANCED SHIPS AND AMPHIBIOUS SHIPS. IN OTHER WORDS, MILITARY AIRCRAFT RECEIVED NEARLY FOUR TIMES AS MANY EXPLORATORY R&D DOLLARS AS NAVAL SHIPS. IF WE BROADEN OUR VIEW OF THESE EXPLORATORY DEVELOPMENT FUNDS AND ALSO INCLUDE, INDUSTRY, NASA, MARITIME ADMINISTRATION AND THE COAST GUARD, IN 1976 APPROXIMATELY 10 TIMES AS MUCH MONEY WAS SPENT ON AIRCRAFT AS ON SHIP R&D OF AN EXPLORATORY NATURE.

THE CLIMATE FOR SURFACE SHIP R&D IS NOT IMPROVING. IN FISCAL YEAR 1976 ONLY SLIGHTLY MORE THAN 2.2% (OR \$75 MILLION) OF THE TOTAL NAVY R&D BUDGET OF \$3.3 BILLION WAS DESIGNATED FOR SURFACE SHIP PLATFORMS, EXCLUDING SHIP DESIGN.... HOWEVER, IN FISCAL YEAR 77 THERE HAS BEEN A NOTICEABLE DECREASE IN SURFACE SHIP R&D TO THE EXTENT THAT IT IS NOW ONLY SLIGHTLY MORE THAN 1.5% ( OR \$61 MILLION) OF THE TOTAL NAVY R&D BUDGET OF \$3.7 BILLION.....

IN DISCUSSING THESE DOLLAR COMPARISONS, IT IS IMPORTANT TO KEEP IN MIND THAT SHIPS AND SUBMARINES DO NOT HAVE A STRONG INDUSTRIAL TECHNOLOGY BASE AS AIRCRAFT HAVE BECAUSE WARSHIPS BEAR LITTLE OR NO RESEMBLANCE TO THEIR COMMERCIAL COUSINS, AND THE TECHNOLOGICAL TRANSFER IS SLIGHT. IT IS FOR THIS REASON THAT IT IS INCUMBENT ON THE NAVY TO MAINTAIN A STRONG IN-HOUSE TECHNOLOGY BASE FOR SHIPS AND, AS I STATED EARLIER, THAT TAKES MONEY."

One may now question that surely, after thousands of years of building displacement monohulls, the naval ship designer knows everything he or she needs to know about designing these hull forms. The following additional excerpt from Rear Admiral Lisanby's address to the 18th ATTC adequately answers this question:

"SINCE TONIGHT WE ARE CONCERNED ESPECIALLY WITH HYDRODYNAMICS RESEARCH, I WAS APPALLED TO LEARN THAT IN FISCAL YEAR 1977 THERE WAS ONLY \$354 THOUSAND--OUT OF THOSE SEVERAL BILLIONS--SPECIFICALLY DEVOTED TO SEAKEEPING R&D EFFORTS IN SUPPORT OF SURFACE SHIP DESIGN. I UNDERSTAND THAT R&D FUNDING FOR THIS IMPORTANT WORK WILL BE REDUCED IN FISCAL YEAR 1978. DOES THIS MEAN THAT WE KNOW EVERYTHING WE NEED TO KNOW ABOUT SEAKEEPING IN NAVAL SHIP DESIGN? OF COURSE, IT DOES NOT. IT REFLECTS RATHER POORLY ON OUR OWN SHORT SIGHTEDNESS. BECAUSE WHAT COULD BE MORE CENTRAL TO OUR NAVY THAN THE ABILITY TO SAIL AND FIGHT INDEPENDENT OF SEA STATE?"

The effects of the funding disparity afforded surface ship R&D and the short sightedness of assuming that the ship designer knows everything he or she needs to know are particularly hard felt in the hydrodynamics design of displacement monohulls for conventional surface ships. In fact, since the beginning of the decade, when the more than one million dollar annual appropriation for the Budget Project-32 (BP-32) Program for Surface Ship Hydrodynamics R&D was redirected exclusively to advanced surface/high-performance ship R&D, at a time when it was beginning to

yield significant benefits, there has been no similar comprehensive R&D program for the development of improved hydrodynamics design criteria and practices for conventional surface ships. However, during this time, the workload in the area of surface ship hydrodynamics has increased considerably, as a result of a number of new, technically-demanding (e.g. cost, weight and space constrained) ship designs, and a general increase in the level of technical capability required to meet the needs of the U.S. Navy. This growing divergence between ship design needs and the designers' available capability has resulted in a wide-range of deficiencies in the operational performance of recent ship designs.

These three items - (1) the ship designers' needs, (2) the ship designers' available capability and (3) hydrodynamic design deficiencies of recent ship designs - will be discussed in subsequent sections. These discussions will demonstrate the need for the Advanced Development (6.3) Surface SHIP (Ship Hydrodynamics - Improved Performance) RDT&E Program.



## II. GENERAL NEEDS OF HULL FORM DESIGNER

The surface ships of the U.S. Navy face continuing requirements for increased levels of performance against an expanding threat that is superior in numbers and is improving in quality. For many years, it has been a stated policy of the United States not to engage in a "numbers race" with its principal adversary, but instead to exploit superior science and technology to develop and maintain a qualitative edge in military forces.

The development and maintenance of the qualitative superiority of U.S. Navy surface ships requires continuous effort to improve all aspects of the ship system. This includes the hydrodynamics aspects of the total system performance of surface ships; yet, in many cases our ships are inferior to those of the U.S.S.R. and our allies in just these respects. The speed, maneuverability, and seakeeping characteristics of U.S. surface ships have frequently been noted as inferior when compared to those of similar foreign ships. A specific instance was noted by Vice Admiral R. E. Adamson, Jr., USN (COMNAVSURFLANT), who, in his address to the NAVSEA Seakeeping Workshop held in June 1975, stated that:

"ON A FLEET EXERCISE OUR SHIPS WERE FORCED TO SLOW TO PREVENT OR LESSEN THE IMPACT OF DAMAGE; EXERCISES WERE CANCELLED; WE COULD NOT REFUEL OUR SHIPS; EQUIPMENT WAS DAMAGED; AND PERSONNEL WERE INJURED. HOWEVER, SEVERAL SOVIET WARSHIPS WHICH WERE IN COMPANY AS OBSERVERS DID NOT APPEAR TO SUFFER THE SAME DEGREE OF DEGRADATION WE DID. THEY STEAMED SMARTLY AHEAD AND APPARENTLY WITHOUT DIFFICULTY."

Existing deficiencies stem largely from ineffective or non-existent application of new hydrodynamics technology, developed by the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) under existing Research (6.1) and Exploratory Development (6.2) RDT&E Programs, to ship system design. Because this technology is not translated into practical design tools, there are potential significant improvements in ship performance that are sacrificed. Examples of these improvements in ship performance are discussed in subsequent sections. The issue at this point in the discussion is (1) to identify the need to strengthen the technical (hydrodynamic design) capabilities of NAVSEC by providing NAVSEC with advanced hull form design tools and practices, and (2) to demonstrate that these design capabilities must be provided by concentrating R&D resources on the application of existing and evolving surface ship hydrodynamics technology to new conventional displacement hull designs.

The need to strengthen the hydrodynamic design capabilities of NAVSEC has been especially apparent to the hull form designers of NAVSEC with the advent of new computer-aided hull form design techniques, such as the Hull Generation (HULGEN) and Hull Definition (HULDEF) computer

graphics programs. For example, the HULGEN is an interactive computer graphics program which permits the designer, with the aid of a light-pen and scope, to develop a number of hull form body plans in just a few hours; whereas, to draw a single body plan by hand requires from four to six days. An example of a body plan (which is drawn early in the Concept Design stage of ship design in order to show the longitudinal distribution of the hull's underwater volume) developed with the HULGEN program is shown in Figure 1.

The HULDEF is a batch-type computer graphics program which is used by the designer to develop a faired-hull lines drawing in only a few days; whereas, to develop a lines drawing by hand requires from four to six weeks. Additional information on these two very useful hull definition computer programs is presented in reference (1).

There are at least three significant ship design advantages of these computer programs:

1. The hull form designer can now develop a large number of alternative hulls in the early ship design stages (i.e., Concept Design and Preliminary Design) that heretofore had been physically impossible.
2. Revisions and further delineation of the hull can be rapidly accomplished by the hull form designer such that others in the ship design can all be working to the same baseline hull.
3. With adequate definition of the hull form early in the ship design, the hull form designer now has the potential to evaluate the hydrodynamic performance of a large number of alternative hulls.

However, although the hull form designer now has these two computer programs in his or her "arsenal" of design tools, hull forms continue to be developed initially on the basis that they "look OK" to the designer; and analyses of hydrodynamic performance still require days, sometimes months, before the designer can evaluate even the primary hydrodynamic characteristics of alternative hull forms. Considering the existing ship hydrodynamics technology base, such delays and the possible adverse impact on the ship design are inexcusable!

Thus, in order to realize the full potential of these computer programs and to strengthen NAVSEC's ship design capabilities, some of the needs of the hull form designer are, in general, described below:

#### PREDICTION OF SHIP RESISTANCE.

Despite considerable progress in theoretical treatments of ship resistance problems, the naval ship designer continues to need analytical methods to predict accurately the effects of various hull form parameters on hull resistance, particularly for the higher beam-to-draft (B/T)



ratios of today's naval ship designs. (A typical list of the many hull form parameters that should be included in such analytical predictions is presented in Table 1.) These analytical methods must be validated with extensive model and full-scale testing. An especially critical need in this area is to develop both analytical and experimental (model test) techniques for predicting appendage drag.

#### PREDICTION OF SHIP POWERING.

Another hydrodynamic design problem area is that early design methods for predicting hull-propulsor interactions (that is, thrust deduction and wake fraction), which are crucial for a reliable prediction of the Propulsive Coefficient (PC) and hence powering requirements, are based largely on historical, empirical data. However, the ship designer again needs more analytically-based methods to determine the effects of changes to the underwater hull form and appendages so that he or she can investigate refinements to alternative designs and ascertain their impact on hydrodynamic performance. Also, analytical methods for predicting the wake of the hull, or the velocity distribution in which the propeller can be expected to operate, would not only permit the hull form designer to assess the impact on propeller performance of variations in the aft-end of the hull, but would also allow the propeller designer to begin work much earlier in the ship design instead of waiting for the results of model tests.

#### PREDICTION OF HYDRODYNAMIC LOADS.

A third hydrodynamic-related design area for which the ship designer needs analytical methods is the prediction of the loads associated with slamming and wave-slap. This lack of knowledge in sea loading could adversely affect the ability of the local structure to withstand high sea states, a critical situation which already has, in the past, resulted in serious structural damage to flight deck sponsons, deck-edge elevators, and other structures exposed to the sea.

#### PREDICTION OF CAVITATION.

The ship designer also needs both analytical and experimental methods for predicting, as well as increasing, the speed at which the inception of cavitation occurs. This capability is necessary in order to design the configuration and shape of control surfaces (e.g., rudders and fins), appendages (e.g., struts and propulsion shaft fairings), propellers and even the bow stem, such that the occurrence of cavitation is minimized. Too often, the adverse effects of cavitation (such as, reduced performance and material damage) are only revealed after construction, requiring costly and time-consuming alterations.

#### PREDICTION OF HYDRODYNAMICALLY-INDUCED VIBRATIONS.

Although the ship designer has empirical design criteria ("rules of thumb") for the minimum vertical clearance between the propeller tip and the underside of the hull and the minimum longitudinal clearance between the propeller and the rudder, there is a critical need for both analytical and experimental methods to quantitatively assess the hydrodynamics characteristics of alternative hull-propeller-rudder arrangements. That is, due to the many constraints in the arrangement of the aft-end of naval surface ships, the ship designer is being forced to consider arrangements which do not satisfy existing criteria for the aforementioned minimum clearances. Therefore, the ship designer needs validated methods for predicting propeller-induced fluctuating pressures which could excite unacceptable levels of hull and/or rudder vibrations before their attendant effects are revealed after construction.

In addition to the hydrodynamic design needs described above, there is also a critical need to develop analytical and experimental methods in the following areas:

- Prediction of Speed and Powering in Waves
- Prediction of Dynamic Stationkeeping Performance
- Prediction of Maneuvering in Waves
- Prediction of Control Surface Torque/Power



### III. ASSESSMENT OF EXISTING HULL FORM DESIGN CAPABILITIES.

The majority of the hull form designer's needs, which were briefly described in the preceeding section, pertain to the early stages of ship design where analytical prediction methods should be used to establish ship performance requirements and to select the primary hull form characteristics which affect performance. The early stages of ship design are also characterized by the demand to evaluate numerous alternatives in a relatively short time and to do so with an incomplete geometrical description of the hull forms under consideration, thus, the need for analytical prediction methods (or mathematical formulations in terms of primary hull form parameters).

One may rightfully question how such predictions are now accomplished, with the inference that prediction methods are available and why are they inadequate. The following discussions will briefly explain some of the more prevalent prediction methods now used by the hull form designer in early stages of ship design and assess some of their shortcomings with respect to the demands on the designer during these important stages of ship design.

The earliest stage of ship design is the Conceptual Design Stage, which is initiated in response to an operational requirement issued by the Chief of Naval Operations (CNO). This design stage is composed of two parts, Feasibility Studies and Concept Design. The Feasibility Studies are performed to establish the major ship characteristics and cost. During this portion of the design, ship concepts are generally defined and evaluated using gross parameters. The Concept Design portion is used to resolve the technical risks associated with the concept and define the ship in terms of overall geometry, weight, type of propulsion plant, speed, endurance, and payload.

The accuracy of the processes used to estimate the hydrodynamic performance of each alternative hull form during Concept Design is somewhat limited, as mentioned above, by the lack of ship definition. Inasmuch as the requirements of this stage frequently dictate that several alternative designs be evaluated, it is not practical to develop the fine geometric details of each one. Typically, the known features of each design would consist of at least the principal dimensions (length, beam, draft, and displacement), the type of hull form (e.g., a destroyer or a tanker), an estimate of the maximum transverse sectional area and the wetted surface, and the general propulsion arrangement (single-screw, twin-screw, quadruple-screw, and whether-or-not the shafting will be exposed). Naturally, the selected techniques used in the estimation of hydrodynamic performance should be the best available that are consistent with the availability of hull form geometry.

## PREDICTION OF SHIP RESISTANCE AND POWERING.

The general approach to predicting ship resistance and powering in calm water during the early stages of ship design is shown in Figure 2. This approach, which is described in more detail in Appendix A and reference (2), utilizes empirical methods that are based primarily on the interpretation of model test data for similar hull forms. The limitations of these empirical methods are also described in more detail in Appendix A, but some of the more significant limitations are summarized below:

1. The credibility of an estimate derived by these empirical methods is somewhat less than that of a prediction derived from experiment (or model test) of the specific hull form, and a fairly accurate estimate can only be made if the hull form is well defined and a good sample of model test data for similar hull forms is available. Also, none of these empirical methods is able to quantify all the effects of shape and anomalies which may evolve in the development of a hull design.

2. These empirical methods treat the complex subject of ship resistance in an overly simplistic manner as shown in Figure 3 (which is taken from reference (3)).

3. The designer must apply a correction factor to account for the major differences between the parent hull form of the widely used Taylor Standard Series model test data (as shown in Figure 4) and the hull forms of naval surface ships (a typical example of which is shown in Figure 5). An example of this correction factor (commonly referred to as the "worm" curve and described in Appendix A) is shown in Figure 6.

4. There is still a major problem associated with the validity of model test results due to the unknown relationship between model test results and the actual full-scale ship performance, i.e., the scale-effect problem (particularly for the small dimensions of the model appendages). For example, Figure 7, which is taken from reference (4) and based on the results published in reference (5), indicates that, for the usual ship model lengths of 12 to 20 feet, the shaft strut drag of the subject ship is approximately one-half of that measured on the models.

5. As Johnson and Gale (4) point out, substantial changes in the Propulsive Coefficient (which is a critical factor in predicting ship powering and is described in Appendix A) can result from relatively small changes in the values of its components. For example, Table 2 (which is taken from reference (4)) compares the variations in Propulsive Coefficient component data derived from model tests on a recent naval ship design.



Consequently, due to the empiricism and resulting limitations of the ship resistance and powering prediction methods currently available to the hull form designer, it is obvious that much research work still needs to be done in this area, in order to develop analytical prediction methods that can be used by the hull form designer, during the early stages of ship design, to more reliably predict and thus to significantly improve the speed/power performance of naval surface ships.

#### PREDICTION OF SEAKEEPING PERFORMANCE

There are many dissimilarities between predicting the calm water speed-power performance and the seakeeping performance of the displacement monohull; some of these dissimilarities are as follows:

1. Whereas there is a large accumulation of model test and full-scale trial data for the calm water speed-power performance of previous hull designs, there are little model test data, and even fewer full-scale trial data, on the seakeeping performance of previous hull designs.
2. Whereas there are no analytical methods for predicting calm water speed-power performance, there are analytical methods for predicting the ship motions of displacement monohulls, but these analytical methods require a well-developed definition of the hull design.
3. Whereas there are specific speed-power performance requirements in the Top Level Requirements (TLR) for new ship designs, there are few, if any, specific seakeeping performance requirements.
4. Whereas there is one specific numerical measure of calm water speed-power performance, there is no one single numerical measure of seakeeping performance which is meaningful to those decision-makers who establish the TLR for new ship designs.

Consequently, in the past seakeeping performance has not been seriously considered in the early stages of ship design. This deficiency in the ship design process has been recognized, and in 1975 a Seakeeping Workshop was sponsored by the Naval Sea Systems Command (NAVSEA) in order to identify actions necessary to integrate seakeeping into the ship design process. One of the key results of the Workshop was to identify those essential concepts and analyses which relate to seakeeping performance and which must be developed, improved and introduced into each phase of the ship design process in a manner consistent with the information at each phase of design.

For the purpose of presenting the proposed integration of seakeeping into the ship design process, the following phases were addressed:

1. Pre-Feasibility Study Phase
2. Feasibility Study Phase
3. Concept Design Phase
4. Preliminary Design Phase
5. Contract Design Phase

For each phase, a table was developed which contains the elements of the proposed integration and the supporting rationale, grouped as follows:

- A. Design Events and Decisions
- B. Implications for Seakeeping Performance
- C. Seakeeping Analyses Required
- D. Prerequisites for Analyses

These tables have been extracted from the Workshop Report (6) and are included herein as Tables 3 through 7, in order to present an assessment of the capabilities which are, or are not, now available to the hull form designer.

It is noted, however, that those deficiencies and/or gaps in the existing seakeeping technology which relate to seakeeping performance requirements have not been included in Tables 3 through 5. In particular, the need for relationships relating personnel and equipment performance degradation to ship motion response intensity would have to be repeated in each case under item D of the five tables. It should be understood, therefore, that seakeeping performance requirements are envisioned to be stated, in the context of overall ship mission requirements, as maximum allowable performance degradations for given ship functions and ship subsystem elements. Given the relationships between the degree of performance degradation and ship motion response intensity, the maximum allowable performance degradation can then be translated into a maximum allowable ship motion response. Such a requirement then provides the basis for the designer to rationally decide on platform proportions and the need, if any, for active means for motion response control (roll stabilization tanks, active fins, etc.).

Another key result of the Workshop was that a new Exploratory Development (6.2) Seakeeping R&D Program was initiated in Fiscal Year (FY) 1976, in order to develop the many performance-oriented seakeeping design methods and criteria listed in Tables 3 through 7. Although some progress has been made, especially in implementing new/improved descriptions



of the environment in ship design and in developing for the first time numerical measures of seakeeping performance, the overall assessment provided by Table 3 through 7 is still valid today. Consequently, it is obvious that substantial research work remains to be accomplished in this area in order to integrate seakeeping performance into the ship design process.

#### PREDICTION OF MANEUVERING PERFORMANCE

The maneuvering performance of new surface ship designs receives less attention during design than any other aspect of hydrodynamic performance. As Johnson and Gale (4) emphasize, the primary reasons for this lack of attention are as follows:

1. A lack of comprehensive, reasonably accurate, and easy to use analytical prediction methods.
2. In general, a lack of specific, critical maneuvering requirements.
3. The relative ease with which deficiencies identified during model testing can be corrected by appendage alterations (rudder, skeg, etc.).

In Concept Design, for example, the Top Level Requirements pertinent to maneuvering are developed generally on the basis of past experience and without benefit of actual performance predictions for the design alternative under consideration. The specific Top Level Requirements which are developed are usually restricted to: (a) a statement requiring the new design to be dynamically (directionally) stable when steaming ahead; and (b) a maximum acceptable tactical diameter at full power and with full rudder. This latter requirement is generally based more on what is readily achievable than on specific operational requirements.

The same is true for the initial selection of the rudder area and skeg length which are usually based on the geometrics and associated performances of previous ship designs rather than on analyses of alternative configurations with respect to specific performance requirements. In fact, the rudder area is normally based on a certain percent of the underwater lateral area of the hull.

It is emphasized that in this area of ship design, the U. S. Navy is far behind its counterparts in the merchant marine sector, where computer simulations of maneuvering performance are extensively utilized in ship design. However, these computer simulations, many of which are based on the U. S. Navy research work presented in reference (7), require captive model tests in order to determine the hydrodynamic coefficients for the maneuvering equations of motions. Such model tests would not be feasible nor practical during the early stages of naval ship design.

Therefore, NAVSEC, with its own limited funds, has sponsored research work at MIT (8) to develop empirical/analytical techniques to estimate these hydrodynamic coefficients so that available computer simulations can be employed during the early stages of naval ship design to evaluate the maneuvering performance of alternative design configurations. But, as noted in reference (8):

"A disappointingly small amount of (experimental) data was available for analysis of transom stern (naval) vessels. Many more data were available for full form tankers, so most of the results are more applicable to that class of ships .... Eventually, a function (relationship of hydrodynamic coefficients to critical design parameters) will become evident, but for now .... much more experimental work is desirable."

#### PREDICTION OF CAVITATION

Presently, there are no acceptable analytical methods for predicting, in the early stages of ship design, the inception of cavitation or the degree of cavitation that will cause adverse effects on ship performance and material condition. As a result, the hull form designer has developed (through sad experiences) certain "rules of thumb" for determining the shape and configuration of the bow stem, shaft struts and shaft fairings in order to minimize cavitation. For example, NAVSEC's Design Data Sheet (DDS) for Shaft Struts specifies elliptical-parabolic-hyperbolic (EPH) shapes.

The effects of cavitation are especially critical in the design of the propeller. As stated in Section 16, Chapter VII of reference (9):

"Cavitation is a phenomenon met with in highly loaded propellers in which, beyond certain critical revolutions, there is a progressive breakdown in the flow and a consequent loss of thrust. In its extreme form, it may prevent the ship from reaching the desired speed. Before this stage is reached, however, it manifests itself by noise, vibration and erosion of the propeller blades, struts and rudders...."

Although the consequences of noise, vibration, and erosion can be detrimental to the ship or its mission, the consequence of a thrust loss may mean a significant reduction in the attainable speed for a ship. Therefore, an effort must be made, early in the design process, to determine whether-or-not there is a possibility that cavitation will be a problem. If there is such a possibility, estimates of powering performance must be adjusted to reflect the effect of cavitation.

Prior to experiments with a model of the design propeller, estimates of a possible thrust loss are made using reference (10). After these experiments have been conducted, which is usually at the end of Contract Design, the estimates are refined based on the results from these experiments. It is emphasized that the accuracy of initial estimates is not actually



determined until after these tests are completed. Consequently, it is obvious that much research needs to be done in this critical area so that last minute surprises can be avoided at the end of a ship design which, even more recently, have necessitated recycling of the propeller design and have been very costly in terms of both time and money.

#### PREDICTION OF HYDRODYNAMICALLY - INDUCED VIBRATIONS

With the increasing amount of horsepower per propulsion shaft, there is a greater demand on the hull form designer to predict during the early stages of ship design the levels of propeller-excited hull vibrations. These vibrations result from the wake distribution into which the propeller is rotating and thus generating fluctuating pressures which are then transmitted through the water to the rigid hull surfaces (including the rudder and appendages), in the vicinity of the propeller, which are operating in more uniform inflow. In addition, cavitation conditions may give rise to irregular, higher frequency vibrations. As pointed out in references (4), (11) and (12), these fluctuating pressures are primarily dependent on the following hull design parameters:

- a. Vertical clearance between the propeller blade tip and the adjacent hull.
- b. Longitudinal (as well as lateral) clearance between the propeller and the leading edge of the rudder.
- c. Clearance between the propeller and the shaft struts.
- d. Clearance between the propeller and the skeg.
- e. Shape of the hull surface in the vicinity of the propeller.

In order to predict these hydrodynamically-induced vibrations, the hull form designer must first be able to estimate the surface forces or the fluctuating pressure field. Although there are theoretical and experimental techniques available to the hull form designer for estimating these forces or pressures, there are many reasons why they are inadequate for evaluating alternative arrangements of the hull, propellers, rudders and appendages; some of these reasons are as follows:

1. Existing theoretical techniques have not been validated for use in ship design; that is, extensive computations with these theoretical techniques and comparison with model test and full-scale trial data have not been made.
2. Based on very limited comparisons for a few specific ship designs, existing theoretical methods correlate poorly with model measurements, although experience indicates that the model measurements are more in question than the calculated values. For example, Table 8,

which is taken from reference (4), compares for a recent surface ship design the vertical hull surface force calculated by an existing theoretical method with that measured from a model test; the wide disparity between the estimated forces is startling.

3. There are no standards of comparison (to the knowledge of the author) to determine acceptable levels of hull vibration; that is, the reliability, or practical utility, of existing theoretical and experimental prediction methods depends on the availability to the individual designer of data on the levels of service vibration or the exciting forces/pressures for ships actually in operation.

As a result, the hull form designer at the present time uses only the crudest "rules of thumb", based on past experience, for the propeller-hull-rudder-appendage clearances noted above. The crudeness or insensitivity of these rules to the many variables that actually affect the vibratory forces is demonstrated by the recent work of Kerwin and Zolotas (12). With a water tunnel simulation of a recent surface ship design, they measured the propeller-excited vibratory forces acting on the rudder as a function of longitudinal and lateral clearance between the propeller and the rudder. They found that:

- o Vibratory forces are strongly influenced by propeller cavitation; for example, vibratory forces measured at a cavitation number corresponding to full power are three times the corresponding values measured without cavitation (which is not accounted for in the designer's "rule of thumb").

- o Vibratory forces on the rudder are critically dependent on small variations in the longitudinal clearance between the rudder and propeller; for example, for the particular design studied, the design clearance ratio of 0.57 (longitudinal propeller-rudder clearance divided by propeller diameter), which was established based on one of these "rules of thumb", coincided with a local maximum, see Figure 8 (which is taken from reference (12)). A reduction in vibratory force by a factor of ten could be achieved either by reducing the clearance ratio to 0.41 or increasing it to 0.68. The hull form designer's "rules of thumb" are not that sensitive!

Consequently, it is obvious that much research work must be done in this critical area in order to develop methods for predicting propeller excited vibratory forces which include hull, propeller, rudder, and appendage geometries as well as the ship wake field into which the propeller operates.



#### IV. NEED FOR SURFACE SHIP R&D EFFORT

The previous section documents the numerous inadequacies of existing capabilities for the design of displacement monohulls and demonstrates that much research work must be accomplished to strengthen NAVSEC's hull form design capabilities. This section emphasizes that such a research effort is not underway and that there is a critical need to immediately initiate a comprehensive Surface Ship Hydrodynamics R&D Program.

As stated at the beginning of the paper, NAVSEC had a comprehensive Surface Ship Hydrodynamics R&D Program, referred to as the Budget Project-32 (BP-32) Program, but it was essentially cancelled around 1973. The funding was redirected primarily to high performance ships and program management was recently assumed by the Naval Material Command (NAVMAT) and is now "block" funded by NAVMAT directly to DTNSRDC. Although it is still considered a ship platform-oriented R&D Program, there is now virtually no direction provided by either NAVSEA or NAVSEC, and attempts by NAVSEA to recover the program have been unsuccessful thus far.

The importance of the BP-32 Program stemmed from the fact that it emphasized the translation of new hydrodynamics technology into useable design tools, with the needs being identified by the users, i.e., the ship designers. Under this program, many ship design practices and criteria were developed which are still in use today. In fact, no new hull form design techniques, with the exception of a few that have recently been developed under the Seakeeping R&D Program, have been adopted by the surface ship designer in the past ten years which were not initiated or supported by BP-32.

While many of the products of the BP-32 Program are still in use today, this does not imply that they are necessarily adequate for today's requirements. In many cases, they must be updated, extended, refined and even validated in some cases. This fact is well documented in other sections of this paper.

Furthermore, in addition to the need to update and extend the results of the BP-32 Program, the increased technical demands of today's ship designs also require the development of numerous new design practices and criteria. This critical need was further identified recently when NAVSEC invested considerable resources to document its existing hull form design practices and criteria and to point out deficiencies that must be addressed. However, there is no comprehensive program currently funded, nor has there been one since about 1973, to provide the necessary development effort to resolve these deficiencies in surface ship hull form design.

In contrast to the absence of a comprehensive hydrodynamic R&D program specifically for surface ships, there are major programs for

both High-Performance Ships and Submarines. There are no equivalents to these programs for conventional surface ships at either the Exploratory Development (6.2), the Advanced Development (6.3) or the Engineering Development (6.4) levels.

In many cases, however, the basic surface ship hydrodynamics technology is either available or under development. It is the further development of this knowledge and the means for the designer to apply it which are lacking. For instance, work in the area of general hydrodynamics R&D is performed under existing Research (6.1) and Exploratory Development (6.2) Programs, such as:

- o General Hydrodynamics Research (GHR)
- o Seakeeping R&D Program
- o Numerical Hydrodynamics Program

However, the purpose of these efforts is to expand the technology base. It is also necessary that the new technology be further developed and applied directly to the problems of ship system design. This necessary continuation is currently lacking.

Since the hydrodynamics R&D effort is not continued to the point where improved design criteria and practices, or improved hydrodynamics systems (e.g., active fin stabilizers), are available for application to all surface ship acquisition programs, the complete benefits of the valuable work performed under the 6.1 and 6.2 programs are seldom fully realized. The lack of a complementary organized effort to implement the results of the 6.1 and 6.2 programs, coupled with effective decreasing funding (in constant dollars), limits the realization of the potential value of these programs. In addition, these programs are limited in technical scope to only a few aspects of surface ship performance. For instance, the Seakeeping R&D Program, initiated in FY 76, is yielding results which are being used to improve the seakeeping performance of ongoing ship designs at NAVSEC. Yet the program is very limited in scope, both technically (it does not address all hydrodynamics aspects of ship performance) and financially (in fact, at the present FY 78 funding level, it should no longer be considered a major program).

To correct this situation, there is a critical need for a comprehensive, unified Advanced Development (6.3) RDT&E Program, in order to advance the level of technology for, and more importantly, to apply existing and evolving hydrodynamics technology to the surface ship design process. Such a 6.3 RDT&E Program, referred to as the Surface SHIP (Ship Hydrodynamics - Improved Performance) R&D Program, has been proposed by NAVSEC to fill the present void in the RDT&E process as shown in Figure 9. The Program has been endorsed by NAVSEA and NAVMAT, but has not yet been established by OPNAV.



The need for the Surface SHIP R&D Program is not to develop more sophisticated design techniques for the intellectual stimulation of the designer, but to improve the total-system performance of naval surface ships through the enhancement of "designer-preparedness". By increasing the practical capabilities of the hull form designer in the area of surface ship hydrodynamics, the hydrodynamic performance of new ship designs will be improved, and as a consequence, their overall military utility will also be improved.

To effect the basic purpose of the Program, effort would be concentrated on the advanced development of ship hydrodynamics technology and its implementation into performance-oriented hydrodynamic design methods which would enable designers to effect significant improvements in surface ship performance, or, conversely, to reduce the cost of meeting given performance requirements. In addition, the Program would identify critical needs for the development of new hydrodynamics-related systems, such as motion stabilization (e.g., active fin stabilizers) or maneuvering systems, (e.g. unidirectional thrusters), which would contribute to the goal of improved surface ship hydrodynamics performance. The design, testing and evaluation of such systems may then be undertaken either by separate hardware development programs, or by the Surface SHIP Program itself, as circumstances dictate.

Furthermore, due to the critical needs for a broader-based Exploratory Development (6.2) Hydrodynamics R&D Program for conventional surface ships, the newly-established and currently limited 6.2 Seakeeping R&D Program must be expanded in scope to address all aspects of hydrodynamic performance (including speed-power, maneuvering, etc.) or, the 6.2 Naval Hydrodynamics R&D Program (formerly the BP-32 Program), which is now managed by NAVMAT and is primarily directed to high performance ships hydrodynamics, must be returned to NAVSEA and, under the technical direction of NAVSEC, be redirected to solving the many hydrodynamics - related problems of surface ship design.

## V. CONSEQUENCES OF LACK OF SURFACE SHIP R&D EFFORT

The failure to develop the techniques necessary to meet today's design requirements has produced two types of related deficiencies:

1) deficiencies which have arisen during the design of certain ships, resulting in degradation of the effectiveness of the ship designs concerned. These hydrodynamics deficiencies, and the associated cost of correcting them, could frequently have been avoided if better tools had been available to the designer at the time the ship was being designed.

2) deficiencies representing failure to meet potential performance capabilities, or excessive cost required to attain a given performance level. That is, though a ship may meet its established performance requirements, it is quite possible that significantly improved performance could have been obtained at little or no cost, or the same performance could have been achieved at less cost, had the designer had available to him the requisite tools.

Deficiencies of the second type are, by their nature, difficult to identify specifically. In fact, it may be said that all existing designs suffer from them, in the sense that their performance would have been better, had the appropriate design tools been available. In particular, uncertainties in the accuracy of prediction techniques (such as for ship resistance and rudder torque) should be noted here. To compensate for such uncertainties, margins are introduced at various stages of the ship design, resulting in some cases in weight, volume and cost increases.

Brief descriptions of some recent examples of deficiencies of the first type are presented here:

1. Sonar Effectiveness Degradation - During recent trials of many high-speed combatants, fluid cavitation near the waterline was experienced. The cavitation was attributed to the shape and surface condition of the bow's stem. This hydrodynamic phenomenon, if uncorrected, would have caused significant degradation of sonar performance effectiveness. Fortunately, in this instance an existing prediction technique for estimating pressure distributions (referred to as the Douglass Program), though based upon rather gross assumptions (e.g., ideal potential flow vice viscous, compressible flow), proved adequate in evaluating the problem, and a 'fix' was found. However, this may not always be the case. More importantly, the problem might never have arisen, if prediction techniques or validated design practices had been available during the ship design stages. The need for the 'fix' (with the resulting additional costs, contract claims and delays) would then have been eliminated. The total cost of the required 'fix', including indirect costs, was at least \$150,000 per ship.

2. Ship Design Speed Reduction - The many uncertainties associated with the technique for estimating the hull-propeller interaction factors



of the propulsive coefficient (as explained in Section III and Appendix A) resulted in an overly optimistic prediction of the sustained speed of a recent ship design, causing serious design problems. The deficiency was "corrected" by requesting CNO to reduce the required design speed of the ship. The consequent inferior performance is readily apparent. In this instance, due to the cancellation of the Program, no great harm was done. However, in other circumstances, the same deficiency in prediction might affect the viability of the ship concept under consideration. Furthermore, as a result of this problem, a policy of incorporating power margins into new ship designs was subsequently adopted. Such margins may imply significant size and cost increases in ship designs, simply to absorb uncertainties in prediction methods.

3. Active Fin Stabilizers, A "Sad Story" - The deficiencies related to the use of fin stabilizers in the U.S. Navy are many. Though their value in reducing a ship's roll motions has been well known for some time and though the benefits of reduced roll motions are recognized, not only by every foreign navy, but even more recently by many USN senior officers, the U.S. Navy still does not have proven, highly reliable active fin stabilizer systems. The technology exists, although that which is available to the USN has been developed by the Royal Navy; the problem has been a lack of R&D funds to develop (i.e., design, fabricate, test and evaluate) such proven systems. Consequently, our new ships are not usually fitted with fin stabilizer systems. Yet, most foreign navies, particularly the British and Soviet navies, have successfully applied existing technology to the design and development of such systems; and these systems are installed aboard virtually all of their combatant ships. Therefore, the seakeeping performance of the ships of foreign navies continues to be superior to that of most U.S. Navy ships.

4. Hull Redesign to Reduce Resistance - As described in Section III, ship resistance predictions during the early stages of ship design are very empirical, and the consequent uncertainty in the predictions for many recent ship designs has been further increased due to the lack of historical model test data. In the case of a high-speed combatant, certain hull form parameters were sufficiently far from the "normal" values (e.g.,  $B/T = 3.0$ ,  $L/B = 8.8$ ,  $\Delta/(L/100)^3 = 64.1$ ) that, although they fell within the range of existing data, the accuracy and applicability of the data could not be relied upon. In the case of a high-speed patrol craft, its size (e.g.,  $\Delta/(L/100)^3 = 60.0$ ) was such that there were virtually no historical model test data in the region of its

design speed. Furthermore, in the case of an auxiliary ship, the bare-hull resistance from model tests was about 30% higher than predicted, due to the lack of historical model test data which accounted for a number of thruster openings in the hull. In each case, the hull was redesigned, a perturbation which adversely affected the ship design schedule. Also, the uncertainty in the resistance predictions precluded the profitable use of resistance optimization techniques, thereby resulting in more costly designs than necessary.

5. Concept Viability Dependent on Sponson Loads - During feasibility studies of a recent combatant design, the viability of the entire concept was dependent upon assurance that the sponsons supporting the flight deck would not be subject to unacceptable slamming loads. No analytic methods exist for assessing the hydrodynamic loads imposed upon sponsons at various heights above the waterline during the early stages of design. In the subject case, development of the concept was delayed three months until a complex assessment involving model tests could be made. In the time frame of today's ship acquisition programs, a delay of three months may force an option to be discarded because a decision must be made, and no one can assure that the option is sufficiently risk-free to warrant continued development.

6. Increased Costs to Avoid Hull Vibrations - On recent amphibious ship designs, the hull form designer has had to resort to the use of tunnel sterns in order to maintain an acceptable hull-propeller tip clearance, to meet an operational/design constraint that the propellers not extend below the baseline and to ensure adequate flow into the propeller. Figure 10 shows the resulting arrangement with a tunnel stern which increases construction costs due to the large, high tensile steel plates of double curvature. As stated in Section III, the existing hull-propeller tip clearance criterion is a crude "rule of thumb", but one which the hull form designer will not violate because of past experience of unacceptable levels of hydrodynamically-induced hull vibrations (see Figure 11). However, based on the results of limited model test investigations published by Tachmindji and McGoldrick (11), there may be only a slight increase in vibratory forces at hull-propeller tip clearances much less than NAVSEC's existing criterion. Nevertheless, until validated methods for predicting hydrodynamically-induced hull vibrations are developed, which permit the hull form designer to adequately evaluate alternative hull-propeller-rudder-appendage arrangements that may not meet existing clearance criteria, many ships will continue to be designed with sterns that significantly increase the cost of hull construction.

The above are but a few of the instances in which the performance capabilities (either real or potential) of surface ships have suffered as a result of inadequate designer preparedness, due to the lack of a coherent program to improve the hydrodynamics aspects of surface ship designs. The need for a coherent effort should be emphasized. The present piece-meal approach of attempting to conduct such effort under individual ship acquisition programs or through limited Exploratory Development (6.2) RDT&E Programs is, at best, inadequate and inefficient.

The necessary development work in these cases should be the responsibility of a general Advanced Development (6.3) RDT&E Program such as the Surface SHIP R&D Program mentioned in Section IV, not a ship acquisition program. This is because:



- o The design phase of the acquisition program is generally completed before such developmental work can yield results;
- o the acquisition program frequently cannot afford to fund the necessary work - consequently, it may attempt to "make do" with whatever is available; and
- o even if it can, the results are likely to assume "program bias" - that is, the program will only fund work whose results are directly applicable to the program, or will only document the results in a program-specific way.

An example of this situation comes from the hull form design for a recent combatant design. Due to the fact that a large waterplane (LWP) area hull form may offer significant advantages in seakeeping performance over a conventional hull form, two alternative hull forms were developed for comparison. As a result of the knowledge gained, the seakeeping performance of the conventional hull form was then improved to the extent that it became difficult to choose between the two solely on the basis of hydrodynamic performance. However, the LWP area hull form provided the significant naval architectural design advantages of (a) improved stability (i.e., increased allowable vertical center of gravity, KG), (b) increased amount of space (for the same ship length, beam and displacement of the conventional hull form), (c) more efficiently arrangeable deck area and (d) potential for reduced ship size and acquisition cost (for the same degree of stability as the conventional hull form, the beam of the LWP area hull form could be significantly reduced; or for the same amount of space as the conventional hull form, the length of the LWP area hull form could be reduced). Thus, the development of both alternatives was carried through Preliminary Design. Though this was fortunate for the understanding of the LWP area hull form, it was also expensive. Furthermore the program:

- o did not study the generic LWP concept, but simply one point design;
- o may drop the LWP hull at any time for a reason peculiar to the program; and
- o may only document the results to the extent needed for the program without regard for other, future designs.

Obviously, such work should be conducted under a more general 6.3 RDT&E Program - that is, the Surface SHIP R&D Program - if NAVSEC's ship designers are to develop total ship systems which will fully achieve the increased mission capabilities of new combat systems and will not continue to suffer from the hydrodynamics - related design deficiencies briefly described in this section.

## VI. PROPOSED TECHNICAL APPROACH FOR SURFACE SHIP R&D PROGRAM

The following Section discusses the approach that would be taken under the proposed Surface SHIP R&D Program to the general needs and specific problem areas described in previous Sections, in order to meet specific performance improvement goals. It should be emphasized that these discussions represent initial outlines only, based upon knowledge of existing design deficiencies and promising methods for correcting them. Obviously, as work would progress, other avenues of approach would be revealed, and those which appear most attractive would be pursued. However, it is necessary to have a firm basis from which to commence the development effort, and the intent of this Section is to demonstrate that such a basis exists. In addition, Section VII is included to illustrate the potential economic payoff which the proposed Program could provide.

The scope of the proposed Surface SHIP Program would cover all aspects of the hydrodynamics of surface ships. However, within this broad scope, the Program would concentrate on those areas which promise to yield the greatest value in terms of enhanced operational effectiveness for the Fleet through improved surface ship hydrodynamic performance.

While the Program would cover all aspects of surface ship hydrodynamics, it would cover them only at a level appropriate to the Advanced Development (6.3) Phase. Thus, the hydrodynamics technology base would be expanded only to the extent that this is necessary for the development of the design tools needed to correct existing deficiencies or improve the efficiency of the design process. Expansion of the technology base would not be pursued as an end in itself.

Initial work would concentrate on analyzing the large volume of existing model test data, in order to develop parametric relationships that could be computer programmed for convenient and timely access by the hull form designer during the early stages of ship design. In developing improvements in the various technical areas, however, the relative emphasis placed on each would also be based partially upon the adequacy of existing design tools within each area, thereby directing relatively more effort to those which are currently deficient. A basis for determining the relative emphasis to be placed on each area is already available in the existing NAVSEC documentation of hydrodynamics design criteria and practices; this work would serve to identify those areas in most urgent need of development.

Particular emphasis would be placed upon the use of experimental and full-scale tests for the development of validated practices and criteria for hull form design during the Conceptual and Preliminary Design stages. In addition, attention would be given to the development of efficient experimental techniques, for use early in the design process, to aid in making design decisions. By making more effective use of



model testing early in the design process, it is hoped that the cost and time associated with model testing for particular ship designs could be reduced. The specific approach to some of the individual technical areas of interest is discussed in Appendix B.

Based on the above discussions and the assessment of existing hull form design capabilities presented in Section III, a firm basis has been established from which an Advanced Development (6.3) RDT&E effort can be commenced.

## VII. BENEFITS/PAYOFFS OF NEW SURFACE SHIP R&D PROGRAM

There are many benefits to be derived from the proposed Surface SHIP R&D Program in terms of both improved surface ship performance and actual economic payoffs as a result of improved "designer-preparedness". These benefits are described below.

### PROGRAM BENEFITS

Within the broad area of surface ship performance, the opportunity for improvement exists in the following technical areas:

#### (1) Speed and Power Performance

- o Ship Resistance - Opportunities exist for applying advanced hydrodynamics technology to the design of hull forms, resulting in decreased fuel consumption, reduced ship size and cost needed to meet given operational requirements, or increased speed, endurance or payload.
- o Interaction Between Hull and Propeller - An understanding of these complex interactions, and application of this understanding to the design process, together with effective integration of improved hull forms with new, advanced propellers would also allow for considerable improvement in speed/power performance. For example, results of such improvement would include reductions in present ship design power margins, allowing for smaller, less costly ships for given operational requirements.

#### (2) Maneuvering Performance

- o Tactical Maneuvering - Significant opportunities for improved tactical maneuvering can be exploited to enhance the operational effectiveness of maneuverability-critical ships. In particular, the development of more definitive descriptions of the maneuvering characteristics of surface ships, and of their impact on ship system effectiveness, would enable OPNAV to establish specific performance requirements in the maneuvering area.
- o Directional or Coursekeeping Stability - Opportunities exist for improved coursekeeping characteristics in aft-quartering or following seas, allowing for increased course flexibility during UNREP operations, and other, similar seamanship-critical operations.



### (3) Seakeeping Performance

- o Ship Motions - The application of seakeeping technology directly to the design process would enable the designer to reduce ship motions, resulting in increased speed in a seaway; improved weapon and sensor performance; reduced maintenance requirements; improved habitability; and improved crew performance in watchstanding, equipment operation and underway maintenance.
- o Motion Stabilization System - In addition to the direct reduction of ship motions, development of validated motion-prediction and hydrodynamic design methods, leading to the development of improved motion stabilization systems (fin stabilizers, roll stabilization by use of the rudder, etc.) would yield further improvements in seakeeping performance, with consequent enhancement of operational effectiveness.
- o Hydrodynamically-Induced Loads - An understanding of slamming-induced loads, and development of appropriate design methods are necessary to insure the successful design of the ship's local structure exposed to the sea, such as flight deck sponsons, or ships that must maintain speed in high sea states. In addition, more accurate definition of structural loads may allow for reduced safety factors in structural design, and, hence, reduced ship weight and cost.

### (4) Unique Hydrodynamic Phenomena

- o Effect of Ship Hydrodynamics on Sonar Performance - Improved hull form design, particularly bow design, would reduce the degradation of sonar effectiveness caused by poor hydrodynamic flow.
- o Hydrodynamically-Induced Fluctuating Pressures - With the development of validated analytic techniques for predicting the effects of hydrodynamically-induced fluctuating pressures on the hull structure, the ship designer would have more flexibility to design hulls that would be much less costly to construct.

### PROGRAM PAYOFFS

To illustrate the potential payoffs of the Surface SHIP R&D Program, in terms of economic benefits alone, Table 9 has been prepared. This Table shows the potential payoff resulting from improvement in just one area of importance to the Program, namely, ship powering.

The information presented in Table 9 has been prepared by use of NAVSEC's ship synthesis computer model and assumes a reduction in shaft horsepower of about 15% at cruising and sustained speeds. Such a reduction appears readily achievable through the application of such methods as the Sharma's bulb optimization technique and Baba's longitudinal wave cut techniques mentioned in Appendix B. In fact, greater improvement may be realized.

In preparing Table 9, it has been assumed that the benefits to be derived from improved speed/power performance would generally be realized in the form of smaller, cheaper ships meeting the same performance requirements. In the case of the gas turbine destroyer, this assumption is invalid, since gas turbines are discrete units whose size and weight are fixed. In contrast, a steam plant can be designed to yield practically any increment of power, and its size and weight would vary accordingly. Consequently, Table 9 shows a speed increase for the gas turbine destroyer, which represents an enhanced military performance whose utility can only be determined by OPNAV. However, even in this case, considerable savings can be realized in reduced fuel costs.

To put the figures of Table 9 in perspective it can be seen from Table 10 that, for example, the potential acquisition cost savings on four ships of a new class of AOE's would be more than 20 million dollars. Obviously, similar improvements throughout different ship classes would also produce proportionate savings. Again, it should be emphasized that Table 10 merely represents an estimate of the potential direct savings (acquisition and fuel costs) in just one area of performance improvement. For instance, even though the size of the gas turbine destroyer cannot be reduced much (because of the fixed power plant size), the reduced power levels required to meet the design speed profile would result in dollar savings, whose magnitude cannot be estimated at present, as well as qualitative benefits to crew performance in other shipboard maintenance tasks.

It is apparent, therefore, that the financial investment involved in the proposed Surface SHIP R&D Program could be recovered many times through cost savings to be realized as a result of improved surface ship performance.



## VIII. CONCLUSIONS

In conclusion, therefore, it can be seen that:

### 1. The problem is understood.

STATEMENT OF THE PROBLEM: The operational effectiveness of conventional surface ships of the U.S. Navy is compromised by many design deficiencies related to the hydrodynamic aspects of surface ship performance. These deficiencies in many cases have resulted in ships which either fail to meet performance requirements, or which are larger and more costly, both to acquire and to operate, than necessary.

PROBLEM ANALYSIS: These deficiencies are not isolated problems to be corrected individually, but symptoms of an underlying problem. Specifically:

- . There has been no comprehensive R&D Program for the development of hydrodynamic design tools for the surface ship displacement monohull since the demise of the Budget Project-32 (BP-32) Program in 1973.
- . The BP-32 Program was cancelled when it was beginning to yield significant benefits - in fact, no new hydrodynamics techniques have been adopted by the surface ship designer in the past decade (with the exception of a few that have recently been developed under NAVSEA's Seakeeping R&D Program) which were not initiated or supported by BP-32.
- . There is currently no organized effort aimed at implementing the results of existing Research (6.1) and Exploratory Development (6.2) programs in the area of surface ship hydrodynamics.
- . The growing divergence between the inability to adequately apply evolving hydrodynamics technology to surface ship design and the increasing technical capability required to meet the needs of new ship designs has resulted in a wide range of deficiencies in the operational performance of recent ship designs.

### 2. A solution has been found.

RECOMMENDATION: ESTABLISH A SURFACE SHIP (SHIP HYDRODYNAMICS - IMPROVED PERFORMANCE) R&D PROGRAM

An Advanced Development (6.3) RDT&E Program, aimed at the development of performance-oriented hydrodynamic design methods which effect either

significant improvements in surface ship performance, or cost reductions for given performance requirements, must be established. In addition, the program must point out the need and provide the basis for the design, testing and evaluation of new hydrodynamics-related systems (such as motion stabilization and maneuvering systems), whose potential application extends to multiple ship acquisition programs.

3. And the means for implementing the solution are available.

**BENEFITS:** That is, through increased capabilities of the hull form designer, the benefits to be derived from the proposed Surface SHIP R&D Program include improved capabilities for surface ships in all hydrodynamics-related performance areas, leading to reductions in ship acquisition and operating costs. In fact, it has been shown that the financial investment involved in the program could be recovered many times through cost savings to be realized as a result of improved ship performance.

4. All that is required now is the formal establishment of the proposed Program, together with the funding to implement it.

Hopefully, this paper has demonstrated the need to once again reinstate the surface ship displacement monohull to its rightful inheritance of R&D funds, so that it will no longer be treated as "The Stepchild of R&D". An even more appropriate closing remark, however, is that from Rear Admiral Lisanby's recent address to the 18th ATTC:

"IN THE MEANTIME, LET US CONTINUE TO PUSH FORWARD, KEEPING IN MIND THAT OUR ABILITY TO MAKE OUR NAVAL SHIPS EFFECTIVE IS THE BASIS ON WHICH OUR FLEET AND OUR NATION WILL JUDGE US."



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COMNAVSEC, to quote from his recent address to the 18th ATTC.**



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## APPENDIX A

### DESCRIPTION OF SHIP RESISTANCE AND POWERING PREDICTION METHODS

#### PREDICTION OF SHIP RESISTANCE

The first step in estimating the total calm water resistance of a ship during Concept Design is to determine the bare-hull resistance (or effective power) of the underwater hull. Following this step, the appendage resistance and the wind drag are then estimated. These components of total resistance are described below:

A. Bare-Hull Resistance. The bare-hull resistance is usually expressed in terms of the bare-hull effective power ( $p_E$ ) of a ship, which is that amount of power which would be required to tow the bare-hull through water at any particular speed and can be determined from the following formulation:

$$C_T = C_R + C_F + C_A$$

where

$C_T$  = total resistance coefficient

$C_R$  = residuary resistance coefficient

$C_F$  = frictional resistance coefficient

$C_A$  = incremental resistance coefficient for model-ship correlation (correlation allowance)

Ever since it was postulated many years ago that the frictional resistance of a hull form is dependent on its Reynolds' number ( $R$ ), most investigators have attempted to fit a continuous function of "Reynolds' number, based on the hull's waterline length (LWL), through model-scale frictional resistance data gathered by many experimenters with equivalent flat plates. Although the dilemma between "small-model" and "large-model" data has not been completely resolved, the U.S. Navy uses the International Towing Tank Conference (ITTC) 1957 Model-Ship Correlation Line as formulated below:

$$C_F = \frac{0.075}{(\log_{10} R_n - 2)^2}$$

where  $R_n = \frac{(V)(LWL)}{\nu}$  (Reynolds' Number)

$V$  = ship or model speed

$LWL$  = waterline length

$\nu$  = kinematic viscosity

Another of these components, the correlation allowance ( $C_A$ ) which was formerly called the roughness allowance ( $\Delta C_F$ ), is assigned a value of 0.0005 for most naval ships and auxiliary ships painted with a vinyl resin. Essentially, it is a correction factor which accounts for the effects of many variables that are too small and/or too imprecisely known to be individually determined. Since many variables affect the correlation allowance, there still remains an uncertainty as to its value for a specific ship. A complete description of the physical meaning of the correlation allowance and the procedures by which its value has been determined are presented in references (2) and (13).

The last of these components is the residuary resistance which is the most difficult to estimate since it accounts for the effects of wavemaking resistance and other forms of resistance as shown in Figure 3. The basic assumption used in the prediction of the effective power of a ship is that the model and ship have the same residuary resistance coefficient at "corresponding" speeds, i.e., the same Froude number ( $F = V/\sqrt{gL}$ ) or speed-length ratio ( $V/\sqrt{L}$ ). Since this resistance coefficient is entirely dependent on the shape of the underwater hull form, it can be most accurately determined by resistance experiments with a geosim (model) of the ship. During the earlier stages of ship design, however, it is virtually impossible to construct models of alternative hull forms and conduct experiments, since either the specific hull form geometry has not been developed or the available time and/or funding do not permit an experimental program. Consequently, empirical methods to estimate the residuary resistance have been developed which, using three or more hull form parameters, interpolate between the experimental data of similar hull forms.

One of the most well-known sets of systematic series model test data is the Taylor Standard Series. A reanalysis of this Series, as described in reference (14), is used at NAVSEC. These data are presented as contours of the residuary resistance coefficient ( $C_R$ ) versus speed-length ratio ( $V/\sqrt{L}$ ) for numerous values of the longitudinal prismatic coefficient ( $C_P$ ), the volumetric coefficient ( $C_V$ ), and the beam-draft ratio ( $B/T$ ) covering the range of hull variations in the series.

Although the Taylor Standard Series can be very useful, there are many disadvantages to its use during Feasibility Studies and Concept Design. In addition to the disadvantages previously mentioned, it is rather cumbersome to use the data and significant modifications (or corrections) must be made to the data to account for major differences between the parent hull form of the Taylor Standard Series (as shown in Figure 4) and the hull forms of naval surface ships (a typical example of which is shown in Figure 5). The obvious hull form differences are the transom stern and bow sonar domes of naval combatant ships. The correction factor to account for such hull form differences is commonly referred to as the "worm" curve and is applied as shown in Figure 2. Essentially, a worm curve traces the functional relationship between a resistance correction factor and speed. The appropriate worm curve may be determined by the following technique:



- (1) Find a hull form and/or hull forms which,
  - a. have substantially the same shape as the design, and
  - b. were developed in a manner similar to that used in the design, and,
  - c. whose hull form parameters fall within the limits of the Taylor Standard Series.

- (2) Determine the ratio of the actual resistance to the resistance estimated from the Taylor Standard Series data at several speed-length ratios for each of the hull forms that is applicable.

The information determined in (2) above becomes the so called worm curve. (It is emphasized that such information usually is not readily available to the hull form designer). Since worm curves are frequently based on data for hull forms that are not parametrically similar to the designed hull form (e.g., they differ in displacement-length ratio, and/or prismatic coefficient, and/or  $L/B$ , and/or  $B/T$ , etc.), a further complication arises when the hull form designer must decide if additional corrections should be made to these worm curves in order to arrive at a final worm curve for the hull form design in question as shown in Figure 6.

Because of these complexities, and the complexity involved in developing a mathematical model of how the components of residuary resistance interact, no theoretical methods have been developed which accurately estimate the residuary resistance for conventional surface ships. Thus, there are no prediction methods available which are capable of quantifying all the effects of shape and anomalies that may evolve in the development of a hull design. Consequently, it is obvious that much research work still needs to be done in this area in order to develop analytical prediction methods that can be efficiently used by the hull form designer to meet the demands of the early stages of ship design.

#### B. Appendage Resistance.

The typical complement of appendages for a modern twin-screw naval ship, which would normally include shafting, shaft struts, shaft fairings and rudders would lead to a resistance increase in the neighborhood of 25-30% of the bare-hull resistance. Since the resistance of the appendages can be such a significant part of the ship's total resistance, it is quite important that an accurate estimate be made early in Concept Design.

Normally, estimates of appendage resistance are developed using model test data for similar ships. The data from which the estimates are to be developed must be selected with great care, since not all ships are configured with similar appendage arrangements. The usual output from this procedure is a ratio of the fully-appendaged effective power to the bare-hull effective power. This ratio is generally plotted versus speed-length ratio, for each of the similar ships selected. The estimated

fully-appendended effective power for the Concept Design is then obtained at each speed by multiplication of the bare-hull effective power by the appropriate ratio. A discussion in greater detail of this procedure and others is given references (2) and (15).

In addition to the limitations previously mentioned in Section III, there are several others which are as follows:

1. It is necessary to review the model test data for several hull forms.
2. The appendage arrangements thus selected must be quite similar to the design under consideration; that is, subtle differences in appendage arrangements can significantly affect the resistance.
3. The designer, in many cases, must interpolate between two or more of these sets of model test data.
4. These data are usually not readily available to the ship designer.
5. This approach is very crude and cumbersome in that it is not only extremely difficult for the ship designer to evaluate alternative appendage arrangements, but it is also virtually impossible for the ship designer to determine which appendages should be redesigned in order to minimize their drag.

Consequently, it is obvious that much research work also needs to be done in this area in order to develop analytical and experimental methods that can be efficiently used by the hull form designer to design appendages with minimum drag characteristics, as well as minimum cavitation characteristics.

C. Wind Resistance. Wind resistance, commonly referred to as still air drag, is that due to the passage of the ship through zero true wind. (True wind is that wind which is due to natural causes and exists at a point above the sea whether or not the ship is there; zero true wind is still air.)

Recently, there has been an increased interest in the still air drag of ships (see reference (2)), which is normally 2 to 3 percent of the fully-appendended resistance of the hull. In the past, still air drag was not included in estimates of total ship resistance, primarily because it was considered insignificant and because model tests do not account for this component. However, it is now included by NAVSEC in all estimates of the ship's total resistance. The only area requiring additional research is in determining the wind drag coefficients for various superstructure arrangements.



## PREDICTION OF SHIP POWERING

The total estimated shaft power ( $P_S$ ) for a ship can be obtained by dividing the total effective power ( $P_E$ ) by the estimated Propulsive Coefficient (PC). The Propulsive Coefficient (PC) defines the performance of the propeller when operating with the hull and appendages, and is generally expressed as follows:

$$PC = n_O n_H n_R,$$

where  $n_O$  = open-water propeller efficiency

$n_H$  = hull efficiency, which is

$$= (1-t)/(1-w_T),$$

where  $(1-t)$  = thrust-deduction factor

$(1-w_T)$  = thrust-wake factor

$n_R$  = relative rotative efficiency, which is

$$= n_B/n_O$$

where  $n_B$  = propeller efficiency behind the hull

The propeller open-water efficiency ( $n_O$ ) defines the performance of the propeller in an undisturbed fluid (uniform inflow). The hull efficiency ( $n_H$ ) defines the effects of the propeller on the resistance on the hull, when the propeller is operating in the wake of the ship. The relative rotative efficiency ( $n_R$ ) defines the difference in propeller performance attributable to the nonuniformity of the inflow velocity. The relative rotative efficiency ( $n_R$ ) and the two hull-propeller interaction factors ( $1-t$  and  $1-w_T$ ) are generally estimated from data accumulated during the search for relevant worm curve and appendage resistance data. The estimate of the open-water propeller efficiency ( $n_O$ ) is generally developed from propeller model series test data (Troost or others) or by actual propeller design calculations (lifting line or lifting surface theories) based on the total ship resistance, the two hull-propeller interaction factors and the propeller design speed (rpm). A more detailed discussion of these efficiencies is given in references (2) and (16).

Although the accuracy of predicting the open-water propeller efficiency is quite satisfactory, there are several major problems associated with predicting the overall Propulsive Coefficient. As Johnson and Gale (4) point out, these problems pertain primarily to  $n_R$ ,  $(1-t)$  and  $(1-w_T)$  and include:

1. Considerable variations are found in collected test data with no apparent explanations, including large, unexpected increases in the ship's wake resulting from minor appendage changes.

2. Lack of knowledge regarding the influence of various design parameters makes interpretation of available data difficult and unreliable, even when making estimates within bounds of existing data.

3. It is virtually impossible to make estimates for new designs whose parameters lie outside the bounds of existing data.

4. As with appendage drag, substantial scale effects between model and full-scale data are generally ignored.

5. Inaccuracies are compounded since the Propulsive Coefficient components are also utilized in the design of the propeller.

Due to the empiricism of the resistance and powering prediction techniques available to the hull form designer, as well as the numerous uncertainties during the early stages of ship design, a power margin is applied throughout the entire speed range. Naturally, this power margin should be commensurate with the actual level of uncertainty and should be applied directly to the estimated power at each stage of design. As described in more detail in references (3) and (17), an investigation, which consisted of a comparison of trial data with powering performance predictions, has recently been conducted to determine what the power margin policy should be during each stage of ship design. The recommendations from this investigation regarding a power margin policy, which were issued as a NAVSEC instruction (Ship Engineering and Design Department Instruction 9020.8 of 18 October 1974), are as follows:

a. 11% during Conceptual Design; prior to the issuance of a body plan and an appendage sketch.

b. 9% during Preliminary Design; prior to model tests

c. 6% at the end of Preliminary or Contract Design; based on model test data from propulsion tests using stock propeller(s), results adjusted to reflect the estimated performance of the contract design propeller(s).

d. 3% at the end of Contract Design; based on model test data from propulsion tests using the design propeller(s).

These margins are applied to the fully-appendended effective power (or resistance) as shown in Figure 2.



## APPENDIX B

### SPECIFIC APPROACH TO CERTAIN TECHNICAL AREAS OF THE SURFACE SHIP R&D PROGRAM

#### PREDICTION OF SHIP RESISTANCE

1. Reduce Bare Hull Resistance - Improvements in this area would be divided into those affecting the early design stages, and those which would be applicable to later stages.

For the early design stages, emphasis would be placed upon improving the designer's ability to select hydrodynamically-optimum hull form parameters. Specific projects would include:

- o the computerization of existing model test data for easy access by the designer;
- o expanding the Taylor Standard Series to include data for ships with higher beam-to-draft ratios; and
- o performing additional systematic series model tests, particularly for transom stern naval ships, to improve the accuracy of resistance predictions.

For the later stages of design, the development of new experimental and analytic techniques for reducing residuary resistance would be undertaken. Two particular projects would be performed initially:

- o extensive model tests (longitudinal wave cuts) to implement Baba's underwater hull form design techniques and Sharma's bulbous bow design and sonar dome location techniques; and
- o an investigation of the theoretical/analytical techniques of Pien, Lin, Wehausen, etc., to assess their applicability to naval ship design.

2. Reduce Appendage Resistance - Improvements in this area would consist of two parts: the development of the techniques necessary for accurately predicting appendage resistance; and the translation of the information obtained thereby into convenient, usable design methods. Specific projects for developing resistance prediction techniques would include:

- o the analysis of existing model test data to determine the critical parameters affecting appendage resistance;
- o the development of a sound mathematical foundation for a resistance prediction technique;

- o the development of experimental technique(s) necessary to accurately measure appendage resistance;
- o the performance of systematic model tests to verify and refine the mathematical foundation; and, finally,
- o the development of a convenient method for utilizing the results of the above projects during ship design.

#### PREDICTION OF SHIP POWERING

1. Improve Hull-Propeller Interactions - The approach to this area would be very similar to that used for improvements in the appendage resistance area, and would consist of:

- o the analysis of existing model test data to determine the critical parameters affecting the thrust-deduction ( $1-t$ ) and thrust-wake ( $1-W_T$ ) factors;
- o the formulation of a mathematical foundation, similar to that of Cox and Hansen (18) for several stern propeller-body-of-revolution configurations;
- o the development of experimental techniques necessary to accurately measure the hull-propeller interaction factors;
- o the performance of systematic model tests; and
- o the translation of the information gathered from the above into useable hull form and propeller design methods.

#### PREDICTION OF MANEUVERING PERFORMANCE

The initial effort in this area would consist of two parts: the development of maneuvering performance prediction techniques/methods for use in early stages of ship design; and the development of quantitative measures of merit for maneuvering performance. Of these, the first is addressed here.

In undertaking the development of techniques enabling designers to predict the maneuvering performance early in ship designs, the following specific projects would be performed:

- o a systematic series of captive model tests (rotating arm and planar motion tests) for a wide variety of hull forms, to obtain the various hydrodynamic coefficients which appear in the maneuvering equations of motions;



- o computer simulations, utilizing the hydrodynamic coefficients determined from the above tests, to predict the maneuvering performance of surface ships;
- o regression analyses of the above hydrodynamic coefficients, to obtain empirical formulas relating the coefficients to various hull form parameters, thus establishing relationships for predicting the coefficients during the early stages of design; and
- o the reduction of the bulk of information generated through the above projects into a convenient form for use by the ship designer.

The above tasks would provide a firm basis for the establishment by OPNAV of specific maneuvering requirements, and would also provide the designer with the ability to predict the maneuvering performance of alternative ship concepts during the early stages of design.

#### PREDICTION OF HYDRODYNAMIC LOADS

As with the other areas of investigation discussed in this Section, the approach to the problem of slamming-induced loads would involve the systematic employment of both model testing and theoretical analysis. Specific projects would include:

- o model tests on a wide variety of hull forms, to investigate the effects of the following parameters on slamming loads for various ship speeds, ship headings and sea states: longitudinal sponson location; longitudinal sponson extent; vertical sponson location; horizontal sponson extent; and sponson-hull re-entrant angle;
- o development of a statistical description of loadings caused by relative motions, utilizing energy density spectra techniques;
- o analysis of data generated by model testing, with the aim of developing relationships between the parameters of the loading energy spectra and the characteristics of the sponson; and
- o the condensation of the information generated by the above tasks into a form suitable for use by the hull designer to provide input to the structural designer.

**TABLE 1. LIST OF TYPICAL HULL FORM PARAMETERS  
THAT AFFECT SHIP RESISTANCE**

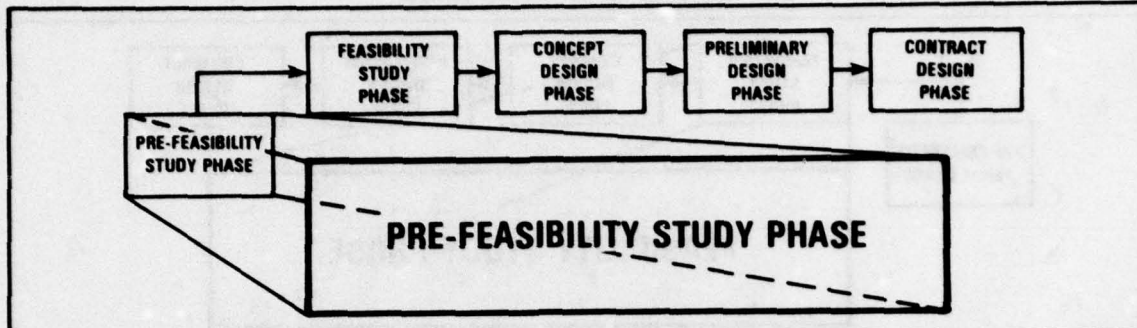
<b>PRIMARY PARAMETERS</b>		<b>SECONDARY PARAMETERS</b>	
LBP	Length between perpendiculars	C <sub>wp</sub>	Waterplane area coefficient
LWL	Length on waterline	LCB	Longitudinal center of buoyancy from forward perpendicular
B <sub>x</sub>	Beam at waterline at transverse section of maximum area	LCF	Longitudinal center of flotation from forward perpendicular
T <sub>x</sub>	Draft at transverse section of maximum area	B <sub>20</sub>	Beam at waterline at transom
C <sub>p</sub>	Longitudinal prismatic coefficient	T <sub>20</sub>	Draft at transom on the centerline
A <sub>x</sub>	Area of maximum transverse section	A <sub>20</sub>	Area of transom
C <sub>x</sub>	Maximum transverse section coefficient	i <sub>B</sub>	Slope of buttock lines at stern
C <sub>∇</sub>	Volumetric coefficient	i <sub>E</sub>	Half angle of entrance (slope of design waterline at forward perpendicular)
Δ <sub>BH</sub>	Bare-hull displacement, weight	i <sub>R</sub>	Half angle of run (slope of design waterline at aft perpendicular)
Δ	Total displacement, weight		
∇	Total displacement, Volume		
S	Wetted surface area		



**TABLE 2. COMPARISON OF PROPULSIVE COEFFICIENT  
COMPONENTS (AT A SPECIFIC SPEED)**

(1-t)	0.90	0.93	0.92
(1-W <sub>T</sub> )	0.97	0.98	0.96
n <sub>R</sub>	0.98	1.00	0.99
n <sub>0</sub>	0.66	0.68	0.69
P.C.	0.59	0.64	0.66
Remarks	Powering Model Tests with Stock Prop.	Powering Model Tests with Design Prop. - Minor hull, prop. dia. and appendage changes	Powering Model Tests with Design Prop. - Minor appendage changes

**TABLE 3. SEAKEEPING IN SHIP DESIGN  
PRE-FEASIBILITY STUDY PHASE**



**A. Design Events and Decisions:**

- Operational Requirements are defined.
- Platform Type Selected: conventional monohull displacement type vs. one of the several alternatives (hydrofoil, SES, SWATH, multihull, etc.)
- "Ballpark" size and cost established

**B. Implications for Seakeeping Performance:**

- Platform type and "ballpark" size has a first order effect on seakeeping behavior. Most unconventional platform configurations were developed in an attempt to improve seakeeping behavior.

**C. Seakeeping Analyses Required:**

- Studies of alternative force structures (numbers, sizes & types of platforms) must address relative seakeeping behavior (environmental operability).

**D. Prerequisites for Analyses:**

Status:\*

- Simple prediction tools to assess relative environmental operability, given primary mission and major payload items, for various platform sizes and types.

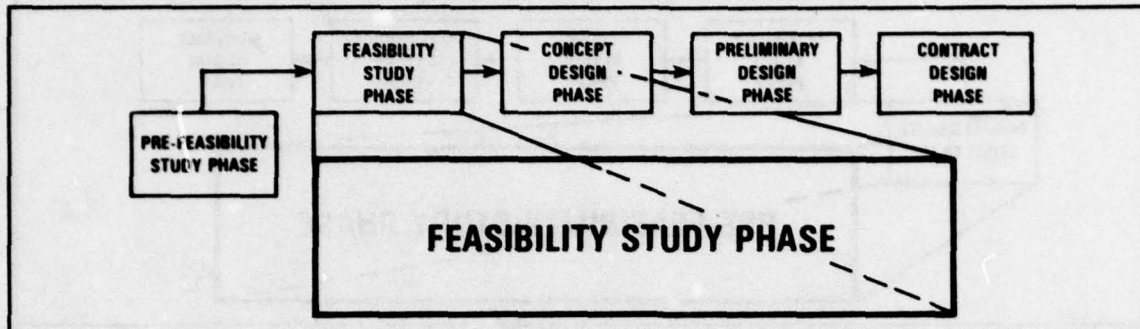
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\*Legend: ○ Available;  
Must Be Improved.

(X) Not Available:  
To Be Developed.



**TABLE 4. SEAKEEPING IN SHIP DESIGN  
FEASIBILITY STUDY PHASE**



**A. Design Events and Decisions:**

- Primary military payload and performance features (speed, endurance, protection, etc.)

**B. Implications for Seakeeping Performance:**

- Primary payload and performance features have the major effect on platform configuration and size and hence a dominant effect on seakeeping behavior.

**C. Seakeeping Analyses Required:**

- In studies of alternative payload and performance features, analyses are required to ensure that Operational Requirements can be satisfied.

**D. Prerequisites for Analyses:**

- Simplified prediction tools for use with existing ship synthesis computer models to predict: pertinent ship motions, speed limitations by power, slamming or wetness, etc.
- Improved freeboard criteria based on seakeeping considerations:
  - to weather deck for most ships.
  - to hangar deck for aircraft carrier types with deck edge elevators
- More appropriate environmental descriptors

**Status:\***

(X)

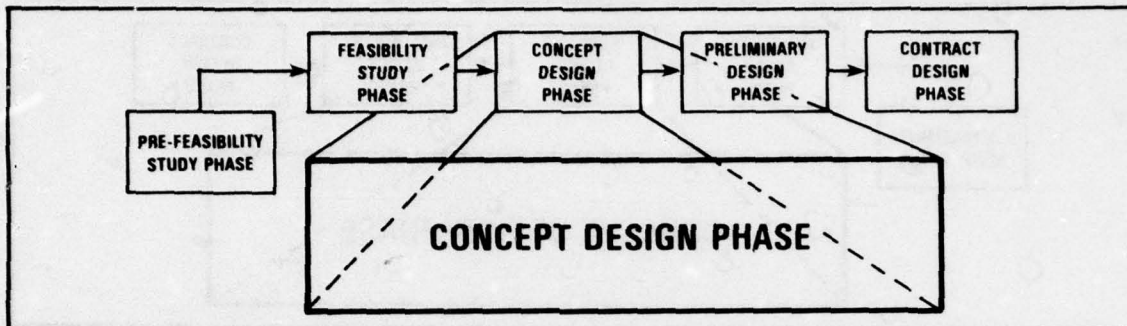
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\*Legend: ( ) Available; (X) Not Available;  
Must Be Improved. To Be Developed.

**TABLE 5. SEAKEEPING IN SHIP  
CONCEPT DESIGN PHASE**



**A. Design Events and Decisions:**

- Principal hull dimensions (L,B,T,D) and form coefficients ( $C_p$ ,  $C_x$ ) established; Baseline hull form developed, specific features, however, still to be optimized.
- Motion stabilization system requirements established and approximate solution (system size/type) incorporated into design.
- Draft TLR document developed, Conceptual Baseline established.

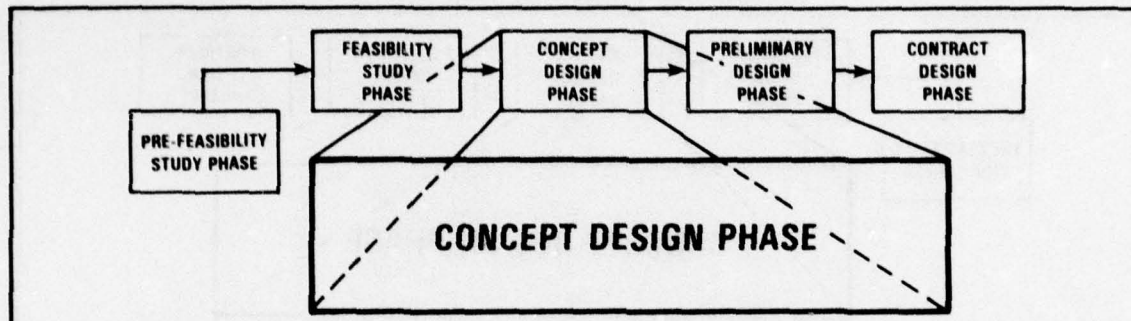
**B. Implications for Seakeeping Performance:**

- Seakeeping behavior has been largely defined (say 80-90%). Many aspects have not yet been evaluated and some modifications of behavior are still possible through: (1) hull form and weight distribution changes (not principal dimensions or  $C_p$ ,  $C_x$ ) resulting from optimization studies, and (2) the development of the rudder and motion stabilization system designs.

(CONTINUED)



**TABLE 5. SEAKEEPING IN SHIP DESIGN  
CONCEPT DESIGN PHASE (CONT.)**

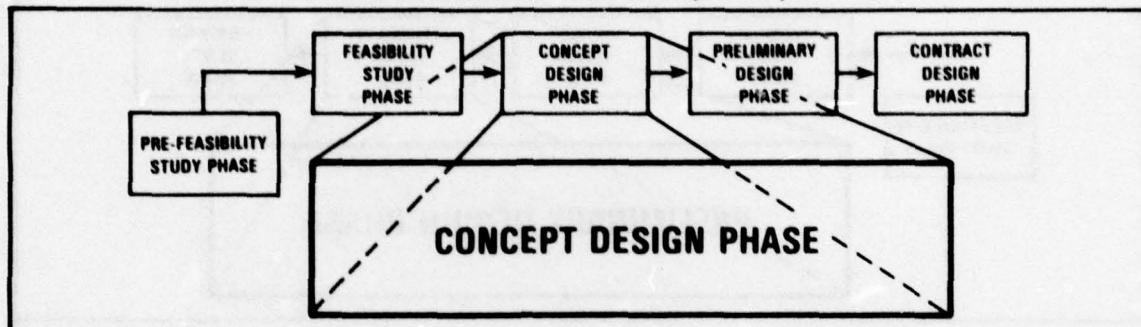


**C. Seakeeping Analyses Required:**

- Explore a range of feasible combinations of principal hull dimensions and form coefficients with the aid of ship synthesis computer models.
- After L,B,T,D, Cp and Cx have been tentatively selected and a baseline hull form drawn up, refine evaluation of the seakeeping behavior of the baseline hull.
- Assess adequacy of freeboards along hull (modify as required) and need for motion stabilization (for critical subsystems, compare actual motions at their locations with limiting acceptable motions).
- If stabilization is required, select system size/type and incorporate in Conceptual Baseline Design.
- For major subsystems, derive design requirements from overall environmental operability requirements.
- Identify the natural periods of oscillation of the ship platform and major subsystems such as landing craft in a wet well.

(CONTINUED)

**TABLE 5. SEAKEEPING IN SHIP DESIGN  
CONCEPT DESIGN PHASE (CONT.)**



**D. Prerequisites for Analyses:**

**Status: \***

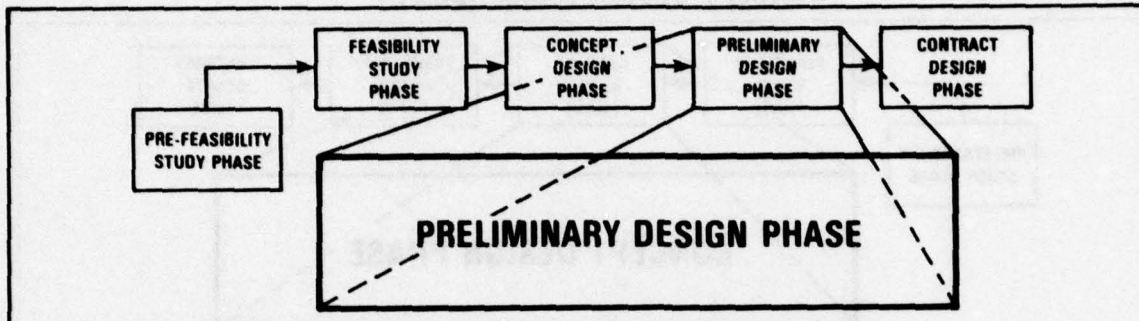
- Simplified prediction tools incorporated into ship synthesis computer models (same as for "Feasibility Study phase"). ⊗
- Develop refined environmental descriptors; e.g., directional spectra. ⊗
- Six degree of freedom motion prediction (better assessments of bulb and wide, shallow transom effects are needed). ○
- Deck wetness prediction at any points along hull given hull form (including flare) and sheer line (freeboard along hull). ○
- Prediction of powering characteristics in a seaway at all headings (adequate assessment of propulsive coefficient effects not available). ○
- For various stabilization system sizes, types (and combinations), prediction of stabilized platform motions at all headings (relatively easy to use). ○
- Keel slamming characteristics prediction in a seaway considering effect of hull shape (evaluation of scale effects and full scale validation required). ○

\*Legend: ○ Available;  
Must Be Improved.

⊗ Not available;  
To Be Developed.



**TABLE 6. SEAKEEPING IN SHIP DESIGN  
PRELIMINARY DESIGN PHASE**



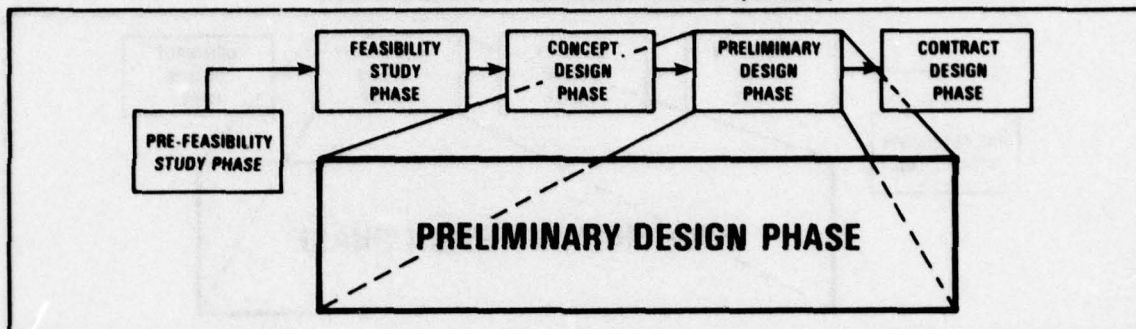
**A. Design Events and Decisions:**

- Hull form defined with possible exception of minor shape details.
- Primary features of appendage configuration (including rudders, bilge keels, and above water sponsons) are defined.
- Primary features of motion stabilization system geometry and control system are determined.
- Internal subdivision of hull is defined.
- TLR and TLS completed, Functional Baseline established.

**B. Implications for Seakeeping Performance:**

- For all practical purposes, seakeeping behavior has been completely defined (say 96%-98%). Certain aspects have not yet been evaluated and minor modifications of behavior are still possible in the course of the development of further details of the hull form and the steering and motion stabilization system designs (configurations and control systems).

**TABLE 6. SEAKEEPING IN SHIP DESIGN  
PRELIMINARY DESIGN PHASE (CONT.)**



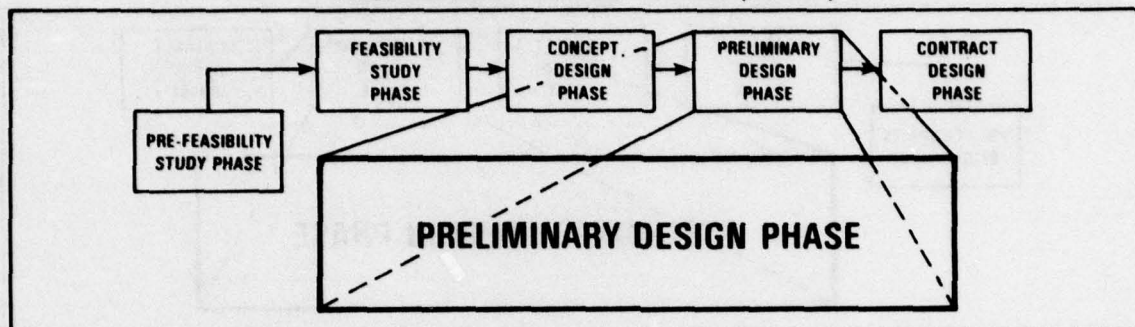
**C. Seakeeping Analyses Required:**

- Influence on seakeeping behavior of below water hull form variations (LCB and LCF positions, bulb size and shape, transom width and immersion, etc.) from the conceptual baseline form.
- Influence on seakeeping behavior of above water hull form variations from the conceptual baseline form (flare/knuckle variations).
- Optimization of motion stabilization system location, principal geometry and primary control system features.
- Location, shape and loads definition for above water sponsons.
- Assessment of survivability aspects (emphasis on intact condition):
  - structural loads (local and hull girder)
  - broaching and/or capsizing in extreme and resonant, less-than-extreme, conditions

(CONTINUED)



**TABLE 6. SEAKEEPING IN SHIP DESIGN  
PRELIMINARY DESIGN PHASE (CONT.)**



**D. Prerequisites for Analyses:**

**Status:\***

For assessment of influences of below water hull form variations, see "Conceptual Design Phase" (motions, deck wetness, powering and keel slamming).

- Develop refined environmental descriptors (multi-parameter sea spectra including swells and wind-generated seas, atlas of extreme environmental conditions, etc.) (X)
- Techniques for predicting the effects of above water forebody flare/knuckle variations on added resistance in a seaway, slamming forces and accelerations, deck wetness and spray characteristics, etc., for head and bow seas. (X)
- Techniques for locating, shaping and predicting impact loads for designing the structure of above water sponsons. Given a hull form and a sponson size and location, frequency of immersion together with slamming frequencies and forces are needed for a range of ship speeds and headings. (X)
- Prediction methods for local loads:
  - on weather decks due to green water. ○
  - on superstructures and deck mounted equipments due to wave slap ○
  - on above and below water hull surfaces due to slams/wave slaps ○

\*Legend: ○ Available;  
Must Be Improved.

(X) Not Available;  
To Be Developed.

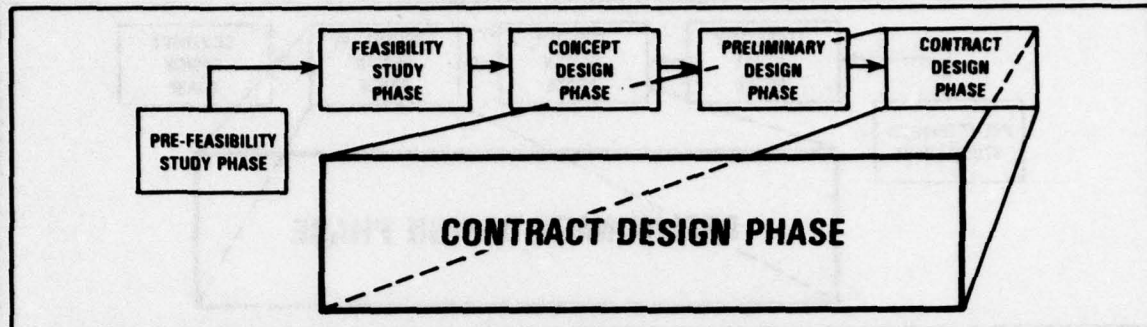
(CONTINUED)

**TABLE 6. SEAKEEPING IN SHIP DESIGN  
PRELIMINARY DESIGN PHASE (CONT.)**

<pre> graph LR     A[PRE-FEASIBILITY STUDY PHASE] --&gt; B[FEASIBILITY STUDY PHASE]     B --&gt; C[CONCEPT DESIGN PHASE]     C --&gt; D[PRELIMINARY DESIGN PHASE]     D --&gt; E[CONTRACT DESIGN PHASE]     subgraph "PRELIMINARY DESIGN PHASE"         B         C         D     end         </pre>	
	Status: *
<ul style="list-style-type: none"> <li>● Prediction methods for hull girder loads: <ul style="list-style-type: none"> <li>– wave induced (non-impact) loads</li> <li>– loads due to forebody slamming (above and below water)</li> </ul> </li> </ul>	<input type="radio"/> <input type="radio"/>
● Questions related to life-cycle fatigue failure of exotic hull materials need resolution	<input type="radio"/>
● Hull stiffness requirements must be defined	<input checked="" type="radio"/>
● Continued research into the dynamic aspects of survival in extreme conditions with respect to broaching, capsizing and foundering, leading ultimately to prediction techniques and improved design criteria.	<input checked="" type="radio"/>
● Prediction of accelerations due to hull girder whipping after a slam (investigation of suitability of existing vibration analysis methods).	<input checked="" type="radio"/>
● Prediction of lateral forces and motions.	<input type="radio"/>
● Development of improved stabilization fin hydrodynamic coefficients.	<input type="radio"/>
● Development of an integrated design procedure for the determination of desired fin geometry and control system characteristics.	<input checked="" type="radio"/>
● Passive anti-roll tank design procedure for both flume and U-tube configurations. Further research into equations of motion, hydrodynamic coefficients and performance predictions is required.	<input type="radio"/>
<p>*Legend:    <input type="radio"/> Available;                      <input checked="" type="radio"/> Not Available;                       Must Be Improved.                      To Be Developed.</p>	



**TABLE 7. SEAKEEPING IN SHIP DESIGN  
CONTRACT DESIGN PHASE**



**A. Design Events and Decisions:**

- Details of appendage configuration (including rudders, bilge keels, shafts and struts, skegs and sponsons) are defined.
- Details of motion stabilization system geometry are defined and the system contract specifications are developed (addressing both hardware and control system features).
- Similar specifications are developed for the steering system
- All hull shape details are defined in the Contract Lines Drawing.
- Allocated Baseline established.

**B. Implications for Seakeeping Performance:**

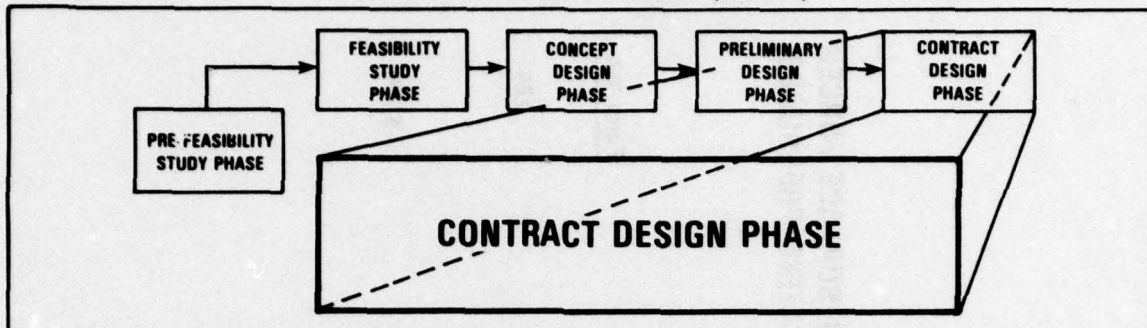
- Relatively minor. Hull shape details can affect spray characteristics. Steering and motion stabilization system control system specification details will affect motions and control in special situations such as quartering seas.

**C. Seakeeping Analyses Required:**

- Model experiments to verify prior analytical predictions of performance, particular structural loads, etc., observe behavior, and support the development of design details as required.

(CONTINUED)

**TABLE 7. SEAKEEPING IN SHIP DESIGN  
CONTRACT DESIGN PHASE (CONT.)**



- Typical measurements would include:
  - motions
  - accelerations
  - deck wetness frequency and severity
  - keel, flare and sponson slamming frequency and severity
  - powering characteristics in a seaway
  - controllability in quartering seas
  - motion stabilization system behavior

**D. Prerequisites for Analyses:**

Status:\*

- In general, additional correlations between model and full-scale measurements are required. Such correlations are especially important for the following aspects in order to resolve scale effect questions and establish realistic expansion methods:
  - deck wetness
  - slamming (keel, flare and sponson)
  - wave slap and deck loads due to green water
- Model test techniques for:
  - stability and controllability in following/quartering seas (broaching/capsizing)
  - powering in oblique seas
  - evaluation of anti-roll tank effectiveness

☒ X  
☐  
☒ X  
  
☐  
☒ X  
☐

\*Legend: ☐ Available; ☒ Not Available;  
                   Must Be Improved                   To Be Developed.



**TABLE 8. COMPARISON OF VERTICAL HULL SURFACE FORCES  
CAUSED BY PROPELLER-EXCITED FLUCTUATING PRESSURES**

<u>Prediction Method Using Stock Propeller</u>	<u>Force, lbs.</u>
Model Test (with 12 pressures measured and integrated)	266
Calculation (by method of W.S. Vorus)	5,700

**TABLE 9. POTENTIAL ECONOMIC PAYOFF FROM IMPROVED  
SPEED/POWER PERFORMANCE**

SHIP TYPE	AOE (50,000 TONS)	GAS TURBINE DD (3,600 TONS)	STEAM DD (3,900 TONS)
Reduction in ship size (tons)	1,661	73	220
Reduction in light ship (tons)	482	9	105
Speed increase (knots)	—	1.1	—
Fuel savings (barrels per year)	22,900	21,300	14,300
Fuel savings (\$ per year)	350,000	319,000	214,000
Acquisition cost savings (\$)	5,300,000	200,000	2,800,000



**TABLE 10. EXAMPLES OF POTENTIAL ACQUISITION AND OPERATING  
COST SAVINGS**

**(All figures undiscounted and in 1976 Dollars)**

**ACQUISITION COST SAVINGS**

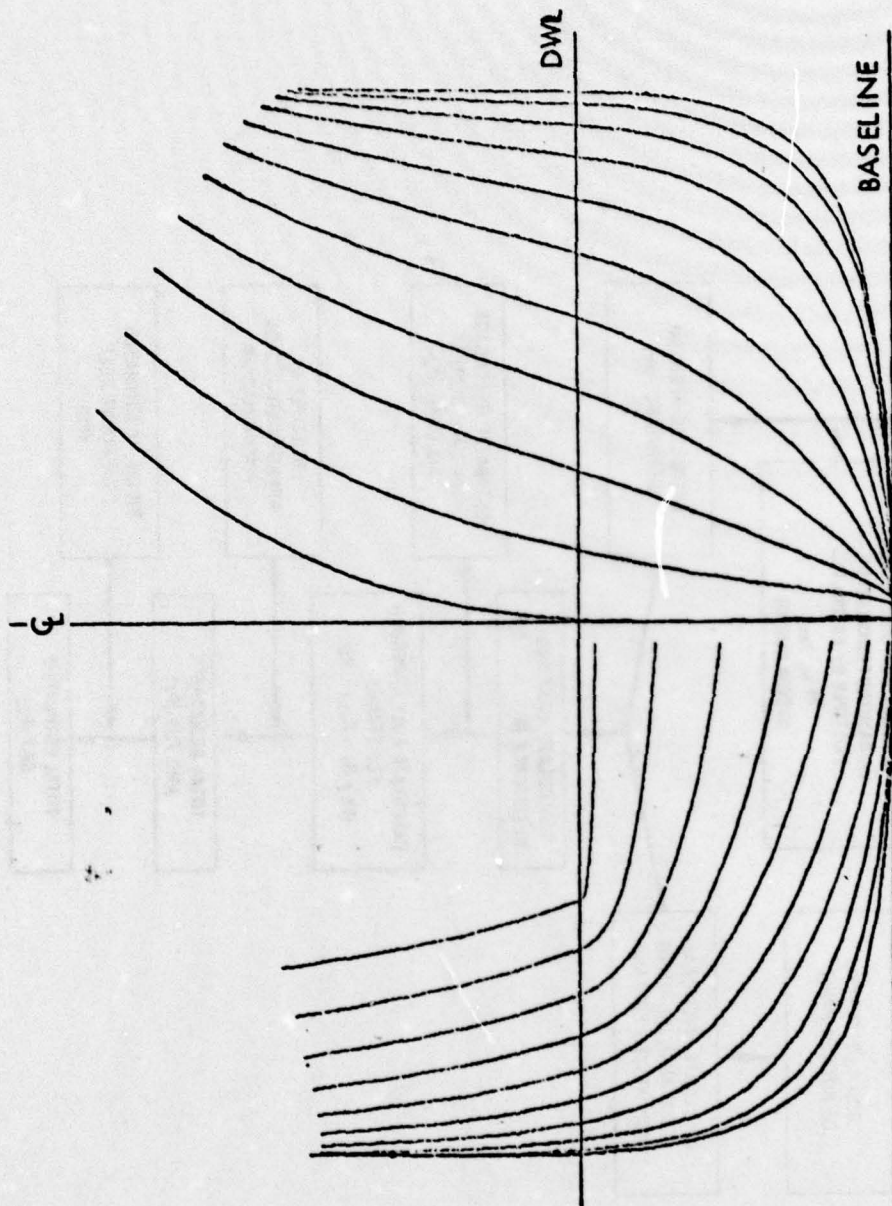
**ON *FOUR* AOE's**

**= \$21.2M**

**10-YEAR FUEL SAVINGS ON CLASS**

**OF 10 GAS TURBINE DD's**

**= \$31.9M**



**FIGURE 1. TYPICAL BODY PLAN FROM  
NAVSEC'S HULLEN COMPUTER PROGRAM**



(AT EACH OF A NUMBER OF SELECTED SHIP SPEEDS.)

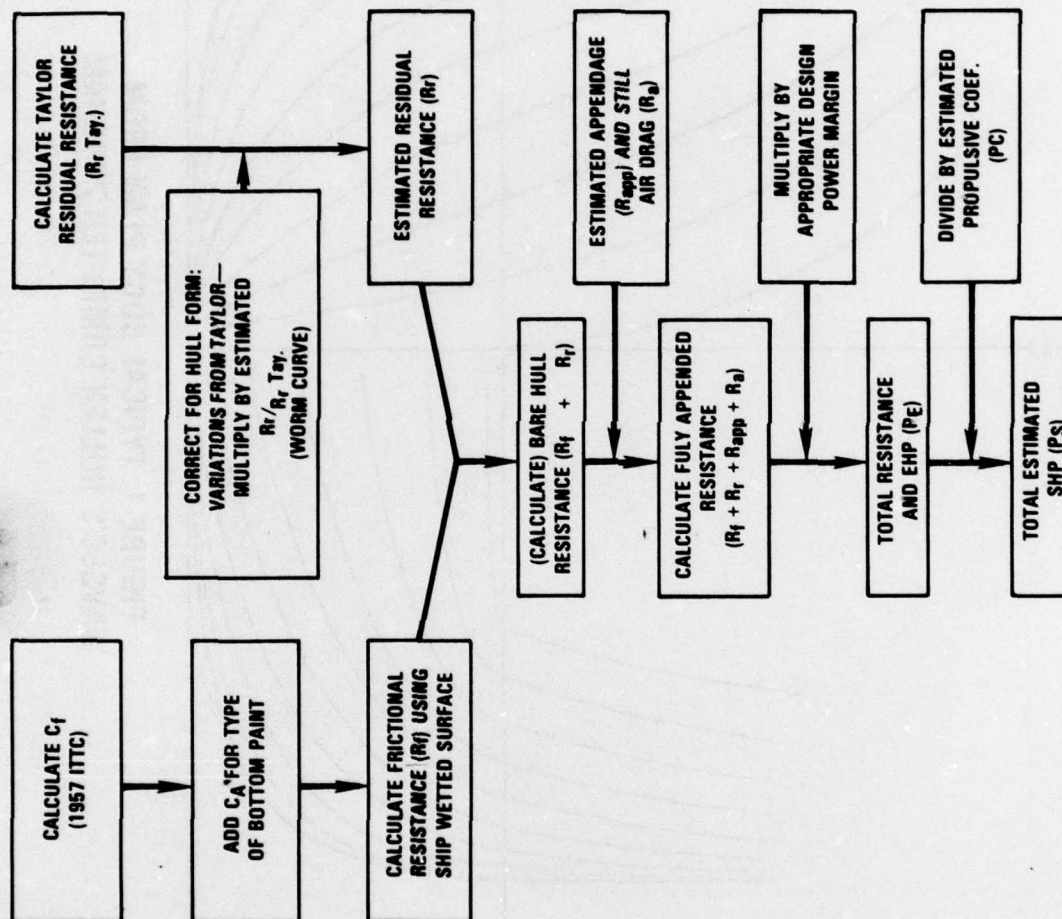
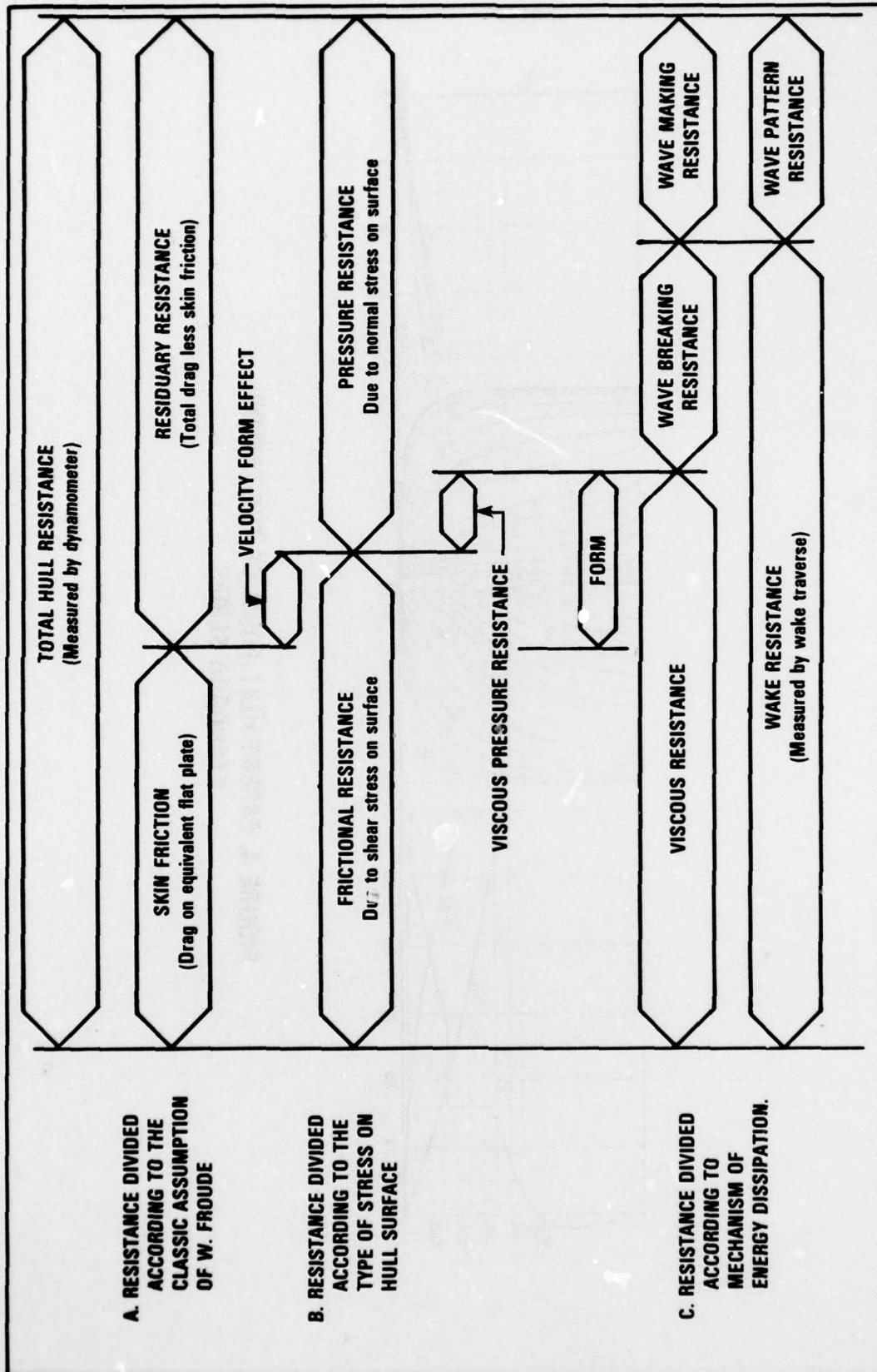


FIGURE 2. GENERAL APPROACH TO CALM WATER  
SPEED/POWER ESTIMATES



**FIGURE 3. SUBDIVISION OF SHIP HYDRODYNAMIC RESISTANCE COMPONENTS**



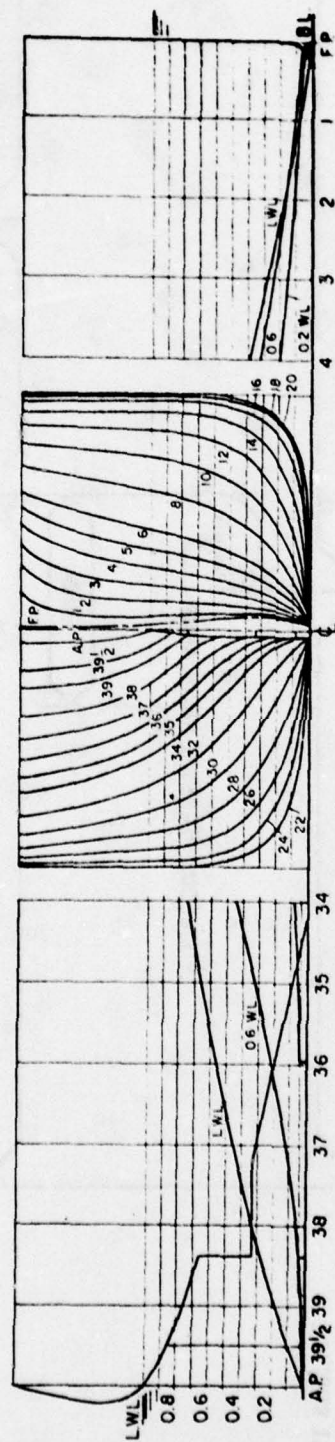


FIGURE 4. PARENT HULL FORM OF THE TAYLOR  
STANDARD SERIES

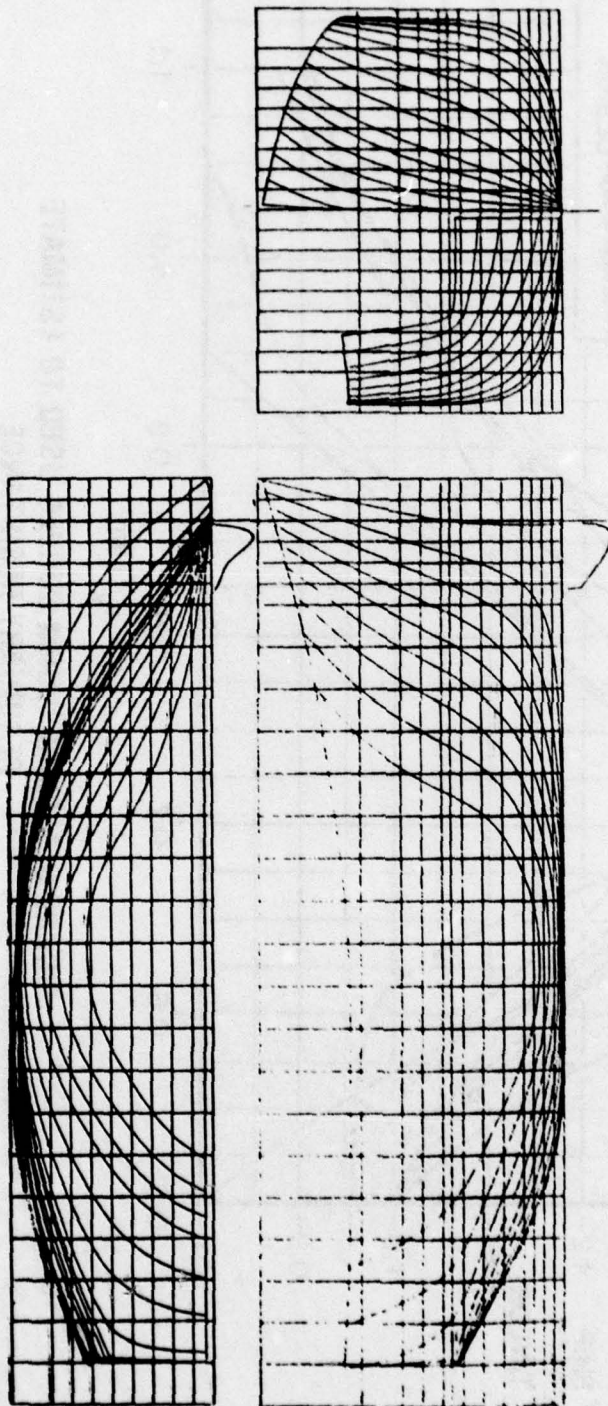


FIGURE 5. TYPICAL HULL FORM OF NAVAL  
SURFACE SHIP



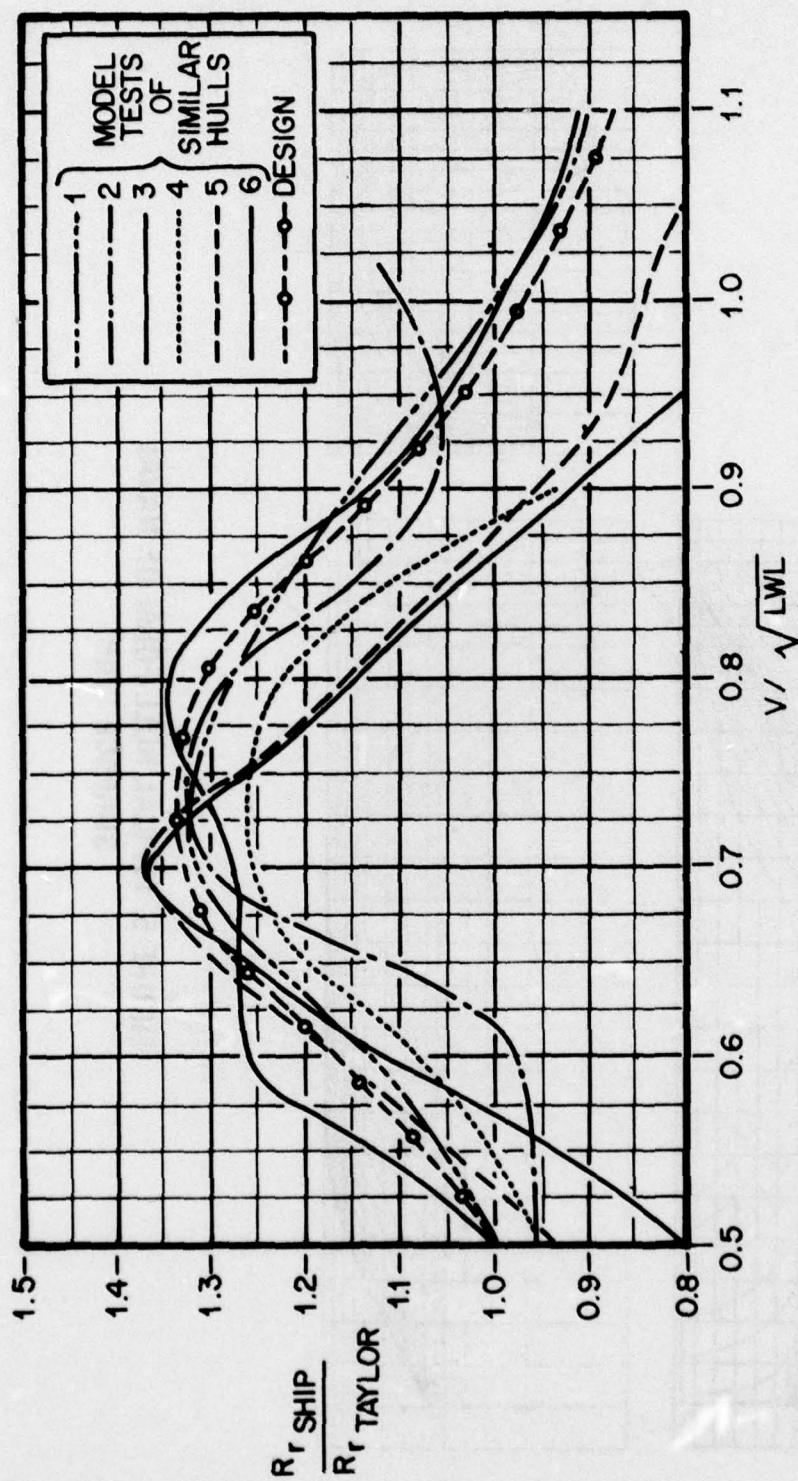


FIGURE 6. TYPICAL WORM CURVES USED TO ESTIMATE RESIDUARY RESISTANCE

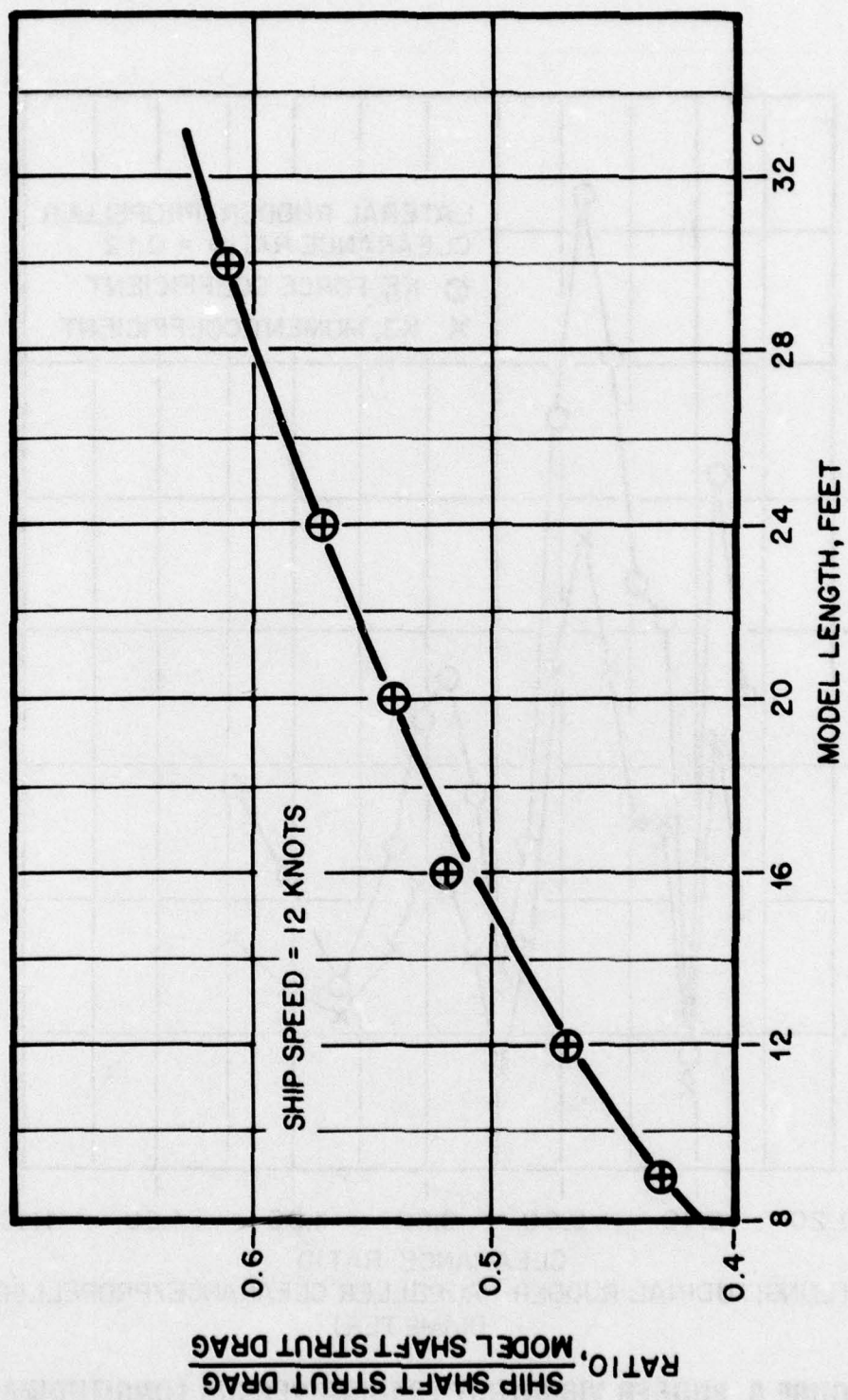
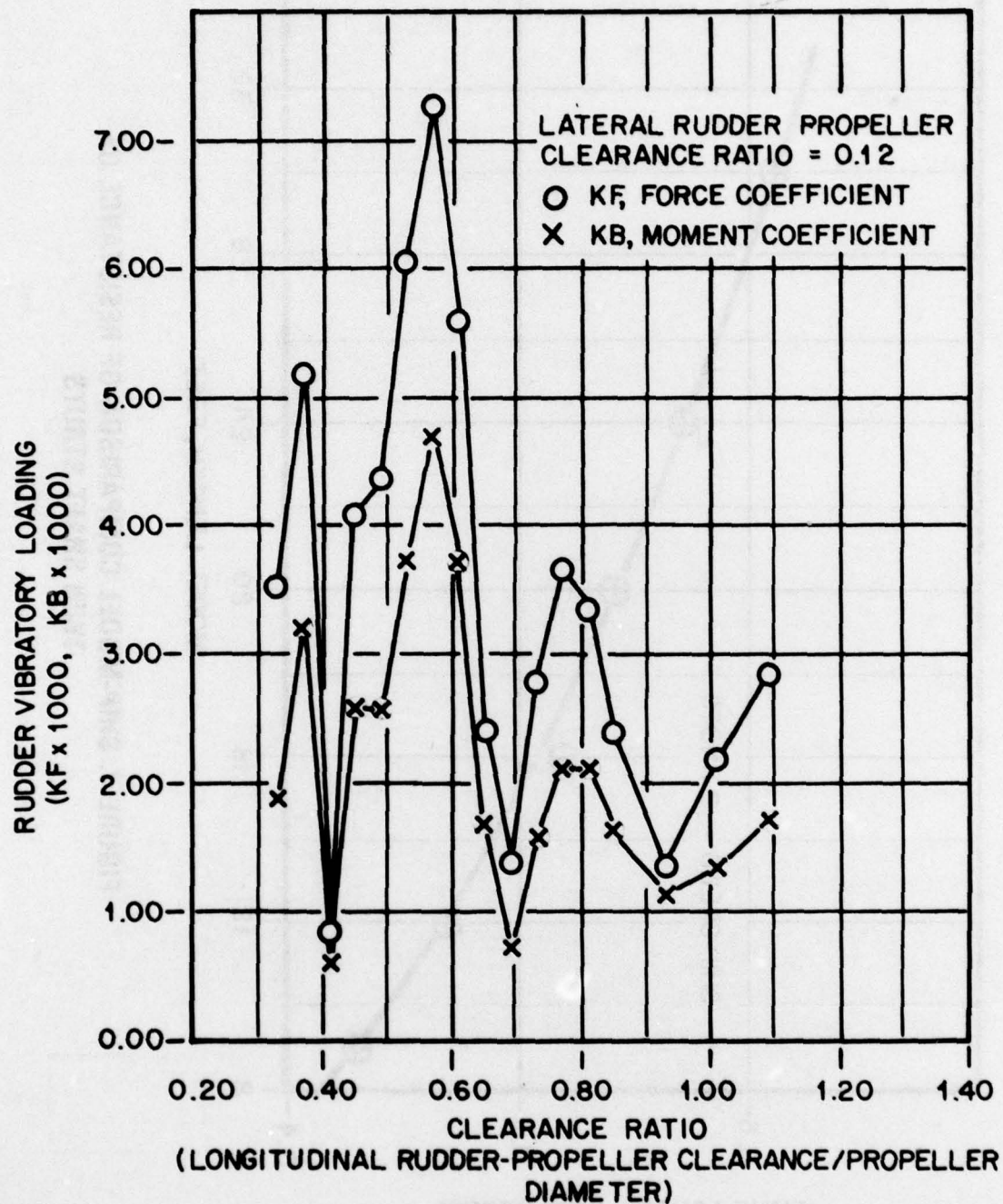
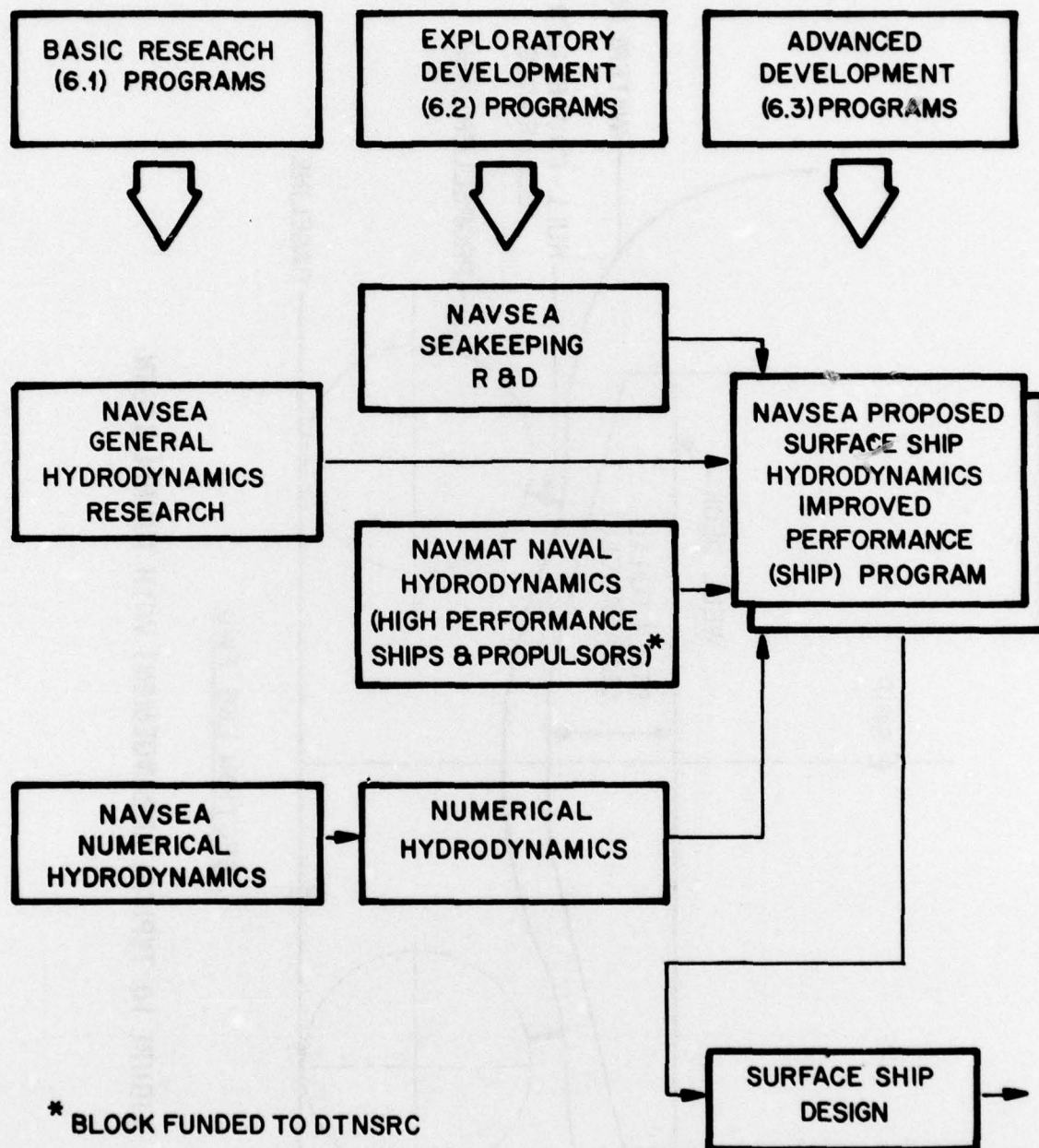


FIGURE 7. SHIP-MODEL COMPARISON OF RESISTANCE OF TWIN SHAFT STRUTS



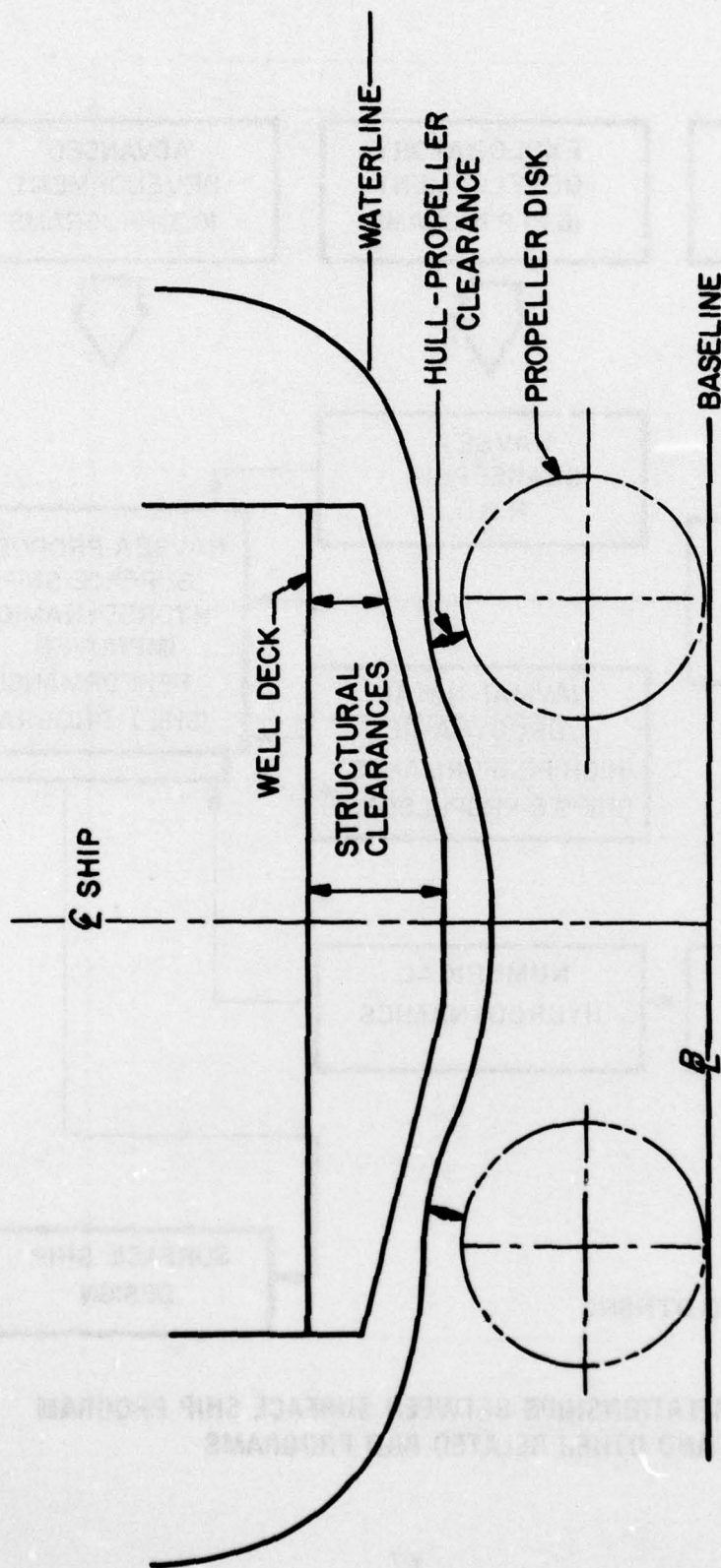


**FIGURE 8. RUDDER VIBRATORY LOADING VERSUS LONGITUDINAL  
RUDDER-PROPELLER CLEARANCE RATIO**



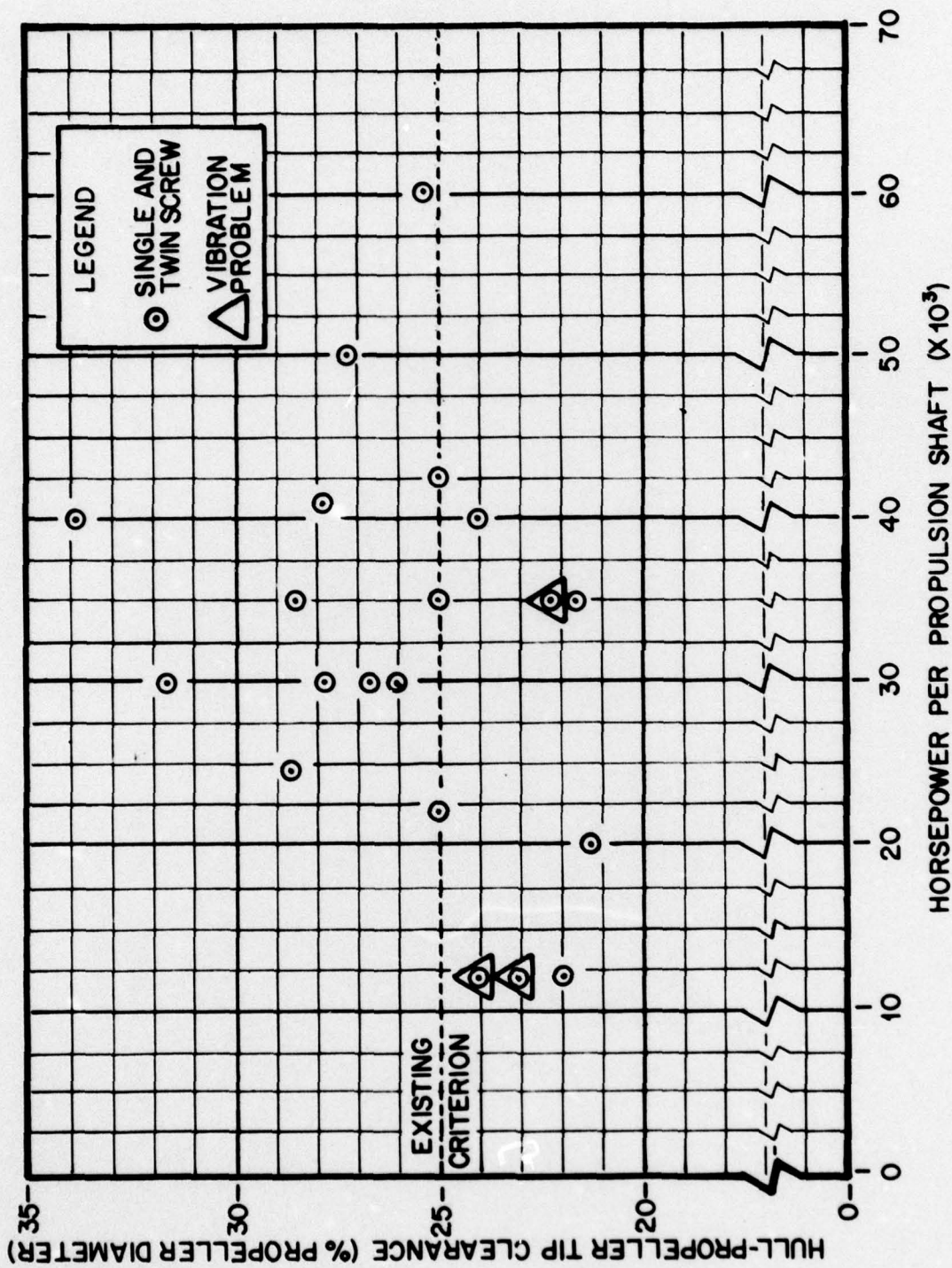
**FIGURE 9. RELATIONSHIPS BETWEEN SURFACE SHIP PROGRAM AND OTHER RELATED R&D PROGRAMS**





SECTION LKG FWD

**FIGURE 10. TYPICAL ARRANGEMENT WITH TUNNEL STERN**



**FIGURE 11. HULL-PROPELLER TIP CLEARANCES FOR SINGLE AND TWIN SCREW SHIPS**