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A Guide to Assess the Operational Implications of New Ship Design Concepts.

Part III

by
E. L. Holmboe

28 February 1974

Prepared under Contract No. N00014-70-C-0426, Task NR 274-121
for Naval Analysis Programs (Code 431)
Office of Naval Research
Department of the Navy
Arlington, Virginia 22217

Operations Research, Incorporated.

OPERATIONS RESEARCH, Inc.
SILVER SPRING, MARYLAND

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This report covers concluding work performed for the Office of Naval Research, Naval Analysis Programs, under Contract N00014-70-C-0426. Two previous reports have been published under the same title: Part I, ORI TR 667, 11 June 1967, AD 728003; Part II, ORI TR 741, 22 March 1973, AD 759376. (continued on reverse side)

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Part III provides basic guidance and understanding to the planning analyst in the area of inherent operational advantages and limitations of the three major high-performance ship concepts under development today: (1) Small-Waterplane-Area Twin-Hull (SWATH); (2) Submerged-foil hydrofoil; and (3) Air Cushion Supported Vehicles (ACV and SES). Many other concepts are briefly introduced.

Concept descriptions, basic trade-offs, basic operational qualities, size range limitations and operational implications/potential applications are included. Discussion tends to be subjective and is designed to alert the analyst to potential problem areas rather than provide quantitative assessment of the concepts.

SUMMARY

This report covers concluding work performed for the Office of Naval Research, Naval Analysis Programs under Contract No. N00014-70-C-0426; two reports have been published.[1,2] The broad contract objective has been to develop analytical methods for evaluating the potential of advanced ship design concepts such as the hydrofoil, Air Cushion Vehicle (ACV), Surface Effect Ship (SES) or Small-Waterplane-Area Twin-Hull (SWATH) ship.

REPORT OBJECTIVE

This report summarizes the results and observations of three years of analysis and investigation into the potential military applications of the broad spectrum of advanced ship design concepts without extensive numerical displays. Instead, this report focuses on the advantages, limitations, trends and trade-offs associated with the platform with the intention of improving the planner's basic understanding of and appreciation for the potential capabilities of the ship concepts currently being pursued by the U.S. Navy.

This report is therefore directed primarily toward the planning support analysis that must be done at the OpNav level and above although it should be useful for any planning level at which a general knowledge of ship concepts is required.

It is the basic intent of the information presented here to suppress the normal tendencies toward overoptimism, an undesirable input to objective planning, and to guide the planning analyst to identify the critical uncertainties and address the appropriate issues.

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[1] E. L. Holmboe, J. M. Sheehan and A. D. Evans, A Guide to Assess the Operational Implications of New Ship Design Concepts, Part I, ORI TR 667, 11 June 1971, AD 729003.

[2] E. L. Holmboe and A. D. Evans, A Guide to Assess the Operational Implications of New Ship Design Concepts, Part II, ORI TR 741, 22 March 1973, AD 759376.

BACKGROUND

The previous reports concentrated on methodology development and demonstration. Part I presented an abstract approach based on a consistent set of measures of platform capabilities referred to as platform indicators and the hypothesis that a limited set of design parameters representing basic technology could be related to these indicators. Simple platform indicators highlight the speed, range, payload and survivability features; compound platform indicators are more mission-oriented, including patrol-type and transport-type missions. The most significant aspect of the indicators proved to be the adequate handling of the seakeeping/seakindliness qualities of the platform. (Following publication of Part I, the state of knowledge regarding ship's motions and added drag in waves was found to be inadequate to permit the development of an algorithm that could be easily employed in the analysis of conventional ships, even less for most unconventional ships.)

In Part II, work concentrated on the development of a model relating basic design variables to the indicators and the demonstration of the hypothesis put forth in Part I. The hydrofoil concept was used because of the availability of considerable design data, current interest in the hydrofoil as a patrol unit, and the lack of serious seakeeping problems for the submerged-foil concept. A deterministic model to compute patrol indicators was successfully developed and exercised to show the type of results that may be extracted from such an approach. Also included in Part II was an approach to synthesize the payload configuration for a hydrofoil, or any ship, in an ASW mission role.

During the performance of work under Parts I and II, opportunities existed to examine many analyses of future, hypothetical, advanced ship design concepts and the research efforts to strive for those hypothetical ships together with the extant technological uncertainties. The observed disparity between analysts' projections or assumptions and the state of technology suggested the need for this report as Part III of the three-part series. Part III therefore attempts to expose the limitations and/or uncertainties in the potential operational characteristics of the various concepts currently under development.

SCOPE OF REPORT

This report concentrates on three generic types of advanced ship design concepts:

- Hydrofoil, fully submerged types
- All known variations of the multi-hull, reduced waterplane, displacement ships, known collectively as SWATH or individually as MODCAT, SSS, TRISEC, Sea Sulky, etc.
- Air cushion-supported vehicles (ACSV) including rigid sidewalls (SES) or full-peripheral skirting (ACV).

For each basic type, the concept and its variations are described and the technological uncertainties and potential design trade-offs highlighted. General discussion is presented about basic platform operational qualities and includes cautions to be exercised in performing analysis. Growth potential is also noted. Limited subjective discussion is presented on the potential military applications and future operational implications of the concept.

In addition, certain other concepts are briefly introduced and their differences in potential operational qualities noted. These include such concepts as SWASH, Sea Knife, aerodynamic-lift concepts, sea plane, etc. In view of the rising concern for ecology and energy conservation, both the airship and the sailing ship are also included.

SUMMARY OF OBSERVATIONS

The following observations about the new concepts in general or each individually are more subjective and intuitive than accurately quantitative and are devised only to alert the planning analyst to specific advantages or disadvantages. Furthermore, these observations can only reflect the current state of technology and cannot reflect technological breakthroughs, concept improvements or the results of the ongoing research efforts. This discussion therefore should be treated as merely a guide, as the report title implies, and not a rigorous evaluation in itself.

Implications of "High-Performance"

The class of ships under examination here have also been referred to collectively as "high-performance" ships, the implication being that the reduced-drag characteristics of each may be exploited to yield increased speed potential. For example, the SES or CAB (rigid-sidewalled ACSV) has been widely advertised as a potential 100-knot ship whereas the full-peripheral-skirted type and the hydrofoil can operate in the 40-60 knot regime. If supercavitating foils are employed, the hydrofoil can also move into the 80-knot and above range. Even the SWATH-type ships have been viewed as 40-knot-potential platforms.

Such performance achievement requires the universal use of gas turbines. Gas turbines, while very good in power-to-weight ratio, are generally less efficient and perhaps more difficult to maintain than steam or diesel units. Because of further reduced efficiency at off-design conditions coupled with the "hump" in the drag vs. speed curve characteristic of most high-performance concepts, gas turbines tend to restrict operational flexibility by penalizing operation severely over a significant portion of the speed range. Furthermore, fuel consumption becomes a major, if not driving, consideration in high-performance ship design and operation.

Speed Loss in a Seaway

A former speed measure for conventional ships was the "calm-water" speed. More recently, speed in a reference wave height has been used to achieve a more realistic estimate of expected speed capability. Both are considered inadequate to reflect the speed capabilities of the various new concepts.

There is a definite need for a better measure of speed more adequately reflecting seakeeping performance. This need existed for conventional displacement ships but has become critical for consideration of the various new concepts that behave in a seaway much differently than conventional ships and from each other. A measure, or set of measures, that averages over all conditions, including wave height, sea direction, wind speed and direction, swell magnitude and direction and air temperature, is suggested (originally proposed as a methodology concept in Part I). Such a measure, termed "average sustained speed," should be calculated for reference geographic areas and time of year.

Maximum sustained speed for a specified set of conditions may be limited by power (added drag or reduced available power) or by motions (a criterion defining what motion is unacceptable is required). Under certain combinations of heading, sea state, etc., operation may not even be permissible. Again, each concept is uniquely different.

The ACSV concepts, as presently configured, appear to suffer most and the hydrofoil (submerged foil in flying mode) least. The SWATH-type are also well-behaved over much of the spectrum but are sensitive to certain combinations of speed, heading and sea conditions.

Habitability

In addition to motion-related speed constraints, crew comfort in various operating conditions is still an unknown quantity, particularly with the ACSVs, and limitations based on crew comfort must not be assumed to be nonexistent. Difficulties in scaling up from model and test craft data to full-scale ACSVs exist and create uncertainty in the ship motions area.

Maneuverability

The value of maneuverability is seldom addressed in evaluating the military potential of a concept. However, considerable differences exist among the current concepts, the hydrofoil with a Canard foil configuration being highly maneuverable and the ACSV and SWATH being relatively sluggish.

Hull Structure Weight

High-performance ships tend to be weight-critical and, in order to carry sufficient fuel for endurance and sufficient payload for military capabilities, hull structures must be kept as light as possible. Thus, aluminum becomes the primary construction material with an attendant increase in cost along with corrosion and fire protection problems. Only in the case of the SWATH ship is consideration being given to steel construction but deckhouses may likely be aluminum.

Major Trade-Offs Available

Although many design trade-offs apparently exist, there are only a small number that have impact on the operational characteristics in such a way that one characteristic must be degraded to improve another. The major characteristics that drive most trade-offs involve speed, endurance and payload. All other characteristics may often be unconsciously sacrificed to optimize these, primarily because only these three parameters are incorporated quantitatively into any planning-level system analyses. (For example, radiated noise is too often ignored as a significant operational characteristic and thus is inadvertently traded off for speed and/or endurance.)

Common to all high-performance concepts is the propulsion plant specification in terms of total power, number of turbines and propulsor which affects speed, endurance, payload and radiated noise.

Two major trade-offs peculiar to the CAB, or SES, are the length-to-beam ratio (L/B) and bubble pressure, both of which may be increased from the optimum values for high calm-water speed to improve seakeeping and payload capacity.

A major area of trade-off for the SWATH concept is the geometry of the submerged pods and struts. There are conflicting requirements for speed, motions and payload capacity; the differences between the SSP and TRISEC configurations emphasize the extremes of the trade-off.

A critical parameter peculiar to the hydrofoil is the foil-loading, i.e., the hydrodynamic lift per unit area of foil required to support the ship while flying. Low loading is advantageous with respect to take-off speed and power and drag at lower flying speeds while high loading is advantageous at higher speeds with respect to better range and higher maximum speed. The weight distribution on fore and aft foils appears to have little effect on speed, endurance or payload, but the Canard configuration (weight mostly aft) is generally preferred because of better machinery arrangement, dynamic stability and the requirement for towing submerged systems.

Size Range and Growth Potential

For the SES, there is no apparent restriction on generating lift, providing the required power, or structural design that would prevent some variation of the concept to be built. However, seakeeping problems for an ocean-going SES suggest that the low L/B is not desirable in sizes less than 2,000 tons or so. In larger sizes, practical considerations relative to the wide beam also prevent the use of the low-L/B, ultra-high speed SES. In both cases, the trend must be toward high L/B.

For the SWATH-ship being a displacement-type ship, there is no inherent limitation on size other than the wide-beam and draft limitations on the larger sizes. Some speed potential may thus be lost in the larger size range. Pod and strut geometry can likely be varied to give reasonable performance in the lower size ranges.

As with all concepts that derive most of their lift dynamically, the hydrofoil does not grow gracefully, for the foil area must increase out of proportion to other dimensions unless design speed is increased with increasing size. However, this growth-inhibiting characteristic should not detract from the fact that the submerged-foil hydrofoil offers a stable, ocean-going platform in relatively small sizes which has already been demonstrated.

Allowance for Concept Evolution

There are two paths of evolution to be followed. First, each concept can receive the benefit of some technology improvement or breakthrough that improves its operational qualities without significant changes in the basic principles. Examples include structural design improvements, increased propulsion efficiency, etc. The Small-Waterplane-Area Single-Hull (SWASH) evolved directly from SWATH with no change in the basic principle of reduced waterplane.

Second, certain features of one type of concept may be incorporated into another in a complementary manner. An example might be the addition of a submerged, actively controlled foil, or foils, to the SES or SWATH to improve seakeeping. Such combinations should permit a more continuous spectrum of operational characteristics for the planner to choose from and will likely have synergistic effects on the Navy's somewhat independent technology programs.

While the separation of R/D programs encourages a sense of competition, which is good, it discourages the cross-coupling efforts that may be vital to the success of any one concept.

Potential Applications for High-Performance Ships

There is little question that, if all other operational characteristics and costs were held fixed, increasing speed would increase a ship's military value in nearly any mission; however, other characteristics and costs are not fixed. The question really is just how much can be sacrificed and still show an increase in military value due to the increased speed. Despite efforts to establish these bounds, the question remains moot with two notable exceptions:

1. Hydrofoil patrol craft—a small, rough-water, stable platform for use in coastal or limited area defense against hostile ships of much greater value (a very favorable exchange ratio). The PHM is the result.

2. ACV landing craft—the uniqueness and obvious advantages of the amphibious quality of the full-peripherally skirted ACV, combined with reasonable speed, so outweigh the disadvantages that the match between concept and mission is sound. The AALC is under development.

In neither case is speed the only, if even primary, operational consideration. It is the stability of the hydrofoil and the amphibious capability of the ACV that, when combined with a speed potential of 50± knots, made the concept-mission match.

There are few mission areas for which the Navy will dedicate ships. There are many other missions that must be carried out and are generally covered by ships dedicated to the few primary missions. The SES, SWATH and larger hydrofoils have been matched to certain naval missions for which they appear uniquely well-suited, but most of these missions are not primary and therefore do not provide justification for ship development.

The one mission area for which a ship requirement may likely exist is ASW, including both escort-type and sea control-type missions. The SES, with its 80± knot speed, offers an inherent speed advantage over a submarine which, if properly exploited, could be an effective ASW unit. The SWATH, being a relatively stable platform with large deck area, could operate ASW aircraft in nearly all types of weather and could also represent a good sonar platform. The hydrofoil has only a modest speed advantage over a submarine but does offer a very stable platform from which to operate.

However well-suited the platform appears to be to the ASW mission, ASW is very much a sensor-oriented game and platform/sensor combinations are more easily demonstrated on paper than under actual operating conditions. Consideration of enemy tactics relative to their ultimate objective and the stand-off potential of submarine-launched cruise missiles may well offset the apparent advantages of a high-performance ship. In short, the complete ASW mission analysis becomes so complex and wrought with threat uncertainties that a particular concept can look either good or bad depending on assumptions. Therefore, using the ASW mission as the sole justification for the development of a ship of a new design concept is subject to irresolvable differences of opinion.

High Performance Ships vs. Energy Crisis

Should the energy crisis persist and eventually have long-term impact on the overall national defense posture, the need for high-performance, or more appropriately high-fuel-consumption, ships to serve as "backbone" naval elements becomes even more questionable than now. If fuel consumption becomes an issue on the same order of importance as cost, then the planner will strive to configure the future navy to maintain an adequate naval posture based on minimum cost and minimum energy. This suggests that high performance ships should be economical from a fuel consumption viewpoint at normal operating conditions and yet possess a high burst speed capability. Current concepts do not follow that general philosophy.

Energy considerations should increase interest in three areas: (1) alternative energy sources, perhaps more nuclear power in a wider range of power plant sizes of higher energy-to-weight ratios; (2) smaller conventional ships to reverse the current trend of increasing displacements for a given class, reduction being achieved by more miniaturization, automation, etc.; and (3) new low-energy-requirement concepts, particularly the airship and perhaps even the sailing ship, the airship being much more likely to be revived than the sailing ship.

Combining the existing nuclear power technology with the ever increasing threat to surface ships, the submarine may well become a serious contender for the more traditional surface ship roles.

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I. INTRODUCTION

There exists today a common belief that the next ten years and beyond will be a time of transition for naval combatant forces brought on by new ship design concepts categorically referred to as advanced high-performance ships. The U.S. Navy is still basically a displacement monohull navy with few exceptions, but the planners are being tantalized with new technology that promises to relax the traditional constraints imposed by the conventional displacement ship under which all navies have labored.

At this point in time, no large, ocean-going high-performance ships exist, but technologists can now claim with limited uncertainty that such ships are achievable. In particular, the hydrofoil, the Surface Effect Ship (SES) and the Small-Waterplane-Area Twin-Hull (SWATH) concepts are approaching that status.

While the technologists have pursued the development of these concepts and others, the planners have struggled with the question of the exact utility of such ships in the future naval force structure. Extensive mission studies have been performed, many different configurations and tactics examined and the potential cost-effectiveness of these ships widely touted. In the sobering aftermath of these efforts, the basic question still remains.

Before the planner can have confidence in his projections of future requirements vs. future ship types, he must possess a clearer understanding of the high-performance ship concepts, particularly the operational advantages and limitations, trade-offs available and areas of uncertainty. This report attempts to provide that basic understanding as objectively as possible. It should be used only as a guide since there is no way to predict technology breakthroughs or even concept modifications that overcome noted operational deficiencies.

OVERVIEW OF CONCEPTS

The new ship design concepts are generally categorized according to the primary lifting force, i.e., hydrostatic (buoyant), hydrodynamic, aerostatic and aerodynamic. All ships in the latter three categories are generally referred to as "high performance" which also may include certain high-powered hydrostatic concepts.

The conventional monohull displacement ship is a hydrostatic concept; so is SWATH. There are other unconventional hull forms that are conceived to reduce drag, increase power and achieve "high-performance" status, but such hulls still achieve speed more through brute force application of power rather than significant reductions in drag. However, any displacement ship becomes very efficient, in terms of lift-to-drag ratio (L/D), at low enough speeds because hydrostatic lift is "free." (L/D is infinite at zero speed.) Moving away from the interface, claims can be made for high speed submersibles based on newly conceived ultra-low drag shapes that appear to offer excellent potential for higher speeds or substantially improved endurance or range.

The hydrodynamic-lift concepts include conventional and unconventional planing craft as well as the hydrofoils. Any concept that achieves most of its lift from a hydrodynamic lifting surface, whether hull bottom or wing, is inherently limited in size, but in the appropriate size range, such concepts, especially the submerged-foil hydrofoil, can offer relatively high L/D ratios for higher speeds than displacement ships.

There is an intermediate category between hydrostatic and hydrodynamic known as transition or semi-displacement ships. High-speed destroyers approach this status while the PG ASHEVILLE Class gunboat is well into this transition region.

The aerostatic concepts, such as the Captured Air Bubble (CAB), Air Cushion Vehicle (ACV), and other variations create lift by pressuring an air cavity, allowing the craft or ship to rise up on a cushion of air. To reduce leakage from the air cavity, sidewalls may extend down into the water and/or flexible skirts fitted around the periphery. Propulsion may be provided by water- or air-propulsors. If no sidewalls or water-propulsors are used, the concept may be considered amphibious. Because lift power must be supplied, the lift-to-drag ratio is not too meaningful unless an "equivalent" drag, given as power/speed, becomes infinite. However, at design speeds, the lift-to-drag ratio is favorable.

Finally, the aerodynamic-lift concepts appear more as aircraft designed to operate in ground effect although certain concepts such as the ram-wing are closely coupled to the surface. The intent is to achieve very high speeds, up to 300 kt at acceptable L/D ratios. Such concepts require other lift mechanisms, either hydrodynamic or aerostatic, to lift off. It has the somewhat conflicting requirements of sufficient lifting surface area and ability to operate or survive in the water.

Status of U.S. Efforts

Table 1.1 presents a summary of current major U.S. Navy programs in high performance ships that are driving toward the ultimate deployment of major fleet units. As seen in the table, the hydrofoil has had more extensive development and evaluation for a much longer period than any other concept of current interest. More discussion on the status of these development efforts is included in later sections.

Up-to-date status reports on the hydrofoil, SWATH, SES and AALC programs were presented at the AIAA/SNAME Advanced Marine Vehicles Conference, February 25-28, 1974. Specific papers are as follows:

- "Hydrofoil Development--Issues and Answers," AIAA Paper No. 74-306
- "Recent Progress in Surface Effect Ship Development," AIAA Paper No. 74-312
- "JEFF Craft - Navy Landing Craft for Tomorrow," AIAA Paper No. 74-319
- "The Small Waterplane-Area Twin Hull (SWATH) Program--A Status Report," AIAA Paper No. 74-324.

MEASURES OF BASIC OPERATIONAL QUALITIES

The basic elements of operational quality are speed, range, payload, seakeeping, maneuverability, etc. Each concept offers a unique combination of qualities that differ from those of other concepts, including the conventional displacement ship. These differing sets of quality drive the planner to perform elaborate analyses attempting to weigh the advantages and disadvantages of one set vs. another, but a satisfactory outcome is seldom achieved. One of the major difficulties is the inability to trade off one quality for another; e.g., high speed in calm water vs. good stability in rough water.

High-performance concepts are only "high-performance," i.e., higher L/D ratios at higher speeds than those of displacement ships, but that should be interpreted as "efficient." Furthermore, describing concepts by L/D alone is limited and may be misleading. The better measures of quality should relate more directly to the operational characteristics, e.g., speed, range and payload, on which L/D impacts.

There are at least three basic issues common to the evaluation of the operational implications of all high-performance ships: (1) what is an adequate speed measure; (2) how are the limitations imposed by gas turbines measured; and (3) what are the limits and implications of lightweight structures? (Cost is momentarily ignored.)

TABLE 1.1

STATUS OF HIGH-PERFORMANCE SHIP CONCEPT DEVELOPMENT (U.S. NAVY)

Generic Type (Primary Lifting Force)	Specific Concept	Operational Craft	Maximum Speed, kt	Gross Weight, tons	Remarks
SWATH (hydrostatic)	SSS	NUC Workboat	25	190	Launched 1973
	TRISEC	Litton test craft			
	MODCAT	(Design studies and model tests only)			
Hydrofoil (hydrodynamic)	Subcavitating, Submerged-foil	PGH-1,2	> 40	60	Fleet Experience
		PCH-1	> 40	110	Fleet Experience
		AGEH-1	50	320	Experimental testbed
		PHM	> 40	220	Under construction as NATO patrol unit
		DEH	50±	1300±	Feasibility study only
	Supercavitating, Submerged-foil	DFH	30+	?	Long-term objective
ACSV (aerostatic)	Low-L/B SES	SES-100A SES-100B	70±	100	Launched 1972
		SES2K	80±	2000±	Concept design studies
		XR-1, XR-3	30-40	20±	Extensive testing
	Hi-L/B SES	XR-5	?	$3\frac{1}{2}$	Launched 1973
		(Other design and model test studies)			
	ACV	SK-5	60	8	British-originated, Extensive fleet experience
		AALC	50	160	2 under construction
		Arctic SEV	(many variations studied; requirement to clear 15-20' obstacles over ice; efforts significantly reduced)		

Average Sustained Speed as a Measure

One speed measure is hereby proposed to overcome the use of calm-water or specified sea state conditions as the basis for comparing concepts. Such a measure has always been needed but the existence of new, radically different ship concepts now force serious consideration of a measure that highlights the differences in seakeeping characteristics among the concepts. The measure should therefore reflect variations imposed by real-world conditions.

The basic approach is simple in concept. First, define representative sets of probability distributions for the pertinent environmental variables, a set reflecting the anticipated conditions for a geographic area and season of interest. Second, develop the probability distribution of maximum sustained speed for each set based on power-limiting and motion/habitability-limited conditions. Third, from the maximum sustained speed distribution, determine the expected value, or average sustained speed, as the primary measure. Secondary measures might include the magnitude of the variance of the distribution, probability of exceeding some specified speed, average range of headings to be avoided, etc. Also, the fuel consumption rate distribution should be developed and used to estimate an average fuel rate based on distance, i.e., fuel weight consumed per mile.

Implied is the requirement for extensive knowledge of the relationships of power and motions vs. every possible combination of environmental variables. However, even rough approximations may be adequate, or at least better than ignoring that set of conditions completely. Basically, maximum sustained speed should be expressible in the following form:

$$\begin{bmatrix}\text{Maximum}\\ \text{Sustained}\\ \text{Speed}\end{bmatrix} = f\left(\begin{bmatrix}\text{Wave height,}\\ \text{length and}\\ \text{direction}\end{bmatrix}, \begin{bmatrix}\text{Swell height,}\\ \text{length and}\\ \text{direction}\end{bmatrix}, \begin{bmatrix}\text{Wind speed}\\ \text{and direction}\end{bmatrix}, \begin{bmatrix}\text{Air}\\ \text{Temperature}\end{bmatrix}, \begin{bmatrix}\text{Ship's}\\ \text{Desired}\\ \text{Heading}\end{bmatrix}\right)$$

Summary-type statistics on each of the environmental variables are available from standard references. What is not so available is the degree of correlation among the variables. Also, ship's desired heading may be uniformly distributed over 360° or may be biased toward east-west headings for the North Atlantic, for example.

Differences among the concepts can be easily shown. For example, the hydrofoil, and possibly SWATH, may suffer little speed loss over a wide range of conditions from the calm-water conditions. The ACV and, to a lesser degree, the SES suffer more noticeable speed loss and increased motions for even modest sea conditions but the SES has a much higher calm water speed from which to degrade. Also, at some point, a concept has inadequate power to get over the "hump" and may then suffer a sharp drop in sustained speed. Furthermore, as with conventional ships, certain conditions are to be avoided; that range of conditions may vary considerably from concept to concept.

It should also be noted that average sustained speed does not necessarily reflect performance comparisons at less-than-maximum speed conditions because of the hump and requirement for lift power. Perhaps, an approach similar to the above but based on maximum range or minimum fuel rate (per mile) instead of maximum speed could be followed.

Implications of the Gas Turbine

The gas turbine has been widely touted for making high-performance ships possible—and rightly so; no other state-of-the-art power source approaches the high power-to-weight ratio of the gas turbine. However, there are two operational limitations of the gas turbine that impact on overall performance: (1) lower efficiency at design power when compared to steam or diesel units (can be minimized but at the expense of complexity and weight); and (2) even lower efficiency for off-design operation. The best operating regimes tend to be at power levels where turbines are operated at full power or are shut down; i.e., a two-turbine plant may tend to be operated at one turbine at full power and one shut down or both at full power. This limitation, when combined with the avoidance of hump speeds for sustained operation, may well limit overall operational flexibility.

The Need for Light-Weight, High-Strength Structures

High-performance ships tend to be as weight-critical as aircraft. However, the ship must survive seaway-induced loads which are normally resisted by more massive structure. These conflicting requirements force, or at least encourage, the introduction of light-weight, high-strength materials as well as more efficient structural design. Here is where the great schism between the traditional naval architects and the aerospace "high-technology" is manifested, or overpessimism vs. overoptimism about ultimate structural weight achievements. Unfortunately, projections for hull structure weight for large high-performance ships such as SES tended to be based on overoptimism; payload and/or range are very sensitive to any added hull weight.

In general, all high-performance ships currently under development have hull forms that require the inefficient use of structure material: the hydrofoil with its foil system and attachment to a hull that must resist slamming loads; the SWATH with its U-shaped hull with increased surface, bridging structure and uneven torsion-producing loads; the SES also with its U-shaped hull, thin sidewalls and low cavity height. Only the SWATH, being a displacement-type hull, may permit the very efficient use of steel.

Two additional considerations must be included relative to the use of aluminum for structural material: (1) aluminum's strength sags rapidly with rising temperatures, resulting in possible catastrophic damage from otherwise minor shipboard fires; and (2) corrosion.

ORGANIZATION OF REPORT

In the next three sections, each of the three basic concepts under serious development in the U.S. is discussed, with primary emphasis on the operational advantages and limitations inherent in that particular concept. The order of presentation is as follows:

Section II - SWATH

Section III - Hydrofoil

Section IV - SES, ACV

Much subjective analysis is offered as insight and areas of trade-off are suggested.

To round out any report on advanced ship concepts, Section V identifies other concepts under development by foreign governments or small groups in the U.S. Also, possible variations of existing concepts are indicated.

II. LOW-WATERPLANE MULTI-HULL SHIPS

The concept of reducing a ship's waterplane area in order to reduce wavemaking drag and motions has led to a number of variations of current interest. Because most current interest is centered around a double-hulled configuration, the term "Small-Waterplane-Area Twin-Hull," or SWATH, has become common. The SWATH ship generally consists of two submerged bodies attached to the bottom of struts which pierce the water surface and are attached to a bridging structure. There may be two, four or more struts of various sizes depending on the extent of waterplane reduction desired.

Three basic variations are shown in Figure 2.1. The Semi-Submerged Platform (SSP) has four small struts, two submerged cylindrical bodies and submerged foils added for improved stability control. The other two are similar in that the struts, whether two or four, are sufficiently large to forego active control. The TRISEC concept developed by Litton Industries and the Navy's MODCAT series fall in this grouping. There is also the Sea Sulky which is similar to the SSP except that the static waterline is at the top of the submerged cylinders and the control surfaces provide negative lift to submerge the ship to the proper depth at the proper speed.

STATUS OF U.S. PROGRAMS

There have been basically three lines of development for SWATH-type ships within the past decade.

1. Litton Industries conceived the TRISEC, performed many conceptual design studies and eventually built a 25-ft manned model which has been tested in open water.

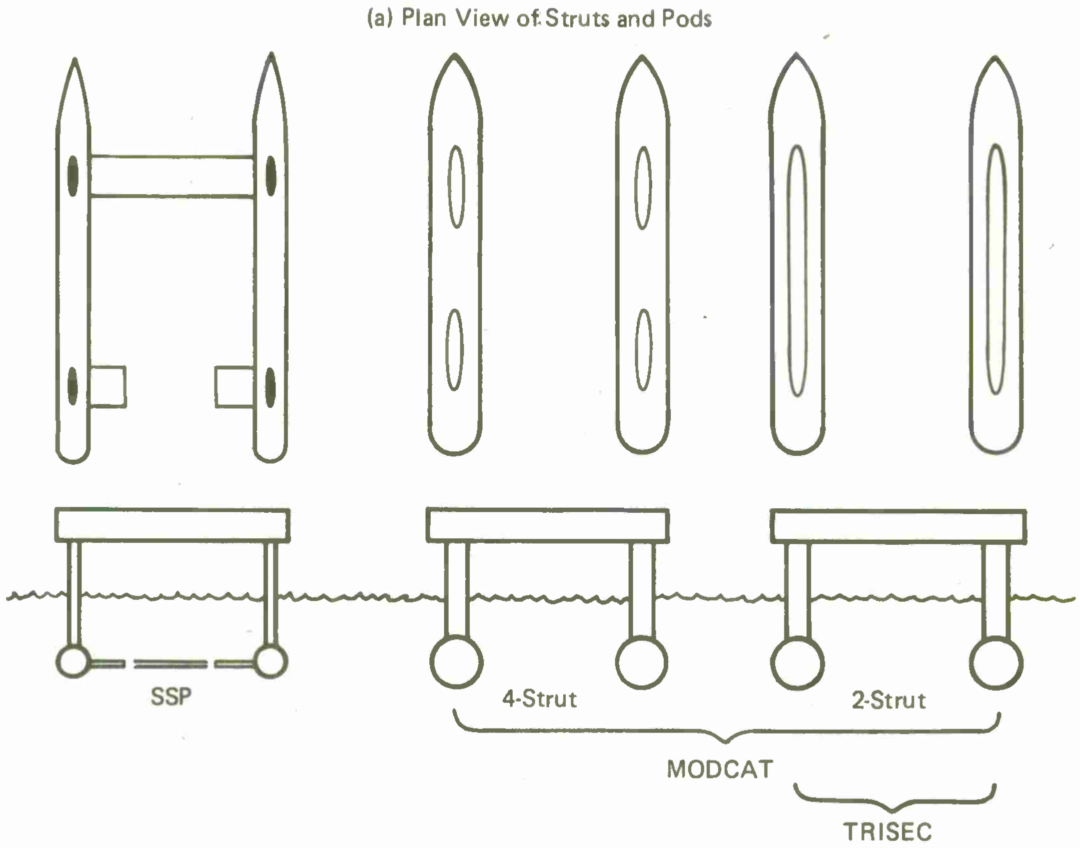

FIGURE 2.1. THREE BASIC VARIATIONS OF SWATH

2. NUC, San Diego, conducted model, theoretical, and conceptual design studies on the SSP which have led to the construction of a 190-ton testbed launched in August 1973.
3. NSRDC, partly under the direction of NAVSEC, has pursued the MODCAT series with at least three models being tested.

A project office has been established at NSRDC to permit an orderly development of the technology and general body of knowledge required to eventually build SWATH ships.

Although future plans are always subject to change, the U.S. Navy appears committed to continue the MODCAT program with an eye toward building a prototype of a next-generation PF, SCS or related ship type. Because MODCAT and TRISEC are parallel concepts, no in-house Litton efforts are apparent. Plans for the SSP appear limited to testing of the 190-ton craft which will serve as a workboat for the center.

As a matter of interest, foreign ventures into the SWATH-ship field include a Dutch drilling rig[1] launched in 1969 and the Sea Sulky which is yet to be brought to practice in terms of a test craft.

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[1] The Mohole project comes to mind here as well as other U.S. drilling rigs with reduced waterplane structures. However, such rigs were not designed as hydrodynamic hull forms.

BASIC PLATFORM TRADE-OFFS

The trade-offs available to achieve the proper balance of operational qualities are complex and not yet fully understood. The basic areas of trade-off are discussed here.

Hull Form and Structure

The geometry of the struts and submerged pods represent a wide range of possible variations, some of which may not yet be fully understood. Some of the basic variables include strut number, width, thickness and length, and pod number, shape, volume, and spacing. Also, stabilizing or lifting foils may be added.

Restoring moments are proportional to strut waterplane areas, strut spacing, and/or pod spacing. Pods provide damping. To minimize motions, a proper balance of strut and pod dimensions is desired. To minimize drag, the underwater forms should be designed for minimum surface and maximum surface wave cancellation; this implies reduced-size pods and struts. To carry payload, increased underwater volume or displacement is needed. Because this conflicts with the drag requirements, increased fuel or decreased speed is needed to maintain range.

The SSP represents the one extreme of a minimum drag configuration; i.e., four small struts, long narrow, torpedo-like pods, and active stabilizing outboard foils plus a fixed foil connecting the pods. To achieve a disposable load capacity (fuel plus payload), the entire structure is aluminum.

The TRISEC represents another extreme of maximum payload with acceptable motions; i.e., two very wide struts, large pods, no active stabilizers and steel construction to minimize cost.

Propulsion

If high performance is the goal, a conflict develops between the desire for narrow, small struts and small-diameter pods and the installation of gas turbines with gearboxes in the pods. In the 190-ton SSP, the gas turbines are installed above with a chain drive down through the strut. Even with larger-size pods and struts for slower-speed hulls, machinery space is still a problem and gas turbines, because of the high power-to-weight (and volume) ratio, are desirable. At some point, for large displacements and low speeds, diesel or steam power becomes desirable because of the increased efficiency.

Control Systems

Fixed, or perhaps adjustable, foils may be installed for motion damping. Actively controlled foils may be installed to counteract disturbing forces. Such added foils require additional structural complexity and represent added weight and added drag. In general, active control is more of a necessity for the configurations with slimmer underwater dimensions.

BASIC OPERATIONAL QUALITIES

The basic operational qualities vary in degree according to the selected trade-offs described above. However, certain qualities are inherent to the concept. Even though the variations possible are many and not yet fully understood, some discussion is included here as a guide to better understanding the concept's potential.

Speed

Sustained and/or burst speed capability in excess of 40 kt have been claimed and sought after by advocates of the different SWATH variations. This speed potential results from the reduced wavemaking drag of each strut-pod configuration as well as the favorable wave interference effects between the two sides. These effects are felt beyond a "hump" speed in the range of 25-35 kt; but note there is a hump and therefore a speed regime to be avoided for sustained operation.

As the ship increases in size, two factors relating to increased ship's length shift the hump up in speed until eventually the high speed potential disappears: (1) the increase in ship's length for fixed length-to-beam hulls of increasing size; and (2) width restrictions dictated by construction/repair facilities, canals, etc., will cause length-to-beam ratios to increase with ship size, thus making length increase even faster with size.

Furthermore, the high speed potential of configurations such as TRISEC using pods and struts that are relatively large may not be realized because of the power required to exceed hump speed, especially in the presence of seaway-induced added drag. However, the improved behavior in waves due to the small waterplane area will, in general, result in much less speed degradation than conventional ships under most conditions.

Although power requirements for a SWATH-type ship operating at above-hump speeds are much less than a conventional ship of equal displacement, the increased surface area of the SWATH compared to that of the conventional ship results in increased power requirements at lower speeds.

Endurance

Endurance, or range, should be an anticipated problem area for two reasons: (1) increased drag at the more conventional speeds where high endurance in conventional ships is expected and where SWATHs may be forced to operate frequently; and (2) the high structural weight, combined with payload, machinery and outfitting, will squeeze the fuel allowance, especially if projected hull structural efficiencies cannot be realized. However, the SWATH concept does have the potential for reasonably good endurance characteristics relative to the other weight-critical high-performance concepts because it can operate comparatively efficiently at low speeds.

Payload

Because fuel and payload are considered interchangeable, concern over fuel capacity applies to payload as well. Also, because of the volume available within the bridging structure and the large deck area on which to place superstructure or exposed payload, the SWATH concept should be considered more likely to be weight-critical than volume-critical with regard to payload. In fact, such features suggest missions in which low-density payload is required.

Motions

The SWATH ship can be quite stable in heavy seas depending on heading and speed (encounter frequencies can be well above resonance). However, there are also some likely combinations of sea state, heading and speed at which resonance occurs and therefore must be avoided. At moderate speeds, active control can be effective but its effectiveness decreases rapidly at lower speeds. However, all fixed or active control surfaces can provide some degree of damping to vertical motion at all speeds.

It should be emphasized that the high vertical accelerations witnessed on the Navy's two conventional catamaran ships are considerably reduced with the SWATH concept because of the decrease in waterplane area and therefore a corresponding decrease in restoring forces.

The remaining uncertainty appears to be the effect of complex torsional vibratory modes that are possible with the SWATH on high frequency vertical acceleration. The addition of control foils to dampen such motion may prove to be necessary.

Maneuvering

The solid, wide strut of the 2-strut SWATH offers good directional stability but this generally implies poor maneuverability. The use of smaller, multiple struts should alleviate this problem somewhat. It is possible to gain some advantage by using differential loads on the propulsors to assist in turning. However, for the wider-strut configurations, maneuverability will likely remain sluggish.

SIZE RANGE LIMITATIONS

Being a displacement-type ship, there is probably no serious structural limit to growth. However, beyond some point, geometric proportions cannot be maintained for two very practical reasons related to beam and draft limitations: (1) construction facilities; and (2) channels, canals, etc. Therefore, growth in length will be a greater tendency so that the above-hump speed potential will be lost.

There is probably no real lower limit on size down to the 190-ton size currently being tested, but there would be a tendency to approach the SSP configuration with active control as the size decreases. In very rough terms, this suggests an interesting evolution of configurations across the size spectrum with the SSP on the ≤ 1000-ton end, the high length-to-beam configuration at the ≥ 5000-ton end, and a high speed-potential MODCAT somewhere in between.

OPERATIONAL IMPLICATIONS/POTENTIAL APPLICATIONS

To summarize the potential operational characteristics to be exploited:

- A stable platform over an expanded operating regime relative to a conventional ship of equal size
- A possible dual sonar platform
- A possible high burst speed potential
- Large deck area, relatively large volume
- Damage control potential; large excess buoyancy in bridging structure.

The drawbacks are related to weight (and/or costs) and payload (and/or endurance) which may be restricted unless alleviated by one of two ways: (1) increased displacement, or (2) increased use of light-weight, high-strength materials; either way increases costs.

Suggested Uses

The uses suggested for the SWATH ship reduce down to three major areas: (1) as a VTOL/STOL aircraft support platform for ASW, amphibious support, mine countermeasures support, etc., offering improved weather resistance for its size and large deck areas; (2) as a logistics or general support platform for use as a tender, high-value cargo transport, repair ship, etc.; and (3) further exploiting its habitability features, as a troop transport, CIC ship, intelligence-gathering, surveillance, hospital ship, etc. All these uses tend to require low-density payload; i.e., aircraft and/or personnel habitat/work space.

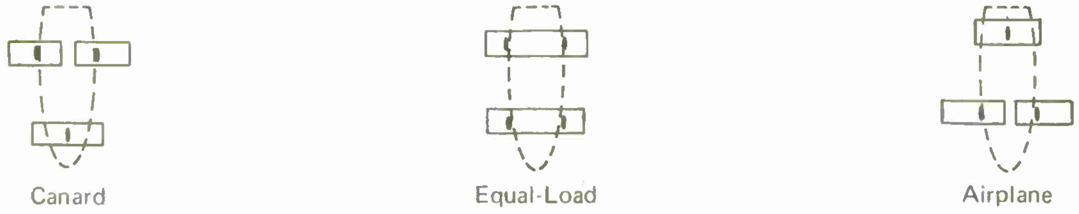
III. HYDROFOILS

The hydrofoil has been under active development by the U.S. Navy since the 1950s with effort concentrating on the submerged-foil approach. Submerged foils require active control to maintain stability but, in general, surface-piercing foils require no active control. In this section, discussion will center mainly around the submerged foil concept.

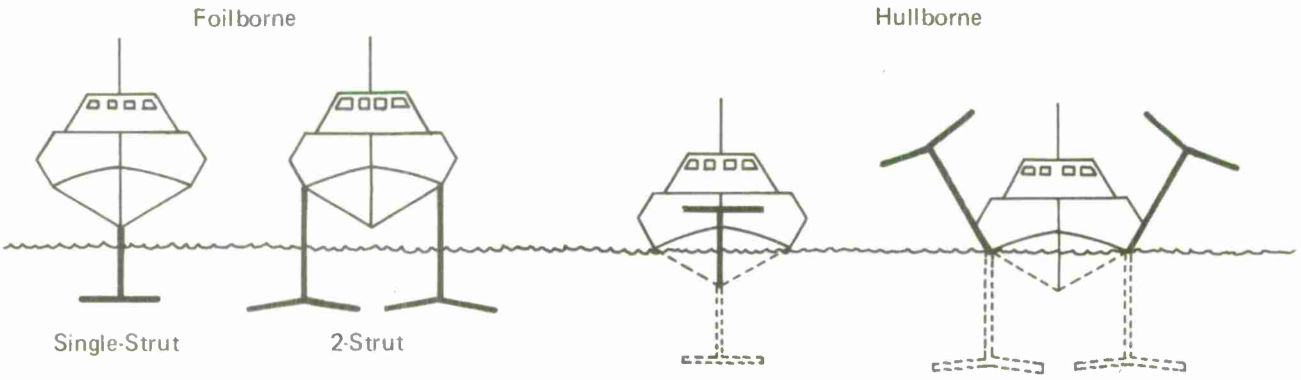
The incentive for U.S. hydrofoil development is basically twofold: (1) high speed potential relative to conventional ships; and (2) a stable platform, even in rough water, even in small sizes.

The basic submerged-foil concepts are shown in Figure 3.1. Hydrodynamic lift generated by the foils provide most of the total lift in the flying mode and maximum speeds on the order of 45-60 kts are achievable with subcavitating foils. Supercavitating foils, which are not yet state-of-the-art technology, would permit speeds in the 80+ kt speed range. In Figure 3.1(a), three basic foil configurations are shown: (1) Canard—most weight on after foils with forward foils used for control; (2) airplane—the reverse of the Canard; and (3) equal weight distribution. Foils may be retractable or fixed.

Because of the added foil structure, the hydrofoil is definitely weight-critical and light-weight, high-strength materials are required.



(a) Foil Arrangements



(b) Bow-On View

FIGURE 3.1. BASIC SUBMERGED-FOIL CONCEPTS

STATUS OF U.S. PROGRAMS

Of the advanced high-performance ship concepts, the hydrofoil, aside from the planing hulls, has acquired the most operational experience in the open ocean as a naval unit. Two 60-ton gunboats, one 120-ton coastal patrol boat and one large (320-ton) experimental craft have been built and operated in various experimental configurations. Operational experience includes coastal patrol operations in South Viet Nam, open sea surveillance in the Mediterranean and Coast Guard operations in the Atlantic. Unfortunately, during night operations in the Caribbean, the 60-ton TUCUMCARI experienced one of the drawbacks noted for hydrofoils by running aground on a reef and suffering severe damage.

A class of 200+-ton missile patrol boats, known as the PHM, is under construction by Boeing Co. to serve NATO countries and closely parallels Boeing's current efforts to build and sell a 100-ton commercial version.

Recent R/D efforts have concentrated on the development of a 750-1500 ton conventional hydrofoil (DBH) and later a high-speed, smaller hydrofoil using supercavitating foils (DFH). Both efforts have been delayed but some interest persists in an escort hydrofoil (DEH) but no firm construction plans are apparent.

No other submerged-foil hydrofoil development is known to exist outside the U.S. although Canada built and operated the 63 kt, 200-ton Bras D'Or with fixed surface-piercing foils successfully in rough water.

BASIC PLATFORM TRADE-OFFS

Most of the important basic trade-offs lie in the foils and the propulsor.

Foils

Foils may be retractable or fixed, the retractable type requiring more structure, mechanisms, etc., which generally means increased weight. However, draft restrictions, among other minor considerations, encourage this feature. All current U.S. Navy hydrofoils have retractable foils.

The foil configuration, i.e., Canard, airplane or equal load, can be simply described by load distribution fraction, the Canard being around 35% forward, 65% aft, whereas the airplane is nearly reversed at 70, 30. There appears to be very little difference in weight among the alternatives but the Canard has three attractive features: (1) high maneuverability using a steerable forward foil; (2) large foils aft in which propulsors may be located; and (3) larger foils aft permit higher towing loads. There is little reason why the Canard should not be preferred.

The major variable to be selected for the foils is the foil loading, i.e., dynamic lift per unit area of foil. A minor variable is aspect ratio but high aspect ratio is always good so that this variable is controlled more by technology or other considerations.

The major components of foil-related drag, which is most of the total drag, are associated with lift-induced drag and frictional drag. For decreasing flying speeds, lift-induced drag increases and frictional drag decreases whereas the opposite is true for increasing speeds so that lift-induced drag can dominate at the lowest flying speed (until stall occurs) and frictional drag dominates at higher speeds.

For a high foil-loading, the total foil area is smaller so that frictional drag is lower but lift-induced drag is higher. This implies two features of highly loaded foils: (1) higher maximum speeds for the same power levels; and (2) higher take-off speed coupled with higher required take-off power. In fact, take-off power requirements tend to dominate power plant specification for hydrofoils of high foil loadings. The opposite, of course, is true for lower foil loadings; i.e., lower take-off and flying speeds, lower take-off power, lower maximum speeds.

The choice of foil loading depends heavily on anticipated application, e.g., high loading for high speed potential, low loading for low, sustained flying speeds. Ideally, one desires the best features of both, which can be achieved by somehow reducing foil area as speed increases; ideas include retractable flaps on foils or retractable additional foils. It should be noted that surface-piercing foils can achieve this feature automatically; i.e., as speed increases, the ship rises further so that less foil is submerged.

Propulsor

Two basic types of propulsors are used: (1) waterjet and (2) waterscrew (propeller). The waterjet intakes are generally in the junction of the foils and struts and the water is then carried in ducts in the struts to the pump in the hull and ejected to the air through the transom. Large intakes and ducts are desired to minimize head losses but the large entrained volume of water represents noticeable added weight and encourages smaller ducts, etc. The waterjet is basically simpler than the waterscrew which requires mechanical transmission down through the foil struts, which are retractable, to an enlarged pod on which the propeller is mounted or an angled shaft which is exposed and likely difficult to retract.

In the 40-50 kt range, the waterjet is generally less efficient than the waterscrew but becomes a necessity in the 60-80 kt range. Its performance degrades more at lower speeds and generally requires a secondary diesel engine/waterscrew unit for hullborne propulsion. However, the waterjet, including the entrained water, may have slight weight advantage over the waterscrew, which is an important comparison in such a weight-critical ship concept. Finally, the waterjet is likely quieter with respect to underwater radiated noise.

BASIC OPERATIONAL QUALITIES

Speed

As indicated above, the hydrofoil with subcavitating foils and either type of propulsor can achieve maximum speeds on the order of 45-60 kt depending on foil loading and installed power. The other significant speeds are: (1) take-off speed, generally 20-30 kt, again depending on foil loading; (2) minimum-fuel-consumption flying speed, generally 25-40 kt, depending on foil loading, propulsor type and gas turbine configuration.

The most important aspect of the submerged-foil hydrofoil's speed quality is the ability to maintain high speeds in rough water, even for small sizes. For example, a 60-ton hydrofoil will show little speed loss in sea state 3 and can remain flying in even higher sea states. Larger hydrofoils, such as the PHM, will perform even better. This yields an average sustained speed (see Section I) for many geographic areas and seasons which may well exceed even that for the SES, particularly for similar size craft.

Endurance

The hydrofoil has had an endurance problem. Even operating at its optimum speed and with minimal payload (maximum possible fuel load), it was long believed that range is generally limited to 1500-2000 nmi or less, regardless of size. However, recent design studies suggest an increasing disposable load fraction with size, reaching perhaps 50% at 1000 tons; the gain is mostly in machinery. This could yield ranges over 3000 nmi by carrying more fuel, not improved efficiency. As seen in Section V, there are possible ship concepts achieving a lesser part of their lift from submerged foils that may relax this range limit; therefore, the range limit applies only to the true hydrofoil concept.

Payload

Being very limited in payload/fuel capacity, there is an incentive to increase ship size, not to increase range or improve stability necessarily, but to provide some capacity for a reasonable payload package, particularly in light of the increasing disposable load fraction. It should also be noted that the good seakeeping/seakindliness qualities of the platform seem to reduce the frequency and severity of shock loads on equipment and perhaps certain payload elements may be made lighter, e.g., radar masts.

Motions

As already indicated, the submerged-foil hydrofoil offers a stable platform for most sea conditions up to very high sea states. However, as with most ships there are still conditions of heading, sea, state and speed that must be avoided; running in a following sea can result in loss of lift and/or control because of reduced, variable water velocities across the foils. The hydrofoil is therefore also not unrestricted over its range of operating conditions, but these restrictions are likely less severe than most other ships.

In the hullborne mode in rough water, the foils must not be retracted and do provide considerable motion damping even at low speeds.

Maneuverability

The combination of a properly configured foil system including a steerable foil and a properly designed control system which can actively control banking to maintain a vertical (relative to craft) acceleration vector permits small-radius turns unmatched by any other concept under active development. (Some reference should be made here to the Sea-Knife concept described later in Section V.)

SIZE RANGE LIMITATIONS

The "cube-square" law is often referred to when describing the growth potential of hydrofoils, or any dynamic-lift vehicle for that matter. The observation is made that, if the vehicle were scaled up geometrically in size, the gross weight would increase as the cube of the dimensions but the dynamic lift would only increase as the square of the dimensions at constant speed. This then implies that foil dimensions must grow disproportionately faster with size than other dimensions. The technologists, however, point out that the lift contribution due to buoyancy offsets the dynamic lift requirements somewhat so that the effect is not quite as severe as "cube-square." Increased design speed, which might not be desirable otherwise, can also reduce lift area requirements.

An example of the cube-square effect could be seen on a Boeing conceptual design of a 4400-ton hydrofoil with a main foil span nearly equal to the ship's length.

There are concepts, as seen in Section V, currently being investigated that achieve only a portion of the total lift dynamically with as much as 80% being provided by buoyancy. These really must be classified as foil-augmented displacement ships. As for the true hydrofoil, its upper limit is reasonably firm.

It must be recognized that the hydrofoils offer some very unique features as relatively small ships, primarily its seakeeping performance. This uniqueness should probably be exploited more aggressively than attempting to enlarge it into a size range where this uniqueness wanes and serious competition from other concepts begins.

OPERATIONAL IMPLICATIONS/POTENTIAL APPLICATIONS

The operational characteristics to be exploited are: (1) stable platform, even in small sizes and in the open ocean environment; (2) speed potential of 45-60 kt, even under most environmental conditions; and (3) good maneuverability. The basic drawbacks are payload/range limitations and vulnerability to a control failure or ramming a floating object.

As a result of existing experience and in light of the above discussion, there is an obvious application for coastal defense or limited area defense that is already being pursued with the PHM. It can operate effectively in heavy seas against much larger ships, thereby showing possibly a very favorable exchange ratio and speed advantage as well as a consistently high area coverage rate.

Although used as a surface surveillance unit in the Mediterranean, its limited endurance restricts its use to close support situations in which aircraft can also compete.

Much interest has been exhausted on the use of hydrofoils to combat submarines, primarily because demonstrated ASW applications are generally sufficient justification to build new ships. High-speed towed sonars, low-speed towed sonars used in a sprint-drift mode, foil-mounted sonars, dipping sonars used in a sprint-stop mode, sonobuoys, etc., have all been considered but the sensor/platform match in a realistic tactical situation is still uncertain. Because, in larger sizes, it could have the capability to operate helicopters, AAW systems as well as some sonar capability, it has seriously been considered for an escort role.

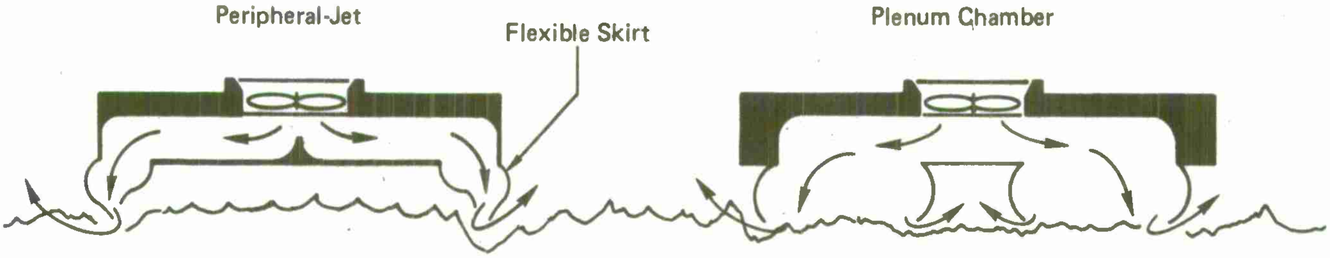
IV. AIR CUSHION SUPPORT SHIPS (SES, ACV)

The SES and ACV fall under the general category of aerostatic lift concepts; i.e., lift is provided by pressurized air being fan-forced into either cavity or through downward-directed jets. The early versions of Ground Effect Machine (GEM), or ACV, were platforms using high volumes of forced air to maintain lift; the addition of flexible skirting around the periphery considerably reduced air volumes, and therefore power. Increased drag resulted but was minimized by better skirt design.

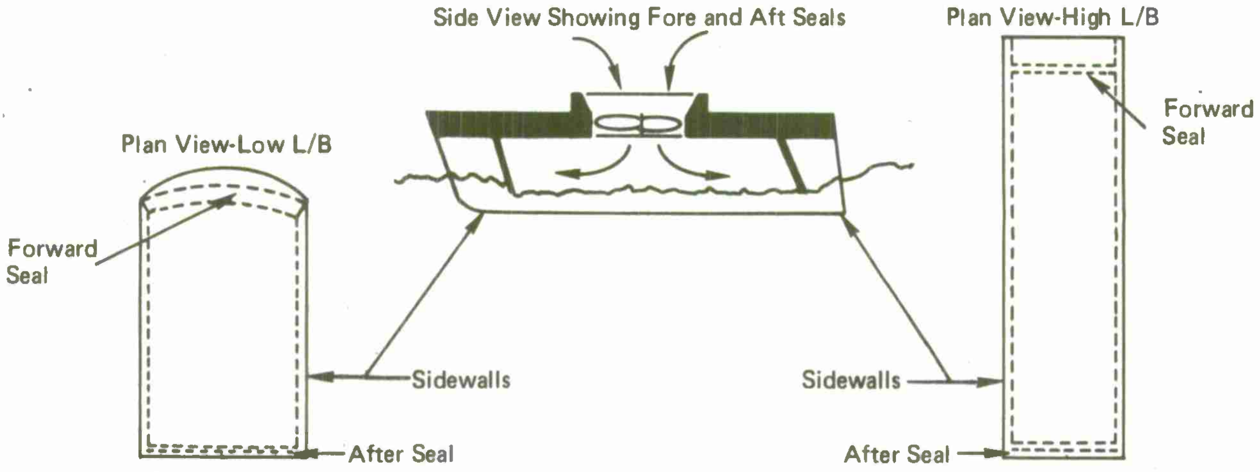
In recent years, the British have concentrated on the full-peripheral skirted ACV using air propulsors in order to maintain the amphibious capability. There are two basic variations followed to overcome the stability problems inherent in a single-cavity vehicle: (1) air jets around the periphery just inside the skirts; and (2) division of the air cavity into separate chambers. Both these approaches are designed to provide restoring moments as the vehicle rolls. The British have followed mainly the peripheral-jet approach.

The Captured Air Bubble (CAB), or SES, is a further extension of the concept in which the amphibious capability is sacrificed by adding rigid sidewalls that extend into the water, thus reducing air leakage for lower lift power, permitting higher air pressures for greater lift capacity, and permitting the use of water propulsors for greater power levels. Flexible skirts seal the fore and aft boundaries of the cavity.

At this point in time, the three basically different concepts as shown in Figure 4.1 may be distinguished by their basic operational properties: (1) the full-peripheral-skirted ACV, whether peripheral-jet or plenum chamber, amphibious and capable of 50± kt maximum speeds; (2) the low length-to-beam ratio ($L/B \sim 2$) CAB or SES with rigid sidewalls and a maximum speed potential of 80-100 kt; and (3) high length-to-beam ratio CAB ($L/B \sim 6$) with rigid sidewalls, a speed potential of only 50± kt but improved seakeeping and reduced power requirements.



(a) Fully-Skirted, Amphibious ACV



(b) Captured Air Bubble

FIGURE 4.1. AIR CUSHION SUPPORTED CONCEPTS

The components of drag, each of which are significant over some portion of the speed range, include air profile drag, wave-making drag created by the displacement of the pressurized air bubble, momentum drag resulting from accelerating the lift air, wetting or spray drag, and water profile drag for submerged parts. The wave-making drag causes the familiar hump in the drag-vs-speed relationship. The speed at which the hump occurs again depends on length; therefore, the low-L/B ACV and CAB can operate above hump but the high-L/B CAB operates below hump.

Lift power should always be included in any discussions of total power requirements, fuel consumption estimates and lift-to-drag (L/D) ratio if comparing with other concepts. If an equivalent drag were calculated as lift power/speed, then as the speed approaches zero equivalent drag approaches infinity; therefore, effective L/D approaches zero. This suggests possible problems with efficient operation at low speeds if the bubble is maintained.

STATUS OF U.S. PROGRAMS

The major U.S. Navy effort in full-peripheral-skirted ACVs is currently the development of the AALC, a 150-ton, 50-kt amphibious assault landing craft. Two prototypes are to be built to examine various technology differences, including peripheral jet vs. plenum chamber.

Another program, the Arctic Surface Effect Vehicle (SEV), was started but is now in limbo even before a firm configuration that could clear 20-ft obstacles and travel at high speeds over pack ice could be decided upon. Consideration was given to possible use of aerodynamic lifting surfaces as well as aerostatic lift.

The program currently receiving the most attention is the Navy's efforts to develop the low-L/B CAB into an 80- to 100-kt naval ship. Two 100-ton test craft are operational and contract design on a 2000+ -ton SES has been conducted. In the mid 1960s, the Navy inherited sole responsibility for SES development when the Maritime Administration backed out of a joint venture with the Navy because of the uncertainties about the concept's potential for future commercial transport. At this point in time, the Navy has paused for a serious reevaluation and the future of the SES, as it is presently configured, is at best uncertain.

The seakeeping problems that became more apparent during the testing of the 100-ton, low-L/B test craft encouraged the Navy to pursue high-L/B SES concepts. Plans for more than small test craft are probably only in the formative stages.

BASIC PLATFORM TRADE-OFFS

The major trade-offs that affect operational characteristics appear limited once the L/B ratio is chosen and the sidewall-vs-full-peripheral skirting decision is made. There may be some limited variation possible on bubble pressure; higher pressure means more lift power and higher drag, particularly at hump speeds but it also means greater payload-carrying potential. However, increased fuel weight to maintain range tends to offset this.

Air propulsors are generally used with the ACV concept to maintain the amphibious quality, whereas water propulsors are generally desired with rigid sidewalls. For the 80- to 100-kt SES, waterjet, supercavitating propeller or a semi-submerged propeller may be used with roughly comparable efficiencies. For the 40- to 60-kt SES, waterjet or subcavitating waterscrew are possible although the screw is slightly more efficient.

Some consideration has been given to venting the bubble aft for low-speed propulsion or for maneuvering assistance.

BASIC OPERATIONAL QUALITIES

Speed

Much data have been compiled on ACV performance in calm water and various wave and wind conditions for craft sizes up to 160 tons. The ACV is very sensitive to even modest wave conditions; in fact, for equal sizes, the ACV's performance degrades faster than any other known concept. Therefore, the calm water speeds reaching as high as 60 kt are not realistically achievable in open water.

The rigid-sidewall, low-L/B SES, capable of 80-100 kt in calm water, also suffers speed degradation in relatively modest waves but percentage speed loss is not as pronounced as that of the ACV. The SES has a low hump speed, say 30-40 kt, relative to its maximum speed and drag beyond hump is fairly constant out to 80 kt so that the SES may permit a wider range of relatively efficient operating speeds, depending on the gas turbine arrangement.

The high-L/B CAB operates below hump since the increase in length increases hump speeds out to beyond the operating speed range of ≤ 50 kt. It therefore has no hump to contend with. Further, it is not as sensitive to the sea conditions as either the ACV or low-L/B of similar size.

However, compared to the hydrofoil and SWATH concepts, all current ACS concepts suffer noticeable speed loss over most environmental conditions and, in turn, suffer differently relative to one another. This observation is largely responsible for the author's interest in creating a realistic speed measure by which more valid comparisons are made. (See Section I for definition of average sustained speed.)

Endurance

The ACV, because of the constant lift power to overcome leakage and the limited pressure that can be maintained thus limiting fuel load, has an upper limit on time endurance. Also because of the limited fuel load, range is limited, particularly in a seaway because of the significant added drag at the normal best operating speeds. It should be noted that, in larger size, the leakage, which is approximately proportional to the peripheral distance, increases only as the cube root of gross weight (for constant pressure). Therefore, in very large sizes (≥4000 tons), pressure may increase and leakage decrease to the point that makes rigid sidewalls unnecessary for sealing; the ACV and low-L/B concepts may then tend to merge in the large sizes.

Compared to the ACV in sizes less than 4000 tons, the CAB concept with rigid sidewalls uses less lift power with increased bubble pressure permitting higher fuel capacity, and therefore can realize higher time endurance. The low-L/B SES may achieve higher ranges because of the relatively modest power required at very high speeds. However, if sea conditions limit speeds appreciably, say to below 50 kt, range capability suffers. In the 50 kt and under range, the high-L/B should show much better range capability because of the reduced power requirements in that range and improved seakeeping.

Current estimates of disposable load (fuel + payload) capabilities for projected SES configurations may be optimistic; there remains some uncertainty about the achievable hull structure weights. The concern is based on the observation that a U-shaped hull configuration must represent a challenge to minimize weight without sacrificing the ability to survive extreme conditions. Wave impact loads at ultra-high speeds or off-bubble conditions must be seriously reexamined. In fact, design criteria relative to surviving such conditions may ultimately be sufficiently stringent to force heavier structures than currently projected. Thus, combined with the probable addition of active forward control foils for motion control, some disposable load must be sacrificed.

Payload

The above discussion on disposable load weight applies here on payload weight limitations. However, all considerations included, the SES very likely will show improved payload capabilities over hydrofoils or ACVs over the appropriate size ranges. Also, payload deck space and volume are probably not limiting. However, speeds of 80 kt, or even 50 kt, encourage aerodynamically smooth exteriors, suggesting that weapon systems, radars, embarkable craft to be as flush-mounted as possible, thus consuming interior space not usually allowed for such systems. This may, however, represent a weight savings because of reduced weight of mounts resulting from reduced exposure.

Motions

Motions represent the one area where an order-of-magnitude improvement would be gratefully appreciated. British experience with ACVs up to 160 tons show high vertical accelerations which are tolerable for short periods of time. Therefore, such motions are probably acceptable for an AALC which spends 1 to 2 hr in transit to the beach. For the longer endurance SES, crew comfort considerations are more important, possibly seriously restricting speed and heading for many sea and/or swell conditions. With the concept as currently envisioned, the suspected motion problem creates the incentive to increase ship size and/or increase the length-to-beam ratio.

It is interesting to note that motion prediction for all aerostatic ships of larger sizes is uncertain due to problems in scaling from model and small craft test data to much larger sizes. The uncertainty centers around the behavior of the pressured air volume involving volumetric changes due to water surface changes, venting, lift-fan variations, etc., and air compressibility. Programmed lift-fan variations may help attenuate vertical motions. Therefore, motion problems in the larger sizes can only be suspected but not positively confirmed. This applies to the 2000-ton SES as well.

The addition of other motion-damping systems such as fixed or active foils may help considerably without too much sacrifice in speed or weight. This may come as the SES concept matures.

Maneuverability

The full-peripheral-skirted ACV is intentionally designed to minimize any contact with the water and to avoid protrusions to remain amphibious; it is therefore susceptible to high crosswinds affecting directional stability and sluggish in turning because sufficient lateral forces are difficult to generate. Also, because it tends to roll outboard on a turn, unintentional inboard venting may generate retarding forces, thus further resisting turning.

The rigid-sidewall concepts should not have the same directional stability problems because of the submergence of the sidewalls. However, these same sidewalls, if sufficiently long, restrict turning; the high-L/B concept should be very difficult to turn. As with SWATH, the use of differential loads on the two propulsors should help. The SES should also have low resistance to outboard roll in a turn, possibly representing a serious constraint at high speeds. Question: What is the turning requirement for an 80-kt ship to avoid collisions with conventional or other high-speed ships? Low-profile obstacles? Cruise missiles? Hostile ships? Aircraft? etc.

SIZE RANGE LIMITATIONS

There appears to be no inherent physical limitation, such as the cube-square effect for dynamic-lift craft, to the growth of aerostatic ships. Cube-square limits would apply if air pressure were held constant, but it need not be; pressure can increase with size at a rate consistent with leakage rates, sidewall immersion, etc. The upper limits will be practical ones that restrict beam such as canals, etc.

Motions, however, will dictate a lower limit for true ocean-capable ships, the 2000-ton, low-L/B SES being marginal. Smaller sizes of high-L/B concepts may be ocean-capable because of the increased length relative to its weight. Therefore, the low-L/B concept may be feasible over only a relatively small range of sizes, being bounded on the lower end by seakeeping and on the upper end by practical considerations. Beyond either bound, the high-L/B concept is required.

It has been suggested that, as the low-L/B SES increases in size, full-peripheral skirting becomes more efficient than sidewalls because the reduced drag may more than offset increased leakage effects. This implies that the ACV and low-L/B SES concepts may well merge in the ocean-going size range.

OPERATIONAL IMPLICATIONS/POTENTIAL APPLICATIONS

The amphibious capability of the ACV in the smaller size range sets it apart from the CAB-type concepts and is probably the major operational characteristic to be exploited making it capable of shallow-water, over-the-beach or overland operations. It can clear modest-size obstacles and is practically immune to submerged obstacles that have been historically effective in deterring amphibious assaults. Added to this is a speed potential of 40-60 kts. It also may be difficult to destroy with existing types of sea mines. The ACV's drawbacks are basically: (1) endurance and/or payload-limited; (2) poor controllability in crosswinds; (3) substantial speed loss coupled with motion problems in a seaway; and (4) susceptibility of skirt damage accompanied by loss of control.

Modified versions of the British SR-N5 ACV were used extensively as highly mobile gun platforms in the Mekong Delta region of South Vietnam which is combination canals or channels and marshland in between, unsuitable for most other types of military hardware. Similar units are in use by the Iranian Navy (in fact, Iran will soon have the world's largest hovercraft navy, about 200 units) in the Persian Gulf where much inshore marshland exists. The AALC now under development offers a highly mobile (relative to existing landing craft), amphibious capability for assault-type operations, particularly against well-defended beaches. These current applications all exploit the amphibious quality as well as speed and do not demand extended-time habitability considerations.

Many studies have been performed attempting to justify ACV application to ASW, mine warfare, etc., but ultimately resulted in no or little justification for such applications.

The low-L/B SES offers a speed potential of 80-100 kt as its major, exploitable operational characteristic. Other features such as large deck space, high wind speeds for aircraft takeoffs, reasonable endurance/payload capability, invulnerability to torpedoes, etc., are often cited as well. The drawbacks are basically related to seakeeping: (1) speed degradation, and (2) habitability. Others might include skirt wear or damage, poor fuel economy at lower speeds, limited maneuverability, etc.

A 2000-3000 ton, 80-kt SES has been a long sought goal, with justification provided by a major CNO-sponsored study in 1969 and culminating in the 1973 design competition to eventually build 0, 1 or 2 prototypes. Justification has generally been based on the strategic aspects of examined missions, i.e., shorter reaction times and fewer days at sea than conventional ships; therefore, costs, when based on time-at-sea, make the SES competitive. But the value of shorter reaction times is always difficult to assess. What is the relationship of response time vs. some mission success measure for a fast response mission? Do high transit speeds reduce total time at sea and

and therefore increase sorties per year? Or do the realities of speed loss in a seaway, loitering, logistic support, rendezvous with other forces, etc., minimize that advantage? No attempt is made here to answer these questions.

From a tactical viewpoint, ASW has probably been of greatest interest. The apparent speed advantage of an 80-kt ship over a 30± kt submarine could possibly permit sprint/drift or sprint/stop operations and still close on the submarine, given proper sensor suites. But sensors are a very big problem: attached sensors may be towed, dipped or hull-mounted and are in general sensitive to speed; detached sensors may be rocket-fired sonobuoys, or helicopters with various sensor suites. Competition from land- or carrier-based aircraft is keen and the existence of the submarine-launched cruise missiles may make such dynamic, close-in tactics obsolete.

Claims have been made that the SES is invulnerable to torpedoes and less vulnerable than conventional ships to missiles. This is a very weak argument in light of technologically feasible missiles capable of high-acceleration turns. It may, however, as with ACVs, be less vulnerable to bottom mines, even in shallow water, unless a mine mechanism can be developed to detonate the mine ahead of the ship so that the bubble created by the explosion vents under the ship. This assumes that insufficient sidewall submergence exists for the pressure waves to shock-damage the underwater parts.

Other serious applications contemplated for the SES include logistics, amphibious warfare and possibly patrol/escort/surveillance. Missions such as mining, troop transport, crisis control, etc., do not solely justify its existence. The area of logistics is difficult to justify except in the presence of a special type of threat that can be defeated by speed; the long-range, highly maneuverable missile does not necessarily fall into that category. The potential surprise aspects of SES-based amphibious operations may not be realizable in light of other slower elements of the total assault force. For the patrol/escort/surveillance role, it does not loiter or station-keep with slower units efficiently and may not have the staying power required.

Fundamental to all the above mission applications is its sensitivity to the environment, suffering substantial speed losses in moderate to heavy seas so that 80 kt may not be a realistic achievable speed. Perhaps, an average sustained speed for typical North Atlantic weather may not be half that. As the concept is currently evolving, with overemphasis on speed, it is probably not appropriate for a major naval role. Hybrids with the Small-Waterplane-Area Twin-Hull (SWATH) concept to give up speed and gain payload and stability, or with submerged foils added to improve stability at small costs in speed should be considered.

The high-L/B CAB, in the smaller sizes, has been considered for a patrol craft. In the larger sizes (beyond the range of the low-L/B SES), it has been examined to fulfill nearly any role currently handled by large conventional ships, including aircraft carriers. Such large-size applications may be decades away, but the small patrol boat could be within state-of-the-art technology.

V. OTHER CONCEPTS

In the preceding three sections, discussion centered around three fairly pure concepts that have been actively pursued by the U.S. Navy up to the present. Many other concepts, either variations of these three or uniquely different, have been identified and some pursued privately, by foreign governments,[1] or formerly by the U.S. Navy.

In the absence of some dramatic event that could modify current views, it is appropriate to approach this section with the belief that the future of large, high-performance ships for the U.S. Navy likely lies somewhere outside the concepts currently under pursuit. Therefore, this section attempts to highlight those possible spawning areas where future naval ships could possibly develop. Two types of "other concepts" are presented: (1) evolutions or combinations of the existing technology; and (2) uniquely different concepts.

Not all known concepts and variations are presented here; there are too many. Instead, discussion is directed toward those that appear to offer some unique operational feature, or set of features.

EVOLUTIONS/COMBINATIONS OF CURRENT CONCEPTS

A large body of technology now exists for each of the three pure concepts, the extent of knowledge ranked as follows: (1) submerged-foil hydrofoil, (2) aerostatic-lift (SES and ACV); and (3) small waterplane area (SWATH).

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[1] Refer to Jane's "Surface Skimmers."

Hydrofoil development led the way to understanding of the many high-performance ship problems. Concentrated effort on the SES in recent years has vastly improved knowledge but still lacks the scope of experimental and operational experience of hydrofoils. SWATH research efforts have been primarily paper analysis and model tests with very limited operational experience (the 190-ton SSP just being launched). Each has been shown to have limitations and uncertainties that restrict its utility at this time. However, be reminded that such technology is still in its infancy and that significant improvements should be possible. It is therefore advisable for the Navy to continue its R&D efforts without trying to force a concept into the fleet too prematurely; the conventional catamaran is a prime example—there are likely others. Decades of experience with conventional planing hulls should also not be forgotten. The following variations are described to provide a basis for where to look for large improvements. Most of these are already under Navy study in some form.

Small-Waterplane-Area Single-Hull (SWASH)

The idea of a monohull displacement ship with a small waterplane area is not new (the author knows of model tests run in the early 1950s), but the technology gained through the current SWATH efforts now makes it interesting. The reduction in complexity of the above-water structure should result in an improved disposable load capacity but possibly at the expense of some deck area and payload volume. This suggests increased range and/or increased payload. There is probably little difference in drag or maximum speed potential for similar pod/strut geometries. Pitch and heave motions are probably similar to those of a SWATH but it would have much less resistance to roll; thus the use of stabilizing, active or passive foils may be necessary. With such an addition, the SWASH may have impressive seakeeping characteristics.

The major negative aspects appear to be the power plant placement common to SWATH except that there is probably a necessity to place it in the pod to achieve sufficient static stability. Also, the deep draft relative to its size will restrict its operating profile; it would definitely not make a good coastal patrol unit even in small sizes (assuming, of course, that the pod is not retractable or negative lifting surfaces or flooding down are not used as in Sea Sulky—see Section II).

The use of foils for stability control suggests possible use of lifting foils to provide some dynamic lift. Preliminary research by the Navy indicates that a 20% dynamic lift/80% buoyancy lift concept offers some attractive speed, range, payload and seakeeping features. Thus, the merging of the hydrofoil and SWATH technologists may yield an interesting ocean-capable, long-range, stable platform.

SWATH-CAB

A combination of SWATH and CAB may be approached from either direction: (1) a pressurized air bubble could be added to the SWATH to increase disposable load capacity, or (2) the sidewalls of the SES could be extended with pods added also to increase disposable load and to improve motions. The first is still mostly buoyancy-supported; the second is mostly aerostatic-supported. Some sacrifice in calm-water speed in either approach would likely result, especially with the second concept.

Hydrofoil-CAB

There is definitely some logic to attempting to combine the stability features of the hydrofoil with the lift potential of the CAB. Neither the exact configuration nor the distribution of dynamic, buoyancy and aerostatic lift can yet be rationally described but some observations might be put forth. First, the hydrofoil does not grow gracefully in size and gains endurance only by increased fuel capacity so that, in the 1000-ton and above size range, other means to achieve partial lift efficiently could be beneficial. Second, the SES has motion problems and may be subject to infrequent but severe slams while encountering a random seaway. The use of submerged foils to actively control motions may prevent the occasional slams using the forward-looking sensors now in use with all submerged-foil hydrofoils. Such foils could either be zero-average-lift or provide some dynamic lift. Also, such foils would be placed as far forward as possible. (The pitch point of an SES is well aft.)

Other Hybrids of Foil-SWATH-CAB

Study efforts are under way at NSRDC to formalize the hybrid investigation process and permit an orderly approach to uncovering new configurations and evaluating, by standard means, as many of the new concepts as possible as they are proposed. Other hybrid configurations than the aforementioned ones should be anticipated.

MISCELLANEOUS DISPLACEMENT CONCEPTS

There are many possible variations to the conventional monohull displacement ship. Most are not included here. Such concepts include twin-bulb (large bulbs fore and aft), "coke-bottle" (hull bulges fore and aft, necked down in center), slender ship (very high length-to-beam ratio), etc.

There are however two other displacement concepts worthy of discussion here as offering one or more unique operational features.

Conventional Catamaran

The U.S. Navy has actually built and operated three conventional catamarans: (1) AGOR-16 HAYES, 3080 tons; (2) ASR-21 PIDGEON, 4200 tons; and (3) ASR-22 ORTOLAN, also 4200 tons.

The positive aspects are the convenience of hoisting and lowering equipment in a seaway, the large deck area on which to work or store equipment, the ability to mount structure high in the air without stability limitations and good maneuverability at very low speeds.

The minor negative aspects involve fuel efficiency and navigation in restricted waters but the major problem is associated with seakeeping. Very high vertical accelerations experienced even in modest seaways have caused the catamaran to be viewed unfavorably as a naval ship. In fact, the use of the term "catamaran" is avoided in newer twin-hull concepts for fear of association with the AGOR-16 and ASR-21 problems which the Navy claims to have overcome.

The concept still has possible merit in very large sizes for sea-based logistics bases as presently envisioned—the Sea-Based Expeditionary Force (SBEF) concept. In very large sizes, the motion problems should be minimal and fuel economy problems should be secondary if used primarily as a large stationary sea-base.

Sail-Powered Ships

The U.S. Navy became reluctantly committed to the use of fuel-powered ships in the latter half of the 19th Century. The last major use of sail-powered ships was during WWII when private yachts were put into emergency ASW service in the U.S. coastal areas.

The only known current efforts in applying modern technology to the sail-powered ship is the Dyna-Ship concept, a 17,000-ton deadweight dry cargo ship under development in Germany and anticipated to provide economical transportation for the North Atlantic trade routes. Unconfirmed information indicated construction of a prototype in Japan. The basic performance features have been estimated to show a top speed approaching 20 knots for Beaufort wind force 6 and averaging 12-16 knots for the North Atlantic run. Sails are set and retracted automatically.

In view of the energy crisis, rising fuel costs, the complexity of large power plants, ecology, etc., some serious thought should be given to sail-power as the augmented or total power source for specific naval and/or commercial applications. Certain surveillance and logistics missions come to mind.

The use of a SWATH-type hull would provide deck space, habitability space, use of helicopters, good seakeeping qualities, etc. A quiet ASW surveillance platform employing a long towed array is a possibility.

Could the sail-powered ship cover one end of the High/Low mix approach being widely touted by DOD?

AIRSHIPS

Another interesting choice of low-energy platforms is the lighter-than-air ship, known variously as dirigible, zeppelin, rigid air ship, blimp (non-rigid air ship), poopybag, etc. There are two basic types: (1) the outer shell is framed and serves as an exostructure with separate gas-filled bags interior to that structure; and (2) the outer skin is flexible and serves as the containment barrier for the gas. The blimp falls into the second category.

Two pertinent observations should be made about airships in general: (1) their speed, range and payload envelope is not much different than that of the high performance ships except at lower speeds where airships are much more efficient; and (2) the airship has been flown extensively by the Germans and by the U.S. Navy over a period of nearly 60 years. In 1957, the U.S. Navy blimp SNOWBIRD flew 9000 miles in 11 days, unrefueled, for an average speed of around 30 knots. Then it was retired.

The negative aspects of airships are primarily their sensitivity to high winds and their visibility to enemy surveillance. Their utility as military units are likely limited but, as cold war surveillance platforms, may offer some very desirable features, primarily high endurance aloft. Wilder speculation may include airships as carriers of small embarked craft such as submersibles, surface craft, helicopters, remotely piloted vehicles, etc.

There has been recent private interest on heavier-than-air, yet lightweight, ships that achieve part of the lift by helium-filled chambers and the rest aerodynamically. The proclaimed advantages of such a platform are high payload-carrying capacity, modest power and fuel requirements, and probably less sensitivity to winds. Although higher speeds are likely, compared to lighter-than-air ships, such an airship can no longer hover or loiter at very low speeds. The newest heavier-than-air concept under development is called the "Dynairship."

It can only be said that airships offer many attractive features and have not been fully exploited, technology-wise, to establish their ultimate potential.

OTHER HYDRODYNAMIC LIFT CONCEPTS

Discussion in Section III concentrated on the submerged-foil hydrofoil with some reference to surface-piercing foils. There are other hydrodynamic lift concepts that should be briefly discussed as well.

Surface-Piercing Hydrofoil

There are many different surface-piercing hydrofoil craft in operation all over the world, primarily in protected waters, lakes, rivers, etc. The USSR has one of the largest fleets with European countries close behind. The one notable exception is the ocean-going Bras D'Or developed by Canada as an ASW ship to operate in the North Atlantic. The 140-ton Bras D'Or could exceed 70 knots in calm water and perform reasonably well in rough water. It is now laid up, having never actually towed the sonar unit developed for it.

Although the surface-piercing hydrofoil is inherently stable under most all conditions, it cannot offer the same ride quality, maintain speed in heavy seas, or bank into a turn as the submerged-foil concept can. It is, however, simpler and more reliable.

Although the U.S. Navy has rightfully favored the submerged-foil approach for a pure hydrofoil concept, the development of hybrid concepts using hydrofoils for partial lift may permit the use of surface-piercing foils without serious limitation.

Planing Craft

Although not previously discussed as a high-performance ship, the planing hull concepts fall in that category and in fact represent the only high-speed concept to be extensively deployed as operational naval units, the WWII PT boats being widely written about. Currently in the U.S. Navy force are several classes of patrol craft with planing hulls. Worthy of note is the PG-84 ASHEVILLE Class, 245-ton gross weight and capable of over 40 knots.

The planing hull has two major limitations: (1) it, as a dynamic-lift concept, is restricted in growth potential by the cube-square effect; and (2) more importantly, seakeeping performance is basically poor. The use of very narrow, deep, knife-like hulls are used to alleviate the seakeeping problems but the application of the planing hull will probably always be limited to coastal patrol operations.

Foil-Augmented Planing Craft

The U.S. Coast Guard has in operation a rescue craft with a planing hull forward and a fixed foil aft. The fixed foil tends to improve the ride quality and seakeeping in general. The potential of such a concept for naval use is not known, but it does offer improved performance without much additional complexity.

Sea-Knife

The Sea-Knife is a unique hydrodynamic lift concept, distinctly different from the hydrofoil or planing hull. It achieves 60% or more of its lift from reversing the upward-driven water sheet created by the wedge-like hull form. The bottom of the wedge can be a triangular planing surface by positive trim angle or may be trimmed to provide no lift, so that all dynamic lift is achieved by the water sheet reversing process. Because of the relatively high drag caused by the wetting of the hull sides by the water sheet, reversing rails are added as low on the hull as possible.

Several small craft have been built and operated in rough water; rough water performance has been impressive by trimming down the hull to prevent slamming.

The wedge-shaped hull form produces some peculiar properties that aid overall performance: (1) inherent dynamic stability, observable even at low speeds; (2) inherent ability to bank into a turn, an unnatural property for any other concept which tends to roll outboard; and (3) use of trim control to trim forward part of hull out of water in calm water to reduce wetted area and therefore reduce drag.

Improvement in all characteristics should be anticipated given further research. The concept is interesting because it may offer a similar range of applications as hydrofoils and planing craft for much less complexity than the hydrofoil and much better seakeeping than the planing craft.

Growth potential may not be strictly limited by the cube-square effect since wedge-angle may be increased to maintain sufficient lift up to certain limits. Such limits are not yet known.

AERODYNAMIC-LIFT CONCEPTS

There has been sporadic interest for decades in ultra-high speed ships (100-300 kts) that derive a major portion, but most likely all, of the lift from aerodynamic lifting surfaces. The classical categories of aerodynamic lift concepts are ram-wing, channel flow, and wing-in-ground-effect. Aside from limited experiments and design studies, most recently the Arctic Surface Effects Vehicle, little has been accomplished in this country. The press has recently noted the existence of a Soviet wing-in-ground-effect vehicle, referring to it as the "Caspian Sea Monster," reflecting the development site. Whether the U.S. will react with renewed interest in such vehicles is not known.

Ram-Wing

The ram-wing can be best described as a modified SES, only that the forward skirt is removed and the air stagnation pressure inside the cavity provides the lift and the rigid sidewalls may not actually touch the water. This concept might allow a higher speed potential than that of the SES but speed, range, payload and seakeeping capabilities are not fully predictable.

Channel-Flow

Continuing the SES modification approach, the channel flow concept has the aft skirt removed as well. The concept then becomes a low aspect ratio wing with end plates (sidewalls) to increase lift yet minimize lift-induced drag. This concept was reflected in some of the Arctic SEV designs. In general, the channel flow has a higher speed range than the ram-wing. In fact, some designs were envisioned to start out as captured air bubble craft until a high enough speed is reached to lift the forward skirt and become a ram-wing; at a yet higher speed, the rear skirt is lifted to become a channel flow configuration.

Wing-in-Ground-Effect

It is well understood that an aircraft in ground effect (i.e., flying within 1 or 2 chord lengths of the ground) experiences a "cushion" effect and lift-to-drag ratio can be significantly improved. This then suggests a concept designed to fly in ground effect but yet be able to set down on the water. A tandem-wing test craft was built and tested, resulting in the accidental death of the test pilot because of an unforeseen pitch instability problem due to uncompensated lift variations between the fore and aft wings.

Caspian Sea Monster. In 1968, open Soviet writings discussed the advantages of the tandem-wing-in-ground-effect concept for long-range transport not only over the aerostatic concepts but all other means of transportation as well in the 95-310 kt speed range. Recently, the press has displayed the artist's concept of the giant Soviet craft with the following estimated characteristics: 500 tons gross weight; 350-kt maximum speed; 7000-nmi range; payload weight unknown.

SEA-PLANE

There are possibly many who still tout the virtues of the sea-plane that is rapidly becoming extinct as a U.S. naval force element. The Japanese have a new-generation ASW sea-plane that lands, dips an active sonar and echo-ranges. The sea-plane has interesting potential to replace the SES or hydrofoil in certain missions involving fast response situations where commitment to land within a foreign territory is not desired. Perhaps, with the new VTOL technology, a vehicle that can fly at moderately high speeds, hover, land on the water or ship's deck may prove interesting.

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1. The Naval Analysis Programs, Office of Naval Research, has supported ship design research at Operations Research, Inc., during the last four years. This research has been directed toward developing analytical methods to evaluate the operational potential of future ship design concepts. Enclosure (1) is the third and final report prepared for the Office of Naval Research. Two previous reports have been distributed under the same subject title in June 1971 and March 1973.

2. This final report provides basic guidance and understanding to the planning analyst in the area of inherent operational advantages and limitations of the three major high-performance ship concepts under development today, e.g., SWATH, hydrofoil and SES. Enclosure (1) is forwarded for your information and retention. Recipients of this letter are invited to make comments and suggestions as to the utility of this report for planning purposes. They should be addressed to:

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