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COVER: "Modern Ships and Craft," *is an original painting created especially for this* Naval Engineers Journal *special edition by TRW Defense Systems Group artist Phil Weisberger. Mr. Weisberger studied at the National Academy of Fine Arts in New York and is a graduate of the Art Center College in Pasadena, California.*

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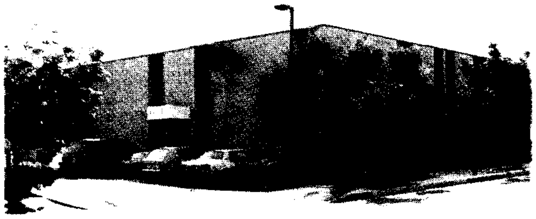

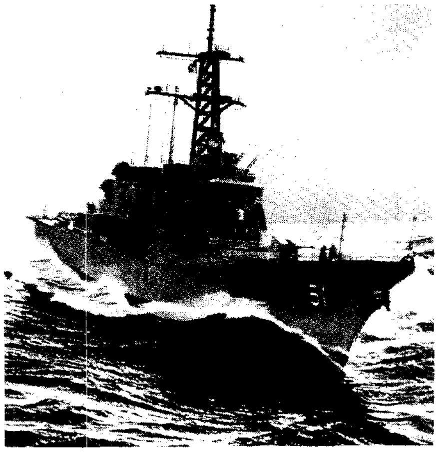

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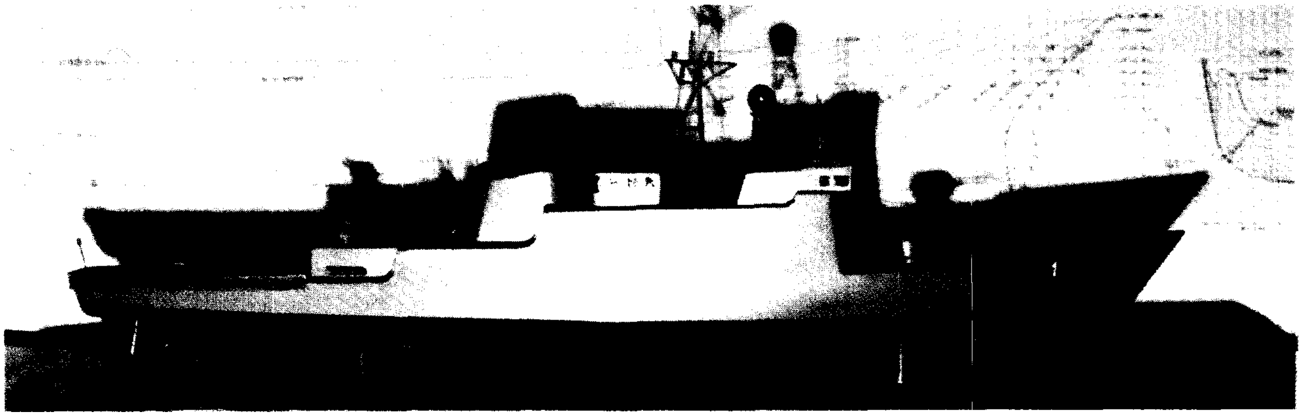

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PREFACE

CHAIRMAN, SPECIAL EDITION EDITORIAL COMMITTEE

William M. Ellsworth *is a graduate of the State University of Iowa from which he received B.S. and M.S. degrees in engineering, majoring in fluid mechanics. Upon graduation in 1948, he joined the staff of the David Taylor Model Basin (DTMB) and during the following ten years held various positions in the Hydromechanics Laboratory. In 1958, he left his position as head of the Towing Problems Branch and joined Cleveland Pneumatic Industries which later became Pneumo Dynamics Corporation (PDC). He was general manager of PDC's Systems Engineering Division and, in 1961, became a corporate vice president.*

In 1964 he returned to DTMB where he became the technical manager of the Hydrofoil Development Program Office. In October 1969 he was appointed to the position of associate technical director for systems development and head, Systems Development Department, David W. Taylor Naval Ship Research and Development Center, a position he held until retirement in January 1983. He is currently a consultant in naval engineering and vice president of Engineering and Science Associates, Inc.

He is a licensed professional engineer in the state of Maryland; an Honorary Life Member of ASNE, and a Fellow of ASME. He also has been the author of a number of papers and reports in the field of naval engineering.

Mr. Ellsworth became a member of ASNE in 1960, and received an Honorary Life Membership when he was awarded the ASNE Gold Medal for 1973. He is also the recipient of the Distinguished Civilian Service Award, Presidential Meritorious Rank, and David Taylor Award for Scientific Achievement.

Richard C. Fay, during his term as president of ASNE, 1981-83, initiated an extensive review of the goals and objectives of the Society. This self-examination and focus on the future produced a number of recommendations for new initiatives which were subsequently adopted by the Society's National Council. One of these was to undertake preparation and publication of special editions of the ***Naval Engineers Journal*** devoted to discrete and cohesive subject areas of particular interest to the naval engineering community. Our current president, RAdm. James K. Nunneley. USN (Ret.), has continued to stress the pursuit of these new goals and objectives. To this end, Dr. Alfred Skolnick, a vice president of the Society, proposed that "Advanced Naval Vehicles" might be an appropriate initial subject for a special ***Journal*** edition. This was communicated to me by RAdm. Nunneley with the request that I undertake the task of editor. Before accepting the honor associated with such an assignment, I sought advice from a number of colleagues regarding the appropriateness and timeliness of a comprehensive publication on this subject.

Certainly, there is already extensive literature on advanced ships and craft. Further, although the military sector continues to have an active interest in the subject, it is not yet at a level to inspire wide enthusiasm on the part of suppliers. As for applications in the commercial sector, they are even more limited, if not nonexistent, in the United States, although this is not true of many other countries. In spite of this not too encouraging picture, I found universal support for the idea of publishing an authoritative and balanced review of the current status of advanced marine vehicles. This was based on the widely held perception that such a publication would stimulate an already growing interest and provide a sound basis for future decision making.

As evidence of a growing commitment to advanced vehicles, the U.S. Navy has aequired a squadron of six patrol hydrofoil missile ships and is in process of acquiring a large number of air cushion landing craft. The U.S. Army also has a growing complement of air cushion vehicles. Both the U.S. Navy and U.S. Coast Guard are actively considering acquisition of small waterplane area twin hull (SWATH) ships and the Coast Guard has purchased three Bell-Halter surface effect craft designated WSES. There is also a growing commercial interest evidenced by the utilization of air cushion and surface-effect craft in the oil industry. In light of the favorable reaction of my colleagues and a brightening picture for the future, I accepted the assignment as editor of this first special edition with pleasure and enthusiasm.

The first action to be taken was to assemble an Editorial Committee comprised of recognized authorities on the subject. After the fashion of so-called "pyramid clubs," each member of the Committee, in turn, solicited contributions from experts throughout the technical community, both in the U.S. and other countries. Thus, this special edition represents the collective thinking of a large segment of the technical community. As such, it should provide a valuable long term reference and broad current assessment of the state of the art.

At the onset there was concern by the members of the Editorial Committee regarding the use of the term "advanced naval vehicle." It was generally agreed that this too frequently connotes the lack of a mature technology base and the need for further research and development before being able to realize the potential offered by these concepts. Although it is true that further research and development efforts are important and must be continued, technology ***is available today*** to exploit the benefits of advanced vehicles for numerous practical applications.

As a result, it was decided to adopt the term "Modern Ships and Craft" as the title for this special edition.

It is comprised of seven chapters, each covering an area pertinent to the subject. With the exception of Chapter I, each of the chapters addresses a particular vehicle concept in six major sections: Introduction, Description of the Concept, Attributes and Limitations, Current and Potential Applications, State of the Technology, and Producibility and Supportability. There is also a listing of pertinent references. The order of the chapters was arbitrarily chosen in relation to a decreasing reliance by each type of vehicle on buoyancy for support. The first chapter is edited by Mr. James L. Schuler, a key research and development program manager in the Naval Sea Systems Command (NAVSEA). In the view of many, he has had a greater impact on the introduction of advanced marine vehicles in the U.S. than any other individual. Mr. Schuler has assembled several "Views from the Bridge" on this special subject by key spokespersons who represent the U.S. Navy, Marine Corps, Coast Guard, Army, and Urban Mass Transportation Administration. There is also a report of a recent NATO long term scientific study on advanced vehicles.

Chapter II, which discusses "Modern Monohulls," is edited by Captain Clark Graham, USN. He and his contributors undertake to examine the benefits to be derived by applying advanced ship technology to conventional monohull displacement ships. Captain Graham has recently been transferred from his assignment as technical director of the DDG-51 Program to assume responsibility for direction of the Navy's graduate program at M.I.T. He is an articulate spokesman for the need to apply innovative thinking in modern conventional ship design.

Chapter III deals with the small-waterplane-area twin-hull (SWATH) ship and is edited by Mr. Jerry L. Gore. He has recently transferred from the David Taylor Naval Ship Research and Development Center to become an R&D program manager in NAVSEA. He has long been an active proponent of the attributes of the SWATH ship and is a leading expert in the field.

Chapter IV covers planing craft which, although having been around for a long time, offer new opportunities for exploitation of new technology. The chapter is edited by Dr. Daniel Savitsky, director of the Davidson Laboratory, Stevens Institute of Technology. Dr. Savitsky has contributed much to the technical literature on planing craft and is clearly qualified as a recognized authority.

Chapter V deals with hydrofoil ships and craft and is edited by Captain Robert J. Johnston, USN (Ret.). He devoted a significant part of his long and distinguished career in the U.S. Navy and industry to the development and exploitation of the hydrofoil concept. Currently, he is president of Advanced Marine Systems Associates Inc., of which he is the founder. AMSA has just completed a study of high speed marine transportation systems for the Urban Mass Transportation Administration. This study, which is discussed in Chapter I, is particularly noteworthy in its assessment of the economic aspects of employing advanced marine vehicles in mass transportation.

Chapter VI covers the subject of surface effect ships and also includes some discussion of wing-in-ground-effect (WIG) vehicles. WIGs have yet to be employed in the U.S. and only in developmental projects in other free world countries, but have produced considerable interest and activity in the Soviet Union. The editor of this chapter is Mr. Edward A. Butler, formerly head of the Navy's Surface Effect Ship Project Office and currently SES program manager in the Naval Sea Systems Command. He has been a key participant in the development of this promising new ship concept and is a leading technical authority on SES design.

Last, only by virtue of its clearance above the surface of the water, is the air cushion vehicle, which is covered in Chapter VII. Long employed in the United Kingdom, where they were conceived, they are now being widely acclaimed as a multi-terrain vehicle for the U.S. Navy, Coast Guard and Army. This chapter is edited by Mr. David Lavis, a founder of Band-Lavis Inc. He has had a long professional association with ACVs, both in the U.S. and earlier in the U.K., and is particularly well qualified to edit this assessment of these exciting and versatile craft.

Having spent a significant portion of my own professional career in research and development associated with modern ships and craft, I would like, at this point, to exercise editorial prerogative and make a few personal observations on the subject. In this country, the road to successful employment of these new hull forms, as they are designated by some., has been long and highly frustrating. Even though demonstration of technical feasibility and availability of criteria for design have been accomplished facts for some considerable period of time, a number of obstacles continue to impede realization of the full potential offered. by these innovations.

Of concern, particularly in the U.S., are the higher costs that have resulted, in part, by the adoption of aerospace approaches in design, construction, and support. The costs have considerably dampened enthusiasm for acquiring these vehicles for either military or commercial purposes. The cost factor is further reinforced, in the commercial sector, by the wide availability of many other forms of transportation. The competition offered by autos, buses, trains, trucks, aircraft, and conventional marine craft and ships is, to say the least, most formidable.

There is also a problem created by the U.S. Navy's prevailing mind-set in favor of large, multipurpose, conventional ships which offer little apparent technical risk. This mind-set has been emphasized in the current focus on the acquisition of a 600-ship Navy and a reluctance to divert any funds from this purpose. It has been a significant deterrent to any "new starts," which otherwise might have included further research, development, and acquisition of new hull forms.

A third obstacle is an apparent predilection to consider advanced vehicles as competitors for *all* roles. This is due, in part, to the eagerness and enthusiasm of their advocates. The modern monohull offers a low cost solution to a variety of requirements and is clearly the option of choice for most applications. It must be recognized, however, that each of these newer concepts has certain unique features which should be emphasized in assessing its potential for a given application. Even in moderately rough seas, the modern planing craft offers a low cost solution to a requirement for high speed and shallow draft in a relatively small craft, The hydrofoil, albeit more complex and with a deep hullborne draft with foils immersed, offers very high speed in very rough seas with reasonable payload, excellent maneuverability, and moderate cost in relatively small sizes. The surface effect ship offers high speed with good payload, large deck area, and the potential for growth to very large sizes. The air cushion vehicle has a multiterrain capability that is unique and a very good payload capability which makes it an excellent choice as a high-speed assault craft. It is also adaptable to many general purpose tasks and payloads and has excellent attributes as a mine countermeasure craft. The SWATH ship offers a low-cost option with moderate speed, excellent platform steadiness in a seaway, large deck area, and a configuration that makes it an excellent choice as an air-capable platform. Such comparisons, of course, represent an oversimplification of the trade-offs which are many and varied. The point is that the emphasis should be upon the unique features and potential benefits offered by each concept rather than making every concept a competitor for all roles.

Finally, there is a perception by many decision makers that the so-called “advocates” have misrepresented or oversold the virtues of their pet programs to a point where it becomes difficult to separate fact from fiction. It is most unfortunate that advocacy has taken on the connotation of “huckstering” since, in this writer’s view, honest advocacy is the cornerstone of technological advance. Anyone who has a firm belief in the merits of a new idea not only is justified in advancing it but, in fact, has an obligation to press for its consideration. In so doing each advocate must be an “honest broker” and not knowingly distort or misrepresent the facts.

Although the editors and contributors to this noteworthy special journal edition may be considered to be “advocates ,” they are keenly aware of their obligation to assess and factually report the status of current developments and technology pertinent to their respective areas of expertise. It is this writer’s observation that they have done an outstanding job in providing this timely review of the subject. It should be of enduring value to the engineering community at large. It is also hoped that it will provide an incentive to the operational community to develop new applications and tactics for the employment of the capabilities offered by modern ships and craft.

CHAPTER I

VIEWS FROM THE BRIDGE

THE EDITOR

James L. Schuler *is the special editor of this lead section. He has been the R&D program manager for advanced marine vehicles for the Naval Sea Systems Command since 1961. He earned a bachelor's degree in naval architecture from Webb Institute in 1947 and a juris doctor from the George Washington University Law School in 1954. He is a past chairman of the Flagship Section and a former member of the National Council of the American Society of Naval Engineers.*

OVERVIEW

This chapter is intended to provide a broad overview of the subject of modern ships and craft from several vantage points. The U.S. Navy, the Marine Corps, the Army, and the Coast Guard are all represented. Also included are insights from the commercial viewpoint, some interesting observations from the NATO perspective, and a few comments provided by Capt. Karl Duff, USN, a long time enthusiast for these concepts.

This synthesis of viewpoints is commensurate with the variety of needs and the diversity in capabilities of modern monohulls, hovercraft (both SES and ACV), hydrofoils and planing hulls as well as the emerging concept of the small waterplane area twin hull (SWATH) ship. One purpose of this multipronged treatment is to deflect the thrust of those who seek simple solutions.

We know that speed is provided by installed power and endurance is provided by available fuel, while combat capability is provided by weapons and sensors. We also know that the effectiveness of the ship, boat or craft is strongly dependent on the people, and that cost is related to both size and performance. When these complexities and interactions are viewed in terms of rapidly evolving technologies, the question, "What is the best ship?" is a moving target.

It is hoped that this collection of perspectives can help the naval engineering community to get some feel for the speed and direction of the changes which these concepts can provide. It is clear that these new technologies will continue to evolve and interact. The goal is not to provide the answers but rather to provide a basis for asking the right questions.

I would like to include a personal observation. Our younger naval engineers, civilian and military, should notice that progress in introducing new ship technology is not measured in fiscal years and five year defense plans. Such progress has to be measured in careers. Two examples will illustrate the point.

The hydrofoil accelerated research program (HARP) started in 1960. It included a $13.2M R&D effort, construction of the 120-ton hydrofoil patrol craft High ***Point*** and authorization for the 320-ton experimental hydrofoil ***Plainview.*** These actions were taken to capitalize on the unique combination of speed, seakindliness and maneuverability of the hydrofoil. In 1965, the U.S. Navy built two hydrofoil gunboats of about 70 tons, ***Flagstaff*** and ***Tucumcari.*** Then. in May of 1968, it started planning for hydrofoil missile patrol craft. The first six PHM class hydrofoils were finally assembled as a squadron (PHMRONTWO) in Key West, Florida in March of 1983.

At about the same tirne, in 1960, the U.S. Navy built the experimental hovercraft SKMR-1. This action was prompted by the unique amphibious capabilities of the air cushion vehicle. In 1965 it started the amphibious assault landing craft (AALC) program to build and test full-scale hovercraft for putting the landing force on the beach. This program included design, construction, tests and trials of the ***Jeff(A)*** and the ***Jeff(B).*** These full-scale craft provided the essential confirmation of technical feasibility, operational capability, and financial suitability to permit production in quantity of the landing craft air cushion (LCAC). The first LCAC was rolled out in May and started builder's trials in November 1984.

Other naval examples included nuclear propulsion, the helicopter, and rifled naval guns. These modern examples are comparable to the switch from sail to steam and the move from wooden to steel ships. The changes were slow for many reasons. But, changes have been made and we can look forward to more. I encourage younger innovators to read this issue carefully, read the references, draw their own conclusions, and work to move the process forward.

The first introductory article has been prepared by Mr. Peter Mantle who was the director of technology assessment in the Office of RDT&E for the Chief of Naval Operations. Mr. Mantle is a world-recognized authority on air cushion vehicles. He served as technical manager of the U.S. Navy advanced naval vehicle concepts evaluation (ANVCE) study. He is in a unique position to provide insights into the problems of introducing new technology. His article provides a background for the technical and engineering communities to understand the difficulty of bringing modern marine vehicles out of the laboratory and into the fleet.

The second article has been prepared by Dr. A. L. Slafkosky who, since 1963, has been the scientific advisor to the Commandant of the Marine Corps. From this position, Dr. Slafkosky has been able to observe and support both Navy-wide and Marine Corps-specific development of modern marine vehicles. His article reveals some of the insights which he has gained from a long and valuable effort to put these new concepts to work where they will pay off for the Marine Corps.

The third article was prepared by Dr. Julius Hein of the U.S. Army Waterborne Craft Program Office in St. Louis, Missouri. He addresses the Army's experience with hovercraft in Vietnam as well as current and future plans for acquisition and deployment of the 30-ton-payload hovercraft designated LACV-30.

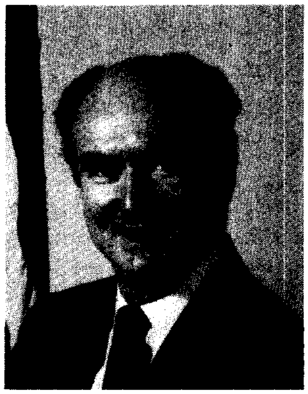
The fourth article was prepared by Capt. George Moritz, USCG. Coast Guard interest in modern marine vehicles covers several aspects. Both international and domestic involvement in regulations governing the design, construction and safe operation of these craft has been complemented by hands on operational experience. The Coast Guard has tested several Navy hydrofoils and commercial hovercraft. The SSP (SWATH) ***Kaimalino*** was constructed for the Navy at the Coast Guard Yard in Curtis Bay, Maryland. The Coast Guard is operating several SES type craft in Key West, Florida and currently designing a small waterplane area twin hull (SWATH) cutter.

The fifth article is by Miss Patricia Cass who is a project manager for the Urban Mass Transportation Administration of the Department of Transportation. She has recently directed a world-wide review of the use of high-speed waterborne transportation systems. She provides some interesting views on the use of these vehicles and some valuable guidance and direction on developing technology to make them more economical and attractive.

Canadian experience in the design and construction of hydrofoils goes back to the earliest days of testing by Alexander Graham Bell and Casey Baldwin. Many years later Canada contracted with DeHaviland for the 200-ton hydrofoil ***Bras D'or.*** The Canadian Coast Guard has also operated hovercraft in the vicinity of Vancouver, British Columbia and has been a pioneer in using air cushion technology in frozen environments. Mr. Michael Eames, senior scientist of the Defense Research Establishment, Atlantic (DREA), has recently led a NATO long term scientific study of research requirements for advanced naval vehicles. He presents some of the insights gained through these many experiences in the sixth article.

Finally, a brief glimpse into the future is provided by Capt. Karl Duff, USN, in his note on readiness and timing. Capt. Duff has had a variety of experiences pertinent to the subject including a tour as officer-in-charge of U.S. Navy Hydrofoil Special Trials Unit and deputy program manager in the PHM Project Office. More recently, he has been the Deputy Chief of Naval Research and Naval Technology and is currently the deputy director of the NAVSEA Office of R&D in the Ship Design and Integration Directorate. On his "upbeat" note, it is our hope that these introductory articles will provide a sound perspective for the detailed discussions of each concept.

INTRODUCING NEW VEHICLES



Peter J. Mantle *has joined the Lockheed Shipbuilding Company after serving as director of the Technology Assessment Division in the Office of the Chief of Naval Operations. He has been closely involved with hovercraft technology since his association with Sir Christopher Cockerell in the early days at Saunders-Roe. His 1980 report on air cushion craft development is a milestone compendium on this technology. He also served in the Office of the Assistant Secretary of the Navy for Research, Engineering and Systems, and earlier was technical director of the Advanced Naval Vehicles Concepts Evaluation sponsored by OPNAV.*

INTRODUCTION

Hydrofoils, air cushion craft, SWATH, and wing-in-ground-effect vehicles have been in existence for a very long time-dating back to the turn of the century. Despite these historical roots, these vehicles are not yet well established in the U.S. Navy's inventory or accepted in the U.S. commercial sector in the same sense as the airplane, ferry, or bus. This article provides some perspective on their limited acceptance by comparing the expectations of early advocates to the realities of operational experience. There are, of course, pockets of acceptance throughout the world. Surface-piercing hydrofoils operate hourly between Messina, Sicily, and Reggio di Calabria, Italy, with the unassuming regularity of a ferry boat. Air cushion craft operate regularly off the south coast of England between Portsmouth and the Isle of Wight. In Japan, the SWATH operates regularly between Tokyo and the Isle of O-Shima. But, here in the United States, the promise has not yet been realized. There are reasons, not all of which are obvious. This article suggests a few of those reasons, hopefully in a constructive way, to serve as a guide for future development.

EVERY CONCEPT IS DIFFERENT

There has been a tendency to categorize the ACV, SES, hydrofoil, etc., as members of a common family of "advanced marine vehicles" and thus lay out a develop-

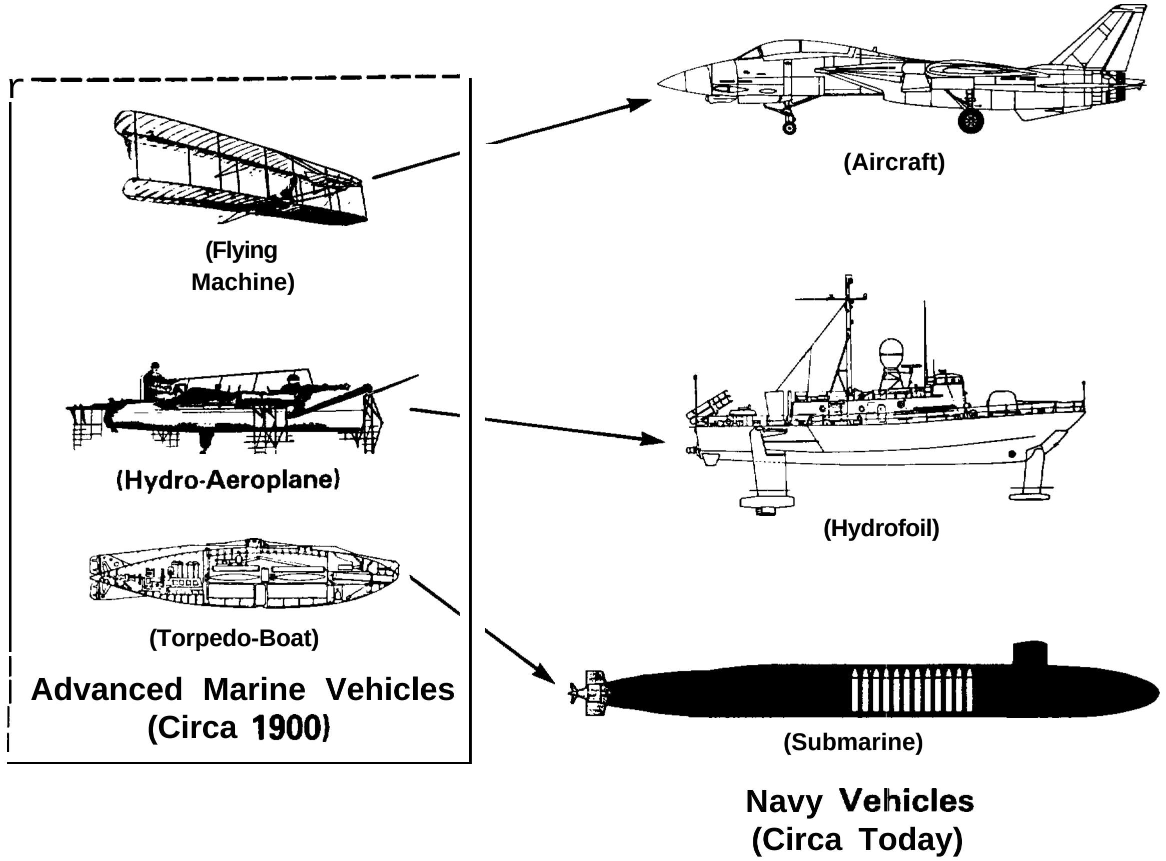


Figure 1A. The Roots of Today's Vehicles.

ment plan for these vehicles as if they were uniquely related. Consider the analogous situation that might have confronted the "systems analysts" at the turn of the century. The advanced vehicles candidates at that time would include the Wright brothers' 'flying machine" (1903); Forlanini's "hydro-aeroplane" (1905), and Holland's "torpedo boat" (1899). Figure 1A shows how these advanced vehicles, circa 1900, evolved into today's airplane, hydrofoil, and submarine.

None of the circa 1900 vehicles developed as members of a common family. On the contrary, each had to survive on its own merits and seek its own development path determined by the operational use best exploited by its own characteristics.

Two points are worth mentioning. The first is the time of development for these vehicles measured from date of concept to first military use. The airplane was unique in that the elapsed time was an untypically short eight years, prompted in part by its truly unique feature of breaking free of the ground and in part by the outbreak of the war just as the concept was demonstrating its capabilities. The hydrofoil elapsed time was thirty-five years. The submarine's incubation period was closer to the average at twenty-five years. Based on an analysis of these and other military systems such as the steamship, jet engine, hovercraft, etc., an average development time of twenty-two years is typical.

The second point is that none of these vehicles is being used as the inventor envisioned them to be used. The aircraft was seen (militarily) as an observation platform for the battle in progress on the ground-a far cry from the supersonic, carrierborne, F-14 air superiority fighter. The hydrofoil's beginnings with Forlanini were tied to uses with seaplanes-quite different from today's PHM, a missile-armed, fast patrol vessel. The third example is even more dramatic in that the submarine has come full circle from being the weapon itself (predating Holland) to one of the most potent strategic weapon systems in the world.

DEVELOPMENT SCHEDULES

Introducing new vehicles into the Navy (or any institution) is not solely a technical matter. Those who would be involved in such endeavors would do well to heed the lessons of history. There appears to be an historical data base that supports the statement that it is normal to expect resistance to change and further that new vehicles or systems are rarely introduced by the established community.

Table 1B. Front End Trend in Acquisition Cycle.

TIME FRAME	ELAPSED TIME "PROGRAM CONCEPT TO DSARC II"
1950-1960	1 1/2 YRS
1961-1970	3 1/2 YRS
1971-1977	5 YRS
	AV: 3 1/3 YRS

It takes time to introduce a new vehicle. Much has been written about the growing complexity in the documentation and review process involved in introducing new systems. In today's parlance this is referred to as the lengthening of the "front end" of the acquisition cycle. In 1978, a task force of the Defense Science Board analyzed the front end of the acquisition cycle over the last 25 to 30 years and reported an increase in the time from program inception to start of detail design of a full-scale vehicle (i.e., Defense Systems Acquisition Review Council (DSARC) Milestone II)[1]. The result of this analysis is shown in Table 1B. This recent experience is not surprising when compared to the examples of new vehicle concepts developed over the last two centuries.

If now, instead of looking back just 25 to 30 years, a broader look is taken over a period spanning the last two hundred years, a slightly different perspective emerges. The data base will comprise some of the major systems existing in the Navy today, together with some advanced ship candidates. While the terminology of DSARC, etc., did not exist prior to 1969, it is possible to pinpoint "start of program" and "start of detailed design" from historical records. Table 1C summarizes this writer's findings.

Table 1C. Representative Historical Front Ends.

	FIRST CONCEPT	ELAPSED TIME "PROGRAM CONCEPT TO DSARC II"	FIRST CONCEPT TO FIRST MIL. USE
STEAMSHIP	1902	5 YRS	41 YRS
SUBMARINE	1975	2 YRS	25 YRS
AIRCRAFT	1903	4 YRS	8 YRS
HYDROFOIL	1905	3 YRS	35 YRS
JET ENGINE	1930	3 YRS	12 YRS
HOVERCRAFT	1955	3 YRS	13 YRS
		AV. 3 1/3 YRS	AV: 22 YRS

Comparing these historical data with the findings of the Defense Science Board, there is indeed cause for concern for the lengthening of the process, especially in the last decade. Much effort is ongoing within DOD, and particularly in the Navy, to ease the process at the front end. It is true that once a new development has reached the point of official acceptance and has entered the systems world, the milestones and other wickets through which it must pass have indeed become more complex. The elapsed time, however, has not changed dramatically.

There is an additional point not brought out in these earlier papers on the acquisition cycle and that is the time for acceptance so that an approved "program inception" can start. With some understandable exceptions, most new vehicles have had a lengthy and sporadic period of acceptance. It is this period that has contributed greatly to the development time that suspiciously approaches a generation. The lack of acceptance of a vehicle that embodies new and unfamiliar technology is an historical fact and might as well be recognized by the developer. For those who yearn for the good old days when the acquisition process was simple, three quotes will illustrate the historical resistance to acceptance of new systems. The first relates to the introduction of steam driven warships (to replace sail):

> "The steam vessel was not a school of seamanship for officers or men. Lounging through the watches of a steamer, or acting as firemen and coal heavers will not produce in a seaman that combination of boldness, strength, and skill which characterized the American sailor of an elder day; and the habitual exercise by an officer of a command, the execution of which is not under his own eye, is a poor substitute for the school of observation, promptness, and command found only on the deck of a sailing vessel."
>
> U.S. Navy General Board (1869)

And when John Ericsson introduced the screw propeller in England in 1836 to replace the paddle wheel:

> " even if the propeller had the power of propelling a vessel, it would be found altogether useless in practice; because of the power being applied in the stern, it would be absolutely impossible to make the vessel steer . ."
>
> Sir William Symonds,
> Surveyor of the British Navy (1837)

More recently, upon introduction of gas turbines:

> ". . even considering the improvements possible . the gas turbine could hardly be considered a feasible application to airplanes, mainly because of the difficulty in complying with the stringent weight requirements . ."
>
> Gas Turbine Committee
> US National Academy of Sciences (1940)

It should be noted here that on 27 August 1939 the Junkers Co. test flew an aircraft powered by a gas turbine designed by Hans von Ohain. Also, Sir Frank Whittle, who originated the idea in 1930, witnessed a Gloster E28/39 aircraft powered by a gas turbine fly on 15 May 1941.

By way of a final example of the length of time it takes to gain that first and sustained level of acceptance of a new vehicle development, the historical development of the submarine is presented. It is informative in that it has all the ingredients of a modern day DSARC program—yet it occurred over one hundred years ago!

The sequence of events shown in Table 1D has been extracted from various sources including a most eloquent treatment in reference [2]. The history of the introduction of the submarine could be mirrored by other development programs down to the present day. The resistance to new ideas, the realities of the budget, the congressional cycle, and other events were as true at the turn of the last century as they are as we approach the next century. Some other pertinent examples that illustrate this delay in acceptance follow.

The British Admiralty rejected Robert Fulton's paddle wheel steamship in 1807 causing him to come to America and build the first steam warship in 1814-a time lag of seven years. In 1836 John Ericsson demonstrated the first screw-driven boat to the British Admiralty; again rejection, causing Ericsson to come to America, team up with Capt. Robert Stockton, and build the first screw-driven warship, the ***Princeton,*** in 1843-a time lag of seven years. The story of the delay in acceptance of John Holland's submarine-some twenty-five years-has been described in Table 1D. Tlne delay in acceptance from Sir Frank Whittle's concept of a jet engine in 1930 while a cadet at the RAF college and acceptance by the Air Ministry in 1938 was eight years.

The hydrofoil and the air cushion craft are more recent examples of the same problem. If the first operational hydrofoil is considered to be Enrico Forlanini's fully-submerged ladder foil craft in 1906, the time to acceptance for military use is thirty-five years when Adolf Hitler sought ways to transport military supplies to Rommel's Army in Africa at high speed over the rough Mediterranean waters from Sicily. Baron von Schertel made this possible with surface-piercing hydrofoil craft in 1941. The air cushion craft is another invention by a private individual, Sir Christopher Cockerell. There were earlier starts dating back to the late 1800s [3], but Sir Christopher, along with Saunders-Roe Co., turned it into a practical reality with a demonstration craft, the SRN1, in 1959. The British Army tried a limited military use in 1968-a period of nine years.

It is suggested, therefore, that while the front end of the acquisition cycle contains several bureaucratic milestones or hurdles that need to be eliminated, the additional factor of "time for acceptance" also needs to be examined.

FORECASTING AND HINDCASTING

Two examples of modern ships and craft will be used to illustrate a particular problem that needs to be identified. These are the hydrofoil and the air cushion craft. First the hydrofoil. Figure 1E shows the history of the hydrofoil as it evolved from the *Supramar-Rodriquez* PT-20 in 1956 and growing in size to the 320-ton AG(EH)-1 ***Plainview*** in 1968. Given this first generation history, projections were made at that time that the development was mature enough to project 4,400-ton hydrofoils by 1980 [4]. This is an important point and will be returned to later. Such a projection did not become the reality. The actual second generation class of hydrofoils had its beginnings in the PGH-2 ***Tucumcari*** in 1968 and has culminated in the six PHM craft that were launched over the period 1974 to 1982. Again, based on this experience, practitioners of the art projected (in 1978) that 3,400-ton hydrofoils were feasible by 1995 [5]. The reality again is that as of today no such large hydrofoils are in any navy (and probably commercial) plans.

The slippage in time between these projections is of the order of 15 years. The difference in hydrofoil size between projection and reality is approximately 10:1.

Figure 1F shows the history of air cushion craft as it evolved from the first generation vehicles starting with the SRN-1 in 1959 and culminating in the 165-ton SRN-4 in 1968. Given this first generation history, projections were made at that time that 4,000-ton surface effect ships

Table 1D. The Holland Submarine Story.

1875	JOHN HOLLAND PRESENTS HIS DESIGNS TO CAPT. SIMPSON AT NAVAL WAR COLLEGE. "LUNATIC" COMMENT RECEIVED BY HOLLAND AND NO ACTION TAKEN BY NAVY.
1877	GROUP OF IRISH REBELS IN NEW YORK, THE FENIANS, ADVANCE HOLLAND FUNDS TO BUILD A MODEL. THEIR PLAN WAS TO BUILD SUCH A CRAFT FOR RAMMING THE BRITISH FLEET TO BRING ABOUT THE OVERTHROW OF BRITISH RULE IN IRELAND.
1881	AFTER 2 YEARS OF CONSTRUCTION THE FULL SCALE VEHICLE, "FENIAN'S RAM" IS READY FOR TESTING IN NEW YORK HARBOR. SEVERAL TEST FAILURES, WITH CRAFT BECOMING SWAMPED
1882	LT. EDWARD ZALINSKI, U.S. ARMY BECOMES INTRIGUED WITH HOLLAND SUBMARINE AND BUILDS SIMILAR CRAFT. CRAFT DESIGNED TO APPROACH WITHIN ONE MILE OF ENEMY WITH CONNING TOWER AWASH AND FIRE GUN. ZALINSKI BOAT STRUCK A PILING AND SANK
1887	ADMIRAL MONTGOMERY SICARD, CHIEF OF BUORD IMPRESSED BY ZALINSKI BOAT AND ALERTS SECRETARY OF NAVY WHITNEY TO PURSUE IDEA.
1887	NAVY ISSUES RFP WITH STRINGENT REQUIREMENTS: CERTIFIED CHEQUE OF 5 PERCENT OF BID TO ACCOMPANY BID AND UPON ACCEPTANCE BY GOVERNMENT 60 PERCENT FOR PERFORMANCE BOND ALSO. PERFORMANCE SPECIFIED AS 15 KNOTS ON SURFACE FOR 30 HOURS: 8 KNOTS SUBMERGED FOR 2 HOURS. OTHER DETAILED REQUIREMENTS INCLUDED. SUCCESSFUL BIDDER MUST MEET PERFORMANCE OR FORFEIT BOND.
1888	TWO BIDS RECEIVED: ONE FROM JOHN HOLLAND'S COMPANY "NAUTILUS TORPEDO BOAT CO." AND ONE FROM CRAMP'S SHIPBUILDING CO. HOLLAND'S DESIGN CAME CLOSEST BUT NEITHER COMPANY WOULD AGREE TO THE PERFORMANCE BOND. NAVY REJECTED THE BIDS.
1888	SECOND RFP ISSUED. TWO BIDDERS, HOLLAND AND A GEORGE BAKER OF IOWA PROVIDED DESIGNS. BAKER'S DISMISSED BECAUSE OF NO GUARANTEES. HOLLAND OFFERS LIMITED FINANCIAL LIABILITY ADMIRAL SICARD RECOMMENDS MOVING FORWARD WITH HOLLAND'S APPROACH.
1888	SECRETARY TRACY REPLACES SECRETARY WHITNEY AND SUBMARINE APPROPRIATION DIVERTED TO OTHER USE.
1890	BAKER CONSTRUCTS CRUDE SUBMARINE USING DOWN HAUL PROPELLERS.
1892	CDR. CONVERSE WITNESSES TRIALS OF BAKER'S BOAT ON LAKE MICHIGAN. DESPITE PROBLEMS. CDR. CONVERSE RECOMMENDS NAVY PURSUE THE DESIGN. BAKER BOAT CLAIMED ONLY 9 KNOTS SPEED AND 4 HOURS ENDURANCE ON THE SURFACE. A SUBMARINE BOARD EARLIER IN 1888 HAD REJECTED THE BAKER DESIGN.
1893	NAVY ISSUES THIRD RFP. ELEVEN BIDS RECEIVED. BAKER'S BIDS AND ALL OTHERS, EXCEPT JOHN HOLLAND'S WERE REJECTED ON TECHNICAL GROUNDS. SUBMARINE BOARD RECOMMENDS MOVING AHEAD WITH HOLLAND'S DESIGN AND DISPENSE WITH PENALITIES. ADEQUATE DESIGN MARGINS WERE INCORPORATED.
1893	NEW CHIEF OF BUORD, ADMIRAL SAMPSON DISAGREES WITH BOARD FINDINGS AND REQUESTED A STUDY BE DONE ON THE TECHNICAL DIFFERENCES BETWEEN HOLLAND AND BAKER DESIGNS.
1894	CONGRESS SUPPORTS SUBMARINE IDEA AND APPROPRIATES IN ITS BILL H.R. 5445, $200,000 FOR SUBMARINE CONSTRUCTION AND TEST.
1894	HOLLAND SUBMITS DESIGN TO BUORD. ADM. SAMPSON STILL UNCONVINCED.
1895	BUORD AWARDS CONTRACT TO HOLLAND'S COMPANY FOR $150,000 ($50,000 OF APPROPRIATION TO BE USED FOR NAVY TESTS). CONTRACT INSISTS ON DELIVERY IN 12 MONTHS OR SUFFER PENALTIES. SUBMARINE IS TO BE CALLED "THE PLUNGER."
1895	NAVY REQUIRES ALL DRAWINGS ON CONTRACT TO BE SUBMITTED TO NAVY DEPARTMENT FOR APPROVAL.
1895	JOHN HOLLAND BECOMES ILL AND UNABLE TO MONITOR DESIGN. NAVY DEPARTMENT CONTINUES TO "IMPROVE" THE DESIGN. ADDING AMONG OTHER THINGS BAKER'S DOWN-HAUL PROPELLERS.
1897	WELL PAST THE ONE YEAR CONTRACT TIME. "THE PLUNGER" UNDERGOES ABORTIVE DOCK TRIALS. NAW MAKES MANY CHANGES THROUGHOUT 1897-1902. MANY CRITICISMS ABOUND ON POOR CRAFTSMANSHIP. SECRETARY HERBERT TESTIFIES TO GENERAL PROBLEM IN NAVY OF POOR SHIP CONSTRUCTION.
1898	JOHN HOLLAND, HAVING WITNESSED THE CORRUPTION OF HIS DESIGN OF "THE PLUNGER" HAD MOVED AHEAD TO DESIGN AND BUILD A SUBMARINE ON HIS OWN. THIS WAS CALLED "THE HOLLAND" AND WAS LAUNCHED IN 1898. THE NAVY TOOK COGNIZANCE SHORTLY AFTER LAUNCH AND RECEIVED FAVORABLE INITIAL TRIAL REPORTS.
1899	"THE HOLLAND" SATISFACTORIALLY COMPLETES "OPEVAL-LIKE" TRIALS FIRING TORPEDOES AT FULL SPEED WHILE SUBMERGED AND ON THE SURFACE.
1900	THE U.S. NAVY PURCHASES "THE HOLLAND" AND PLACES ORDERS FOR SIX BOATS OF THE ADDER CLASS-AN IMPROVED AND SLIGHTLY LARGER HOLLAND.
1902	"THE PLUNGER" FINALLY COMPLETED.

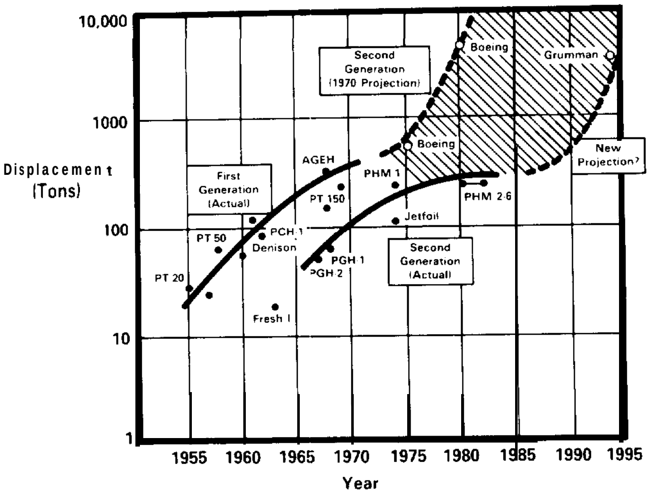


Figure 1E. Hydrofoil: Projection and Reality.

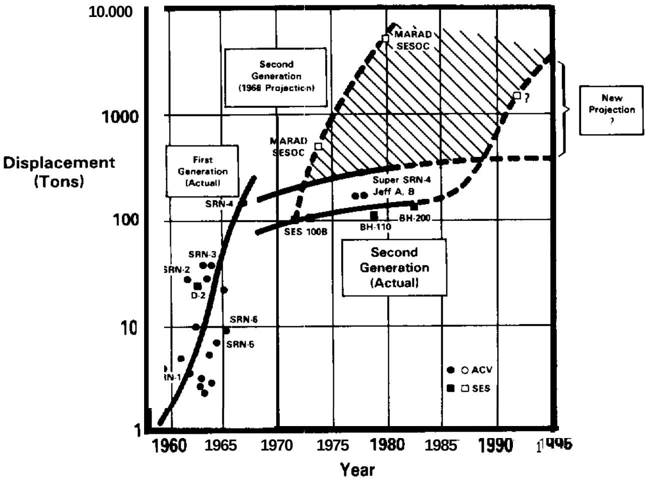


Figure 1F. Air Cushion Craft: Projection and Reality.

would be at sea by 1980 [6]. Such a projection did not become reality. The second generation of air cushion craft evolved at a much slower rate as indicated by the 100-ton SES-100B in 1972, the 320-ton super SRN-4 in 1978, and the 160-ton US Navy amphibious air cushion landing craft (LCAC). As might be expected, projections are being made for a 1,500-ton surface effect ship in the early 1990s—but no firm plans are in the Navy budget.

The slippage in time in these projections is of the order of 15 years. The difference in air cushion craft size between projection and reality is of the order of 10:1.

The similarity between the hydrofoil and the air cushion craft histories is both striking and sobering. There is a striking difference between projection and reality. This difference is persistent (similar stories can be given for other advanced vehicles). It is suggested that a reason other than mere chance underlies the situation. The technologist would maintain that the state-of-the-art would support the projections (to large ocean-going ships) if only the requirements people would allow the jump. The requirements people, on the other hand, maintain that the state-of-the-art has not been demonstrated, so why take the risk when there already exist large ocean-going ships. There is an element of truth on both sides—as is so often the case. The whole truth lies somewhere between.

THE IMPACT OF RELATED DEVELOPMENTS

The development of these advanced vehicles has not occurred in isolation. A fighting vehicle is made up of two parts: the ***platform*** (which is what has been discussed so far) and the ***payload*** or weapon system which has also received extensive and dramatic development over the past century. In many 'ways, weapons system developments have overshadowed many of the platform developments and have strongly influenced programmatic decisions within the Navy. Table 1G illustrates these developments.

If speed is taken as a measure of platform performance (in deference to John Paul Jones), then it is seen, from Table 1G, that the improvement in platform performance from WW II to the foreseeable future is of the order of 2:1. The combat systems improvements (sensors and weapons) during the same time period have been dramatic. Improvements in radar and sonar, for example, have brought about an order of magnitude (10:1) improve-

Table 1G. Improvements in Vehicle Systems.

	EARLY STEAM (1900-1910)	WW II (1939-1945)	TODAY (1950-1980)	FUTURE (1980-2000)	FUTURE IMPROVEMENT OVER WW II
SHIP SPEED (KTS)	10-20	20-33	30	50 + (1)	2:1(1)
SENSOR RANGE (MILES)	12 (EYEBALL)	30 (RADAR) 1-2 (SONAR)	200 (RADAR) 2-8 (SONAR)	300 (RADAR) 10 + (SONAR)	10:1 10:1
WEAPON RANGE (MILES)	8 (GUNS)	23 (GUNS)	80 (SSM) 300 (SAM)	500 (SSM) 700 (SAM)	22:1 30:1
THROW WEIGHT (LB)	2000 (16")	2000 (16")	250 (SSM) 40 (SAM)	100 (SSM) 20 (SAM)	1:20(2) 1:100(2)
WEAPON SPEED (KTS)	1500 +	1500 +	500-2000	2000 580×10^6 (LASER)	1:1 39,000:1

(1) ONLY BY GOING TO SPECIAL HULL FORMS, OTHERWISE NO IMPROVEMENT

(2) THROW WEIGHT CAN BE REDUCED AS ACCURACY, RANGE AND TARGET SELECTION IMPROVES

ment in the range of sensors. Equally dramatic improvements in weapon performance have also occurred.

The effective sensor and weapon ranges are even greater for the battle group if one includes the early warning aircraft (such as the E-2C) and improvements brought about with satellite coverage. Actual scenarios are more complex, but the point can be made with the simplified values shown in Table 1G. The throw weight, from shells to missiles, has actually decreased because of the trade from "high throw weight, poor accuracy" to "low throw weight, high accuracy." A hint of the possible future is seen with the inclusion of the laser or other directed energy weapons where throw weight is a meaningless parameter. If such weapons appeared on the scene, the development of new vehicles could take another path of development entirely. The development of the torpedo is not included in Table 1G. Torpedo speeds are now greater than many vehicle speeds. When coupled to improvements in submarine speeds, this weapon development also influences programmatic decisions on vehicle development.

Given the impressive development in weapon systems, the advanced vehicle designer is faced with several challenges. First, he must contend with own ship survivability. Secondly, he must decide how best to integrate this new weapons capability with the advanced vehicle capability to provide a superior fighting machine. Some options are: (1) the vehicle can be designed to go very fast (many of the concepts seek this option), or (2) it can be designed to disappear-or more correctly, exhibit signatures below the threshold of known sensor levels-or (3) it can be designed to provide a combination of both. Another option is to exploit various countermeasure features such as decoys.

Finally, the vehicle can take advantage of changing its mode of operation on demand. The ACV and SES can operate either hullborne or cushionborne. The hydrofoil can operate either hullborne or foilborne. The wing-in-ground effect vehicle (WIG), in certain forms, can even more dramatically operate multimode by first operating in "ground-effect" very close to the sea surface or pull up and operate at altitude. This feature could be employed for attack avoidance, OTH targetting, or simply rough sea avoidance. The possibilities are intriguing.

THE IMPACT OF SIZE AND COST

Attitudes towards costs vary with time. In 1961, Robert McNamara became Secretary of Defense and introduced the DOD to evaluation of systems based on their cost-effectiveness. Systems were analyzed for their life cycle costs. In the last decade, the concern for cost of weapon systems has influenced decision-making to a marked degree. Further, the decision-making on costs is being dominated by acquisition costs and even more directly by the cost per year and cost growth. In this environment it is difficult to encourage consideration of high performance capabilities offered at the extreme of the concept's capabilities-and thus with high cost label.

Figure 1H shows the acquisition costs of several advanced vehicles. The data, compiled in 1978, shows how cost increases with both size and speed. The projected costs for 80-knot military air cushion craft apply to those designs shown in reference: [5].

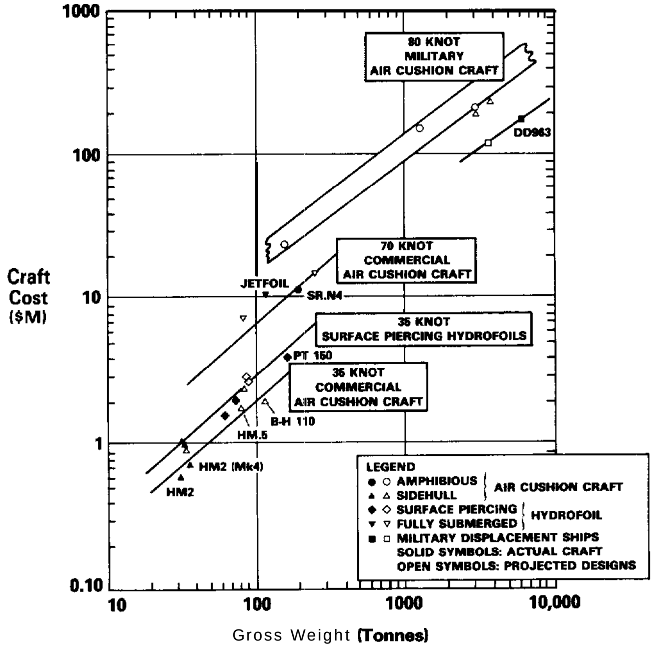


Figure 1H. Acquisition Costs.

Costs are related to speed as well as size. Figure 11 has been compiled for two classes of ships; a 3,000-tonne displacement class and a 1,000-tonne displacement class. The costs of all the designs in Figure 11 have been estimated by a common method. The absolute values are ratioed to an FFG-7 class ship. The cost of going faster increases almost linearly until the dynamic vehicles come into play (i.e., hydrofoils, air cushion vehicles, and surface effect ships), at which time speed comes relatively easily and cheaply. However, it will be noticed that the cost of such vehicles over a conventional warship (FFG-7 class) is greater than 2:1. It is not clear, given the improvements in weapon performance mentioned earlier, that such cost increases can be justified.

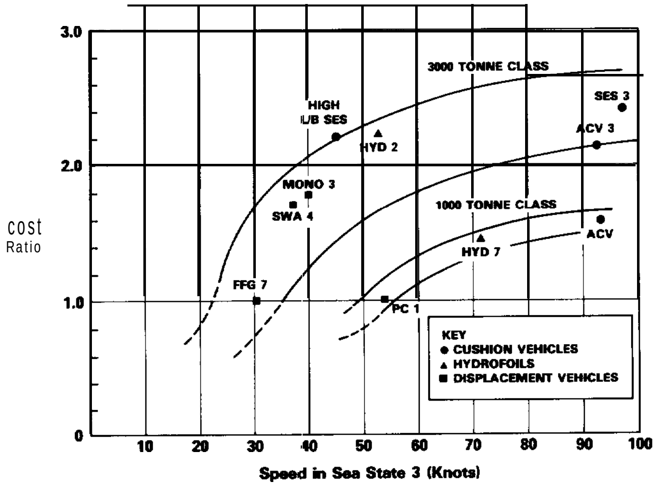


Figure 1X. The Cost of Speed.

CONCLUSIONS AND RECOMMENDATIONS

This article has sought to outline some of the factors that have influenced the current state of development of advanced naval vehicles. It is hoped that it has been shown that introducing new vehicles and overcoming the barriers to their development is not a unique problem of today. Success in introducing new vehicles into the Navy is not the revolutionary change expected by the developer but more the result of the confluence of a set of evolutionary developments matching a perceived need.

Based on the foregoing review, several conclusions can be drawn and recommendations made. They are:

1) In light of the historical comparison between projection and reality, each new vehicle should be pursued in small steps in size.
2) Developers of new vehicles should strive to make the best match between the really unique features of the concept and the real future needs of the user.
3) Given the historical resistance to change, the developer of a new vehicle would do well to understand the approval system and chart his course through it rather than confront the system head on.
4) In recognition of the tendency to resist change and the fact that most major systems considered to be the mainstay of today's Navy were initially developed outside the Navy, Navy R&D managers should (a) encourage innovation, (b) encourage IR&D, and (c) manage in a way to allow failures in the early stages of development.
5) Given the rapid developments in weapon systems, the "new vehicle" designer should look for more than just improved speed or seakeeping and integrate vehicle characteristics with the weapon system improvements to evolve into a fighting system that, like the circa 1900 advanced vehicles, may culminate in uses not yet envisioned by the inventors.
6) Given the limited defense budget and other considerations, emphasis should be given not to developing the highest performance version of a given concept, but to develop lower performance variants first.

It is believed that many of the vehicles discussed herein can bring about significant advances to the Navy, especially when properly integrated with the developments in other technologies. It is hoped that the above observations can help place these new vehicles in proper perspective such that their introduction can proceed in a timely manner with a greater chance of success.

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SHIP-TO-SHORE SURFACEBORNE MOBILITY

Dr. Alexander L. Slafkosky *has been the scientific advisor to the Commandant of the U.S. Marine Corps since 1963. He earned his Ph.D. at Laval University in Quebec, Canada in 1954, served on the faculty at St. John's College in Annapolis, Maryland and was a fellow of the Ford Foundation before coming to the Marine Corps as an operations research analyst in 1957. He has served on a wide variety of studies, boards and committees. He has also served on the Board of Directors and as first vice-president of the Military Operations Research Society (MORS). His continuing support of modern marine vehicles has been essential to the success of many programs. The hallmark of his contributions has always been that they are "in context."*

MARINE CORPS MISSION

The Marine Corps provides the landing force of the amphibious task force in amphibious assault operations. The landing force is the principal power projection element of the amphibious task force. To be effective and successful the landing force must project men, weapons and equipment in sufficient numbers across the beach and into landing zones according to plan at very specific times and during certain time duration windows. This means that the initial assault elements with their weapons and equipment must be carried from ship-to-shore in an efficient ready-to-fight manner both by vertical assault lift vehicles, viz., by helicopters presently (and eventually by more capable V/STOL aircraft such as the JVX) and by surfaceborne lift, viz., assault amphibian vehicles and landing craft. Therefore, the Marine Corps has a natural interest in markedly improving ship-to-shore mobility whether it be that portion for which it has the primary responsibility or that for which the Navy is responsible.

SURFACE ASSAULT

Interest in significantly improving the ship-to-shore lift capability of both the Navy and Marine Corps has intensified during the last two decades for several reasons. The introduction of highly capable missiles and nuclear weapons by potential enemies has dictated that amphibious shipping would have to launch both the surfaceborne and air-lifted units at much greater distances from the beaches than in the past. In addition, ship separation distances would have to be increased considerably to minimize ship losses. These requirements impose considerably increased ship-to-shore distances for the landing force units to traverse especially during the initial assaults, i.e., from 3000-5000 yards off the beach to 12-25 nautical miles seaward.

In order to mass a sufficient assault capability in an acceptable span of time, the speed of both the Marine Corps' assault amphibian vehicles and the Navy's landing craft must be improved by at least a factor of 3 or 4. The assault amphibians are armored personnel carriers which lift the Marine infantry from the ships to the beach for the initial assault. In addition., during the initial assault, the Navy's landing craft are utilized to carry artillery with its prime movers and its basic ammunition loads as well as tanks and other combined arms and heavy equipment. Subsequently, landing craft are also used to lift the rest of the weapons, equipment, rations, etc., not carried by the assault amphibians or helicopters. This accounts for approximately 80-85% of the total lift.

HOVERCRAFT DEVELOPMENT

Two decades ago it was clear to those of us responsible for Marine Corps research and development that, in order for the ship-to-shore lift capability to be improved significantly, new concepts, new technologies and some breakthroughs were a *sine qua non*. One of these new technologies was the air cushion technology which was embodied in rudimentary ground effect machines (GEMs) or hovercraft. The Marine Corps followed the progress of the development of air cushion vehicle (ACV) technology beginning in 1959. During those early years, even though the Marine Corps had an extremely limited R&D budget, it supported GEM/ACV basic and applied research much more heavily than any other U.S. military service. In fact, the Marine Corps bought three different vehicles, GEM-1 and GEM-2 which were used to collect basic data by the David Taylor Model Basin (now DTNSRDC) at Carderock, Md, and a huge, six-propeller craft built by F. Weiland in Zurich, Switzerland. The latter, which was procured principally as a demonstration vehicle and to obtain operator experience:, despite strong misgivings by some of us, turned out to be a turkey. It was affectionately called the "chicken plucker" by those who tried to operate it at the Marine Corps Landing Force Development Activity in Quantico, Virginia.

SHIP-TO-SHORE VEHICLES

In the late 1950s and early 1960s there were three basic types of vehicles utilized in the ship-to-shore movement (lift) of Marine landing forces. The first were assault amphibians, (tracked, armored personnel carriers) which carried Marines at about 5 to 6 mph to the beach from ships 3000 to 5000 yards away. These were Marine Corps vehicles operated by Marines. They were tracked in order to ensure that coral reefs and other such barriers would not deter them from reaching the intended beachheads. The second type were World War II DUKWs developed by the Army by converting standard 2½-ton payload military cargo trucks into wheeled amphibians by the addition of a displacement hull and marine propulsion. These vehicles were primarily for logistics support and were also owned and operated by Marines. The third type was a family of landing craft, developed during WW II or shortly thereafter called LCM-6, LCM-8 and LCU. These were Navy craft operated by Navy crews whose maximum payloads were approximately 30, 60, and 180 tons, respectively. All were relatively slow. In sea states 1 to 3, with full payload, their speeds varied from 5 to 9 knots. Given this capability, it is clear why the Marine Corps was interested in new concepts and new capabilities to replace its surface lift vehicles and was exhorting the Navy to replace its landing craft.

DUKWs & LARCs

In 1960 the Marine Corps' inventory of WWII DUKWs dwindled to an unacceptably low number. The Army was replacing its DUKWs with a family of vehicles called LARC-5, LARC-15 and LARC-60, (LARC = logistics amphibious, resupply, cargo) whose payloads in tons were indicated by the number following the dash. Although the payloads of these vehicles were considerably greater than the 2½ tons of the WWII DUKW, their speeds (6 to 8 knots under most favorable sea state conditions) and sizes left much to be desired.

FAST, AMPHIBIOUS SUPPORT VEHICLE (FASV)

The Marine Corps decided that it would explore the technology available in industry to replace the DUKW with a 5-ton payload, high speed (30 to 40 knot) vehicle, called a fast, amphibious, support vehicle (FASV). The decision to attempt to achieve high water speed via the FASV to replace the DUKW rather than with a replacement for the LVTP-5A1, the then current assault amphibian, was based on the fact that the DUKW inventory was in much more dire straits than that of the assault amphibian, and because it was the easier vehicle to which the new technology might apply. Since the FASV vehicle was to compete with assault amphibians and landing craft for amphibious shipping space, its length, width and height had to fit within constraints that would optimize the numbers to be carried on amphibious ships. Consequently, air cushion technology was eliminated as an approach for two reasons, (1) the technology was in its infancy, and (2) the platform size and power necessary to attain payload and speed requirements within shipping and other constraints militated against utilizing this approach.

Contracts were let, (a) to AVCO (Lycoming) for two hydrofoil vehicles, LVHX1-1 and LVHX1-2, with submerged foils; (b) to FMC for two hydrofoil vehicles, LVHX2-1 and LVHX2-2, with hybrid foils (surface piercing forward and submerged aft); and (c) to Ingersoll-Kalamazoo Division of the Borg-Warner Corporation for LVW1-1 and LVW2-1, two planing hull vehicles. All six of these vehicles had wheels which enabled them to operate as trucks on land. All were powered by gas turbine engines developed for aircraft use. The gross weight of each was approximately 40,000 lbs. Water speeds of 12 to 15 knots in a displacement mode and around 35 knots in the flying or high speed mode were design goals. They were all delivered to the Marine Corps and tested generating technical and operational data that was useful for decision makers and other system development efforts. In 1966 the complexity, expensiveness, poor operational reliability, and difficulty of maintaining these vehicles in a salt water environment induced the Marine Corps not to proceed with further development and production.

While the hydrofoil and planing hull type vehicles were still in development, their high cost became an issue. As a result, the Marine Corps embarked on another, supposedly low-cost, approach to the FASV. The ARCK-1 was an SES type vehicle called a "hydrokeel" or "air-lubricated hull" developed as another option to meet the FASV mission. This craft was designed and built by the Antifriction Hull Corporation which was eventually purchased by Bell Aerospace Corporation. The ARCK-1 also failed to live up to expectations. Consequently the Marine Corps dropped the FASV requirement, deciding to put its weight behind a high speed ACV landing craft effort.

AMPHIBIAN VEHICLES

In the early 1960s the Marine Corps recognized that surfaceborne craft high speed technology could not be adapted successfully to the assault amphibian vehicle, and initiated development of the LVTP-7 via the LVTPX-12 program. The principal objectives of the experimental LVTPX-12 development vehicle were to achieve better water handling via water jet propulsion; land operations capability, especially speed (45 mph); reliability and maintenance characteristics. The resulting LVTP-7, although only capable of optimum water speeds of about 8.5 mph, provided ship-to-shore time improvements of roughly 33% over the then obsolescent LVTP-5A1, and reduced maintainability by a factor of 3. This new assault amphibian was still a rather slow speed vehicle relative to the high speed requirement, but the LVTP-7 program did achieve a noteworthy distinction. When it was introduced in 1971 it was delivered on time and at predicted procurement cost, no small feat for a major program at that time or now.

AIR CUSHION VEHICLE BREAKTHROUGH

In the mid-1960s, as the testing of the FASV candidates was winding down and after the Bureau of Ships ***Hydroskimmer*** (SKMR-I) built by Bell Aerospace was tested in various operational environments, the Marine Corps made a concerted effort to convince the Navy that the best way to improve ship-to-shore surface lift dramatically was via the development of an air cushion landing craft. In addition to relevant analysis, one of the more convincing maneuvers toward this goal, was an OPTEVFOR test of the SKMR-1, SRN-5 (a Saunders-Roe craft), and the VA-3 in the Norfolk, Virginia area. The Marine Corps had funded testing of the Vickers-Armstrong VA-3 in this country including surf tests off Montauk Point, Long Island. When these proved successful, the Marine Corps agreed to fund the OPTEVFOR tests of the VA-3 if BuShips covered the costs of the SKMR-1 and SRN-5 testing.

The principal operational objectives of these tests were to ascertain (a) the maneuverability of the ACVs into and out of the well-deck ships (LPDs and LSDs), (b) how well the craft operated in the surf and transitioned from water to land, (c) the limitations of large ACV mobility on beaches and in coastal areas, and (d) whether a naval aviator, or someone less technically trained, such as a coxswain, would be required to pilot ACVs.

The ancillary (and, in a sense, most critical) objective was to provide the brass of the Navy and Marine Corps an opportunity to observe how these craft operated and what they could do. Almost to a man, every admiral and general who saw these craft operate became a strong believer and advocate. The tests were successful technically, operationally, and programmatically. Shortly thereafter an operational requirement for an air cushion landing craft was generated and promulgated.

FROM AALC TO LCAC

The operational requirement for a high speed air cushion landing craft resulted in an advanced development program entitled Amphibious Assault Landing Craft (AALC). The problem (and it persisted for years) was to keep this program funded and alive. The speeds, dimensions, and lift capabilities of this landing craft were ascertained through a number of analytic studies and weapon/equipment loading exercises. These helped to ascertain the optimum ACV landing craft size required to carry the initial assault artillery, its prime movers, ammunition loads, etc., and the main battle tank as well as other high priority combat arms systems. In addition, the vehicle design was dimensionally optimized so that a maximum number of these craft could be carried in amphibious ship well decks.

Dozens of designs were prepared and assessed. Two contractors, Bell Aerospace Division of Textron and Aerojet General Corporation, were funded to produce two prototypes each of their winning designs. Eventually, with the limited R&D funding environment in DOD both contracts were reduced to producing one prototype each. The NAVSEA (for by then BuShips was converted to the Naval Sea Systems Command) acquisition strategy was to ascertain the optimal features of each company's prototypes by extensive field and sea testing, and then to generate a top level requirement (TLR) which would be the basis for a request for proposal (RFP) for a landing craft procurement. The production version of the AALC was labelled Landing Craft, Air Cushion (LCAC). Presently the LCAC is in limited production, the first craft having had its roll-out on 2 May 1984 at the Bell-Halter facilities in New Orleans, La.

LVT AND LVA

Once the requirement for a high speed air cushion landing craft was promulgated and the LVTP-7 procurement was underway, the Marine Corps commenced planning the next generation of assault amphibians. A high speed assault amphibian vehicle development program was initiated. In addition to having high speed it was also intended to be an infantry fighting vehicle armed with the new 25mm chain gun developed for the Army's infantry fighting vehicle, the Bradley. It was called an LVA (landing vehicle assault), and was intended to achieve water speeds of 25 to 35 knots. Thus, it would complement the speed capability of the air cushion landing craft. In 1979, this program was terminated, because the designs of the competing companies were too complicated, large and expensive. Tactically, the design vehicles were better targets than the main battle tank, but did not possess its armament. Reluctantly, the Marine Corps settled for a service life extension program (SLEP) of the LVTP-7 called the LVTP-7Al. It is currently entering the inventory. At the same time the Marine Corps is initiating its LVT(X) program, which is to replace the LVTP-7Al in the very late 1990s. While not markedly improving water speed, this vehicle is intended to be a low profile assault amphibian that will also be used as an infantry fighting vehicle with the same armament as the Army's infantry fighting vehicle, the Bradley. A revalidation of the required operational capability (ROC) for this vehicle is presently underway. Concurrently an assault amphibian exploratory development program is also being prosecuted. It is oriented to subsystem development. These subsystems could have applications to either slow speed or high speed amphibians.

FUTURE CHALLENGE

No new high speed concepts have been proferred for the past two decades except for a wheeled boat design. This concept is in its very preliminary stages. A ½0-scale model has been demonstrated. It offers great promise if adaptable to the assault amphibian mission. Clearly, with the LCAC, one half of the surfaceborne, high speed craft/vehicle problem has been solved. The high speed assault amphibian mission is a much more difficult and challenging matter. By the turn of the century we may see it resolved also.

U.S. ARMY WATERCRAFT

Dr. Julius Hein *is the deputy product manager and Chief Engineer for U.S. Army amphibians and watercraft. He has a B.S. in mechanical engineering (1958), M.S. in engineering management (1972), and a doctorate in public administration from NOVA University in 1981. He is a member of the American Society of Mechanical Engineers and the Society of American Military Engineers and is a registered professional engineer in the state of Vermont. His varied experience includes developments of guided missiles, fuel cells, power generation and distribution equipment and he is currently managing development, procurement and modernization programs for U.S. Army watercraft.*

INTRODUCTION

The United States Army recently conducted a conference attended by over 200 designers, users, maintainers, operators, and suppliers of watercraft. It addressed the past experience, current requirements, and future needs for watercraft to support combat troops in the field who need to be supplied with ammunition, fuel, equipment, components, and spare parts, to sustain their operations. Both the Army and Navy have logistics-over-the-shore (LOTS) operations. These operations require offloading cargo from the ships to designated resupply distribution points. The key difference is that the Army provides support to Army and Air Force units while the Navy provides supply to the Marine Corps. This review will cover some recent changes in the LOTS operations of the Army, the watercraft which are now being used, and some future plans for development and use of Army watercraft.

WATERCRAFT IN VIETNAM

Combat conditions in Vietnam dictated operational changes in supply support and LOTS concepts. All areas along the shore and rivers were subject to continuous enemy observation and hostile fire. No terrain was totally under friendly control. This compounded the supply and resupply problems. The combat and communication zones were not stable. The demurrage cost for deep draft ships waiting for a berth in Vietnam ports became staggering. These ships experienced a slow port clearance due to inadequate roadways leading from the ports and shortages of vehicles. Ship delays were further aggravated by the shortage of terminal services. More ships and cargo arrived than the ports had the capability to discharge. To resolve these shortcomings, deep and shallow draft ports had to be built and had to be protected. Shallow draft ports were rapidly built through the use of DeLong piers which were quite versatile and were built in different configurations ranging from 80 to 120 feet wide and 450 to 1200 feet long. Barges were towed to the pier side and were quickly implaced at their destination.

PORT OPERATIONS

A variety of Army watercraft were employed in the operation of three major deep draft ports and five shallow draft ports. These included large and small tugs, floating machine shops, floating cranes and numerous types of barges. The Army also used landing craft, utility (LCU), landing craft, mechanized (LCM-8), LARC-V (5-ton), and LARC-LX (60-ton) to perform ship-to-shore, intercoastal, and inland waterways operations.

The U.S. Army beach discharge lighter, *LCol. John U. D. Page*, supplemented the Navy's LST fleet to move priority cargo. She was married to the stern of the USNS *Comet* to receive roll-on/roll-off cargo, the bow ramp having been specifically designed for this purpose.

MARSH OPERATIONS

Marsh operations dictated a need for a craft capable of traversing tidal areas and shallow river overflow areas. To meet this requirement, the Army evaluated three 10-ton Bell patrol air cushion vehicles (PACVs) in Vietnam in 1966. The PACVs were militarized versions of the British SRN-5. These were the first Army air cushion amphibian river patrol boats and were designated SK-5 (Figure IJ). The SK-5 had a cruising speed of 50 knots; armor protection for crew and engine; puff ports in the bow for improved maneuverability; one remote-controlled 40mm grenade launcher, two 50mm machine guns in roof mountings, and two 7.62mm machine guns in the aft cabin windows. The SK-5 was very effective and paved the way for future air cushion vehicle technology usage.

THE. LAVC-30

The U.S. Army planners recognized that the air cushion vehicle might revolutionize the concept of LOTS resupply operations and began to develop and procure the lighter, air cushion vehicle (LACV-30). The mission of the LACV-30 is to carry two fully-loaded containers from deep draft vessels over the beach to the staging point on land. The Army has contracted for 26 LACV-30s with

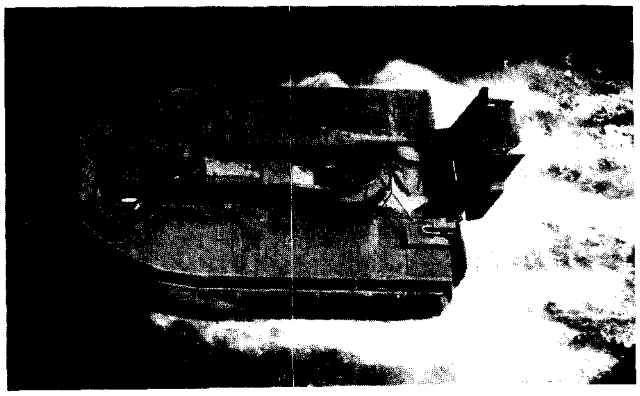

Figure IJ. SK-5 Army Air Cushion Vehicle.

Bell Aerospace, Textron. The first company of 12 is fully equipped and operational at Ft. Story, Virginia. The second company is scheduled to be fielded within a year. The Army is the first of the U.S. Armed Services to have organic air cushion vehicles.

LARGER AIR CUSHION VEHICLES

The U.S. Army has a LOTS resupply requirement to transport heavy equipment such as M-l tanks, tracked and wheeled vehicles, 20 to 40-foot containers, outsized equipment, and general cargo from a deep draft ship to the shore.

To reach planning objectives, greater productivity with fewer lighters must be achieved. To achieve this productivity, it is planned to replace the wheeled amphibian LARC-LX with an air cushion amphibian, the lighter amphibian, heavy-lift (LAMP-H). The LAMP-H will provide a heavy-lift capability to move cargo and equipment over water, marginal terrain, ice, snow and as far inland as practicable. This craft will be capable of operating in at least five-foot surf; have a minimum over-water speed of eight knots, have a minimum gradient traversing capability of 1 in 17 rise, traverse ditches and trenches up to 10 feet in width and 9 feet deep, and be capable of transporting 70 to 140 short tons of cargo. The LAMP-H will be designed to be compatible with roll-on/roll-off vessel discharge systems and will have an integral bow ramp to accommodate loading and discharging of wheeled and tracked vehicles.

PROCUREMENT PLANS

Along with the new air cushion vehicles (LACV-30 and LAMP-H) the Army is also planning to procure commercially designed nondevelopmental items (NDI) to replace the existing fleet. The NDIs are:

A) **Logistics Support Vessel** (LSV). The LSV will have the capability of intratheater line haul of cargo to support unit deployment and relocation. It will also provide tactical and sustained resupply to remote, undeveloped areas along coastlines and on inland waterways. It will also be used to assist in discharging and backloading deep-draft ships in a roll-on/roll-off of cargo and be capable of loading, transporting in integral tanks and off-loading 11,000 barrels of bulk liquid cargo. Procurement is planned for fiscal year 1985.

B) **Landing Craft, Utility** (LCU). The LCU will be constructed of steel and have twin screws and twin diesel drive. It will have an open, self-bailing cargo deck with a minimum of 2,000 square. feet of cargo space and will incorporate a ramp and main deck capable of supporting M-l tanks and fully loaded IS0 containers. It will be capable of transporting 250 to 350 short tons of cargo and attain a bow beaching drafft of not greater than four feet while transporting up to 175 short tons of cargo. The craft will be self-deliverable within a range of 3,600 to 4,500 nautical miles at a sustained speed of 9 to 12 knots in an international sea state code 3. Procurement is programmed to begin in fiscal year 1985.

C) **Coastal, Harbor and Inland Waterway Service Boat** (CHI). The CHI boat will provide command and control, security, passenger and light cargo transport for CHI operations, and is programmed for procurement in fiscal year 1987.

D) **Causeways.** The Army and the Navy will procure four separately configured causeway systems. The systems will be procured by the Navy as roll-on/roll-off platform, powered causeway, floating causeway and elevated causeway. Adverse hydrographic conditions require that lighterage operations will have to be supplemented by these causeway systems to link lighters to the shore or provide platforms for the off-shore discharge of RO-RO ships. Procurement is planned to start in fiscal year 1985.

CONCLUSION

The U.S. Army watercraft fleet is now receiving the much needed commitment for modernization. This planned procurement program must be accomplished at the earliest possible time to achieve the resupply capabilities assigned by the Department of Defense.

COAST GUARD VESSELS TO DO THE JOB

Capt. George Moritz, USCG *received his BS degree in engineering from the U.S. Coast Guard Academy and his MS degree from the City College of New York. In addition to being engineer officer in both medium and high endurance cutters, he has served as communications officer, navigator, executive officer and damage control officer. He has also been a design engineer at Gibbs & Cox, served as industrial manager of a Coast Guard repair base and was chief, Naval Engineering Branch, Seventh Coast Guard District during the maintenance-intensive Cuban Exodus of 1981. He was project officer for the procurement of three surface effect ships now on law enforcement missions in the Caribbean and is presently chief, Naval Engineering Division, U.S. Coast Guard Headquarters in Washington. A member of ASNE since 1970, he serves on the Scholarship Committee and the Flagship Section Council.*

MISSIONS DEFINE EQUIPMENT NEEDS

The United States Coast Guard is a complex organization of people, ships, boats, aircraft and shore stations. Decentralized both administratively and operationally, Coast Guard personnel respond to tasks in several mission areas. A single vessel may carry out roles in law enforcement, search and rescue, marine environmental protection, and icebreaking. Additionally, the Coast Guard is, at all times and in all places, an armed force of the United States. The Coast Guard's multimission approach permits a relatively small organization to be responsive to public needs in a wide variety of maritime activities with the ability to shift emphasis on short notice when necessary.

To effectively carry out its responsibilities, the Coast Guard needs safe, reliable, multimission vessels with high performance or enhanced capabilities. This broad spectrum of responsibilities is reflected in the tabulation of activities noted in Table 1K.

GENERAL REQUIREMENTS

The most important characteristics of any Coast Guard vessel continue to be survivability, reliability, and maintainability. Its vessels, by the very nature of search and rescue and military missions, must be able to withstand conditions and events far more adverse than commercial or private craft are likely to encounter. They must also be ready to respond whenever called upon. That means they must have minimum "down time" whether for maintenance or for casualty repair. In short, Coast Guard vessels must be safe and easy to maintain in a ready condition.

All Coast Guard vessels must be multimission capable. Ships designed for salvage work are now performing law enforcement missions, cutters built for ocean station duty are patroling controlled fishing areas, and buoy tenders break open ice bound channels. The Coast Guard has to be able to respond quickly with the equipment it has.

In addition to the basic demands for safety, reliability, maintainability, and multimission capability, the primary missions of the Coast Guard now require the high performance and enhanced capabilities of advanced marine vehicles. The mission areas of search and rescue, law enforcement, military readiness and port security all require various combinations of speed, endurance, seaworthiness, and habitability. The requirement for speed is not driven by the need to pursue smugglers, but is actually a broader requirement for quick arrival at a search area or disaster and for military missions. Set against the need for the cutter or boat to reach distant operational areas quickly is the need to remain on the scene for very long periods while its crew performs tasks such as boarding, firefighting, or aiding people, more often than not, in adverse weather. Modern marine vehicles have the potential to meet this need better than similarly sized displacement monohulls.

The expense of personnel and the reduction of the size of the Federal Government mandate smaller crews, The minimum crew size is set by watchstanding requirements. At the same time, the newest missions require that

Table 1K. Activities Involving Coast Guard Ships and Boats.

	1983 Actual	1984 Estimate	1985 Estimate
• **Law Enforcement**			
Cutter operating hours:			
Fisheries enforcement	52,589	65,000	75,000
General law enforcement	170,655	175,000	191,608
General LE flight hours	10,315	22,800	24,700
Vessel seizures	176	200	225
• **Ice Operations**			
Polar ice operations:			
Icebreaker deployment days	720	610	610
Domestic ice operations:			
Cutter operating hours	595	4,400	4,400
Vessels assisted	42	440	440
Marine science activities:			
Cutter operation hours	3,571	3,500	3,500
• **Military Readiness**			
Vessels in refresher or shakedown training	68	55	57
Ship weeks	126	142	149
Independent gunnery exercises	420	530	550
• **Search and Rescue (SAR)**			
Response to search and rescue: cases	58,200	57,500	57,000
People saved or assisted	164,840	160,000	155,000
Property loss prevented (in millions of dollars	614.5	600.0	580.0

vessels arrive on scene and continue to operate while a part of the crew performs some extravehicular function. Thus, platform stability and simplicity of the vessel have become more important. Platform stability of our smaller cutters is important for radar and visual detection effectiveness. It is also an important factor in crew endurance, alertness and effectiveness. Similarly, personnel shortages mean that vessels must be simply operable, reliable, readily supportable, and easily maintained and repaired.

COAST GUARD VESSEL DEVELOPMENT

The Coast Guard has an ongoing program to quantify the effectiveness and costs of modern marine vehicles performing operational missions. Major goals of this program are identification of strengths and weaknesses of each concept and determination of the most cost-effective platform mix to satisfy multimission needs. Activities in this program have included (chronologically):

A) Limited evaluations of a British hovercraft (SK-5 ACV) and the fully-submerged hydrofoil vessel Flagstaff in the late 60s.
B) Operational evaluation of three British hovercraft SK-5 ACVs in San Francisco Bay, Chesapeake Bay and Lake Michigan in 1971 and 1972 to provide performance and maintenance data relative to search and rescue, law enforcement, marine environment protection, and aids to navigation missions.
C) In conjunction with NSRDC, trials at Naval Arctic Research Laboratory (NARL), Pt. Barrow, Alaska during 1971 using a British hovercraft SK-5 ACV to verify computer modeling for the SES design project.
D) The 1972 mission trials of the USN hydrofoil gunboat *Tucumcari* (PGH-2). Coast Guard trials provided performance data and verification of assumptions for a previous study.
E) Underway trials and performance tests of a surf rescue boat, the experimental motor rescue boat (MRBX), in 1973.
F) In 1973, the Coast Guard Yard built SSP *Kaimalino*, a SWATH vessel, for the Navy and conducted an extensive technical evaluation including side-by-side seakeeping tests with a 100-ton patrol boat and a 3000-ton high endurance cutter.

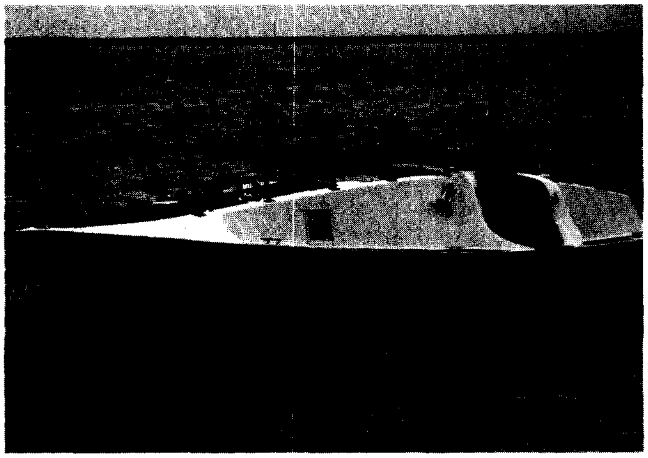
Figure IL. U.S. Coast Guard 30-foot Surf Rescue Boat.

G) In 1975 a Coast Guard team observed the performance of the U.S. Navy's experimental coastal patrol interdiction craft (CPIC), a high speed, advanced design planing craft of patrol boat size.
H) An operational evaluation of the MRBX on the Oregon Coast in 1975 which led to production of the surf rescue boat (SRB) class.
I) Field testing in 1978 resulted in a report entitled "Changes in Crew Performance Physiology and Affective State Due to Motions Aboard a Small Monohull Vessel," describing effects such as seasickness and reduced performance of boat crews.
J) The fully-submerged hydrofoils *High Point, Tucumcari* and *Flagstaff* were evaluated for fisheries law enforcement between 1972 and 1978. A 1975 operational trial of *High Point* (PCH-1) was a one month underway evaluation for fisheries enforcement missions. A 1975 operational evaluation of *Flagstaff* involved running for six months with a Coast Guard crew on search and rescue, fisheries patrols and drug enforcement missions. *Flagstaff* was commissioned a Coast Guard cutter from 1976-1978 and was the subject of a comprehensive operational evaluation for the same missions.

The case of the surface effect ships (SES) is a good example of the success generated by having an operationally ready vessel to test. Coast Guard interest in its first SES started while it was still under construction at Bell-Halter in 1978. Coast Guard personnel rode the boat during its demonstration period in 1979 and conducted an engineering evaluation in early 1980. During the latter part of 1980, the Navy also became interested and eventually purchased the boat with some Coast Guard funding involved. It was modified as a Coast Guard patrol boat and operated from June to December 1981 for an operational evaluation. During this period, commissioned as USCGC *Dorado* (WSES-1), the boat was operated in many Coast Guard mission areas. It was assigned to various commands along the Gulf of Mexico and took part in all of the types of duties typical for Coast Guard patrol boats. These included fisheries law enforcement out of Galveston, search and rescue and law enforcement patrols out of Corpus Christi, and aids-to-navigation servicing out of New Orleans including a pollution control drill in and around the Louisiana Offshore Oil Port. During that exercise, *Dorado* proved to be very effective in transporting the large, bulky oil barriers that are deployed to contain spills. Much of the operational evaluation was spent on law enforcement patrols in the southern portions of the Gulf. These patrols involved coordinated operations with other Coast Guard units working to prevent drug smuggling.

OPERATIONAL DEPLOYMENT

The conclusion drawn from the *Dorado* operational evaluation was that this type of craft could be successfully employed in many Coast Guard missions. When Vice President Bush declared, in February of 1981, that the Coast Guard would increase offshore surveillance efforts to help with the interdiction of drugs, part of the Coast Guard's response was to begin to acquire new resources. Near the end of March, procurement of three surface effect ships was approved. A contract was then negotiated between the Coast Guard and Bell-Halter. All of these boats were delivered on time, at contract cost, with no overruns or claims. The boats in commission today are basically the same as the *Dorado*. Fast and seaworthy, they are very welcome additions to the fleet. The success of the project was due, in large measure, to the reduction of uncertainty and risk through the broad, in-depth operational evaluation.

Another result of an effective operational evaluation is the 30-foot surf rescue boat (30' SRB) shown in Figure 1L. The design was accomplished in-house as was the design of the 44-foot motor lifeboat (44' MLB) which is world famous for its ability to endure a 360-degree roll in breaking surf and continue operations with all systems running. The ability to right itself was also one of the 30' SRB criteria, along with the need to be self bailing, highly reliable, and easily maintained. A prototype was built and was delivered in August 1977. It was tested extensively on the Northwest Pacific Coast. Rollovers were induced in controlled calm water experiments and in the actual operating environment. With only a few changes made to increase speed and visibility, the prototype was considered a success. Twenty second-generation boats and the prototype are now in operation at search and rescue stations throughout the country.

CURRENT PROJECTS

The Coast Guard is currently purchasing 15 patrol craft to improve the law enforcement effort in the Southeastern United States. These boats will be fast, improved monohull vessels with a speed about 20% above the current 95-foot patrol boat (95' WPB) speed. They will have approximately the same seakeeping and human factors characteristics at comparable speeds, but will have degraded characteristics at the higher speeds.

The small waterplane area twin hull (SWATH) vessel is a current design project. (See Figure 1M). Conceptual and preliminary design has been completed in-house and approval has been received to proceed with the final design and construction of the first ship. This prototype SWATH will be approximately 120 feet in length, have a 55-foot beam, about 600 tons displacement and have a maximum speed of 25 knots. It will be able to deploy the newest CG HH-65A helicopters, and will add great flexibility to our patrol boat fleet. The SWATH will be fully-capable in up to sea state 5, including helo operations. Because of its hull configuration, it will be able to maintain full speed in 8 to 12 foot seas and provide optimum crew comfort. Plans are to begin the construction of the SWATH by the summer of 1985.

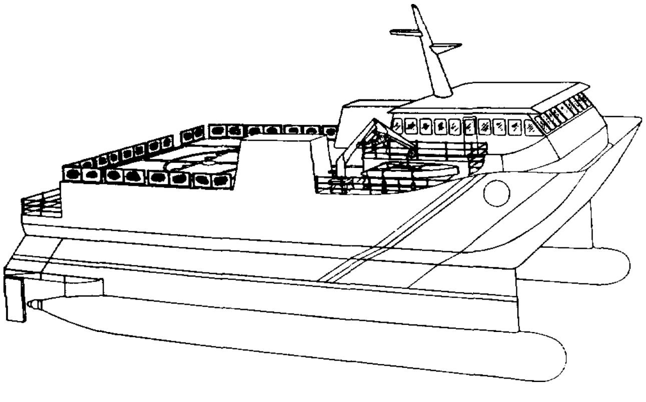

Figure 1M. Coast Guard SWATH Cutter Design.

FUTURE NEEDS

The Coast Guard's capital investment plan calls for acquisition of a patrol craft (WPC), and additional WPBs in FY 85 through FY 89 for a total of 40 fast displacement or planing craft. Also, replacements will be needed for the Coast Guard's utility boat (UTB) and the large motor life boat (MLB). Use of alternative concepts in service (e.g., SWATH, SES, hydrofoil) has begun and will continue through the next decade.

The patrol craft (WPC) is a complementary resource providing mid-level patrol and interdiction capability. Its acquisition is intended to fill the specific capability gap which exists between current WPBs and current WMECs. A mission needs statement to support this acquisition was prepared in November of 1983.

The Coast Guard is seeking authorization to acquire replacement planing or fast displacement WPB patrol craft prior to 1990 and alternative craft concepts between 1990 and 1994. This capability will replace that currently provided by twenty-three 95-foot WPBs and fifty-three 82-foot WPBs which comprise the WPB class. The present boats will have met or substantially exceeded their useful life by 1990. Based on current multimission requirements, it is estimated that the Coast Guard will require the equivalent capability of ninety-four of these vessels. The exploration of concepts will seek to determine the most efficient mix of platform resources and operating concepts, under the guidance of OMB circular A-109, to fill the need. The intent is to satisfy the mission requirements with cost effective craft-not to acquire a predetermined number of hulls.

CONCLUSION

The shape of Coast Guard cutters and boats is determined by the missions they must perform. Because of the operating scenarios, the foremost requirements in any design are safety, reliability and maintainability. Safety encompasses both survivability of the vessel in hostile environments or after damage and crew safety under all conditions. The financial environment dictates multimission capability, labor-saving design plus low schedule, technical and cost risks. Such factors are balanced against the need for speed which, in turn, is affected by the need for endurance and platform stability.

The Coast Guard has spent considerable time and effort in evaluation of modern marine vehicles and will continue to do so. The use of operational experience as a large part of the evaluation process to reduce risk has resulted in successful deployment of new vessel classes.

The current building and modernization projects are parts of a continuing effort to keep the Coast Guard equipped to do its job. The process must continue with upgrades, new construction, and the ongoing application of new concepts to meet mission requirements in the decades ahead.

A NEW ECONOMIC ANALYSIS OF HIGH-SPEED FERRY SERVICE

Patricia Cass *is a program manager with the U.S. Department of Transportation's Urban Mass Transportation Administration (UMTA). She has been responsible for the Congressionally mandated demonstration and study of high-speed waterborne passenger transportation since 1978. Miss Cass developed the study design to accomplish the Congressional requirements and has managed the contractor effort for the past two years. She is also in charge of the UMTA research program to improve transportation services for handicapped persons. Miss Cass has been with the Government since 1971. Prior to that she was a consultant in Boston, New York and San Francisco.*

SCOPE OF THE UMTA STUDY

The Urban Mass Transportation Administration (UMTA) was charged by the Congress to study high-speed waterborne passenger services and vessels worldwide and to apply the lessons learned to specific sites in the U.S. in order to determine the feasibility of such service domestically. This was an attempt to answer the question of why these services proliferate in many countries throughout the world but are virtually nonexistent in the United States. The analysis concentrated on advanced marine vehicles which operated in revenue passenger service (obtaining information from both builders and operators). The sites picked for study included the New York, Washington, D.C., Seattle, San Francisco and Boston metropolitan areas, Lake Michigan, San Juan and the Virgin Islands, the Hawaiian Islands, and a joint service operating from Providence to Newport and the Cape Islands in the summer and from Fort Lauderdale to the Bahamas in the winter.

CHARACTERISTICS OF INTERNATIONAL OPERATIONS

Many operators have been in the business of marine transport for a long time, in some cases well over a century. Operating high-speed vessels is simply a way of improving service. This is generally not true of the few ferry boat operations in the United States.

Many high-speed waterborne operators provide a diversity of transportation services. Trucking is often one of them, also travel agencies, conventional ferries, and other related businesses. In the United States the ferry boat operator is usually only in that business.

High-speed waterborne patrons worldwide use the service for a multitude of trip purposes. In the Mediterranean, patronage tends to be for recreation with some commutation. In Scandinavia, patrons are mostly commuters and business persons. Cross-channel operations (between England and the Continent) carry every kind of traveler. Cross-harbor operations in Hong Kong carry mostly commuters. Hong Kong to Macao services carry mostly gamblers. In Japan, fast ferries are used for business purposes or for recreation. In South America, depending on the particular service, ridership is made up of commuters or tourists to the country. In the United States, conventional ferry boat patronage is mostly commuters.

With few exceptions, worldwide, most operations are subsidized, though not necessarily by the government. In Scandinavia and Italy, the federal governments have a policy of providing fast ferry service to outlying islands and hence subsidize that service. In Japan, there does not appear to be any subsidy at all. Cross-channel operators and one operator in Scandinavia as well as Condor in the Channel Islands rely heavily on revenues from duty free goods. Some services are subsidized by hotels, casinos and the like.

SERVICES IN THE UNITED STATES

At the time this article was written there were few high-speed waterborne services in operation in the U.S. Primarily, these are seasonal services using hydrofoils; one vessel on the Great Salt Lake, one on Lake Superior and three at Sea World in San Diego. Several private companies have expressed interest in running high-speed waterborne passenger service from New Jersey to New York and from New York to Atlantic City. There are also operations under consideration in California, Alaska and Florida.

SELECTING POTENTIAL LOCATIONS FOR ANALYSIS

As mentioned earlier, 10 places in the U.S. which appeared to have good potential for implementation of high-speed ferry services were studied in some depth. The following considerations governed the analysis in each site:

- The most conservative approach to estimating ridership was used,
- every boat was initially considered though some were later dropped if they drew too much water,
- all boats were screened for ride comfort. If a vessel could not provide the ride quality necessary to carry passengers over a particularly rough stretch of water, that vessel was dropped. from that site,
- a two boat fleet was the: minimum size allowed,
- a ten year loan with 12% interest and a 20% salvage value of the vessels were assumed, and
- all sites analyzed assumed private sector investment and operation with no Federal subsidy except San Francisco and Seattle (where ferry services already receive government subsidy).

ANALYSIS OF POTENTIAL LOCATIONS

The results of the domestic site analyses are briefly described below. A financial summary of a typical route is provided in Table 1N.

BOSTON

A commuter route was analyzed supplemented by a summer service to Provincetown. Due to shallow water in the Hingham harbor, hydrofoils were dropped from the analysis. Due to open water across Massachusetts Bay, small boats were dropped. It was determined that the commuter service could not sustain itself and would have to be subsidized by the seasonal recreational service.

HAWAII

An interisland route (Oahu to Maui stopping at Molokai) was analyzed and found to be profitable using the more expensive boats such as the Jetfoil and the Japanese built SWATH ***Seagull.*** One intraisland route from Honolulu Airport to Waikiki Beach also appeared to be potentially successful if transfers from plane to boat were made convenient.

LAKE MICHIGAN

A passenger/cargo/car ferry from Milwaukee to Muskegon could make a profit using the SRN-4 if a fairly high level of container freight was maintained. On a route from Muskegon to Chicago using a foot passenger, fast ferry, a profit could be made with a market capture of 14% of existing travelers at a fare comparable to driving costs.

NEW YORK

Five routes were initially analyzed and then various combinations of these put together in order to determine the highest potential for profitability. At a fare slightly higher than existing commuter transit fares but lower than the cost of operating a car, high-speed ferries could make a profit on a route from Monmouth County, New Jersey to Battery Park on Manhattan using catamarans, the smallest surface effect ship or the small air cushion vehicle. A breakeven analysis was done on the New York to Atlantic City route. It was found that with a relatively small market capture even the most expensive boat (the SRN-4 was not considered) could recover costs at a reasonable fare. If transfers between boat and plane could be made convenient it was determined that small, fairly low draft, fast ferries could make a profit on a route from Manhattan to LaGuardia Airport at a fare less than bus or taxi. A recreational service to Sandy Hook, New Jersey was shown to make a profit if this route bore no capital costs of the vessels, i.e., the capital cost was allocated to another primary route on which the vessel was used. A

Table 1N. Financial Summary of Sample Route.

Craft	Number Passengers Annually	Total Annual Revenue	Capital	Annual Costs (for 2 boat fleet) Fixed	Operating	Total	Annual Profit or Loss
Hydrofoils							
PT-20	136,000	$846	$595	$150	$503	$1,248	$ - 402
PT-50	286,000	1,590	909	150	796	1,855	- 265
RHS-70	151,800	931	752	150	548	1,450	-519
RHS-150	396,000	2,035	1,380	150	1,087	2,617	-581
RHS- 160	45 1,000	2,263	1,694	150	1,246	3,091	- 828
RHS-200	660,000	2,903	2,322	150	1,667	4,135	- 1,235
Jetfoil	930,000	3,878	4,833	150	2,708	7,692	-3,814
ACV's							
MV-PP5	180,950	1,126	1,317	150	967	2,424	- 1,308
AP. 1-88	3 10.200	1,755	752	150	771	1,673	+ 82
SES							
BH-340A	677,600	2,752	1,537	150	1,545	3,232	-480
HM-218	189,200	1,129	501	150	587	1,238	- 109
HM-527	572,000	2,610	1,568	150	1,289	3,007	- 397
Catamarans							
W-86D	330,000	1,697	626	150	698	1,474	+ 223
W-95D	479,600	2,300	783	150	1,090	2,023	+ 277
CP-20-HF	5 10,400	2,397	1,725	150	1,502	3,337	-980
JC-F1	473,000	2,280	1,160	150	1,142	2,452	- 173
29 Meter	400,950	1,949	642	150	690	1,482	+ 467
SWATH							
Seagull	719,400	2,811	2,667	150	2,165	4,982	-2,171

Notes:
1. Trip length was 21.4 n.m.
2. Passenger fare varies depending on the speed of the vessel.
3. Revenues, costs and profits are shown in thousands of dollars

commuter service down the Hudson River was not found to be profitable no matter what other route it was combined with.

PROVIDENCE TO NEWPORT, NEW BEDFORD AND MARTHAS VINEYARD AND FORT LAUDERDALE TO THE BAHAMAS

This service was modeled after PBA Airlines which concentrates on Southern New England in the summer and on Florida in the winter. With a very high market capture, at fares comparable to existing travel costs, the Narragansett Bay/Cape Island service could make a profit. Only the largest boats were used in this service since they had to be able to cope with the Gulf Stream in the Florida/Bahamas service in the winter. Only one 200-passenger hydrofoil is able to make a profit in both the New England and Bahamas service.

SAN FRANCISCO

No craft could make a profit without a Federal capital subsidy if the fare charged by the Golden Gate Ferry System was charged. If a slightly higher fare was charged, the three largest catamarans could make a profit. This is on the satne route now served by the Golden Gate Ferry System. All other routes analyzed could not make a profit.

SEATTLE

At the request of Washington State Ferry, an agency of the Washington State Department of Transportation, foot ferries were substituted on two of the most popular car ferry routes. Assuming a Federal capital subsidy of 75%, and using the same fare now charged, all craft except the most expensive made a profit. A service from Anacortes to Vancouver, B.C. without Federal capital assistance was analyzed, but could not sustain itself.

VIRGIN ISLANDS AND PUERTO RICO

Only the larger vessels were used in this analysis due to the open water from San Juan to St. Thomas and from St. Thomas to St. Croix. At a relatively low market capture (7%) the breakeven fare ranges from $19 on the large catamaran to $77 on the largest hydrofoil on the St. Thomas to St. Croix route. With a fairly high market capture (23%) on the San Juan to St. Thomas route, the breakeven fare ranges from $9 on the large catamaran to $37 on the largest hydrofoil.

WASHINGTON, D.C.

No profitable routes could be identified. The metropolitan area has a very comprehensive transit/highway network. It was determined that high-speed waterborne services could not compete in either time or dollars.

CONCLUSIONS

Some routes within sites could possibly make money for the private entrepreneur, however, contrary to the study team's expectations, there were not as many of these as originally anticipated. High-speed waterborne passenger vessels, both domestic and foreign built, are expensive, both from a capital and operations standpoint. It must be remembered that the sites analyzed by the study team were representative only, and do not purport to exhaust all opportunities for high-speed waterborne passenger service in the United States. Also, the average American is used to fairly rapid, inexpensive (at least from his perception) tripmaking either in his own car or by commercial transit. Often overlooked in this type of analysis is the substantial subsidy of both the U.S. road and transit systems.

Detailed analyses of the international operations and vessels are available from the U.S. Department of Transportation and the National Technical Information Service. Also available are tlhe details of the domestic site analyses as well as an implementation guide for potential operators of high-speed waterborne passenger transportation services in the United States.

*FUTURE NAVAL SURFACE **SHIPS***

Michael C. Eames *is the senior scientist of the Canadian Defense Research Establishment Atlantic (DREA) in Dartmouth, Nova Scotia. He has also been adjunct professor of naval architecture at the Technical University of Nova Scotia since* 1979.

He was born and educated in England and emigrated to Canada in 1952 later becoming the naval architect responsible for hydrofoil research at DREA. He originated the concept which led to construction of the open-ocean, antisubmarine hydrofoil skip, HMCS Bras D'or. *He has been directing broad studies of future skips for NATO and for the Canadian Forces since 1974.*

INTRODUCTION

A summary of possible advances in the naval architecture of surface warships, as forecast for a recent NATO long-term scientific study, was published in 1981 [1]. This overview is a sequel to that paper. Having forecast what is possible in ship-platform technology, the next step was to examine the operational need for such advances and how they might best be exploited.

These ideas are intended to encourage wider discussion of the relative merits of various vehicle types. Progress in advanced naval vehicles has been seriously hindered by advocates overselling their virtues or versatility. A novel type has often been compared with destroyers designed 30 years previously, ignoring contemporary advances possible in conventional displacement ships.

The theme of this paper can be summarized by an old seaman's adage, "a place for everything, and everything in its place." The author's interpretation of "the place" for each vehicle type does not reflect any official view of the Canadian Forces. However, the conclusions do reflect constraints appropriate to the smaller NATO navies.

The term "advanced naval vehicles" (ANV) is used herein to cover those which sustain most of their weight by dynamic lift or by powered aerostatic lift. The most encompassing aspect of design common to all ANV is that light weight is essential. Weight control is also the key to producing an advanced ship, intermediate in performance and cost between today's warships and the ANV. Such ships may well prove attractive to the smaller navies and have not received the attention they deserve.

A concept opposite to the weight-reduced, advanced ship is the "enlarged" ship. Steel structure is the least costly part of a modern warship. It might make economic sense to seek additional speed and seakeeping ability by making the hull larger than the minimum size needed for the payload and outfit it carries. It is vital to this concept to keep the additional volume empty, except for fuel and ballast, violating entrenched design practice. Nevertheless, when contemplating concepts which add foils and air cushions to hulls, one: should not overlook the simple idea of adding more hull.

FUTURE TRENDS OF SURFACE NAVIES

The great bulk of the world's trade will continue to be carried in large and relatively slow surface ships because of their unassailable economy. While one can foresee an increasing number of traditional tasks being taken over by submarines and aircraft, they are unlikely to be capable of protecting merchant shipping on their own. There will be a continuing need for surface ships for this and many other tasks.

A fundamental question confronting naval planners is how to maintain effective forces to ensure the freedom of ocean trade in the face of diversifying and more visible local pressures. Beyond the ever-present problem of keeping pace with technological advances simply to maintain the status quo, there is an increasing need to add to the number of ships in the fleets.

A typical 4,000-tonne frigate, the workhorse of today's surface fleets, hardly qualifies as a "high value unit." Yet, with her complement of 2.50 to 300, she must be regarded as a primary target and must be fully capable of defending herself against all threats. The sensor and weapon systems required for self-defence account for most of the ship's capacity for combat systems. The increment available to provide a useful capability (beyond self-defence) is small even today. Such ships will inevitably have to grow with the developing threat, as indeed they have grown from the 1,500- to 2,000-tonne workhorses of World War II.

This trend compounds the difficulty of adding numbers to the fleet. The only foreseen solution is to produce some ships that are so small that they are unlikely to be regarded as primary targets and need not be so strongly defended. There will be a need for the future analogy of the World War II corvette, to supplement fully-capable warships of increased size.

This concept has not been possible to date. The speed and seakeeping capabilities of conventional hulls set a minimum size that is too large and the cost of sophisticated ANVs is too high. When it is necessary to go to high-speed types for small craft to match the sea speeds of larger vessels, there will be an increasing need to develop intermediate types, with improved platform behaviour at sea, but without the extremes of performance offered by aeronautical-engineered ANVs.

In the foreseeable future, only the superpowers are likely to develop sophisticated ANVs in the multi-thousand tonne class. A 3000-tonne, 80-knot surface effect ship, for example, could be expected to cost the same as a conventional cruiser of 12,000 tonnes, even after its initial development. By small navy standards, this is a capital ship. Regardless of its potential capabilities, the technical risk of entering the ANV field is most unlikely to be accepted on this scale. The major ships of the smaller navies will continue to be relatively conventional types until a great deal of experience has been gained with smaller ANVs. It is the small escorts suggested above and offshore patrol vessels that will gradually see more advanced types as the need for larger numbers and better platform behaviour become recognized.

THE REQUIREMENT FOR SPEED

It is currently popular to decry the need for speed in the missile age. Since all surface ships are detectable by satellite, what difference can a few knots make with the speed and range of today's missiles?

Such arguments are valid only in air defence. Assuming comparable weapon performance on both sides, a speed margin will still bring advantages in surface engagements. In protective area operations, transit times and the area covered in a given time will be significant. In close escort, the time spent off station, to investigate an incident or even to refuel, will remain important. The traditional advantages of tactical speed may be reduced, but will continue to hold in many respects.

More significant than tactical speed is the speed which can be sustained for long periods of time in all weather conditions. The same argument that negates the advantage of tactical speed in missile defence also denies the traditional concept of fast ships sailing independently and unprotected. Moreover, it is the faster classes of merchant ships that will be called upon in early stages of a war for urgent military reinforcement and supply. Such ships will impose a protection problem akin to that of naval groups. The service speeds of these large ships, typically around 25 knots, will be unaffected by weather, in strong contrast to the speeds at which conventional escorts can maintain full operational effectiveness.

A special requirement for speed may be set by developments in submarine silencing and the best methods of detection. It may become necessary to operate advanced sonars at very slow speeds to reduce self-noise. Techniques such as sprinting and drifting, or deploying and recovering such sensors, may be needed. These would demand intermittent speeds greatly beyond the speed of advance, and increased numbers of units to maintain continuous coverage.

Figures 1P, 1Q and 1R show the sea speed that can be maintained by various ship types as a function of sea height, for 200, 1,000- and 5,000-tonne ships, respectively. These represent the trends forecast to be typical by the end of the century, based on the most outstanding performance demonstrated to date. Times shown in the figures are mission durations; where no time is shown, performance is power-lim-ited and endurance is limited only by fuel consumption.

FUNCTIONAL CLASSES OF SURFACE WARSHIPS

To study the need for advanced ships more specifically, it is necessary to define the functional classes that are likely to remain or become important. For economic reasons, multipurpose classes will be favoured. The smaller navies are unlikely to justify development of a vehicle for a single task, unless an important and unique capability is promised. Some examples of such special applications are suggested, but this article is primarily concerned with prospects for multipurpose warships.

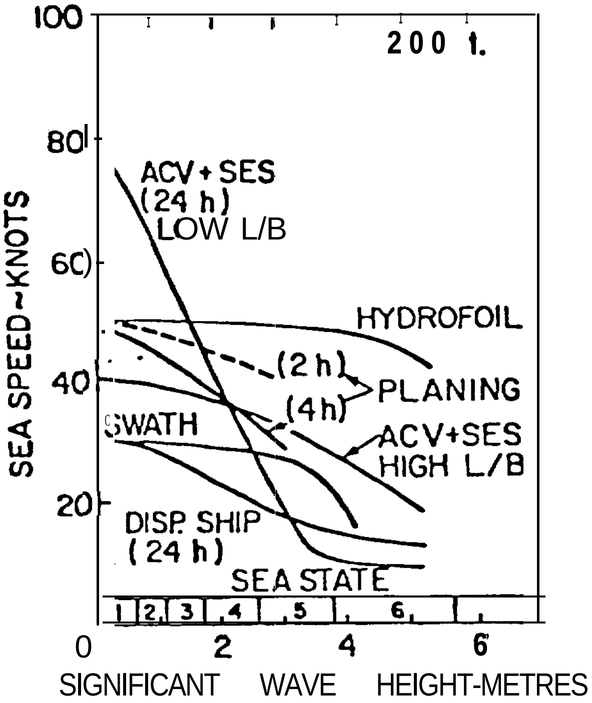

Figure 1P. Maximum Sea Speed of 200T Ships.

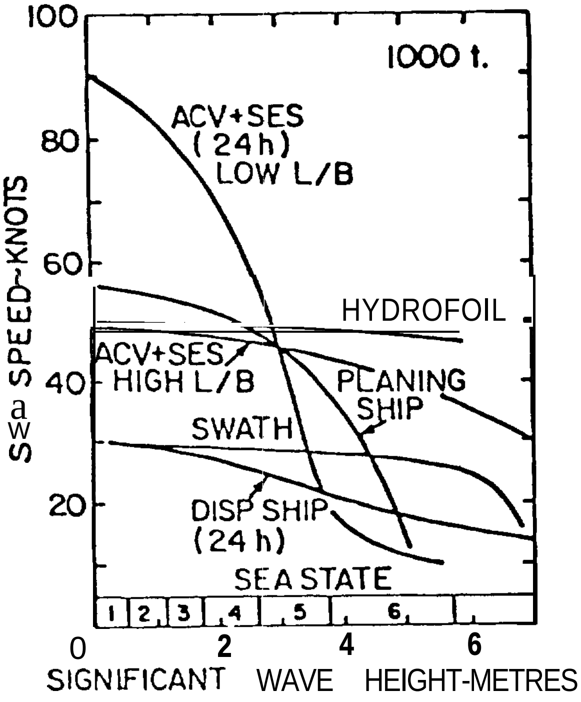

Figure 1Q. Maximum Sea Speed of 1,000T Ships

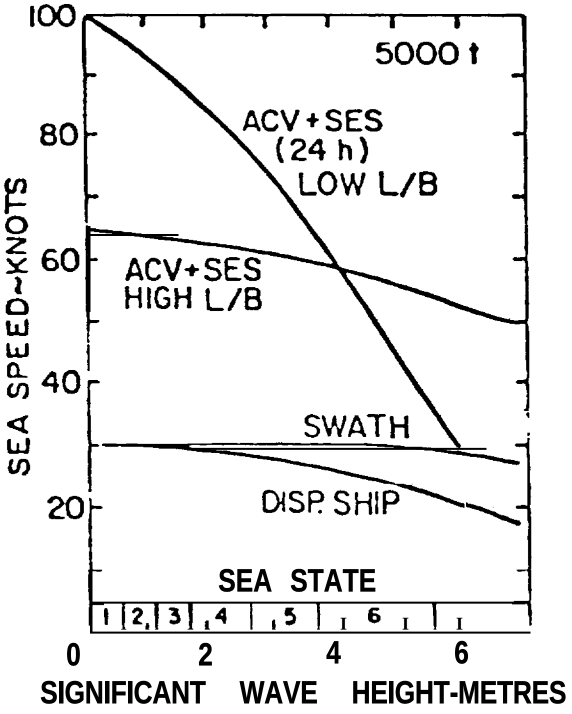

Figure 1R. Maximum Sea Speed of 5,000T Ships.

OCEAN ESCORTS

While the convoy system may be superceded by other tactical methods, the multipurpose warship intended mainly for the protection of other ships will remain the workhorse of the fleet. It is convenient to call these "Ocean Escorts," (OE), without necessarily implying close escort.

Conventional ships of escort size (3000 to 6000 tonnes) will be limited either to air defence (AD) or to antisubmarine (AS) protection as their primary function. To provide both capabilities beyond the level of self-defence will require a larger ship, classed as a major combatant (see later).

Apart from the limited capacity of an OE for combat systems, it appears inappropriate to combine both functions. To provide area air defence, an OE/AD must remain close to the high-value units she is protecting; too close in fact to operate passive sensors effectively against quiet submarines. Even if a sufficient number of warships with dual capability were available, it would be wasteful to deploy valuable air-defence systems to the distances from the force at which an OE/AS needs to operate. Moreover, the OE/AS needs to operate manned aircraft, since the helicopter (or future V/STOL aircraft) is likely to remain the primary antisubmarine weapon system. This leads to a volume-limited design for the OE/AS whereas an OE/AD will be weight limited if designed for maximum capacity of air-defence missiles.

An extension of this concept is suggested by the future need for antisubmarine escorts with a speed significantly beyond the speed of advance of the convoy. Such capability will only be feasible, within acceptable cost, in ships of much smaller size than conventional escorts. A third class of OE is therefore indicated. The OE/DS is a fast detection and surface warfare ship. Her primary role would be submarine detection, able to exploit sprint-and-drift or other techniques with future sonars. Being too small to embark manned aircraft, this small ship would be limited in her attack capability, and would have to work with aircraft flown from other ships. Her secondary role would be surface warfare. High speed would enable her to engage before the enemy ship closed within range of the ships being protected.

While intended mainly for shipping protection, these three OE classes will be (capable in many other tasks such as surveillance, barrier patrol, blockade, and less demanding peacetime tasks. Despite the degree of specialization forced upon them, they remain multipurpose and versatile warships, with the emphasis on operations under all open-ocean conditions.

MAJOR COMBATANTS

The need for air superiority in the conduct of naval operations is well recognized. However, this capability has grown beyond the affordability of small navies because of the ship size necessary to operate conventional high-performance aircraft under open-ocean conditions. Development of V/STOL aircraft and the SWATH ship promise to reverse this trend.

The small aircraft carrier (SAC) of 12,000 to 24,000 tonnes could provide aircraft for air defence in a wide area, for antiship and shore strike, for surveillance or for antisubmarine operations. Good seakeeping qualities and adequate length for a ski jump flight deck are critical to this concept.

An even smaller, multiaircraft ship in the 6,000- to 12,000-tonne class could play a leading role in protective operations. Functionally, such an escort carrier (EC) would be more akin to the OE, but with 5 to 10 antisubmarine aircraft and good air defence capability. Her particular strength lies in being able to supplement the air capability of other escorts.

The importance of air capability, coupled with V/STOL developments, will probably cause the small carrier and cruiser to blend. Indeed there are already important examples of this trend. Selection of the most appropriate platform type is likely to be governed by the extent of air capability required. For this reason, the following section recognizes an ocean combat ship (OCS) of classical cruiser class, in the 6,000 to 12,000-tonne size, in addition to the two carrier classes.

OFFSHORE AND INSHORE. PATROL VESSELS

A wide variety of applications are covered by this heading. Indeed, some might regard the suggested OE/DS as a patrol vessel, because of her small size. However, the major impact of environmental conditions on small ships demands a differentiation among open-ocean, offshore and inshore functions.

The OE/DS has to maintain (indeed surpass) the speed of large ships under all conditions in the open ocean. The offshore patrol vessel (OPV) is generally intended for operations within 200 miles of the coast. While a sprint capability may be needed to reduce transit time to an incident, and coastal sea conditions can be as bad as any, the OPV is not intended to maintain high speed indefinitely. The primary function of the OPV is more likely to be surface warfare than submarine detection. It is assumed that air superiority will exist in her area of operations. Essentially, this is a modest ship, intended primarily for peacetime operations, such as protecting fishery and seabed resources, and her capability in wartime will be limited.

The inshore patrol vessel (IPV) has similar duties, but within a more restricted radius of operation. Rather than remaining on patrol for long periods of time, she would operate from a base. A high percentage of time would be spent in transit, at high speed when conditions permit, but some performance degradation in severe weather will be accepted as inevitable.

SPECIAL VESSELS

Within the limitations of their size, all the above classes can be regarded as multipurpose warships. In this article it is not possible to review the host of special-purpose ships that might be involved in future naval warfare. There are three that should be included, however, because ANV concepts offer unique capabilities. These are amphibious assault ships (AAS), amphibious landing craft (ALC), and mine countermeasures vessels (MCMV).

PROMISING CONCEPTS FOR FUNCTIONAL CLASSES

Figure 1S displays a matrix defined by the 11 functional classes described above, and the various platform types that might be considered for these applications. The promising elements of this matrix, discussed in the following subsections, are marked with the appropriate size range, in thousands of tonnes. Those that emerge from the discussion as the most promising options are shown with a check mark.

The operational effectiveness of conventional ships of 3,000 to 6,000 tonnes degrades significantly in heavy weather, at the speeds that fast merchant ships and major combatants will be able to sustain. The OE/AD, constrained to maintain her air-defence umbrella over her consorts, requires only a modest margin over their speed. This is the leading candidate for an enlarged hull, adding length to produce a slender and seakindly form. The high density of her missile payload, in vertical-launch systems, is appropriate to this concept. Added displacement devoted to structures and fuel will provide opportunities for improved passive protection and endurance.

In contrast, the aviation facilities needed in an OE/AS result in more stringent requirements for superstructure volume, stability and control of ship motions. The SWATH form provides a better match to these than a lengthened conventional hull. Design studies of SWATH ships as possible frigate replacements have shown that, because of the deck width and the volume inherently available in this concept, very little penalty is paid for accommodating four helicopters instead of two. The full virtues of the concept can be realized at the resulting size of about 5,000 tonnes. This is considered the most promising first target for SWATH development as a combatant ship.

Neither SWATH nor the enlarged ship have the speed potential needed for sprint-and-drift operations at high speeds of advance. The minimum size of hydrofoil needed to meet the full requirements of an OE/AS will be in the 1,500- to 3,000-tonne range. Technological advances are needed to produce a hydrofoil of this size, and such a ship would cost more than a conventional frigate. She certainly would not be a "small and many" proposition, exploiting the hydrofoil's unique combination of

Classes	Ocean Escorts			Major Combatants			Patrol Vessels		Special Vessels		
Types	OE/AD	OE/AS	OE/DS	SAC	EC	OCS	OPV	IPV	AAS	ALC	MCMV
Conventional Ship	3-6	3-6		12-24	6-12	6-12 ✓	1.5-3 ✓		12-24 ✓	< .8	< .8 ✓
Slender Ship			1.5-3				.8-1.5 ✓	.4-.8			
Semiplaning Ship								.2-.4 ✓		.2-.4 ✓	
Enlarged Ship	6-12 ✓										
SWATH Ship		3-6 ✓		12-24 ✓	6-12 ✓	1.5-3					
Hydrofoil Ship		1.5-3	.4-.8 ✓				.2-.4 ✓	.1-.2			
Air Cushion Vehicle								.1-.2		.1-.2 ✓	.1-.2 ✓
Surface Effect Ship		1.5-3 ✓	.8-1.5		3-6 ✓	3-6 ✓	.4-.8	.2-.4			

Size range shown in 1000s of tonnes
✓ – Most promising options

Figure 1S. Promising Options for Functional Classes of Surface Warships.

speed, seakindliness and maneuverability.

Surface effect ships would have to be even larger than hydrofoils to achieve the required seakeeping ability, but have better potential for this growth. In the far term, this is a promising application for the surface effect ship.

SMALL OCEAN ESCORT (OE/DS)

As discussed earlier, a more probable earlier solution lies in a new functional class of very small escort, providing the capability for submarine detection at high speeds of advance, but cooperating with aircraft from other escorts for localization and attack.

A light frigate in the 1,500- to 3,000-tonne size, using a slender hull and a lot of power, might be developed to meet this requirement for an acceptable percentage of time, but only in moderate sea conditions. This concept was adopted for fast minelayers in World War II. However, with the power plant required, her cost would approach that of a conventional frigate.

A hydrofoil of 400 to 800 tonnes is the leading contender for this class. At this size, a comparatively unsophisticated design is possible, intermediate between current design philosophies of commercial European ferries and aeronautically based USN craft. The cost of such an "intermediate" hydrofoil would be between a third and half that of a conventional frigate, which does introduce the possibility of larger numbers of ships in the fleet.

The capability of a hydrofoil to match the speed and seakeeping qualities of the largest ships in sizes as small as 200 to 400 tonnes makes her unique. In sizes up to 800 tonnes her cost can be kept within reason, if design speed is held below 50 knots. Moreover, a virtue often overlooked is her behaviour when hullborne. A proven capability to heave-to or cruise at slow speed with motions comparable to those of a conventional ship ten times her size gives the small hydrofoil an operational versatility denied all other small craft.

A surface effect ship would have to be larger than a hydrofoil to have the seakeeping ability for the OE/DS role. In the 800 to 1,500-tonne size, adequate capability could be achieved. As a stepping stone between current 200-tonne prototypes and fully ocean-capable ships of the OE/AS class, an SES in this size is logical.

There is danger that a 400 to 800-tonne hydrofoil and an 800 to 1,500-tonne SES will be seen as competitive in the short term, to their mutual detriment. In fact, they address different and complementary objectives; the hydrofoil as the smallest and least costly open-ocean combatant, the SES as a step towards its promise as a larger combatant.

MAJOR COMBATANTS (SAC, EC, OCS)

Subsequent design studies support an original conclusion that SWATH ships offer to smaller navies an affordable prospect of providing tactical air superiority. SWATH carriers of 12,000 to 24,000 tonnes (SAC) would have the motion characteristics of very large conventional carriers. Their inherent deck width and box volume will accommodate more aircraft than conventional ships of the same displacement.

More significantly, the SWATH concept allows carrier characteristics to be achieved in the 6,000 to 12,000-tonne size. In contrast to proposals for conventional min-icarriers, there is no performance or seakeeping penalty involved in providing ample beam for a full-length flight deck alongside a superstructure adequate for the combat systems of an escort carrier.

In sizes greater than 5,000 tonnes, advanced engineering is not vital to the concept. A SWATH is essentially a displacement ship with a different hull shape. Unfortunately, this different shape imposes design problems that are more difficult to solve in smaller sizes, a fact that is hindering the logical progression of development. A small SWATH costs significantly more than the equivalent conventional ship, whereas this difference will be minor once the larger sizes have been reached.

There is one advanced feature likely to prove advantageous regardless of size. This is the development of lightweight electric drives, which offer more flexible power distribution to both conventional and SWATH hulls with many secondary advantages.

The maximum speed of SWATH ships is unlikely to exceed that of conventional displacement ships. The fundamental difference is that speed will be less affected by sea conditions, as indicated in Figure 1R. If the concept of a carrier *with very high transit speed* is required, the surface effect ship is the only vehicle that offers the growth potential required. However, this has to be regarded as speculative at this stage of SES development, primarily because of the enormous power required.

For a major combatant in which aviation facilities are secondary (OCS), there is no compelling reason to depart from the all-round versatility of a conventional displacement ship. In the 6,000 to 12,000-tonne size, adequate seakeeping ability can be achieved at speeds up to 30 knots. If a major advance in speed is required, the speculative 3,000 to 6,000-tonne SES is the only contender.

PATROL VESSELS (OPV AND IPV)

Optimization of the seakeeping qualities of fast slender hulls is an attractive concept for meaningful gains in performance over conventional OPVs of 800 to 1,500 tonnes. The typical OPV has a modest military load, with no excessive topside demands, well matched to a slender hull.

A small payload may enable a SWATH design to be competitive for applications in which seakeeping ability at moderate speed is paramount. A SWATH of 1,500 to 3,000 tonnes would be attractive, for example, in an application requiring helicopter operations in a severe environment.

For OPVs of higher performance, comparative studies have shown that, while much more costly than a planing craft per tonne, the equivalent hydrofoil would cost only about 25% more. Hydrofoils of 200 to 400 tonnes can have better seakeeping qualities than any other OPV, over the full speed range from zero to 45 knots.

The performance of a corresponding SES will be weather dependent. Missions of the ferrying type, involving a large proportion of time at high speed, best suit the SES. The air cushion concept is not appropriate for extended operations at slow patrol speeds. This is why an ACV, which is even less suited to loitering, is not a promising OPV.

For the less demanding environment and size of the inshore patrol vessel, examples of almost every type already exist.

If a high-speed sprint from base with short time on station is regarded as the mission characteristic of the IPV, in contrast to extended patrols of the OPV, then an improved semiplaning ship is probably the leading contender.

Simple hydrofoils of the European surface-piercing type will continue to prove effective in the 100 to 200-tonne sizes. The choice between planing craft and hydrofoils will depend on prevailing sea conditions. There is no point in selecting a hydrofoil ship unless it is required for seakeeping.

ANVs more sophisticated than this will be difficult to justify for the limited versatility that an IPV offers. Existing ANVs are seen as necessary steps to more capable warships in the OPV and OE/DS classes. Special requirements will introduce exceptions, of course. On some coasts, the amphibious capability unique to the ACV will prove invaluable to an IPV

SPECIAL VESSELS (ALC, AAS, MCMV)

ACVs offer unique capabilities for amphibious warfare which are already being exploited in assault landing craft. Their high speed reduces critical transit time to the beach and allows parent assault ships to be dispersed over a wider area. Apart from vulnerability in transit, the very different motions of a small craft can have serious effects on tense troops, and this is a function of exposure time. Depending on the terrain, ACVs may also be able to traverse formerly inaccessible beaches and proceed some distance inland, finding earlier cover for the disembarking troops.

However, planform dimensions of an ACV greatly exceed those of an equivalent conventional or semiplaning landing craft. The latter's more efficient use of critical space aboard assault ships will ensure their continued use for later stages of landing operations.

Since a large proportion of assault forces will probably be landed by helicopters and aircraft in the future, SWATH ships can be expected to play a major role in amphibious operations. These are more likely to be multipurpose carriers than specialized assault ships. No short-term competitor to a conventional displacement assault ship is foreseen.

In the long term, but beyond the resources of smaller navies, a desire for a rapidly deployable assault force may justify an SES in the 6,000 to 12,000-tonne class. A less ambitious concept involves the use of amphibious ACVs of maximum size. The difficulties of extrapolating air propulsion, or retractable screws, necessary for a true amphibian, will probably hold such vehicles below 1,000 tonnes so that special ocean transports would be needed and only a final leg of the deployment could be at high speed.

There is no shortage of special applications for small ACVs. They have already proved themselves in riverine warfare and for various duties in the Arctic. Undoubtedly their most promising future lies, not in competing with other types of ships, but in going where conventional ships cannot go.

Another interesting application is in mine countermeasures, where ACVs can exploit a different aspect of their separation from the water surface. Their low pressure, acoustic and magnetic signatures, coupled with invulnerability to underwater shock, offer a unique capability. Small hydrofoils can also be designed with appropriate signatures; unmanned hydrofoil sleds towed by helicopters are already being used for minesweeping.

CONCLUDING REMARKS

This article has presented a summary of conclusions drawn from a number of studies. It is difficult to summarize further, without detracting from the essential point that no single type of vehicle is likely to prove, or remain, superior.

It has been difficult for naval planners to accept the passing of the small general purpose warship. Being selective in combat capability, rather than seeking to do everything and doing nothing well enough, has involved hard lessons, even when it has essentially required only a selection of combat systems. In the future, the increasing importance of integrating combat systems and platforms will extend this need for selection to a wider variety of platform concepts.

SHORT-TERM OPTIONS

In terms of potential return on investment, the most promising near-term concept is the SWATH ship. In sizes of 5,000 tonnes and larger, development costs should be modest because conventional ship technology can be employed. The progressive development of 5,000, 10,000 and 20,000-tonne SWATH ships would yield the most promising options for ASW escorts, escort carriers and small V/STOL carriers respectively.

Other types of advanced displacement ships, involving modest costs, are also among the promising options. Attractive concepts include enlarging the hull of an air-defence escort, improving the seakeeping of slender hulls for OPVs requiring a sprint capability, and improving semiplaning forms for assault landing craft and IPVs.

Hydrofoil development should proceed in the direction of simplification, cost reduction and improved range, even with some sacrifice in speed. This simplified hydrofoil will be attractive up to about 1,000 tonnes. In these smaller sizes, the concept offers its unique capability of matching the seakeeping and exceeding the speed of major combatants. A small escort of 400 to 800 tonnes is seen as the future "corvette," offering open-ocean capability at the lowest possible cost. A smaller, 200- to 400-tonne hydrofoil is the most promising OPV when sprint capability is required.

In contrast, the promising applications for small SES (and OPV of 400 to 800 tonnes and an OE/DS of 800 to

1,500 tonnes) are seen as stepping stones towards a long-term 1,500 to 3,000 tonne SES having full capability as an ASW ocean escort.

Air cushion vehicles should continue to be developed, not in competition with ships, but to exploit their capability in amphibious warfare, mine countermeasures and Arctic operations.

LONG-TERM OPTIONS

Hydrofoil and SES escorts of 1,500 to 3,000 tonnes would be feasible. At this size, the hydrofoil has advantages over the SES in seakeeping, but it has little further potential for growth. Consequently, such a hydrofoil may be hard to justify, in competition with both the long-term prospects for SES, and the short-term rewards of smaller hydrofoils of the intermediate type. Eventually, the SES may be seen as an all-round ocean combat ship, escort carrier and possibly as an assault ship. Such development is speculative. Requirements for such advanced ships have yet to be established.

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READINESS AND TIMING

Capt. Karl M. Duff, USN *is the deputy director for research and development in the Ship Systems Directorate of the Naval Sea Systems Command. He earned a doctorate in mechanical engineering from Massachusetts Institute of Technology. His prior service includes a tour of duty aboard the USS* Brown *(DD-546). He was project officer for construction of two hydrofoil ships, PCH and AGEH. He also served as officer-in-charge of the Hydrofoil Special Trials Unit before his appointment as deputy project manager for the NATO PHM Acquisition Program. Captain Duff then served on the staff of the Chief of Naval Material with responsibility for acquisition programs. He later served as head of the Ocean Warfare Division of the Tactical Technology Office, DARPA and as assistant chief of Naval research and development.*

THE NEXT FIVE YEARS

The U.S. Navy is approaching watershed decisions which will dramatically change the appearance of many of its ships and the make up of its forces in the twenty-first century. Analogies of the past two hundred years are the development of the fast frigate in the late 18th century, the shift from sail to steam in the 19th century and the development of naval aviation and the nuclear submarine in the 20th century. Each transformation took years of gestation and struggle involving many dedicated careers. The transformation to widespread use of alternative hull forms for surface ships is, in the same fashion, now upon us. Within the next five years we will see significantly larger numbers of these ships appear in the acquisition programs of U.S. and foreign maritime forces. A confluence of factors is now working to accelerate these events.

FOUR FACTORS

(I) The U.S. Navy is about to complete, in its 1986 shipbuilding budget request, the expansion and restructuring program to achieve its major corporate objective, the “600 ship” Navy. This goal has been difficult to achieve, involving singleminded leadership and a focus of resources toward reestablishment of depleted conventional forces and readiness (in the face of strong competition for resources in a high deficit budget economy). Many consider it to be nearly miraculous in its success. Now that goal is nearly achieved. It is certain that a new major corporate naval objective must come into place within the next year or two as a basis for future naval programs. That this objective must deal with the longer term issues of technology and force structure for the 21st century will be almost irresistible.

(II) Over the past twenty years or so, in various U.S. naval or commercial programs and some foreign programs, the technology and business maturity to produce a variety of effective alternative hull forms for practical application to naval and maritime missions has been accomplished. The “trench work” has been done. Means of performing many missions more effectively are at hand, subject to the perceptions of naval planners that these naval capabilities are needed.

(III) There is an emergence of naval needs which will press the U.S. Navy, in particular, to obtain ships with vastly improved seakeeping and mobility. These needs, discussed further below, are still only dimly perceived by some, but will become well understood over the next few years as more and more adversarial spokesman take up the question as to whether a surface navy of any kind is viable in the projected 21st century environment.

(IV) The inexorable constraints of budget and disproportionately increasing unit costs for defense forces of all kinds will force the Navy to consider weapons systems contained in smaller affordable packages. This will exacerbate and amplify the search for compensating performance attributes needed to bring about ships capable of filling emerging needs. Only alternative hull forms are capable of providing performance improvements in the face of budgetary unit cost. constraints.

TRENDS

Let us consider some of the things faced by the U.S. Navy which make these needs for new ship capability so paramount. We know that the Soviet Union is rapidly expanding its numbers and capability. Considerations of geography and naval strategy confront the United States with new requirements for naval operating capability.

One trend is the need for extended presence and improved ship capabilities in northern latitudes. These needs derive from a number of primary operational scenarios in the Northeast Pacific, North Atlantic and Norwegian Sea which require mobility of surface ships and effective performance of men, sensors, and weapons systems in severely adverse weather. The scenarios involve battle group operations in the defense of the NATO northern flank, defense of Iceland and Japan, closure of the GI/UK gap and other operations, as well as defense of the strategic Arctic ice and near-ice regions against use by Soviet submarines. The increasing sophistication of Soviet submarines, improved quieting and increased numbers estimated to be capable of operating in the Arctic argue strongly for the surface Navy to increase its capability and role in contributing to Soviet submarine attrition ratios which would be needed in a protracted Arctic conflict. More destroyer and frigate class ships are going to have to operate in the Arctic and will need operating proficiencies vastly improved over those of current ships.

A second trend is that of the constantly expanding envelope of the outer air battle which, because of the inherent size, weapons payload and reload capability of the landbased air threat, offers the prospect of a threat which will ultimately out range and "outgun" defenses situated only near the center of the battle group. There is a high probability that successful defense will ultimately require some portion of the outer air battle to be fought from surface ships stationed in remote screen, which by nature of their logistics dependence upon the battle group and need to restation must be highly mobile in all weather scenarios, yet small enough to resist "roll back" targeting and allow reasonable numbers to be built.

Projected overhead surveillance capabilities are another consideration which argue persuasively that a portion of our surface forces must be either of high mobility or low signature, or both. Advanced hull forms which offer better opportunities for structural shaping for signature management as well as unimpeded speed and weapons systems performance in heavy seas will promote margins of superiority in a number of areas simultaneously, provided they can be built in affordably small sizes.

OTHER TRENDS

There are two other related trends which also suggest the need for more capable hull forms, greater sustained mobility and affordable small sizes. The U.S. Navy is already well embarked in distributing the strike capability previously concentrated in its carriers, to other surface ships and submarines. This will continue to be a vital feature of its force capability. But, it should be noted that many of the platforms being currently exploited for this purpose are platforms of opportunity (battleships and submarines). The Navy should be alert to recognize opportunities for future low vulnerability ships of lower cost which might serve as effective cruise missile platforms. Another general concern is in the enemy's known preemptive strike option and coordinated strike tactics. The ability to reduce coordination between air and submarine threats to SLOC and strike forces is influenced by the mobility of these forces. This mobility, rather than being restricted by transport or logistic ships, is now restricted by the limitations of existing escort ships.

The aggregate of these considerations strongly supports the case for the application of alternative hull forms to some future ship classes. The combined considerations of surface ship signature reduction, emerging northern latitude operational requirements, unrestricted mobility, dispersion of forces and lower unit cost require the Navy to provide better mobility and seakeeping in smaller ship sizes.

The "dues" have been paid; technology is ready. Timing is right politically, economically, and militarily. The joint efforts of many hundreds of people in government and industry over the past 25 years are about to bear fruit. It is time to be expectant and encouraged.

CHAPTER II

THE MODERN MONOHULL

THE EDITOR

Capt. Clark Graham, USN, *is one of the Navy's recognized leaders in the area of surface combatant design. He recently* completed *a five year tour of duty in the Naval Sea Systems Command as the ship design manager and technical director* of Arleigh Burke *(DDG-51) destroyer design. Previously, he was a member of the Navy design reams for* Spruance *(DD-963) and* Virginia *(CGN-38). Cnpt. Graham served us assistant technical director of the Advanced Naval Vehicles Concepts Evaluation and has been active in the field of comparative ship design analysis. His operational experience includes a tour as a cruiser chief engineer. Capt. Graham is currently the professor of naval construction and engineering at M.I.T.*

INTRODUCTION

As one looks into the future to envision tomorrow's ships, a modern monohull will serve as the baseline for comparison. Today, monohull displacement ships represent all but a small fraction of both naval and commercial ships in service. Are there features of the monohull which make it irreplaceable? Will the "modern" monohull be much different than today's monohull in configuration, size. performance or cost? This chapter will briefly discuss the special attributes and limitations of today's monohull and then project into the future to portray the changes that might be expected through the application of advanced technologies. A realistic evaluation of not only the potential improvements but also the cost to develop and introduce these technologies and the resulting improvements in performance also will be presented.

Monohulls have such a wide application in today's society that we have chosen to narrow the scope in discussing the modern monohull to a frigate size surface combatant. This is the application most appropriate for several of the alternative hull forms and thus the modern monohull frigate will serve as a baseline for comparison.

A knowledgeable team of experienced designers and ship builders of monohull surface combatant ships has authored this chapter. The three principal contributors, Messrs. Sims, Scott, and Caskey, have been and currently are leaders in the field. Mr. Philip Sims of the Naval Sea Systems Command has been a member of the surface combatant preliminary design branch for 14 years where he has participated in numerous conceptual designs. He is currently the principal naval architect on the U.S. Navy's future frigate designs, the NFR-90 and the FFX. Mr. Sims is also a noted historian in the technical aspects of naval ships. Mr. Robert Scott, a vice president of Gibbs and Cox, has participated in various phases of every U.S. Navy surface combatant design for the past 25 years. His most recent experience has been as a key member of the DDG-51 system engineering team. Mr. Maury Caskey has been a systems engineer for Ingalls Shipbuilding for 10 years and has been a part of the Navy's efforts to design and produce the three *Spruance* heritage ships (DD-963, DDG-993 and CG-47). He has had a key role in the DDG-51 ship design as Ingalls' producibility team leader. Three other individuals have provided assistance to the principal contributors: Messrs. Rains, Moy and Judge. Dr. Dean Rains, president of Decision Engineering. was a member of the Ingalls design team that produced the *Spruance* destroyer and is well known for his analysis of future combatant designs. Mr. James Moy and Mr. Samuel Judge both work for the Naval Sea Systems Command. Mr. Moy, a cost analyst, has been a member of numerous design teams providing cost estimates for current and future naval ships. Mr. Judge's contribution to naval ship design has been primarily in the area of integrated logistics support. This team brings to the discussion of the modern monohull an authoritative, first hand perspective of current monohull ship designs and a clear vision of the potential for improvement for tomorrow's ships.

DESCRIPTION OF CONCEPT

A monohull ship is a displacement ship with a single hull which provides static buoyant lift. As Archimedes discovered in the second century B.C., the weight of the volume of water displaced by the monohull equals the total weight of the ship. All ships, boats and watercraft up through the twentieth century have been displacement craft. Unlike the other ship types discussed in this *Journal,* the monohull displacement ship requires no dynamic or powered lift to support its weight at any speed.

The "modern" monohull which will be discussed here makes no change to the lifting forces of the ship. What differentiates a modern from a conventional monohull are subtle changes in the hull form to improve hydrodynamic performance and motion characteristics, and incorporation of advanced subsystem and component technologies. Indeed, as the U.S. Navy or any other navy introduces a new ship class incorporating a displacement monohull, the ship can be considered a modern monohull as it inevitably reflects the latest in hull form technology and incorporates up-to-date subsystems. In this chapter, an attempt will be made to describe the next generation of modern monohull-one that could be introduced in the late 1990s.

The improvements in hydrodynamic performance resulting from refinements in hull form design are modest as compared to those of alternative hull forms exploiting dynamic and powered lift. Increases in calm water speed and range for monohulls will be caused more by power plant improvements which result in higher power densities and improved energy efficiency.

Likewise, improvements in the motion characteristics of monohull displacement ships due to hull form changes can also be expected to be modest. The recent *Arfeigh Burke* (DDG-51) design promises to reduce vertical motions and deck wetness in high sea states as compared to previous destroyer designs of similar length. These improvements have the result that a given size monohull responds like a larger ship in a given seaway-motions remain but are not quite as severe. More significant improvements in seakeeping performance can be expected from advances in active motion control such as fin stabilizers rather than from the basic hull form.

The principal differences between current and future modern monohulls will be caused by advances in subsystem and component technologies and ship integration techniques. Advanced technologies and ship integration techniques have the potential for:

- Reduced structural weights resulting from use of stronger materials and more exacting structural design techniques,
- Reduced machinery sizes and weights resulting from higher power density designs,
- Increased system automation resulting in reduced operational manning,
- Improved energy efficiency of equipment resulting in reduced fuel loading or greater endurance,
- Improved component reliability and maintainability with the potential for reducing redundancy and on board repair capability to produce a given system availability,
- Tighter ship design integration caused by expected trends of reduced size components.

For combatant ships, the most significant improvements will occur in the area of combat systems. Recent trends in combat systems design, which have improved sensor performance, drastically reduced reaction time, increased the lethality of weapons and, at the same time, reduced the physical size of components, will continue. The development of the modern monohull, as well as any of the alternative hull forms, must support tomorrow's combat systems design--that indeed is the raison d'etre of the hull and machinery of any warship. This chapter on the monohull will not deal with advances in combat systems and the potential impact on monohulls even though that is the area where the greatest improvements will occur. Other forums are available which address this subject and anyone analyzing future warships must concentrate the majority of their efforts in the combat systems area. However, this chapter will address only the hull and machinery aspects of tihe modern monohull as that is focus of this special issue.

The monohull ship designer can exploit the advances in subsystem and component technologies in four basic ways [1]:

1) Reduce overall ship size and weight and improve mobility for a fixed installed propulsion power. Reduced component size and weight will result in a ship with less total volume and displacement. If the installed propulsion power and fuel load is kept constant, improvements in calm water speed, range and fuel usage will occur. On the negative side, ship size reduction could result in reduced seakindliness unless improvements in hull form and active motion control are incorporated.

2) Increase system capacities and improve mobility performance for a fixed size ship. The higher power density, more efficient machinery can be exploited by increasing the capacity (for example the installed propulsion power) of a subsystem while keeping the physical size and weight equal to a subsystem designed with today's technology. The resulting modern monohull would be the same size as the conventional monohull but would have improved speed (due to more installed propulsion power) and range (due to improved fuel efficiency).

3) Improve subsystem/ship performance by reallocation of weight and volume. A ship designer could exploit a reduction in component/subsystem weight in one functional area by increasing the weight/volume allocation to another functional area tlhereby increasing that functional area's capacity and system performance. For example, the structural weight savings resulting from higher strength materials could be reallocated to propulsion permitting an increase in installed horsepower and thus improved mobility performance.

4) Reduce ship size and cost for a fixed overall ship performance. Advanced component and subsystem technologies have the potential for reducing subsystem costs directly and for further reducing overall ship costs through ship size reduction. For example, high power-density reduction gears incorporating through-hardened gear design are smaller and lighter and promise to be less expensive for a given horsepower and noise characteristic. The smaller gears might also lead to a reduced length ship which is less costly to build. Experience has shown, however, that in the past designers have opted to increase performance rather than reduce cost through exploitation of advanced technologies. This is one explanation for the ever increasing cost of ships. *Modern monohulls could be less expensive than today's conventional monohull if we could be satisfied with today's performance.*

The designer of the rnodern monohull has many options available to exploit advances in shipbuilding tech-

Table 1. Variations in Current U.S. Navy Monohull Ships.

Type	Ship	Displacement (Tons)	Propulsion Power (SHP)	Speed (KTS)
Cruiser	USS *Ticonderoga* (CG-47)	9,200	80,000	30+
Frigate	USS *Oliver Hazard Perry* (FFG-7)	3,700	40,000	30
Amphibious Assault Ship	USS *Tarawa* (LHA-1)	42,000	70,000	22
Landing Craft	LCU-1610 Class	390	2,000	11
Ocean Minesweeper	USS *Constant* (MSO-427)	750	2,300	15
Replenishment Oiler	USS *Wichita* (AOR-1)	38,000	32,000	20
Seamanship Training Craft	YP-654 Class	70	660	13

nology. Ship performance can be improved through direct improvements in related components and subsystems (e.g., speed and range improved by advanced propulsion concepts, survivability enhanced through stronger materials, availability increased due to inherently simpler and more rugged components). Ship performance can also be improved in one or more functional areas due to reallocation of resources from one area to another (e.g., combat systems capability improved by increased missile capacity caused by weight, volume, and cost savings in the machinery area). And overall ship size and cost can be reduced for a fixed level of performance. *The successful modern monohull designer must be systems engineering oriented in order to identify the high leverage areas in improving the cost-effectiveness of the ship system.*

The differences in a modern versus a conventional monohull are far more subtle than those between a monohull and other vehicle types. To the uninitiated, there is little difference in appearance, and the performance improvements are not overly dramatic and difficult to attribute to specific modern monohull design practices. In addition, the differentiation between modern and conventional is really in the eye of the beholder. What might be considered modern or advanced to a monohull designer would indeed be commonplace to a designer of alternate vehicle types where the higher cost of such technologies is more easily justified. Nevertheless, there *are* performance improvements and/or cost reductions to be realized. This chapter will illustrate examples of the improvements and point out the advantages as well as the disadvantages of exploiting these more advanced monohull concepts.

CURRENT APPLICATIONS

Monohulls are by far the most widely used hull form in shipbuilding. The displacement monohull ranges in size from small pleasure boats and service craft to mammoth tankers and aircraft carriers. Table 1 illustrates the wide variation in application, size, propulsion horsepower and speed of current ships in the U.S. Navy employing a monohull displacement hull. Two of these ships are pictured in Figures 1 and 2. There is an equally wide variation in commercial applications of displacement monohulls. Looking back into history it has been the displacement monohull that has served as the primary waterborne vehicle since prehistoric times. Since the application of monohulls for military and commercial applications are extensively documented in the literature, they do not require further elaboration in this chapter.

SPECIAL ATTRIBUTES AND LIMITATIONS

DESIRABLE FEATURES OF CONVENTIONAL MONOHULLS

Monohulls are widely used in both military and commercial applications because of six desirable features: carrying efficiency, small propulsion power requirements and long endurance, ruggedness and simplicity, tolerance to growth, existing infrastructure and low cost. Together these attributes result in an affordable ship which can carry a nearly unlimited size payload of any composition over great ranges and long periods of time away from home port.

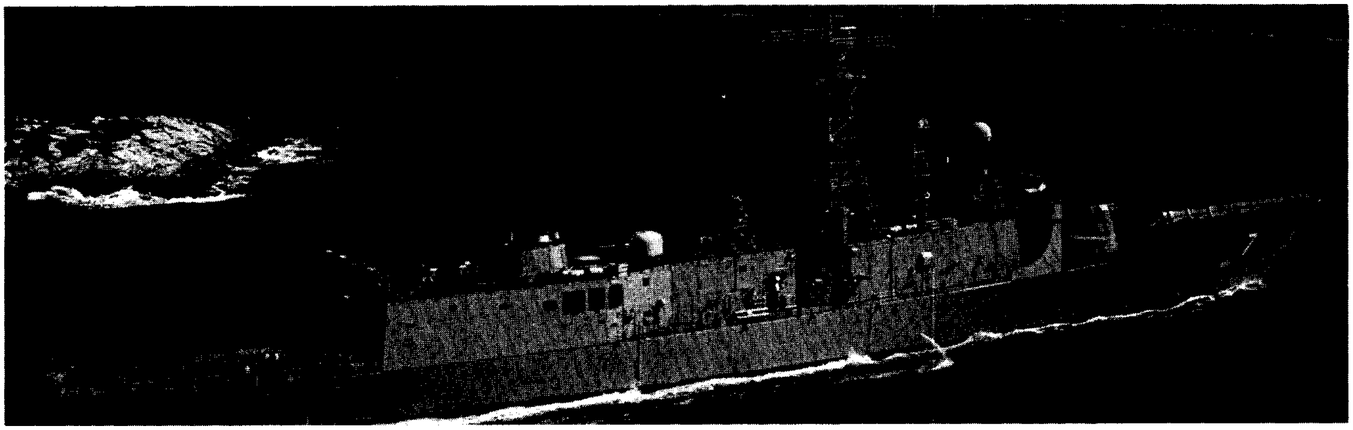


Figure 1. The Frigate USS *Oliver Hazard Perry* (FFG-7).

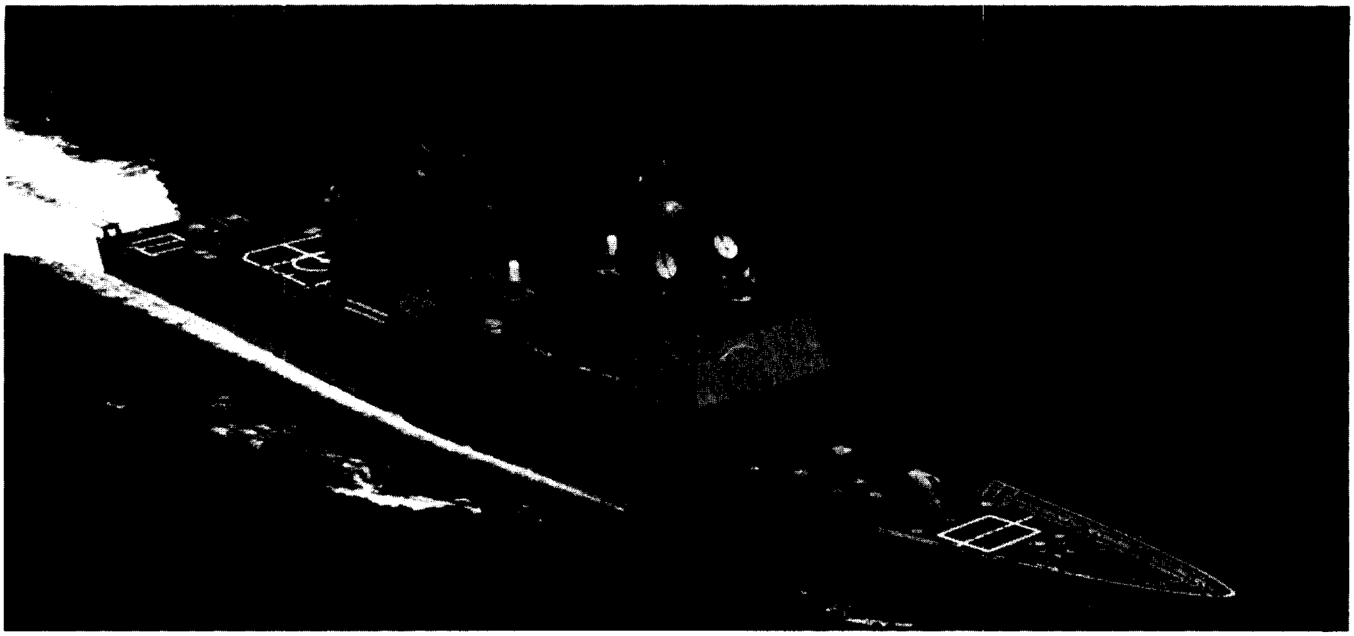


Figure 2. The Cruiser USS *Ticonderoga* (CC-47).

Carrying Efficiency

Displacement monohull ships have extremely high payload carrying efficiency. Figure 3 shows that the carrying efficiency of a monohull increases with ship size. For bulk carriers, the ratio of loads to lightship weight increases with full load displacement. (Loads comprise cargo, fuel, crew and stores and lightship consists of the hull and machinery systems making up the ship). A 10,000 ton full load combination bulk carrier can carry 2.25 tons of loads for each ton of light ship while a 90,000 ton ship carries 3.75 tons of loads for each ton of ship. Thus, the larger ship carries 67 percent more for each dollar invested in the ship.

Unlike other vehicle types, the increase in size does not pose any significant technical problems. However, this increase in size caused by the drive for efficiency has resulted in larger building ways and maintenance drydocks, deeper harbor drafts, the need for frequent sailings for commercial ships or time-on-station for warships, and increases in unit cost and risk.

By way of contrast, a Boeing 737-200C small cargo jet has a loads to "light ship" ratio of approximately .9 while the seven times heavier 747-200F cargo jet has a ratio of 1.3 [3]. Present day aircraft are much faster than cargo ships but carry less total payload as well as less load per ton of light vehicle. There is some favorable scaling as the aircraft gets larger but the scaling is less favorable than with a ship.

It is more difficult to compare the carrying efficiency of modern warships because of differences in combat system (payload) characteristics, survivability features and other ship characteristics. However, Figure 4 provides data for a series of World War II surface combatant warships with the same speed and power plant type and consistent design philosophies. (In this case, military payload is defined as armor and splinter resistant plate, electronics, armament, ammunition, plus aircraft and aircraft fuel.) Figure 4 indicates that for WWII combatant monohulls, a 9500 ton ship had a 25 percent payload weight fraction while a 3000 ton ship had only a 15 percent payload weight fraction.

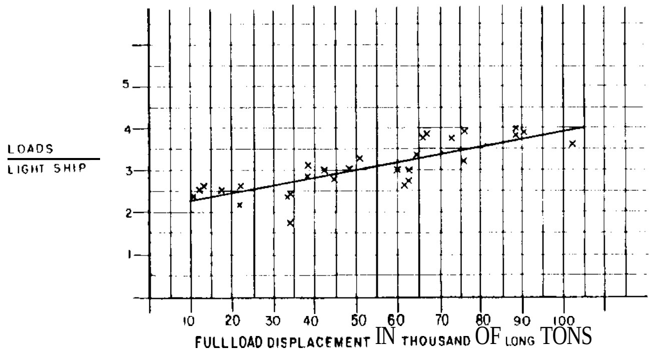


Figure 3. Carrying Efficiency of Combination Bulk Carriers [2].

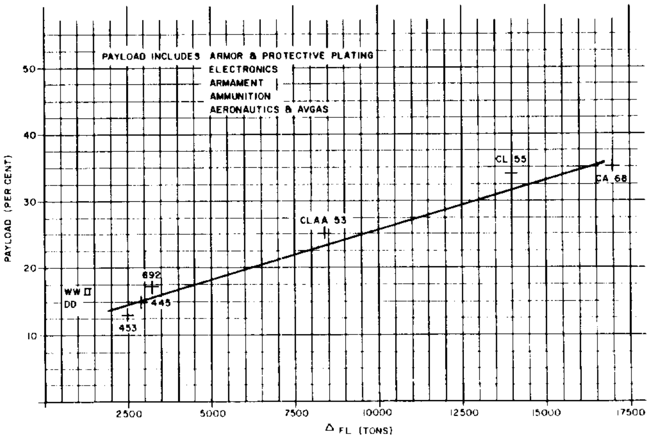


Figure 4. Weight-limited 31 Knot WWII Combatants.

Monohulls have high payload carrying efficiency which scales favorably with size because of their drag characteristics, structural efficiencies and certain minimum operating requirements. A larger ship moving at the same speed as a smaller one uses proportionally less power. The drag of a displacement ship is made up of a combination of frictional and wave making resistance. For a given speed, frictional drag increases directly with the wetted surface area and, hence, with ship size. By contrast, wave making drag decreases with ship length for a given displacement and speed. In Figure 4, the 3,200 ton DD-692 had a 60,000 SHP plant while the 17,000 to CA-68 needed 120,000 SHP to make the same speed. The structural efficiency of larger monohulls results from the proportionately smaller hull girder bending moments in waves as well as lower average life cycle hull girder stresses. Corrosion allowances, the need to avoid thin plates for producibility and the fact that all ships see the same green water loads tends to penalize smaller ships more than larger ones. Finally, there is an economy of size relative to manning (the number of personnel in an underway bridge watch does not increase with size) and certain ship functions (a navigation suite does not increase significantly in size as ships get larger.)

Small Propulsion Power Requirements

An important characteristic of displacement ships is that they get "free" lift and require small amounts of propulsion power to make modest speeds. An extreme example is a World War II Liberty ship which moved 14,000 tons at 11 knots with only 2,500 horsepower. The ability to move large weights (such as fuel) with modest powers makes monohulls good candidates for long independent cruising range. The most extreme example of nonnuclear monohull cruising range was a German commerce raider during WWII which was designed to cruise 84,500 nautical miles at 10 kts [4].

Part of the monohull's load carrying ability is normally allocated to endurance enhancing design features (redundant systems, spare parts, additional crew) to ensure that the ship can remain operational for long periods without returning to a support facility. Ships can not only transfer fuel while in motion, like aircraft, but can also send and receive food, spare parts and personnel to and from other vessels. The small propulsion power requirements at modest speed coupled with the carrying efficiency of a displacement monohull results in an extreme long endurance capability. Naval ships routinely make six to nine months deployments away from home port and can remain on station underway for several months.

Ruggedness and Simplicity

Monohulls are rugged, simple, survivable vehicles. They are large when compared to the damage radius of most weapons used against them. The structural design criteria used in their design is conservative, based on a worst-case sea criteria, so that they can survive in moderate seas with a major portion of their structure damaged. Their load carrying ability and size allow incorporation of a combination of armor, redundancy, separation and alternate electrical power and data transmission paths to ensure retention of some capability after a major hit. Monohulls inherently have large lift reserves in buoyancy provided by the freeboard necessary to keep the decks dry and enclose the needed volume. A monohull warship is designed to survive hull skin and transverse bulkhead rupture for 15 percent of its length.

Monohulls are inherently simple since there is no requirement to provide dynamic or powered lift. The modest speeds of a monohull do not require specialized collision avoidance systems. The rugged design of the components and subsystems of a displacement ship make them tolerant to abuse and relatively easy to operate.

Tolerance to Growth

Monohulls degrade gracefully with increases in weight during their life. As the weight of a monohull is increased, speed and range drop slightly and deck wetness increases as the freeboard is decreased. It is relatively inexpensive to provide, in a monohull's original design, the displacement, structural, and subsystem capacity service life margins to accept growth. If the growth margins were not provided in the original construction, monohulls can accept V-line raises to enhance stability, hull doubler plates to strengthen the structure, and add-on subsystems to accommodate growth as a backfit. Depending on the hull configuration, a monohull can be designed to accept 10 to 25 percent weight growth (direct weight plus ballast) during its life.

Monohulls, due to their ruggedness and tolerance to growth, have historically had long lives. Some warships which were operational during World War II remain in service today. The normal design service life of a warship is thirty years or more.

Existing Infrastructure

Due to their extensive use, monohulls have an existing world wide support base of yards, docks and supply depots. The support facilities range from sophisticated naval yards to back-of-truck welding services available at any pier in the world. Suppliers of components and subsystems for displacement ships abound. The monohull industrial base will be discussed later in this chapter.

Low cost

Relative to their size, monohulls are the least expensive major mobile system. Displacement ships cost, on a per ton basis, up to one fortieth the cost of an aircraft. This low cost makes the displacement ship the most cost-effective means of transporting goods and sustaining naval power at sea.

LIMITATIONS OF CONVENTIONAL MONOHULLS

The intrinsic desirable features of monohulls lead to the undesirable characteristics of limited top speed and sensitivity to sea state.

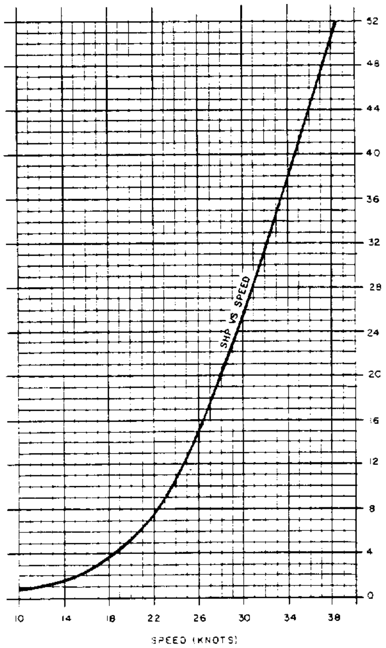


Figure 5. Two Thousand Ton Destroyer Speed-Power.

Limited Top Speed

Monohulls have free lift and have small propulsion power requirements to move slowly. But, due to the nature of wave making resistance, power requirements increase rapidly with speed. Figure 5 depicts the speed power curve of a 341 foot long, 2100 ton destroyer designed with a 50,000 SHP propulsion plant [5]. The first quarter of that power propels the ship to 24 knots, the second quarter adds 5 more knots, the third quarter 3 knots, and the fourth quarter another 3 knots. Up to a speed length ratio of 1 .O (18.5 knots for the ship in Figure 5) propelling monohulls requires very modest power. Beyond that, the power increases rapidly.

Table 2 shows the power installed in 3,600 to 4,000 ton warships between the 1870s and the present. It should be noted that installed power and speed peaked in the late 1930s. Since then the priorities, as shown by the way ships have been built, have placed less emphasis on speed and used the displacement to carry more payload and increase the endurance features of a naval ship. Ships of the late 1930s were expected to chase down a target and fire unguided torpedoes. and projectiles at it. Effective modern warships are equipped with sensors and weapon systems which detect and engage targets at long range. Sensors, such as sonars which lose effectiveness at high speeds. have contributed to this decreased emphasis in speed.

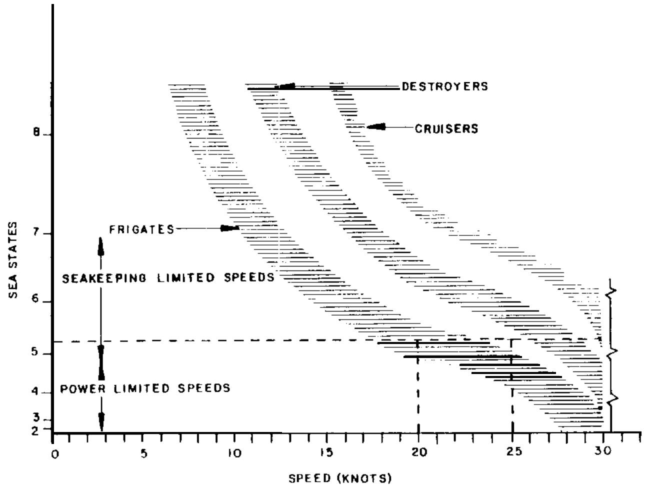


Figure 6. Ship Speed Versus Sea State.

The *Magador* in Table 2 used over 20 shaft horsepower per ton of ship to reach 39 knots. The liner *United States* made 38.3 knots using 242,000 shaft horsepower at a trial displacement of 39,900 tons or 6 horsepower per ton [13]. The big ship is more efficient because it is over twice as long. Speeds that greatly penalize small monohulls are less of a penalty for large ships. Using existing technology, high speed for a displacement monohull requires either large size or a very high power to weight ratio. In either case, 40 knots appears to be an upper practical limit for displacement monohull ships. If operational requirements dictate speeds above 40 knots, alternative hull forms should. be utilized.

Table 2. Power and Speed of 3,600-4,000 Ton Ships.

Ship	Design Date	Full Load Displacement, Long Tons	Main Propulsion Power SHP	Trial Speed, Knots	Ref.
Japanese *Fuso*	1874	3.718	3,900	13	[6]
USS *New* Orleans	1897	3.769	7.500	20	[7]
British *Boadicea*	1908	3,915	18.000	26	[8]
Japanese ***Yubari***	1920	3,587	57,900	35	[9]
French *Magador*	1934	4,018	92.000	39	[10]
British ***Daring***	1943	3,580	54,000	34	[11]
USS *Oliver **Hazard** Perry* FFG-7	1973	3,720	40,000	30	[12]

Sensitivity to Sea State

In addition to calm water speed limitations, displacement monohulls suffer from speed degradation with increasing sea state. The attribute of the displacement monohull of "free lift" turns into a serious limitation as the ship is always in contact with the ocean surface. As any seagoing sailor knows, the displacement ship experiences motions, deck wetness, slamming and other undesirable occurrences in rough areas. Figure 6 shows the degradation of speed with sea state for three sizes of surface combatants and indicates that larger ships are less sensitive than smaller ones.

Reference [14] discusses the operational limitations of warships due to their lack of seakindliness. In high sea states, neither installed systems nor crew members function efficiently. Although some progress has been made to design monohulls with improved seakeeping performance. they will always be sensitive to high sea states because of their contact with the water surface. For small ships requiring continuous operational capability in extreme sea states, the monohull may very well not be the best candidate hull form.

Summary

This section has pointed out there are good reasons why the monohull is the standard surface ship. Monohulls can carry large loads; require only modest propulsion power and have extremely long endurance; are simple, rugged and durable; are tolerant to growth and change; are supported by a mature industrial base; and are affordable. Of course monohull ships also have limitations. They are limited in top speed and are sensitive to sea state because they operate at the water surface.

The modern monohull of the future, through the judicious exploitation of advanced ship technologies, can further improve many of the desirable features and partially overcome some of the limitations. The next section will summarize some of these technologies available to tomorrow's modern monohull and discuss the improvements which can be expected through their incorporation into the system designs.

STATE OF TECHNOLOGY

Improvements in the performance of monohulls as military platforms can be divided into three basic categories:

- Those that reduce weight. either by introduction of lightweight materials or systems, or by reducing volume, or a combination of these.
- Those that increase mobility by improving resistance and seakeeping characteristics, propulsion efficiency or energy efficiency.
- Those that improve mission effectiveness by increasing survivability and reducing detectability.

This section will deal with each of these three technology areas as they relate to tomorrow's modern monohulls. All technologies considered are either state-of-the-art or achievable within the next 20 to 30 years with the application of adequate research and development effort. In many cases, the state-of-the-art advances have been considered too costly for use in current monohulls; however, their cost effectiveness improves with modern monohulls where reduced weight and volume are essential to improved performance.

The following discussion is directed primarily toward medium to large size surface combatants of the frigate, destroyer or cruiser size, which is the most likely range for near-term application of advanced concepts. Many of the items discussed are also directly applicable to larger ships, but their cost-effectiveness is expected to diminish with increasing ship size.

WEIGHT AND VOLUME REDUCTION

Weight and volume reduction are two closely related factors of primary importance in improving the performance of modern monohulls. However, weight reduction can lead to reduced draft and poorer seakeeping characteristics as noted in the previous section. In addition, the benefits of weight and volume reduction can be negated due to the poorer seakeeping of smaller ships unless accompanied by improved hullforms, stabilization devices or changes to mission-related systems to operate in a high-motion environment (for example, haul-down systems for helicopter operations).

Volume Reduction

The factors most likely to contribute to volume reduction will be discussed first. The discussion will consider only those related to improved technology as opposed to relaxation of standards driving volume, such as habitability. The following factors will be considered:

- Reduced deckheights
- Reduced propulsion system volume
- Miniaturization of components
- Manning reduction

Deckheight reduction is one of the most desirable approaches to reducing volume and weight. It is not as efficient as length reduction, which also reduces hull bending moment and has the greatest impact on cost, but deckheight reduction improves stability while preserving length for seakeeping and topside arrangements. Assuming that clear headroom is to be generally kept constant, the reduction must come in structural depth and distributive systems run in the overhead. There are a number of concepts to achieve this reduction, including:

- Tighter spacing of longitudinals and transverse webs, which can save 3 to 5 inches per deck
- Use of lightweight cable (discussed later), which can reduce cableway volume by 50 percent
- High-velocity ventilation ducting to reduce the size of ducts (possibly at the expense of airborne noise)
- Higher velocities in piping systems, which may require more exotic materials such as titanium to combat erosion

- Placing transverse webs above decks where false floors are required
- Accepting reduced headroom in normally unmanned spaces

Recent studies for the DDG-51 program indicated the potential for reducing deckheights by an average of 8 inches, leading to a lightship weight and volume reduction of about 5 percent.

Reduced propulsion system volume can be achieved by incorporating many of the propulsion concepts discussed later, such as superconducting electric propulsion, higher horsepower gas turbines, and “podded” propulsion, which places the propulsion motors and gears in hydrodynamically faired pods external to the hull as shown in Figure 7. Machinery volume reductions of about 15 percent are projected for pod propulsion, or about 4 percent of total volume for a typical combatant. Propulsion concepts that permit gas turbines to be located high in the ship to reduce uptake and intake volume are also attractive, since uptakes and intakes can account for as much as 7 percent of total volume in a combatant. A combination of advanced propulsion concepts can achieve a major volume reduction. A recent modern monohull design [15] included superconducting DC propulsion with two 45,000 BHP and two 4,000 BHP gas turbines. Reference [15] projects a specific machinery volume of 1.13 cubic feet per SHP versus 2.0 cubic feet per SHP for an FFG-7 type plant.

Miniaturization of components is widely recognized as having potential for total ship volume reduction. This has been clearly demonstrated in the last few decades. However, the components with significant potential for further miniaturization are in electronics systems, which currently occupy less than 3 percent of the volume of a typical combatant. Thus the potential for major gains with further miniaturization appears limited, since human factors limit the potential reduction of consoles and many other electronic components.

Manning reduction is likewise recognized as a major contributor to volume reduction, since each member of the crew adds about 5 tons and 600 cubic feet to a typical combatant. Potential reductions due to further automation are often limited by requirements for manning vital functions during Condition I (battle stations). Manning reductions cannot be dictated but must be based upon sound technical logic. Assuming that a 10 percent reduction in manning could be projected, the weight and volume savings for a typical combatant would be less than 3 percent. This does not represent a major gain.

Weight Reduction

The following discussion relates only to the direct impact of adopting specific technologies and not the total ship impacts, which can be quite significant where volume, manning, fuel consumption and support services are also impacted. Each of the seven groups in the NAVSEA ship work breakdown structure (SWBS) will be separately addressed. Much of the data presented below is derived from Reference [15], the ASNE Destroyer, Cruiser and Frigate Technology Symposium held in Pascagoula, Mississippi in 1982. Reference [16], and studies related to the DDG-51 design.

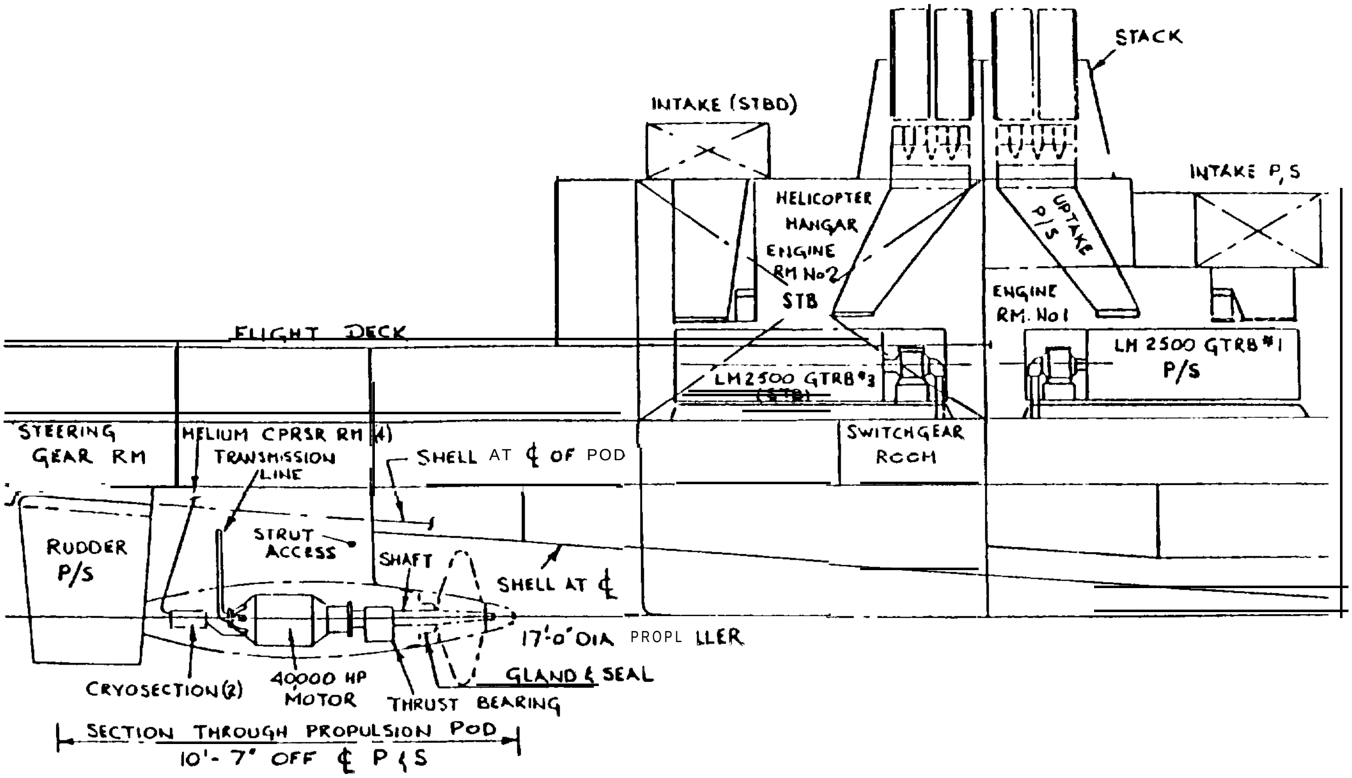


Figure 7. Modern Propulsion Concept-Podded Electric Drive.

Structures. Advances in ship structures generally relate to improved materials or structural efficiency and represent the most promising area for achieving major weight savings. Considering first the primary hull girder, the use of higher strength steel such as HY-80 or high strength low alloy (HSLA) steel offers the potential for reducing primary longitudinal hull structural weight by about 5 percent, assuming its use in the upper and lower flange of the hull girder. The use of 80,000 psi yield strength material such as HSLA can reduce the weight of internal decks, bulkheads and flats by about 15 percent. The greatest potential for reducing hull weight is to use marine-grade (5000 series) aluminum alloy, which affords reductions of from 40 to 50 percent assuming that hull flexibility is not an issue. This weight savings will be partially offset by the need to provide fire insulation on fire zone bulkheads and other vital boundaries and increased firefighting capability.

Reduced structural weight in the deckhouse is particularly important to enhance stability. Here again, aluminum offers a reduction of up to 40 percent relative to conventional steel. Advanced composites such as carbon-epoxy can save up to 60 to 70 percent and hold promise for small relatively isolated deckhouses, stacks and masts in the near future, though at a significant cost penalty.

The efficiency with which material is used can have a significant effect on weight. Orthotropic deck panels using thin plate supported by closely-spaced hat section frames (Figure 8) can save 15 to 20 percent per square foot. Steel sandwich panels employing thin face sheets separated by a corrugated or honeycomb steel core are currently used in marine applications such as uptake ducts, and are as light or lighter than stiffened aluminum. Such panels afford the fire resistance and stiffness of steel but are subject to corrosion unless corrosion-resistant steels are used. Fabrication details of the sandwich panels must also be further developed, though no fatal flaws are foreseen.

Propulsion. There are a large number of advanced concepts which can become reality in a relatively short time if the military need warrants the cost of development. Considering prime movers, next generation gas turbines can be developed with fuel efficiency improvements of up to 30 percent with intercooled regenerative cycles [17]. Conversion of the most recent aircraft fanjets to a marinized configuration offers up to 45,000 BHP per engine as well as cruise engines in the IO-15,000 BHP range to improve cruise efficiency. Prime mover efficiency can also be increased by recovering heat from gas turbine exhaust. The current Rankine cycle energy recovery (RACER) system can produce 8,000 SHP from the exhaust of a 25,000 BHP engine with no increase in fuel flow.

Transmission system weight reductions can be achieved in a number of ways. Reverse reduction gears with fixed pitch propellers reduce weight by about 1.8 pounds per SHP (about one-half attributed to reduced fuel) relative to non-reversing gears with controllable pitch propellers. Use of through hardened gears reduces gear weight about 20 percent, and hardened and ground gears result in a weight reduction of over 35 percent, with corresponding reductions in size. The podded propulsion concept is estimated to reduce propulsion plant weight and volume by about 15 percent.

Table 3 presents a summary of recent FFX propulsion system trade-offs, comparing the equipment (Group 2) weight and propulsion fuel load for an FFG-7 type plant to various single and twin screw plants. The table reflects two additional gas turbines, the 45,000 BHP LM5000 and 15,000 BHP LM1600 as well as several diesel options, with both geared (mechanical) and electrical drive. This comparison indicates that the mechanical drive options with recuperated gas turbine cruise engines are the lightest in terms of total weight due to their improved fuel consumption,

Electric transmission with superconducting electrical equipment offers both weight and volume reduction and flexibility of arranging propulsion equipment, since the generators and propulsion motors are physically independent. The podded propulsion concept shown in Figure 7 illustrates the advantages of this flexibility. The combination of superconducting electric drive with podded propulsion is expected to reduce the displacement of a DD-963 size destroyer by about 15 percent due to reductions in machinery box volume and weight and improved propulsive efficiency, which lead to reduced tankage [18] and [19].

A final weight reduction area to consider is the use of composites for shafting and propellers. The use of carbon-epoxy composites can reduce weight by about 50 percent and afford additional benefits in reduced noise transmission.

Electrical Power. Direct generation and use of 400 Hz versus 60 Hz electrical power can reduce the weight of generators (without prime movers) to about 3 pounds per KW versus 8 pounds per KW for 60 Hz generators. This would be somewhat offset by the need to convert back to 60 Hz for many uses. Power cable weight would also increase due to higher resistance with 400 Hz power.

Gas turbine generators can benefit from the same efficiencies as propulsion gas turbines, such as improved specific fuel consumption and recovery of waste heat. Near-term projections of 20 percent fuel efficiency improvement are not unrealistic. Superconducting generation offers weight reduction benefits especially in combination with a superconducting propulsion system

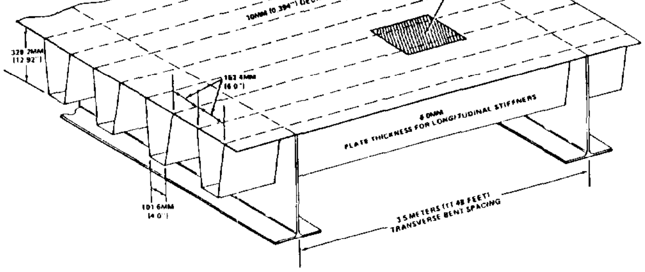


Figure 8. Orthotropic Flight Deck.

Table 3. Comparison of Propulsion Plants.

	Description of Plant				Weights (L. Tons)			
BHP	Propellers	Engines	Transmission	RACER	Equip.	Fuel	Total	Lb/BHP
4 I .000	I-CPP	2-LM 2500 (1)	Mechanical	No	31I	686	997	54.5
51,600	2-FPP	2-LM 2500	Electrical	No	so2	733 (10)	1235	53.6
60,000	I-FPP	I-LM 5000, I-LM 1600 (2)	Mechanical	No	303	551	854	31.2
56,700	I-CPP	I-LM 5000, I-Diesel (3)	Mechanical	No	420	779	1199	47.2
51,600	I-FPP	2-LM 2500. l-4 MW SSG (4)	Electrical	NO	384 (8)	741	1125	48.8
60,000	I-FPP	I-LM 5000, I-LM 1600 (9)	Mechanical	Yes	379	514	893	33.3
67,200	2-CPP	2-LM 2500, 2-Diesel (7)	Mechanical	No	571	515 (5)	1086	36.2
53,400	2-CPP	2-LM 1600, 2-Diesel (3)	Mechanical	NO	555	502 (5)	1057	44.3
55,800	2-CPP	2-LM 1600, I-LM 2500	Mech., Cross	NO	384	659 (5)	1043	41.9
5 I.600	2-FPP	2-LM 2500, 1-4 MW SSG (4)	Electrical	NO	502 (8)	809 (6)	1311	56.9

NOTES:

(I) Sim. to FFG 7; LM 2500 = 20,500 BHP
(2) LM 5000 = 45,000 BHP. LM 1600 = 15,000 BHP (assumed recuperated)
(3) Similar to Pielstick CP 18 PC 2.5 = 11,700 BHP
(4) Integrated electric with 4 MW generator driven by one GT
(5) Split plant operation
(6) Trail shaft
(7) Similar to Pielstik CP 12 PC 2.5 = 7800 BHP
(8) Propulsion equipment weight only, excludes weight of 4 MW generator, propulsion generator/4 MW SSG, combining gear and combining gear lube oil system.
(9) LM 1600 = 15,000 BHP (non-recuperated)
(10) Electrical cross connect, one LM 2500 supplying power to both shafts

where the refrigeration support system can be shared. It is estimated that a superconducting generator with its refrigeration system weighs 3 pounds per KW versus 8 pounds per KW for a conventional 60 Hz generator (without prime mover).

The weight of distributive power and lighting cable is a major item on all surface combatants, and a number of lightweight cable concepts are being developed. In most cases they involve improved insulation systems which can save from 10 to 30 percent, though with a near-term cost penalty of as much as 100 percent in cable cost. Copper clad aluminum cables are expected to save about 20 percent in weight. For a DDG-51 size ship, the current family of lightweight power cables could save up to 18 tons (11 percent of total power distribution system). Additional savings can be achieved in combat system cables. As the range of lightweight cable sizes increases, these potential weight savings will also increase.

Command and Control. As noted previously, this paper does not address the combat system directly, since that would be an input common to all ship types. From the perspective of the HM&E world, future developments of major interest revolve around data transfer. The use of fiber optics and data multiplexing as currently envisioned are expected to reduce the weight of data transmission systems by 50 percent or more and to result in significant reductions in cableway size.

Auxiliary Systems. Near-term advances in the auxiliary system area are not dramatic in terms of individual weight impact, though their cumulative effect could be quite significant. Specific weight reduction concepts include the following:

- Use of waste heat for steam and hot water generation. Equipment weight differences are not significant, but the fuel economy of waste heat systems can reduce fuel load significantly. Use of all-electric auxiliaries and electric heat will generally be more weight-efficient if it is not necessary to increase the generator size.
- Use of high-efficiency electric motors to drive auxiliaries invokes a small equipment weight penalty but can save several tons of fuel. Aluminum frame motors for pumps and auxiliary service can reduce motor weight up to 40 percent.
- High pressure/high velocity ventilation systems can reduce system weight by about 15 percent, but about half of this is offset by the greater fuel load required for the higher horsepower fans. An additional weight savings of about IO percent results if 400 Hz aluminum fans are used.
- Glass reinforced plastic piping, when used in approved applications such as water. plumbing, drainage and cooling can save up to 25 tons in a frigate-size ship.
- Vertical titanium close coupled firepumps will save 5 tons in a frigate size ship but. more importantly, will have only one-fourth the footprint area.
- High pressure (5000 psi) electro-hydraulic steering gear can reduce system weight by about 20 percent. Limited commercial applications have been accomplished in England and Japan. System cost is higher due to more demanding filtration requirements.
- The use of composites for rudders and stabilizing fins can reduce the weight of the fin structure by from 30 to 50 percent, depending on the composite selected and whether a composite stock is used.

Outfit and Furnishings. As with auxiliary systems, potential weight reductions in the O&F area are an accumulation of many relatively small reductions rather than any dramatic breakthrough. Many low-weight concepts have recently been introduced, such as GRP/honeycomb joiner bulkheads and false deck panels. Other O&F concepts to consider for weight reduction in modern monohulls include:

- Aluminum grating and floor plates in machinery spaces, resulting in an approximate 30 percent weight reduction but a degradation in fire resistance
- Epoxy deck coverings versus vinyl tile, saving 2.5 percent
- Use of austere habitability concepts such as submarine practice, which can reduce furniture weight by as much as 35 percent
- Use of conventional versus modular stowages, which will save about 30 percent of the stowage weight

INCREASED MOBILITY

Within the context of this discussion, "mobility" includes both the traditional considerations of speed and range as well as sustainability, the ability to remain on station for extended periods. This latter issue is one of the main attributes of a monohull, since the penalties associated with extra fuel, stores and ammunition are more easily absorbed than with other hull forms.

The factors affecting mobility can be broadly categorized in three areas: hull form, including both resistance and seakeeping, propulsive efficiency and energy efficiency. Many of the latter issues have already been addressed in terms of their weight reduction impacts.

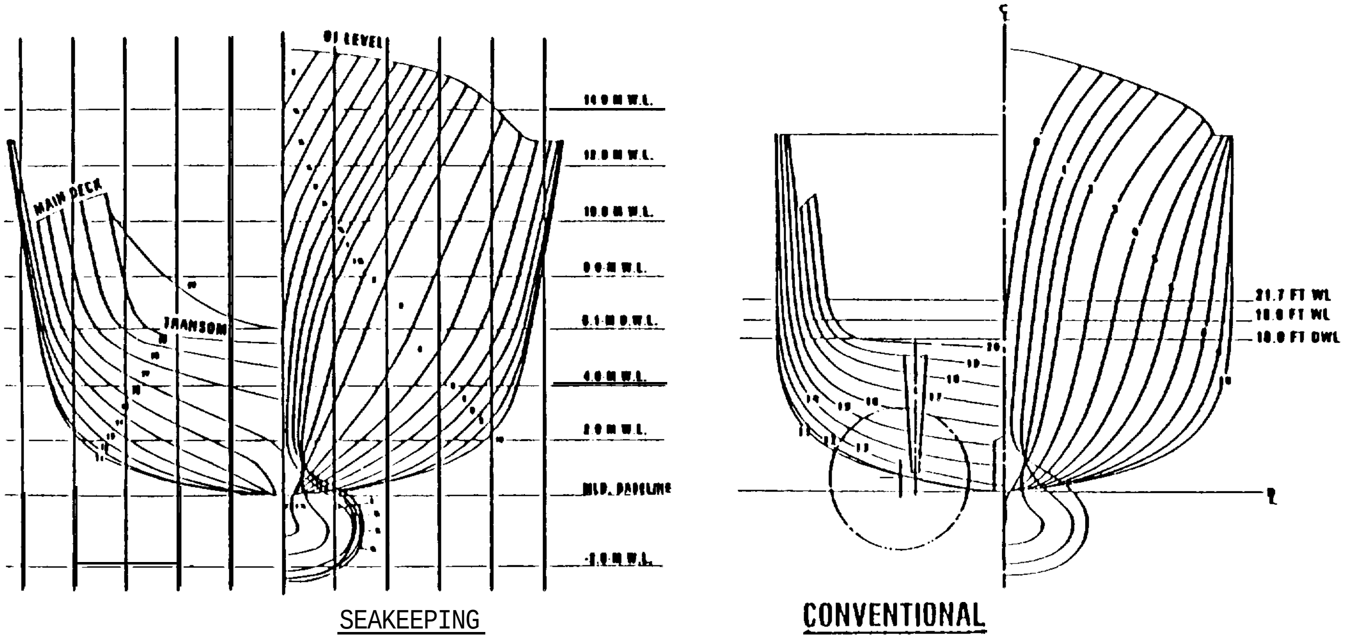
Hull Form

The basic hullform of monohulls has evolved for centuries, and today's higher speed monohull hullform is not radically different from the World War II destroyers and cruisers. Further improvements are expected to be evolutionary rather than revolutionary, involving reduced appendage drag and improvements such as stern wedges to reduce squatting (a potential 0.5 knot speed increase at top speed), bulbous bows and other fine tuning. From an overall efficiency standpoint, the ability to minimize displacement to length ratio by reducing total ship density is of primary interest in reducing EHP.

Ability to maintain speed and military capability in heavy seas is of major importance and represents a potential disadvantage of monohulls. Recent research by the Navy for the FFX program has resulted in a seakeeping hullform which incorporates greater length (about 15 percent), a fuller waterplane and more vee-shaped sections forward in conjunction with adequate flare and freeboard. This hullform slightly improves smooth water performance at maximum sustained speed due to the added length while providing a slight penalty at cruise speed due to increased wetted surface. The use of this type of hullform is expected to produce seakeeping performance in terms of pitch and heave motions equivalent to ships 10 to 15 percent greater in length. Figure 9 illustrates such a hullform as adapted to DDG-51.

Propulsion Efficiency

There are a number of concepts with the potential to increase propulsive efficiency including podded propul-



SEAKEEPING

- V-SHAPED SECTIONS FWD & AFT
- VOLUME DISTRIBUTED HIGHER
- WIDER WATERPLANE FWD
- HARDER BILGE
- KEEL RISE POINT FURTHER AFT
- EXTENSIVE FLARE ABOVE WATERLINE

CONVENTIONAL

- U-SHAPED SECTIONS FWD & AFT
- VOLUME DISTRIBUTED LOWER
- NARROWER WATERPLANE FWD
- SOFTER BILGE
- KEEL RISE POINT FURTHER FWD
- LIMITED FLARE ABOVE WATERLINE

Figure 9. Seakeeping vs. Conventional Hullform.

sion, contrarotating propellers, ducted propellers and others.

The podded propulsion concept mentioned earlier is postulated to reduce EHP by about 10 percent and SHP by as much as 18 percent, while reducing fuel consumption up to 19 percent. This is based upon improved flow to the propeller and reduced weight, including a propulsion plant weight and volume reduction of about 15 percent.

The efficiency of propulsors can be improved by ducting, contrarotation or larger diameters and a number of other concepts which have been analyzed, tested, and in many cases, used in full scale applications. The David Taylor Naval Ship Research and Development Center is continuing to evaluate a wide range of concepts for energy improvement. While results are difficult to generalize and are often quite design-specific, such research points toward avenues to pursue for specific designs.

Waterjet propulsion has been investigated for large monohulls as a means of improving propulsive efficiency due to reduced appendage drag. Recent studies [20] indicate that replacement of the twin screw CP propeller plant on DD-963 with one fixed pitch propeller for cruise and two 20,000 SHP waterjets for boost can reduce annual fuel consumption 23 percent. This is primarily due to reduced appendage drag and lower specific fuel consumption during cruise. The ship impact of waterjet propulsion is significant and must be evaluated in parallel with efficiency considerations.

Energy Efficiency

The previous discussion has alluded to a number of energy-saving concepts which are now being used or are contemplated for naval ships. These include:

- A wider family of available gas turbines so that horsepower required can be more closely matched to horsepower available
- Next-generation marinized gas turbines to take advantage of current aircraft technology
- Improvement in fuel efficiency of current-generation gas turbines by tightening tolerances, raising operating temperatures and improving fuel monitoring and control systems
- Cogeneration and recuperation of gas turbines ([16] and [17])
- Waste heat recovery using boilers installed in gas turbine uptakes (RACER, waste heat auxiliary boilers)
- High efficiency electric motors

It is conservatively estimated that the maximum use of energy-saving concepts using current technology can reduce overall fuel consumption by about 3.5 percent, which was the goal originally established for the DDG-51 program. It is not unreasonable to expect to meet or exceed this goal if proper incentives exist.

IMPROVED MISSION EFFECTIVENESS

The mission effectiveness of the modern monohull will be significantly greater than today's monohull combatant ship due to improved combat systems and improved survivability features.

One only has to compare the effectiveness of the current Aegis combat system to that of the older Talos/Terrier/Tartar systems to project forward the combat system effectiveness improvements which can be expected in the future. Sensors will be able to detect smaller targets at greater ranges in more severe clutter and jamming environments. The reaction time of the future systems will be faster and the fire power greater than those of current systems.

It is difficult to predict the impact of these future combat systems on the HM&E features of the modern monohull. It is well known that the conversion of surface combatant ships from gun ships (pre 1960s) to missile ships (current day) resulted in a significant increase in interior volume and topside space requirements and electrical power and other support system capacities. The modern monohull will and must respond to the needs of the combat systems since the overall effectiveness of any surface combatant is so dlominated by the effectiveness of its combat system.

The survivability of the modern monohull will also be greatly enhanced as compared to current surface combatants. Passive protection will be improved through increased effectiveness in shock hardening, nuclear air blast resistance, nuclear, biological and chemical defense systems, fragment protection, structural redundancy and functional separation. Even more significant improvements can be expected in the area of detectability through the reduction of the ship's radar cross section, noise signature, and infrared signature. As was demonstrated in the design of DDG-51, the key to improving ship survivability at an affordable cost is to system engineer survivability features into the ship at the start of the conceptual design phase.

AN EXAMPLE OF TOMORROW'S MONOHULL

The designer of tomorrow's modern monohull can exploit the advanced technologies in a number of ways to achieve improvements in different ship attributes:

- Reduce ship size and weight and improve mobility performance,
- Improve mobility performance with little change in ship size,
- Improve payload carrying capacity thus increasing combat capability,
- Improve survivability characteristics,
- Reduce acquisition and operating and support costs with little change in performance,
- Combinations of the above.

The component weight and volume savings, the improved subsystem performance, and the improved ship integration techniques caused by the more advanced technologies can be incorporated into the monohull system design to achieve the above types of system improvements.

It should be clearly understood that all of these improvements cannot be achieved simultaneously. The designers will select combinations of technologies and integration techniques dictated by operational requirements and the direction provided in the overall ship design philosophy.

A representative example of a modern monohull ship was reported in Reference [15]. In this design, emphasis was placed on improving mobility performance (speed and range), and reducing ship size and weight. Many of the advanced technologies discussed in this section were incorporated into this design. Table 4 summarizes the design's principal characteristics as compared to the current FFG-7.

The modern monohull does exhibit significant improvement in the areas of emphasis.

	Modern Monohull	FFG-7
Sustained Speed	41 Knots	28 Knots
Range	1.4 x Baseline	Baseline
Displacement	**3600** tons	3950tons

The modern monohull promises a 40 percent increase in speed and range and a 10 percent decrease in full load displacement while carrying approximately the same size combat system. At first look this particular example of a modern monohull design looks extremely attractive. An overall evaluation is presented in the last section of this chapter.

PRODUCIBILITY AND SUPPORTABILITY

One of the attractive features of a monohull is its relative simplicity, ruggedness and ease of operation. This, coupled with the extensive worldwide industrial base in place to build and repair monohull ships of every description, results in a ship system which is highly producible and supportable. Introducing components and subsystems based on technologies not currently existing in today's ships could have an impact on system producibility (building and introducing the ship) and supportability (maintenance and in service support). The

Table 4. Characteristics of Modern Monohull and FFG-7.

Item	Modern Monohull	FFG 7 (FY 79)
Length, Overall, Ft.	440	445
Length, Waterline. Ft.	425	408
Beam. Maximum, Ft.	42.5	47
Draft. Full Load, Ft.	14.2	14.4
Depth Amidships, Ft.	30	30
Sustained Speed, Knots	-40	-28
Endurance	1.4 x Baseline	Baseline
Guns	None	I 76mm. I - 20 mm
Missiles	40 - Standard 24 - Self Defense I6 Harpoon	MK 13/40 missiles
Aircraft	2 - LAMPS, 12 RPV	2 LAMPS
Electronics	Rotating Phased Array 2-D Radar MK 74 FCS Track While Scan FCS 6 - Linear Arrays Towed Array	AN-SPS-49 Radar MK 92 Fire Control System STIR (SPG-6) FCS AN/SQS-56 Sonar TACTAS
Hull/Deckhouse Material	Aluminum/Aluminum	Mild Steel/Aluminum
Propulsion - Type	Superconducting Electric	Mechanical (Geared)
Cruise Turbine	2 - 4.000 BHP	See below
- Boost Turbines	2 - 45,000 BHP	2 - 20,000 BHP
- Propellers	2 - Controllable Pitch	1 - Controllable Pitch
Electric Plant - Main	4 - 1,500 KW Generators	4 - I .000 KW Generators
- Emergency	None	None
Accommodations	140	180
Light Ship Weights (Long Tons)		
Group 100 Structures	830	I.411
Group 200 Propulsion	411	292
Group 300 Electric Plant	146	216
Group 400 Command, Surveillance	80	132
Group 500 Auxiliary Systems	407	540
Group 600 Outfit, Furnishings	325	329
Group 700 Armament	99	100
Margin	345	80
TOTAL Lightship	2.642	3.100
Loads	964	847
Hull Load Displacement	3.607	3.947
Volumes (Cubic Feet)		
Military Mission	96,500	101,500
Ship's Personnel	88,700	105,800
Ship's Operation	254,800	324,200
TOTAL	440,000	531,500

purpose of this section is to review the industrial base supporting today's monohull ships and then to determine whether this base can produce and support modern monohulls of the future.

PRODUCIBILITY

The industrial base of the United States is oriented toward the support of monohull shipbuilding. Table 5 shows the total active shipbuilding base as seen by the Department of Defense [21]. The base includes those builders who are currently producing ships under Navy contracts, as well as those providing regular overhaul and other depot level support work. In addition, there are numerous boat builders who are currently building boats, off-shore oil supply boats, etc. These builders could also be contracted to build small monohull boats in time of a naval forces build up,

The shipbuilding base is supported by a substantial number of subcontractors who supply everything from paint to main engines. Many stock items (such as fasteners, paint, pipe, etc.) are not unique to any one type or feature of construction. Other more complex items are from primarily monohull-oriented suppliers. A recent competitive bid for reduction gears produced five contenders. A shipbuilder competition for fire pumps or other large (50+ horsepower prime mover) pumps can expect four or more technically acceptable bidders.

This supplier base is impacted by the same types of factors which impact the shipbuilders. These include the personnel available and the need for machine tools if new types of components are to be implemented. Navy suppliers experience long lead times to obtain material from lower tier suppliers. Castings, forgings, and electronics connectors are but a few of the items which have long lead times.

Fourteen major components of the modern monohull were categorized for producibility [15]. They represent a cross section of the hull!, mechanical and electrical elements. The results are provided by Table 6. It can be

Table 5. Active U.S. Shipbuilding Base-December 1982.

	Total Plant Employees	Total Production Workers
Total Active Shipbuilding Base	108.245	86,387
Atlantic Coast		
Bath Iron Works	8,464	7.467
General Dynamics. Quincy SB Division	2,285	1,491
General Dynamics, Electric Boat Division	24,550	21.317
Pennsylvania Shipbuilding Co.	850	587
Bethlehem Steel, Sparrows Point	809	545
Maryland Shipbuilding & Drydock	912	726
Newport News Shipbuilding	25,983	19,688
Norfolk Shipbuilding & Drydock	3,810	3,525
TOTAL	67,663	55.326
Gulf Coast		
Tampa Ship Repair & Dry Dock	454	375
Alabama Dry Dock & Shipbuilding	127	101
Ingalls Shipbuilding Division	10,126	7.994
Avondale Shipyards	5,659	4,313
Halter Marine Services	1,526	1,131
Equitable Shipyards	150	100
Levingston Shipbuilding	612	462
Todd Shipyards, Houston	293	203
Todd Shipyards, Galveston	517	325
Bethlehem Steel, Beaumont	700	514
TOTAL	20,164	15,518
Pacific Coast		
National Steel & Shipbuilding Co.	4,948	3,781
Todd Pacific Shipyards, Los Angeles Division	3,650	3,196
Tacoma Boatbuilding Company	2,500	2,075
Todd Pacific Shipyards, Seattle Division	4,037	2.399
Lockheed Shipbuilding and Construction Co.	3,253	2.611
TOTAL	18,388	14.062
Great Lakes		
American Ship Building, Lorain	183	83
Peterson Builders, Inc.	573	457
Bay Shipbuilding	683	519
Marinette Marine Corp.	591	422
TOTAL	2,030	1,481

SOURCE: Maritime Administration

concluded from Table 6 that the modern monohull is well within the capability of the present industrial base, both shipbuilders and major component suppliers.

The modern monohull would not require any extraordinary capital investment. The ship represents a logical extension of current methods and tooling in the same way that today's ships extended previous methods. For example, the introduction of high-yield-strength steels, (HY-80 and HY-100) for common hull usage required shipbuilders to incorporate rod heating ovens, newly qualified welding procedures, etc. The change to gas turbines for propulsion required a significant training effort to ensure that shipbuilder operating crews could safely test the ships. The introduction of wire spray aluminum required new tooling [22]. None of the advanced technology features described in this chapter would require any more significant expenditure of capital funds for plant improvement or labor hours for craft on test crew training than these examples.

The modern monohull could be built with the current production flow methods. No extraordinary measures appear to be necessary to build and outfit the ship. It can be concluded that this particular example of a modern monohull design is producible with today's industrial base.

SUPPORTABILITY

A recent example of an introduction of a major new technology into U.S. Navy combatant ships was the incorporation of the gas turbine propulsion system in the *Spruance* destroyer in the mid-1970s. Ninety-three million dollars (FY84 dollars) were required to introduce the LM2500 gas turbine into the Navy logistic system. This expenditure provided for new schools, overhaul depots, technical manuals, test and support equipment, system testing, operator and maintenance personnel training, and spare parts.

Each of the new technologies discussed in the previous sections will represent a major fleet introduction effort. Fleet introduction costs will vary depending on how new the technology is to the Navy and how much support already exists in the industrial base.

The modern monohull design incorporated new propulsion gas turbine prime movers as well as an electric drive transmission system. Aluminum was selected as the basic hull material. In addition. numerous new but lesser impact technologies were introduced into the electrical, auxiliary and outfit subsystems. An assessment of these new technologies concluded that none of them posed an overwhelmingly difficult task to introduce to the active fleet. No single technology is any more challenging to introduce than that required for the initial introduction of the LM2500 gas turbine. However, since the modern monohull incorporates so many new concepts, the fleet introduction of the ship in significant numbers would represent a major undertaking.

Table 6. Major Component Producibility.

Component	Est. No. of sup. (1)	Status (2)	Est. Lead Time (mos) (3)	Ship Production (4)
Gas Turbine Generators	2	Fleet	28	Old/Med
Superconducting Motor/Generators	3	R&D		New/High
Propellers	2	Fleet		Old/Low
Shaftings/Bearings	3	Fleet		Old/Low
Switch Gear	1	Test		New/Med
400 HZ Inverters	3	Proto		New/High
60 HZ Inverters	3	R&D		New/High
RO Desalinizers	5	Proto	14	New/Low
Air Driven Pumps	3	Proto		New/Low
Halon/AFFF Fire Extinguishing	2	Fleet	12	Old/Low
Graphite Composite Rudders	4	R&D		New/Med
Helo Traversing/Haul Down	2	Fleet		Old/Low
Rigid Inflatable Boat	1	Fleet		Old/Low
Fin Stabilizers	3	Fleet		Old/Low

Notes:

I) Est. No. of Sup. - The estimated number of suppliers that are currently producing the same (or similar) components. The prospective bidders list would be at least this number.

2) Status - The phase of component production:

R&D Research and development. not yet at-sea
Proto - Prototype unit has been (or is) at-sea
Test Some or all product unit qualification testing remains to be completed/approved
Fleet - The equipment is currently in fleet use.

3) Est. Lead Time - The estimated number of months after receipt of order for delivery to the shipbuilder. This includes such factors as any engineering time to adapt to the specified use, subtier procurement, manufacture. and factory acceptance testing.

4) Ship Production The current shipbuilder experience base to install and test the component. Also defined as the level of craft experience to complete the work.

New/ - A new component, not previously built
Old/ - A component with significant learning

/Low. Med, High - The level of craft skill required to install/test.

SUMMARY

With the extensive industrial base already in place for producing and supporting today's monohull, the introduction of tomorrow's modern monohull is well within the Navy's capability. However. the fleet introduction costs of introducing each of the new technologies is significant and must be considered in evaluating the benefits of any changes to the existing monohull.

OVERALL ASSESSMENT OF THE MODERN MONOHULL

Undoubtedly, there will be monohull warships in the future. These modern monohulls will incorporate evolutionary advances in hull and machinery technology and reflect some different integration concepts. The result will be a better ship than is available today. It will be the designers of the modern monohull who will determine how extensive the application of advanced concepts will be as well as how best to exploit the advantages of these concepts.

The modern monohull described previously is representative of a frigate application. This design showed a significant improvement in mobility performance (40 percent speed and range increase), along with a 10 percent decrease in full load displacement as compared to an existing frigate, the FFG-7. There is little doubt that the "basic" overall performance of this ship would be significantly improved relative to its size due to its greater speed and range and particularly due to its more effective combat system.

Before we commit ourselves to this particular example (and, we might add, a rather dramatic example) of the modern monohull, we should recognize its shortcomings by addressing its impact on the inherent desirable features and limitations of the monohull.

CARRYING EFFICIENCY

The carrying efficiency (payload weight and volume fractions) of the modern monohull was held essentially constant despite the substantial increase in speed and range. This was accomplished through the incorporation of low ship impact structural and machinery features.

POWER REQUIREMENTS AND MOBILITY

The modern monohull requires 90,000 horsepower to make 41 knots sustained speed as compared to the FFG-7's 40,000 horsepower to make 28 knots. The increase in speed is achieved primarily due to the incorporation of the high power-density propulsion machinery and to a lesser extent the reduced displacement. The 40 percent increase in range was achieved by including a fuel efficient cruise gas turbine engine along with the decrease in overall ship size. The increase in calm water speed and range increases the combat capability of the modern monohull. The improvement in fuel efficiency represents a substantial savings in operating and support costs.

RUGGEDNESS AND SIMPLICITY

There is little doubt that the modern monohull, with its aluminum hull, more complex and more highly loaded machinery systems, and overall tightened design integration approach, will not be as rugged and forgiving nor as simple to operate and maintain as today's larger counterparts. This in turn will reduce its sustainability. It will be far more challenging to operate and maintain this modern monohull in a long-term deployed status than the larger, more conservatively designed, less demanding FFG-7.

The aluminum hull represents the most significant departure from current practice. The aluminum hull has a definite fatigue life and would be far less durable than proven steel hulls. For these reasons, the U.S. Navy has opted for steel to be used not only for the hull but also for the superstructure of the new destroyer, DDG-51. This particular example of the: modern monohull achieved its reduced size and increased speed and range by sacrificing survivability and sustainability. This represents a significant operational trade-off which must be evaluated by both the operator and the engineer.

TOLERANCE TO GROWTH

The modern monohull was designed with standard U.S. Navy design practices in the area of margins, stability and other factors related to design flexibility and growth potential. However, this initially higher performance monohull will degrade percentage-wise more rapidly with increased weight. In addition, the aluminum structural design of the modern monohull frigate does not include the standard one ton/square inch hull stress growth allowance thus sacrificing some of the ship's future growth potential. The modern monohull has more initial basic performance but would degrade more rapidly during its service life than more conventional designs.

EXISTING INFRASTRUCTURE

The advanced technologies incorporated in the modern monohull could be supported by the existing monohull industrial base. No new shipbuilding or manufacturing capability would have to be developed. Significant fleet introduction costs would be required, however, to provide a full logistic support capability for each new system. This fleet introduction cost must be considered in evaluating the overall cost effectiveness of this design.

LOW COST

The modern monohull would be far more costly to acquire per ton of ship than today's displacement ships. The smaller aluminum hull which accounted for such a significant weight savings will be more expensive to fabricate than a larger steel hull. The higher powered propulsion machinery would also add considerably to the acquisition cost.

The operating and support costs of the modern monohull as compared to an existing ship are more difficult to assess. While there would be a savings in fuel costs and operating personnel, these may be more than offset by increased intermediate and depot level maintenance support and a shorter service life.

A detailed cost analysis is required to assess the fleet introduction, acquisition, and operating and support costs. A safe conclusion at this stage is that this particular example of a modern monohull would represent an increase in life cycle cost as compared to a more conventional design.

SENSITIVITY TO SEA STATE

The rough water performance of the smaller modern monohull will be slightly inferior to that of the larger FFG-7 due to its shorter length, shallower draft and lighter weight. More advanced hull form and active motion control concepts may be able to mitigate some of the affects of the smaller ship. However, the serious limitation of small monohulls is contact with the ocean surface. It is therefore subject to motjons. slamming and green water.

The seakeeping characteristics of monohulls can be improved. However, the emphasis of this particular example of the modern monohull which led to a shorter and lighter ship precluded this rough water performance improvement.

CONCLUSIONS

The authors conclude that:

1) Monohulls will continue well into the future to be the most predominant hull form for commercial and military applications due to their inherent desirable features (carrying efficiency, small propulsion power requirements and long endurance, ruggedness and simplicity, tolerance to growth, existing infrastructure and low cost) despite their recognized shortcomings of modest speed and sensitivity to sea state. Recognizing the monohull's limitations which can not be totally overcome, other hull forms must be utilized for missions which emphasize seakindliness and high speed.

2) Advanced technologies which are available for tomorrow's modern monohull can reduce component and subsystem weight and volume requirements, directly increase mobility performance, and directly improve survivability characteristics. The component weight and volume savings can be exploited in a number of ways by the system designer leading to combinations of smaller lighter ships, increased speed and range performance, greater payload carrying capacity, and lower cost. But these improvements can not be achieved simultaneously in a ship design since some are contradictory. The designer will have to establish priorities consistent with overall ship design philosophy.

3) The advanced technologies which have the greatest leverage for improving performance and reducing costs must be developed independent of any specific shipbuilding program. In this way, the technologies will be mature enough to commit to future major ship acquisition programs. Many of the advanced technologies are required by other than monohull ships (SWATH, SES, ACV, hydrofoil, planing, etc). *A comprehensive evaluation must be made to determine the technologies that are most important and Navy wide commitments made to develop them now.*

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CHAPTER III

SWATH SHIPS

THE EDITOR

Jerry L. Gore *joined the U.S. Navy's Engineering Experiment Station in Annapolis, Maryland, upon graduation from Western Maryland College in 1962. During his 22 years at what is now David Taylor Naval Ship R&D Center, he has had a number of varied assignments in acoustics, machinery silencing, ship and submarine trials, ship propulsion, and advanced marine vehicles. Included were two tours in Vietnam with the Navy R&D Unit, a year as laboratory science advisor to COMOPTEVFOR, and a year as technical staff assistant for vehicle systems in the Office of the Assistant Secretary of the Navy for Research, Engineering and Systems. Mr. Gore's last assignments at DTNSRDC included technical manager for special/inshore warfare craft development and most recently, a similar position as head of the SWATH Ship Development Program Office. Currently he is program manager for the ship and submarine technology exploratory development program in the Naval Sea Systems Command.*

INTRODUCTION

In viewing the past two decades of naval vehicle development and improvement, one might perceive a lack of significant incentive to seek and make fundamental changes. There is a feeling that what we have is good enough, that we can get what we need "off the shelf," that it will be adequate against the opposition, and that "better is the enemy of good enough." The changes which have occurred have only been brought about by great expenditures of energy and funds through consistent and persistent but isolated efforts. Even then, sustained widespread expressions of consensus are required at all levels, including both administration and Congressional approval.

So, one should not be surprised that new and modern vehicle configurations of the type discussed throughout this special Journal issue may be viewed by their advocates as being either unappreciated or underutilized by the operators, or misunderstood by the engineers, or misrepresented by those decision makers and staff people who wish no change in the status quo. As already noted, one must persevere and measure progress in terms of careers and lifetimes, not merely "POMs" and "FYDPs."

In preparing this chapter on SWATH ships a team of knowledgeable professionals has been recruited to present the facts as they are known and to provide some informed opinions about this new ship concept and its utility.

In addition to the *Introduction*, the section on *Description of the Concept* is in a style to stimulate your imagination as you figuratively step aboard for a tour of our "newest Navy SWATH combatant," a ship not yet built, and not yet designed. The third section has been prepared by one of the most experienced SWATH ship designers, Dr. Colen Kennel1 from the Preliminary Design Division of the Naval Sea Systems Command (NAVSEA), teamed with a young member of the SWATH Group of the Advanced Naval Vehicles Division at the David Taylor Naval Ship R&D Center (DTNSRDC), Mr. Richard S. Holcomb. Dr. Kennel1 has nearly 14 years of experience in SWATH design and technology development, while Mr. Holcomb has nearly four, all in association with the U.S. Navy's limited number of practitioners of the art and science of SWATH ship developent. Together they will lead you through a comprehensive discussion of SWATH ship *Special Attributes and Limitations.* You will gain a perspective into the critical issues involved when a designer attempts to seek a balanced solution from among the many variables which must be traded off in seeking an optimum compromise.

Next is a discussion of *Current and Potential Applications* led by Commander David A. Patch, USN, who coordinates all activities related to alternative hull form selection and development for the Director of Surface Warfare (OP32) in the office of the Chief of Naval Operations. He has been in his present assignment three years and has seagoing experience as a weapons officer, an ASW specialist, an operations officer, an engineering officer, and as an executive officer (all in destroyers). In addition, he has served as a planning officer, a repair officer, and an executive officer at an intermediate maintenance facility. He has also been trained as a pilot and was carrier qualified. He recently played a major role in a NATO long term scientific study of advanced ships and their combat systems, and is chairman of NATO Special Working Group 6 on Advanced Naval Vehicles. In preparing this section Commander Patch received contributions and suggestions from Messers R. E. Adler and K. Alderman of the Adler Corporation; Dr. Edward Veazey, an executive scientist at ASG, Inc.; and Mr. R. G. Allen, head of the SWATH Ship Development Group at DTNSRDC.

There follows a rigorous overview of the significant technology areas upon which SWATH is dependent for its performance. Mr. G. Robert Lamb has developed this section on the *State of Technology* with the help of five collaborators in their own special disciplines. Mr. Lamb has devoted more than 15 years of his professional career to developing and understanding SWATH technology and how to apply it for consistently good performance over a wide spectrum of missions. He is recognized as one of the leading SWATH ship designers and is part of the SWATH Group staff at DTNSRDC. His five collaborators and their respective fields are Mr. Alfred Dinsenbacher, twin-hull structures; Ms. Kathryn McCreight, ship motion analysis; Dr. Arthur Reed, ship resistance and powering; Mr. Thomas Waters, ship maneuvering; and Dr. Ernest Zarnick, ship dynamics. All of these contributors are employed at DTNSRDC and have an aggregate of over 50 years of SWATH ship experience.

Last in order of appearance but first in the minds of most decision makers, are the twin issues of *Producibility and Supportability.* Many people believe that, short of building and operating a SWATH ship or two, one can but speculate about such issues. Unfortunately, it was not possible to get contributors to this section from U.S. shipyards in time for publication. This might lead to speculation that our shipyards are behind in SWATH ship technology and that they have not looked ahead to such new concepts. On the other hand, they may indeed have looked ahead and may even now be developing their business strategies and production technologies in private to exploit and pursue emerging opportunities with SWATH ships. In contrast, there has been significant progress overseas with the Japanese having launched their fifth SWATH ship since 1977. With the exception of the Dutch ship *Duplus*, at about 1200 tons; the U.S. Navy's SSP *Kaimalino,* at about 200 tons; and two U.S. private ventures, a 50-ton fishing yacht built for Mr. Leonard Friedman and a 60-ton utility craft built by RMI, Inc.; the Japanese have taken the initiative in building SWATH ships and advancing their technology and design base. As a result of such dedicated activity, Mitsui is the most experienced builder of SWATH ships in the world today.

In the absence of a more qualified author, it has fallen upon your editor to share ‘some thoughts on producibility and supportability, and, in so doing, extend a challenge to our shipbuilders to come forward with *their* views on SWATH ships and the potential of this new hull form to make important contributions to both our naval and maritime fleets.

So, on this note let's take a little journey into the world of SWATH ships. It will be well worth your time.

VEHICLE DESCRIPTION

First, we must recognize that the conventional monohull displacement ship as we use it today is a coat of many colors and a form with many functions; a versatile and very successful platform by any standard. Perhaps, it is very nearly the universal ship, a true panacea. The few alternatives which have been utilized over the years have been very specialized in their missions, and consequently limited in their numbers. Catamarans are one example worth mentioning here. The U.S. Navy operates three catamarans: the USS *Ortolan* and the USS *Pigeon,* both submarine rescue ships (ASRs), and the USNS *Hayes,* an oceanographic research ship (AGOR). These ships have had controversial histories and, in the aggregate, they have left a bad taste in the Navy's mouth. Since they are basically displacement monohulls divided into halves, they have little to gain from their configuration in terms of ship's motion alleviation in heavy seas. In fact, these three ships behaved so poorly in their early years of deployment that they had to be extensively modified to increase their damping to counter excessive vertical plane motions and resultant shell plating damage due to excessive slamming. As one flag officer has said regarding *Hayes,* "We can send one ship to Tahiti (calmer seas there), but we can't send a whole class."

However, the small waterplane area of the SWATH ship results in a totally different species. This acronym for small waterplane area twin hull was coined in 1972 to help clarify the picture surrounding the use of names such as TRISEC (a Litton development) and SSP (a Navy laboratory development). TRISEC came from the word "trisected" where a ship is divided into three parts (underwater, above water, and connecting). SSP comes from semi-submerged platform. An SSP was designed in 1971 and launched in 1973 as a workboat for the Navy's laboratory in Hawaii, which is part of the Naval Ocean Systems Center (NOSC) in San Diego. Figure 1 shows TRISEC. Figure 2 shows the SSP Kaimalino when she became the smallest USN vessel to qualify for SH-2F (LAMPS I) operations. Her nominal 200-ton displacement and 18-knot speed make her a fast craft for her size in heavy seas, because a SWATH suffers very little speed loss in waves up to its design sea state limit which, for a 600-ton stretched variant of the SSP, was in a high sea state 6 with a significant wave height of 19 feet. Under survival conditions, at very low speed in sea state 7, with significant wave heights of about 44 feet, she could still maintain her best heading, which turned out to be in

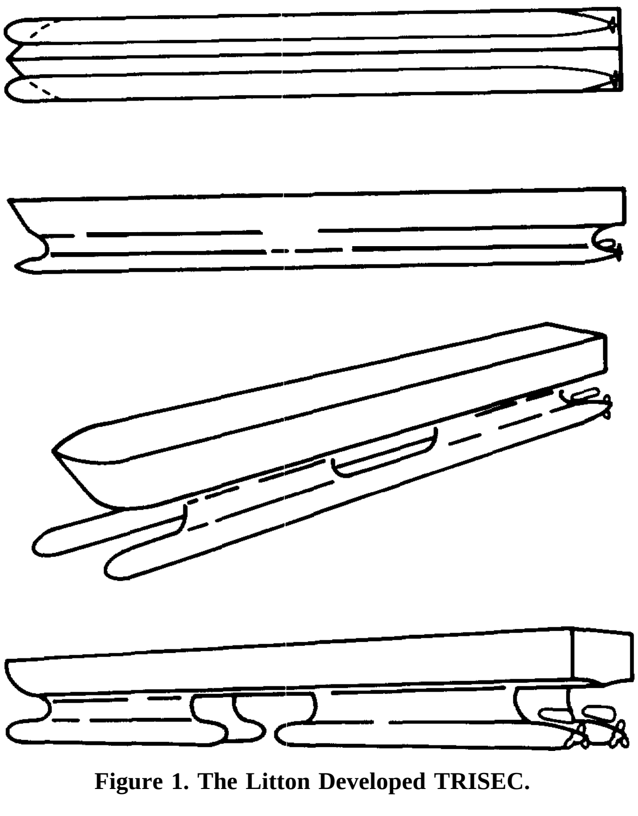

Figure 1. The Litton Developed TRISEC.

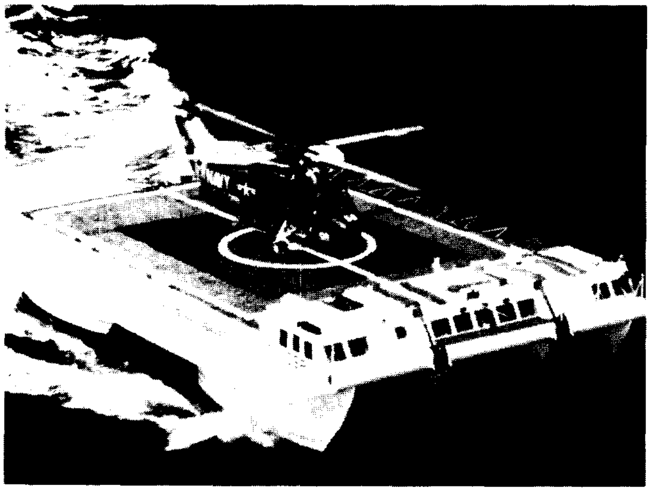

Figure 2. SSP *Kaimalino* with SH-2 Helicopter.

beam seas, where essentially all ship motion was manifested in heave, but of a very low magnitude of displacement and a very low level of acceleration. Without having witnessed the model test, one might be skeptical of the data.

As far as we know, SWATH was "born" in the creative minds of a Britisher and a Canadian-Messers Creed and Lewis, who took their "Aerodome" idea (Figure 3) to the British Admiralty in 1942. It was not considered a serious contender for an aircraft carrier in the U.K. and neither did the U.S. Navy take it seriously at that time. Only later, because of the determined advocacy of a few dedicated NOSC employees led by Dr. Thomas Lang, with a little bit of help from the Washington bureaucracy, did the U.S. Navy build a SWATH at all. Even then it became the subject of a GAO investigation into the legitimacy of its birth. Quite a beginning for a new concept born into a world of established credentials.

Since 1973, the ***Kaimalino*** has been tested and evaluated from A to Z. Because of limited dollars, she was built with "leftovers" from the tables of other programs. Used helicopter engines were scavenged, and chain-drives were used to link engines to propeller shafts. Hand-me-downs of all kinds and the dedicated service of the people who operated her have been essential to the 10 years of visibility and experience that have been gained from her service.

Kaimalino has also set an example for others. In the early 1970s the Japanese firm Mitsui Engineering and Shipbuilding. Ltd. started toward their goal of exploiting the SWATH concept. They built the ***Marine Ace,*** an 18-ton test craft; then the ***Mesa 80*** (now ***Seagull),*** Figure 4, a nominal 350-ton passenger ferry; followed by a 240-ton coastal hydrographic survey vessel called *Kotozaki* Figure 5; and now a 3500-ton deep ocean support ship called ***Kaiyo,*** Figure 6. Another Japanese firm, Mitsubushi, also built a 240-ton hydrographic survey ship, the *Ohtori*.

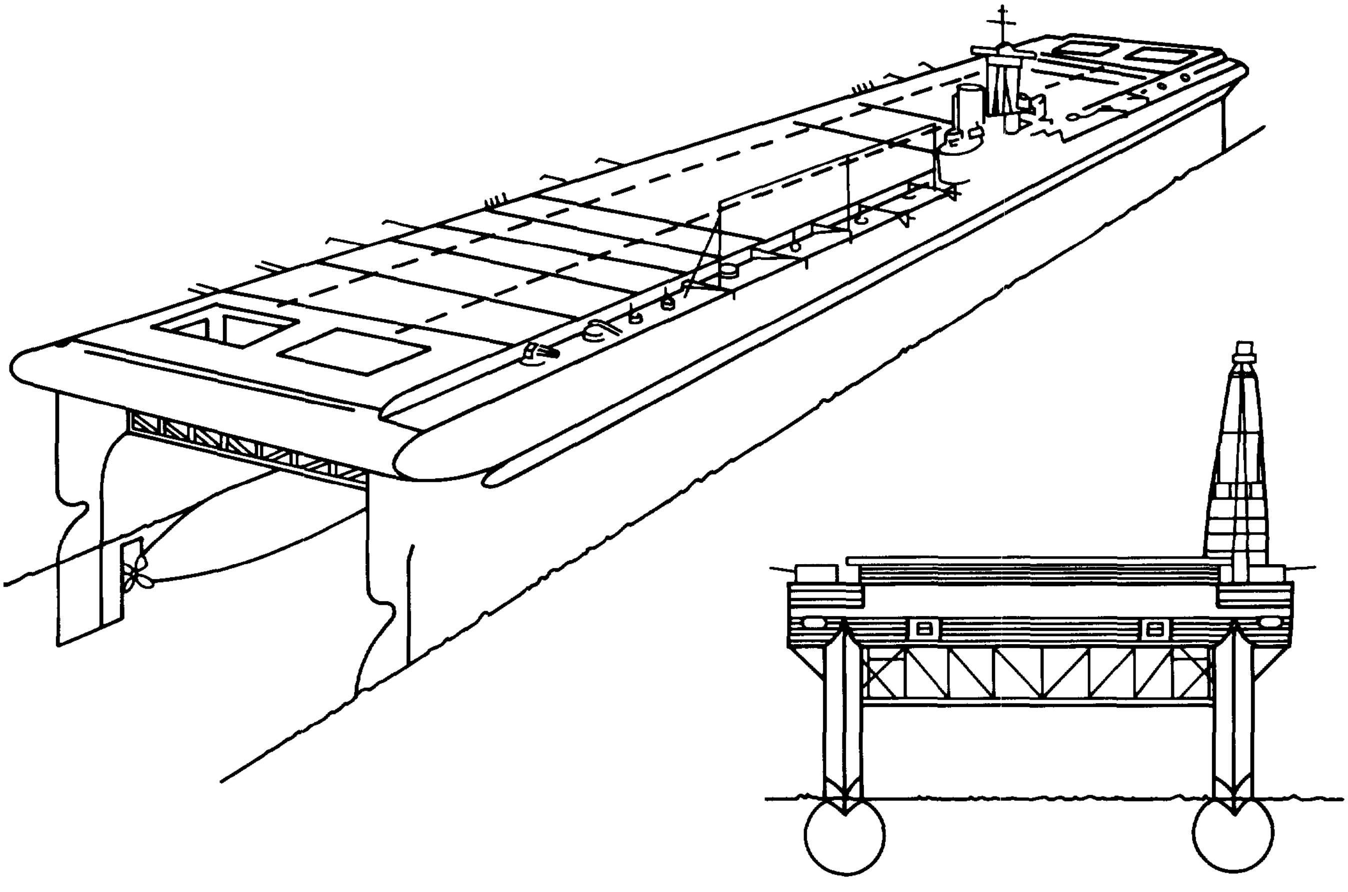

Figure 3. Creed-Lewis Seadrome Proposal (1944).

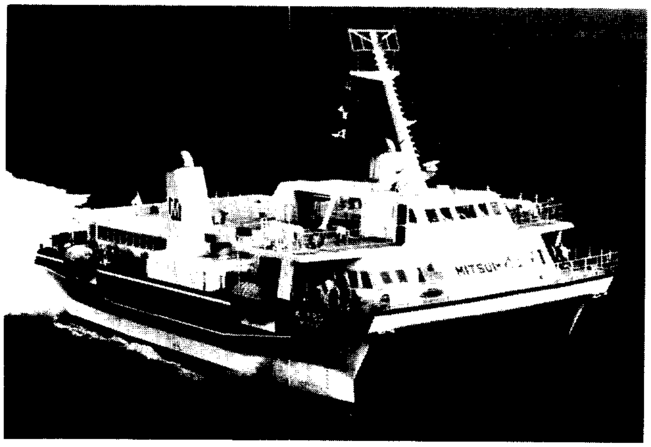

Figure 4. The Mitsui-built Mesa 80, Now Called *Seagull,* a Nominal 350-ton Passenger Ferry.

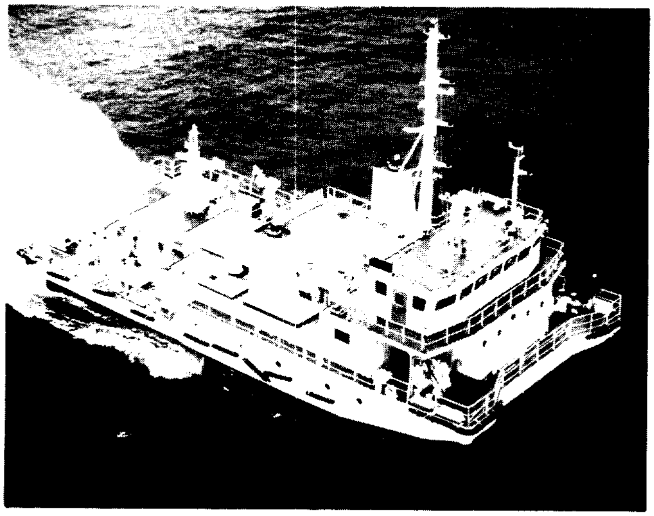

Figure 5. The Hydrographic Survey Vessel, *Kotozaki.*

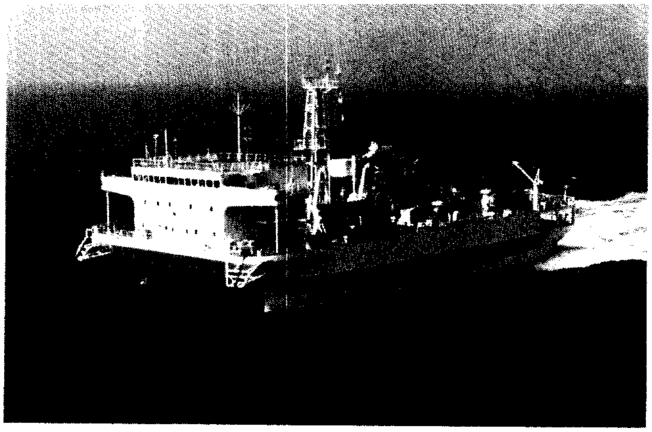

Figure 6. The Mitsui-built SWATH Deep Ocean Support Ship, *Kaiyo.*

As you begin your journey into the world of SWATH, you must prepare yourself for that inevitable first impression-somewhat like going on a blind date. Will he/she be good looking or simply sturdy and functional? More so the latter we think. For those who like ships because of the way they look. SWATH may be a disappointment. Figure 7 shows a rather block-like view of a SWATH which serves the purpose in giving you a quick look at what a SWATH would be like if you saw one on the drawing board. However, as Mitsui has shown in their commercial design (Seagull), SWATH ships can be graceful if the customer wants good looks. It is doubtful, however, that any SWATH ship can be as graceful and as beautifully proportioned as a conventional all-gun destroyer, probably the most beautiful warship ever designed.

Now, let's imagine that you are beginning a tour of our first small SWATH combatant, here on the starboard quarterdeck. At first you look across the wide expanse of beam, then far down at the water, then up and forward and ask, "How much did you say this ship displaced?" Given the answer you might say, "But it seems so much bigger than that!" You will still be suffering from that first impression as you walked down the pier and saw that great span across the bow and! that gaping maw as you looked down between the tall struts, because a SWATH ship contains about 30 percent more enclosed volume than the equivalent monohull. When that volume is distributed by separating it to each side, placing a lot of it up in the box and pushing the rest of it down out of sight for buoyancy, one gets an impression of real size!

Now, out of this general configuration and geometry will come some very interesting possibilities if one can arrange the ship intelligently with survivability and vulnerability features in mind to fully exploit the extra volume inherent in a SWATH ship. Let's walk about a bit as we discuss the possibilities. First, let's look at the all-electric power transmission system which links the main engines to the screws. Even though we've given up a few percent on transmission efficiency, there is a considerable gain in fuel efficiency at cruise speeds. We've put the propulsion motors deep down on short shafts to save weight. The power feeds down these cables which are both redundant and flexilble, and we use different lengths port and starboard to stagger the location of the prime movers and generators fore and aft. We even have the option of moving them toward the centerline or keeping them outboard at the sheer strake to optimize the separation of vital functions. The integration of main propulsion with ship service electrics has gained a better

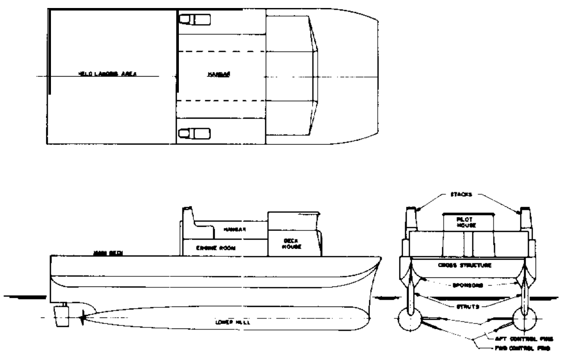

Figure 7. SWATH Ship Features.

utilization of energy, and this big square machinery box has helped the arrangement. Because the machinery is located above water in this big "box" there are silencing advantages to be gained.

Deep cylindrical hulls have made our sonar system think it is mounted inside a submarine, and this impression is reinforced by the fact that a SWATH ship does not slam and pitch, or create anywhere near the turbulent and noisy conditions which become limiting factors for conventional hull-mounted sonar systems. Moreover, its course keeping is outstanding at any heading to the sea. Stabilizers aft and canards forward maintain vertical plane control, and the after stabilizers are mounted at an angle below horizontal to help turn the ship. This type of rudder saves weight, cost and complexity; reduces appendage drag; and, with contrarotating propellers, we have substantially increased propulsive efficiency and decreased noise. Of course, for any application which still requires separate rudders, they can be added.

Another interesting aspect of SWATH is how it behaves when damaged-scares the wits out of some folks at first, but they eventually see the gain to be had. Let's just say that the ship is damaged on the port side in the lower hull. Flooding will be controlled in what are normally unmanned spaces and the vertical permeability and horizontal flooding will have been designed to be minimum. The ship will now start to heel. Meanwhile, counterflooding of ballast tanks, dedicated voids and spaces will be occurring on the starboard side. The ship will stop heeling at an angle of between 15-20° to port, but all systems on the starboard side are OK, thanks to the SWATH ship's separated and redundant features. In just a few minutes it will return to an acceptable heel angle, lower in the water, but still functional. Depending on where the damage occurred on the port side, some of those functional spaces may still be operational. The ship has taken a hit below the waterline from a major weapon and has not been in danger of sinking.

Experience in the Falklands crisis has shown that antiship missiles can create damage radii nearly as large as the beam of a frigate. A small monohull ship might have been broken in half with a single hit from a large missile, but SWATH would be an entirely different case. If the missile did not enter the box, its damage radius through the strut and into the open space under the box would probably not hazard the ship. Even a hit in the box may have fewer consequences due to the substantially larger beam. Unfortunately, we have not yet been able to investigate such intriguing and complex possibilities fully, so they cannot now be quantified.

But this business of damage tolerance and combat survivability means that more than one weapon and maybe more than two would have to be expended to really kill a SWATH frigate or destroyer. It may mean that hits on both sides would be required, and even then the reserve buoyancy of that big box will help keep it afloat-very much like a huge raft.

There isn't enough time on this tour to explore with you all of SWATH's features, but before continuing your journey into the next section on *Special Attributes and Limitations* you really should try to imagine all that this ship can do in a frigate or destroyer role. Everything from the handling of aircraft on that wide stable deck to providing new sonar systems the best ride possible while being able to take real punishment from old King Neptune. It seems that SWATH is a good choice for going down to the sea in ships.

SPECIAL ATTRIBUTES AND LIMITATIONS

SWATH Ship Naval Architecture

The naval architecture of SWATH ships differs significantly from that of conventional displacement monohulls. The few existing ships and craft, as well as the numerous design studies completed to date, show that some of these differences. can be exploited to improve effectiveness. Other differences represent new or more difficult design problems that must be managed to produce effective ships. The purpose of this section is to summarize what has been learned about the SWATH ship's *special attributes and limitations.* The reference frame selected for illustration is the conventional monohull displacement ship.

While most of the SWATH ship research and design work done in the U.S. has been Navy funded and directed toward large ships for naval missions, the nine ships built in the world to date have been relatively small and designed for commercial or workboat applications. The discussion of attributes and limitations that follows will have a naval ship flavor due to the use of this existing work; however, experience gained with the smaller existing commercial craft will be discussed to amplify specific points. The dichotomy between what may be anticipated through further development and what has been accomplished should be kept in mind by the reader of this section.

SWATH ship designs have often been described as conventional surface ship technology packaged in a different form. The different form and the consequences of packaging it are the keys to understanding their attributes and limitations. Figure 8 is a representative SWATH configuration for use as a visual reference point. This figure and the proportions that follow throughout this section are generally representative of good design practice as it exists in 1985.

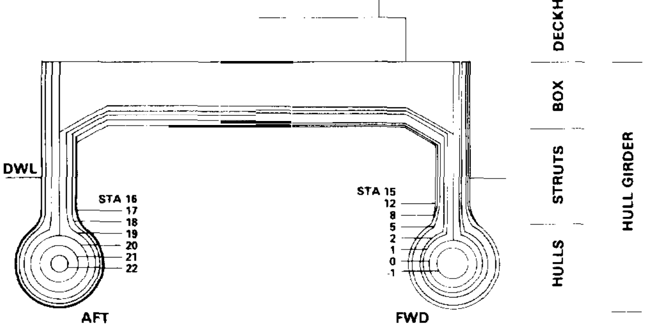

Figure 8. SWATH Ship Geometry.

Most of the ship's displaced volume, 65-90 percent of the total, is contained in the hulls. These hulls most commonly contain about 80 percent of the displaced volume. These slender components usually have circular or oval sections. The length-to-diameter ratio of hulls with circular sections is typically 14-22 with values of 15-17 most common. The higher length-to-diameter hulls have generally been used on designs of 15,000 tons and greater. The prismatic coefficient of hulls on SWATH ships varies between 0.45 and 0.93 with values of 0.7-0.9 most common.

The remainder of the ship's displaced volume is contained in the struts, the thin surface-piercing shapes that give SWATH ships their characteristically small waterplane area. Strut volume accounts for 15-20 percent of the total volume in a representative design and strut thickness is 30-60 percent of the horizontal diameter of the hulls. There are two distinct strut configurations commonly used; two-struts-per-side and one-strut-per-side. Two struts-per-side designs, such as the SSP *Kaimalino,* have length-to-thickness ratios of 5-15. The more common one-strut-per-side designs have length-to-thickness ratios of 20-40. The higher values (30-40) are generally found in designs of large ships displacing 15,000 tons or more. The waterplane area coefficient for struts is usually 0.7-0.8 and the strut shape is generally held constant from the top of the hulls to a point above the design waterline where the shell is flared inboard and often outboard to blend strut structure into box structure.

The remainder of the volume enclosed by the hull girder is contained in the box, well above the design waterline. The box is roughly rectangular in planform with length-to-width ratios of 2.0-5.0. The longer boxes typically are associated with ships displacing over 15,000 lton. Smaller ships generally range in length-to-beam ratio from 2.0 to 3.0. The box for designs under 5000 tons generally contains only one usable internal deck. Two or more decks can be accommodated in the box of designs with larger displacements.

Deckhouses provide usable volume in addition to that enclosed by the hull girder. Existing designs have provided as much as one third of the total volume in deckhouses, with 20-25 percent more common. Some SWATH concepts such as aircraft carrier designs, or the workboat SSP *Kaimalino,* have minimal deckhouses which enclose only a few percent of the total volume.

The volume enclosed in SWATH consists of two distinct parts for arrangement purposes. The box and deckhouse volumes consist of box-like shapes that are easily arranged. The hull and strut volumes are much more difficult to arrange due to small proportions and access requirements. Analysis of existing design studies shows strut and hull volume to be 30-50 percent of total volume with 35-40 percent being most common. As a result, SWATH requires more total ship volume than a comparable monohull to support a given set of requirements. Analysis of existing designs has shown that SWATH will usually require 20-60 percent more total ship volume than a comparable monohull.

There are major differences between the naval architecture of SWATH ships and monohulls that are the direct consequence of smaller waterplane area. These differences affect hydrostatics, arrangements. stability, machinery, structures and performance.

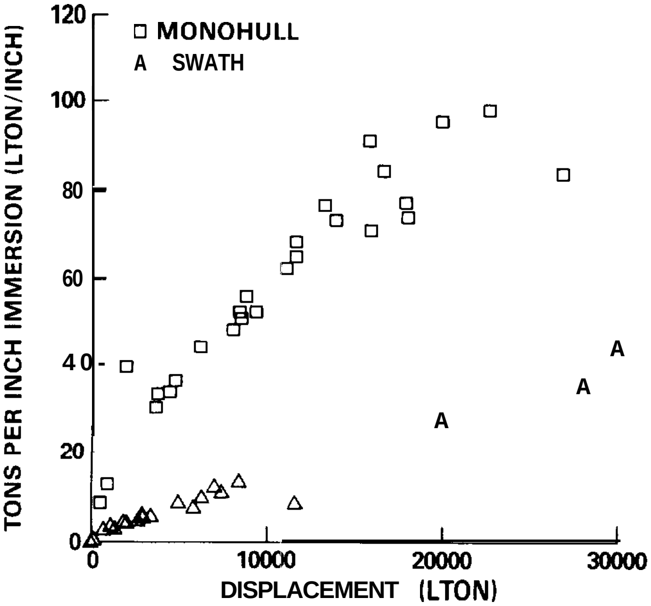

Figure 9. Tons Per Inch immersion Vs. Displacement.

A direct consequence of the small waterplane area is reduced tons per inch immersion (TPI), a measure of the sensitivity of ship's draft to changes in weight during design or while in operation. Figure 9 shows the TPI designs and existing monohull ships for a range of ship sizes. The data shows that the TPI is 20-40 percent that of monohull ships of the same displacement.

Trim sensitivity of a ship is measured by the moment to change trim one inch (MT1″), a function of the longitudinal moment of inertia of the waterplane area. The SWATH ship's small waterplane area and relatively short length result in relatively low values of this longitudinal stiffness parameter. Figure 10 shows that the MT1″ for

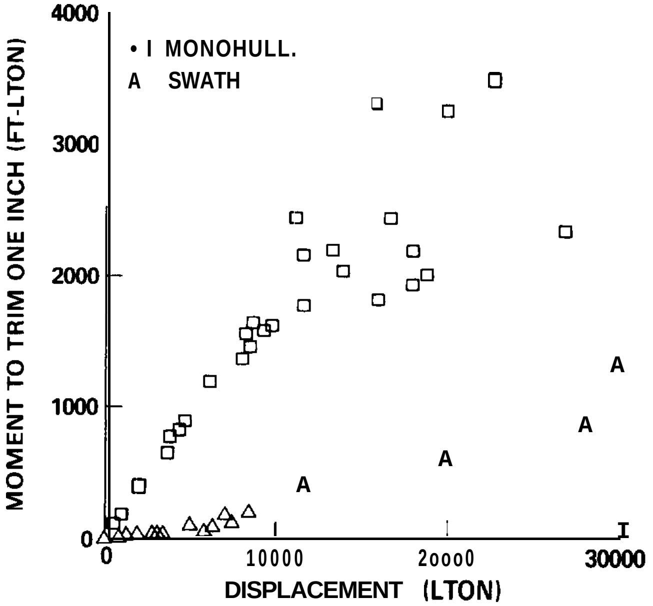

Figure 10. Moment to Trim One Inch Vs. Displacement.

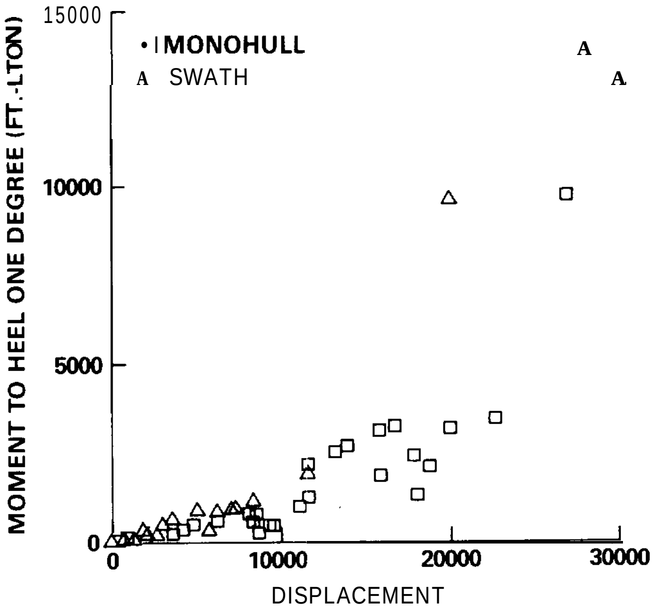

Figure 11. Moment to Heel One Degree Vs. Displacement.

SWATH is 10-20 percent that of monohulls of the same displacement.

A ship's heel sensitivity is measured by its moment to change heel one degree (MH1°), a function of the transverse moment of inertia of the waterplane area. Figure 11 shows the MH1° designs and existing monohulls. The large beam of SWATH compensates for the small waterplane area to provide heeling moments that are typically slightly larger than those of monohulls of the same displacement. Caution is advised with regard to this parameter since it is possible to design SWATH ships with the same moment to heel as monohulls while the larger beam allows larger moments due to changes in load distribution.

The hull girder volume distribution results in intact stability characteristics which are quite different from those of monohulls. Righting arm curves reflect the size of the restoring moment that is applied to the hull when it is heeled to one side. The righting arm of a SWATH ship is comparable to that of a monohull of like displacement for heel angles less than 10-15 degrees. The heeled waterlines intersect only the struts for this range of heel angles. Immersion of the box and/or emersion of the hulls at heel angles above 10-15 degrees cause an abrupt increase in the righting arm curve. These characteristic trends are illustrated in Figure 12 for representative hull forms. The area under the righting arm curve is a measure of the energy available to return an inclined hull to an upright position. The area under the righting arm curve of a

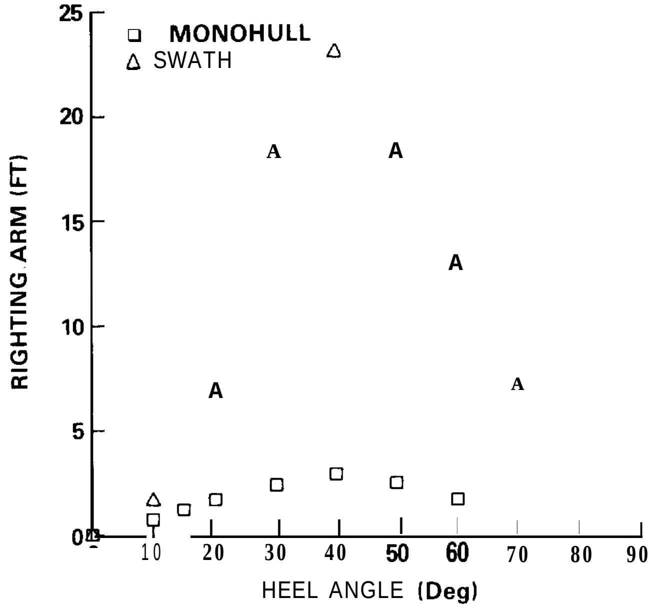

Figure 12. Righting Arm Vs. Heel Angle.

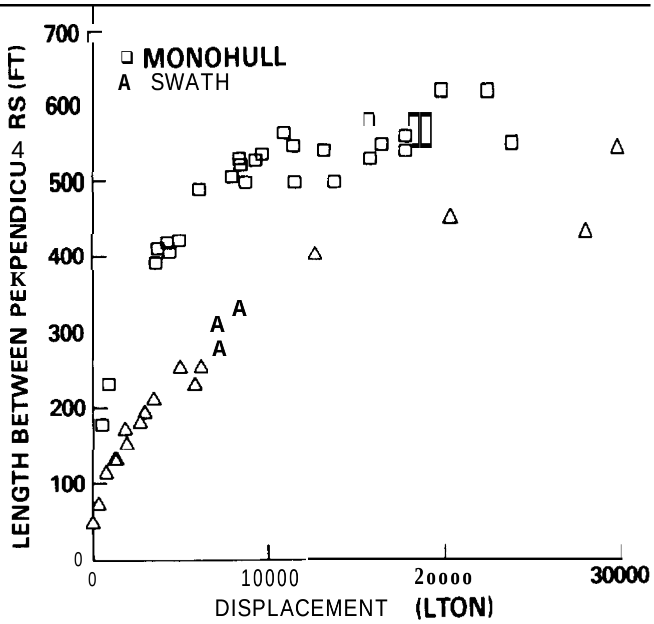

Figure 13. Length Between Perpendiculars Vs. Displacement.

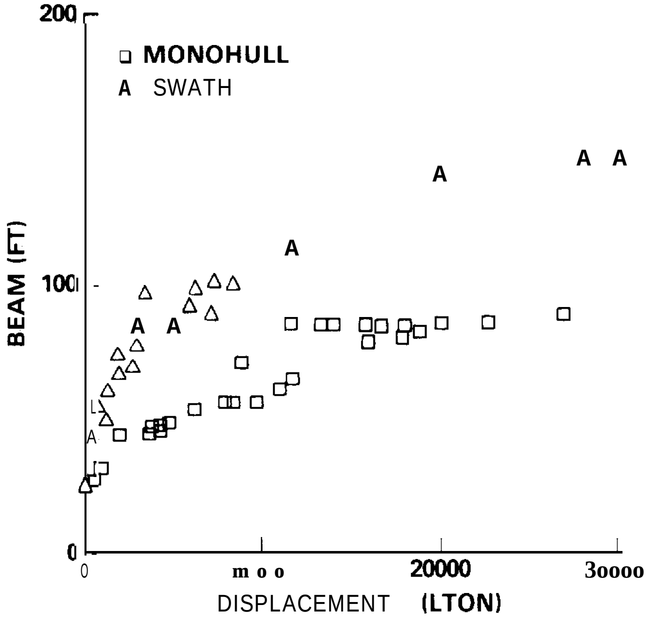

Figure 14. Beam Vs. Displacement.

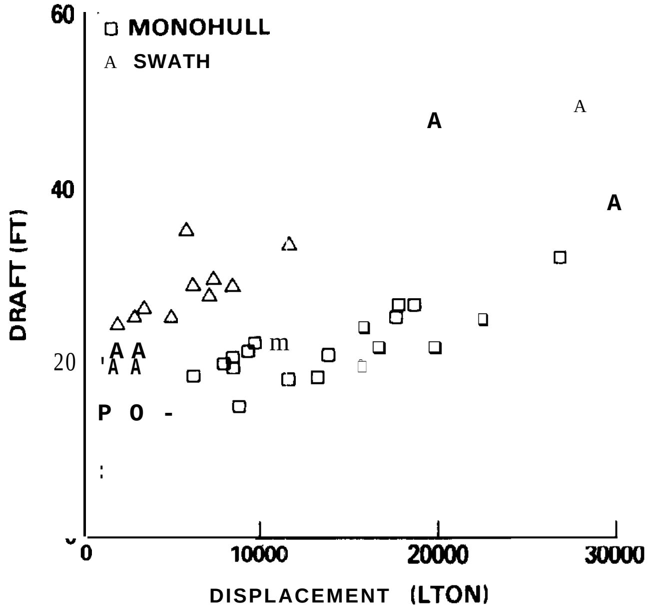

Figure 15. Draft Vs. Displacement.

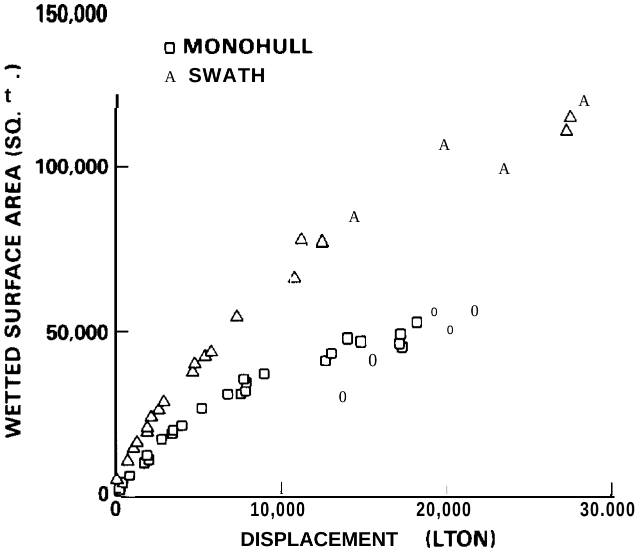

Figure 16. Wetted Surface Area Vs. Displacement.

SWATH ship is typically much greater than for comparable monohulls. The maximum inclination angle with positive righting arm is a measure of the heel angle a ship can survive without capsizing. This limiting angle is typically somewhat higher for SWATH ships than for monohulls.

SWATH ship proportions are significantly different from those of monohulls. Figures 13 and 14 compare length and beam for SWATH ships and monohulls over a range of displacements. The data show the SWATH to be 30-45 percent shorter than monohulls for a given displacement with typically 60-70 percent more beam, and greater draft to the keel. The data in Figure 15 show typically 60-70 percent greater draft for SWATH.

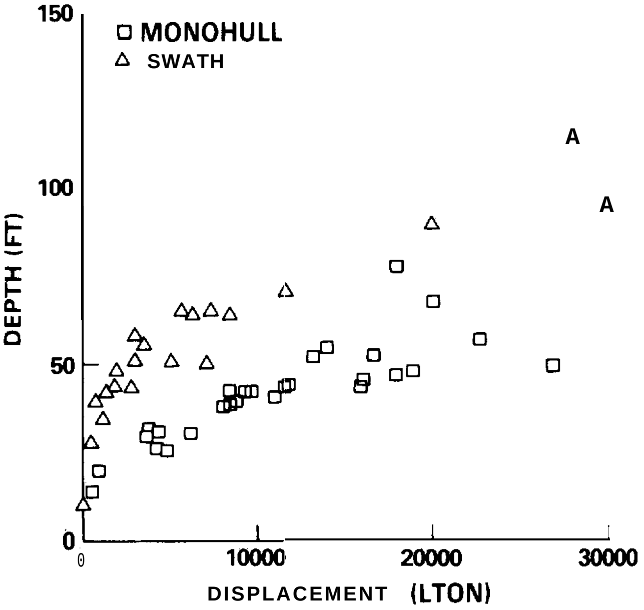

Figure 17. Depth Vs. Displacement.

The slender twin hulls used in SWATH designs inherently have more wetted surface area than monohulls of the same displacement. Figure 16 shows wetted surface area for the two types of displacement hull forms. SWATH ships tend to have about 60 percent more wetted surface area than monohulls of the same displacement.

The cross-structure on SWATH ships is usually designed to be well above the design waterline and the hulls to be well below the design waterline to reduce the effects of waves. Increased depth of the hull girder and increased freeboard to the main deck are consequences of this arrangement. Figure 17 shows hull girder depth amidships. The depth of the hull girder is generally greater than for monohulls; small designs tend to have about 75 percent more depth than monohulls while the larger designs have about 50 percent more depth. Figure 18 shows freeboard to be typically about 25 percent greater than for monohulls of the same displacement.

Most SWATH designs have used conventional marine design approaches and subsystem components which result in designs with cost, reliability, and maintainability characteristics that are well understood. This approach strongly influences the weight and volume. Total ship density (full load weight divided by hull plus deckhouse volume) is a measure of the degree to which these practices have been adopted in individual designs. Figure 19 illustrates the variation in density. The data show that the density of SWATH designs and existing monohull ships is generally between 15-20 lbs/cu ft. The similarities between the densities indicate that the subsystems in these SWATH designs would be very similar to those found in today's monohulls. The lower densities (9-12 lbs/cu ft) of the small ships and craft are achieved through the use of aluminum structure, reduced endurance, and a reduction in, or lack of, the reliability and maintainability features designed into the larger, open-ocean-capable ships. Use of these low-density design features has generally been restricted to displacements of 500 lton and less.

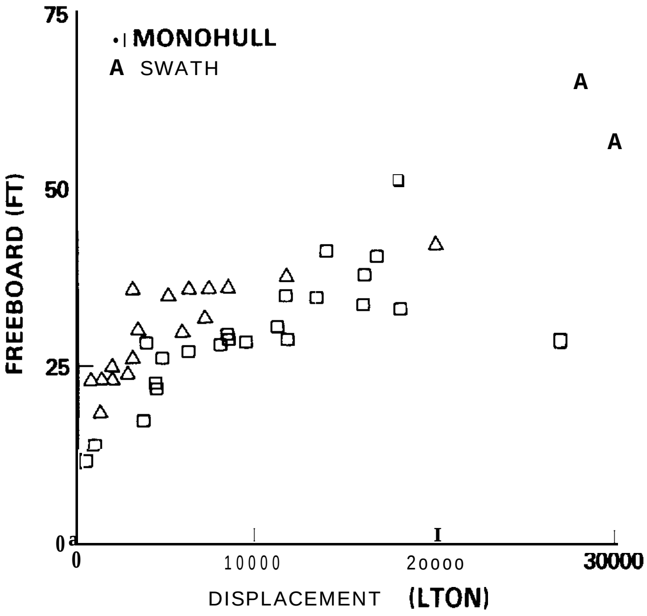

Figure 18. Freeboard Vs. Displacement.

GENERIC ATTRIBUTES

The primary attribute that the SWATH concept provides is comparatively little deck motion in a seaway while at rest or underway. The greatly reduced roll and pitch at very low speeds can only be matched by column-stabilized platforms which have been optimized for zero-speed steadiness and have little or no transit speed capability. The submerged portions of a SWATH ship are slender and more streamlined in shape making it feasible to achieve speeds of 25-30 knots with a reasonable amount of installed power and superior motions throughout this speed range.

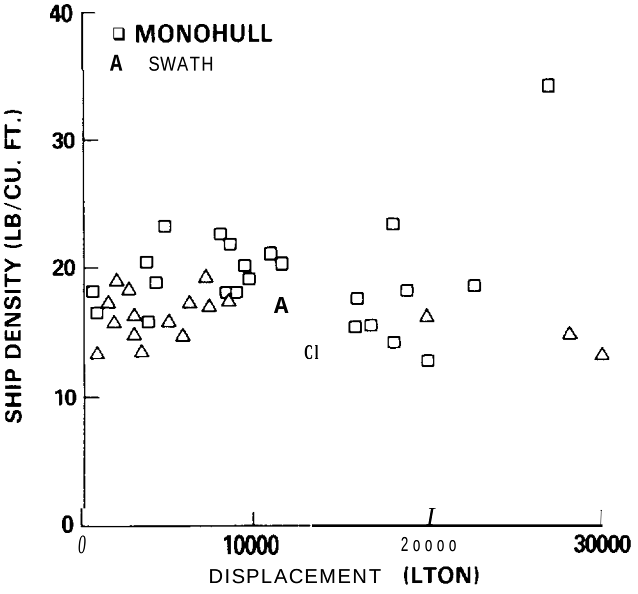

Figure 19. Ship Density Vs. Displacement.

The principal reason for the excellent seakeeping is the small waterplane area which reduces the wave-exciting forces acting on the ship and results in long natural periods of motion. These long natural periods result in low ship motions in moderate seas since most of the energy of a seaway typically occurs at short wave periods. Typically, the heave, pitch, and roll periods are about twice those of a comparable monohull.

In addition, SWATH designs usually incorporate active or fixed control surfaces to improve longitudinal stability and provide additional damping. Active fin stabilizers on monohulls generally improve seaway performance in roll only. Incorporation of canards forward and stabilizers aft on a SWATH ship improves heave, pitch, and roll. Full-scale experience has shown that these active control surfaces can improve the motion characteristics by as much as 50 percent.

SWATH ship and monohull motions differ in both magnitude and acceleration. Monohull pitch and roll motions are usually described as large in magnitude with high accelerations. Seasickness, slamming, shipping of green water, and degraded crew and operational capabilities in foul weather are common occurrences. Operators of monohulls avoid beam and quartering headings in moderate to heavy seas to minimize these effects. In contrast, the pitch and roll motions of a SWATH ship are low in both magnitude and acceleration. Slamming, shipping of green water, and degradation in crew and operational capabilities are confined only to very high sea states. The motions also allow the operator a much wider choice of heading with little motion-related restriction.

The seakeeping characteristics of the SWATH have been amply demonstrated on existing ships such as the SSP *Kaimalino* [1], *Suave Lino* [2], and Seagull (MESA 80) [3]. An excellent comparison of SWATH and monohull seakeeping took place in 1978 when side by side trials were conducted with the nominal 200-lton SSP, a 100-lton USCG patrol boat, and a 3000-lton USCG high endurance cutter [4]. Pitch, roll, and heave measurements for these trials are presented in Figure 20. The motions of the SSP *Kaimalino* are as good as or better than those of the 3000-lton cutter at all headings. Similar trials have been performed on both the Seagull [3] and the Suave *Lino* [2] with similar results.

Improved crew attitudes and performance and the ability to maintain these qualities at a high level for long periods of time at sea should result from the lower accelerations and frequencies of SWATH ship motions. The longer periods and lower accelerations allow the human system greater time to adapt to its constantly changing environment when aboard ship. As a result, shipboard activities such as sleeping., eating, walking, and mission functions are easier to perform, and the crew should be less fatigued and more alert than personnel on a monohull during extended rough water deployments. An attempt to quantify these effects on personnel was made during the USCG side-by-side seakeeping trials [5]. Unfortunately, these results are largely ambiguous due to the difficulty in quantifying human factors such as levels of concentration and fatigue.

Other performance attributes of the SWATH ship result from its maneuverability characteristics. They are very directionally stable and thus have excellent coursekeeping ability. This has been demonstrated on both the SSP ***Kaimalino*** [1] and the Suave *Lino* [2] where the ships have sailed straight courses with one propeller in operation and only a small angle on the rudders to counteract the turning moment induced by the trailing propeller. They also have excellent low-speed maneuvering characteristics resulting from the wide separation of the propellers. This separation permits the operator to apply differential thrust to produce a large turning moment. The SSP, the *Seagull*, and the Suave *Lino* have all demonstrated the ability to turn in a complete circle within one ship length at zero forward speed.

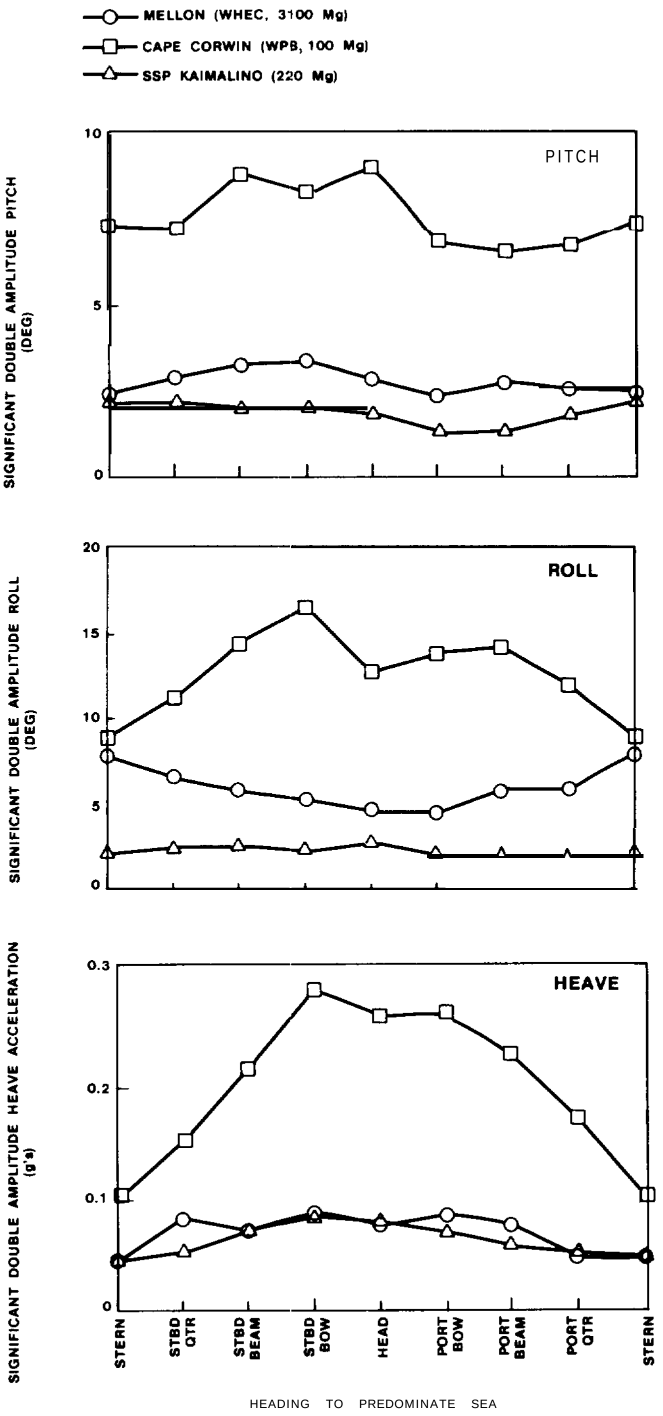

Figure 20. Comparison of Motion of SSP *Kaimalino* and USCG Monohulls.

The deeper draft improves the propeller cavitation/ventilation performance. This, combined with low motions also reduces the frequency of propeller emergences in a seaway.

The geometry has a number of arrangement attributes. The weather deck area is comparable to that of a monohull of similar displacement but shorter length. The approximately rectangular planform is also shared by the lower decks in the cross-structure, in contrast to the more highly shaped and smaller internal decks characteristic of monohulls. The irregularly shaped volume of the struts and lower hulls is amenable to fuel, ballast, liquid storage, and auxiliary machinery.

SWATH ship design and construction practices are largely conventional. SWATH concepts are applicable to naval missions requiring displacements up to about 35,900 hon. Above 35,000 lton, the beam begins to impose construction location difficulties and draft becomes a limiting factor. Today's state-of-the-art SWATH technology allows design, construction, and operation of ships with an expected lifetime of 20 to 40 years with only a modest increase in risk over that inherent in the design of a similar monohull. Furthermore, that risk should diminish as operational experience is gained from fleet exposure.

The designer of SWATH ships can select from a wide range of hull form parameters for hull geometry. This allows the designer to produce a hull form with performance characteristics that reflect the requirements of a given mission. For instance, the designer can change the distribution of underwater volume (hull shaping) and significantly modify the residuary resistance characteristics. The ship can be designed for the prevailing sea conditions expected in the area of operation through selection of metacentric properties, waterplane area, and the locations of longitudinal centers of buoyancy and flotation (LCB and LCF). It can be designed to "platform" up through a particular sea state to enhance operations and "contour" waves in very high sea states to enhance survivability by minimizing slamming.

GENERIC LIMITATIONS

The attributes of the SWATH concept are not attained free of charge. The unique configuration responsible for so many of its generic attributes also leads to a number of generic limitations. The principal one is its small TPI, a direct result of its small waterplane area. As shown previously, the TPI is approximately 25 percent that of a monohull of similar displacement. As a result, it is more sensitive to changes in weight than a comparable monohull. This greater weight. sensitivity impacts the ship during design and throughout its lifetime.

SWATH designs generally include higher weight margins than those used for similar monohull designs. These higher margins are due to the limited number of SWATH ships constructed, the limited number of detailed designs completed, and the greater sensitivity to weight growth. Increased margins frequently, but not always, result in a larger more expensive ship to fulfill a given mission. An alternate approach is to use more stringent weight control practices than commonly used on monohulls. Such design discipline, however, also increases ship cost.

Provision for extra weight-carrying capacity and volume within the hull for future growth is common practice in ship design, particularly in naval ships. This future weight growth is simply absorbed on monohulls by a small increase in draft with some degradation in powering. Future weight growth on a SWATH ship is not as simply accommodated because of its greater sensitivity to that weight growth. Adequate weight growth margins must be included since large changes in weight result in relatively large changes in draft and reductions in cross-structure clearance. If adequate provision for future weight growth is not designed into a SWATH ship, additional mission capability cannot easily be added later. Also, undisciplined growth in weight must be stringently controlled. An alternate approach is to add buoyancy later by means of hull blisters as was done on both the SSP *Kaimlino* and the *Suave Lino*.

Location of the center of gravity on SWATH designs must be accurately estimated and controlled during design, construction, and overhauls to maintain acceptable trim. Failure to locate the longitudinal center of gravity (LCG) near the LCB will result in much higher trim angles than on monohulls due to the SWATH ship's characteristically low values of MTI". The relatively high MTI" values characteristic of monohulls have conditioned designers to expect trim to be small in new designs with LCG location calculated late in the design process. Such "benign neglect" of LCG-LCB separation on a SWATH design can lead to the costly disruption of the design process and/or an unworkable ship design.

A second facet of the weight change sensitivity problem and its effect on a SWATH ship during operations is the greater trim resulting from changing load locations. A related problem is the ship's response to flooding due to damage. Damaged flooding is likely to be asymmetric, resulting in large angles of heel. While there is likely to be little risk of the ship sinking because of the tremendous amount of reserve buoyancy in the cross-structure, these large heel angles may impede damage control efforts until reduced by counterflooding. Tankage, trim control systems, and counterflooding systems must be included in the design to provide this capability.

The amount of usable and arrangeable area and volume is a function of the proportions of the design and the design requirements. All ship designs contain volume that is unusable or only marginally usable. This volume is commonly found in monohulls in the thin forward-most bow sections and in the bilges. The small waterplane area results in thin strut sections that are similarly difficult to arrange. Some of this volume can be effectively arranged such as that. in the flared upper part of the struts amidships where storerooms and machinery spaces have routinely been located. Effective use of the volume in the lower parts of the struts and the relatively narrow forward and after parts of the upper flared strut regions has not been achieved in #existing designs for functions other than tankage. This is due to the small proportions of the struts and the limited requirements in most designs for functions such as storerooms that can be accommodated in strut-like spaces.

Strut spaces also separate readily arrangeable box volume from arrangeable hull volume. While the proportions of hull compartments are compatible with the requirements of many ship functions, each of these spaces must be provided with long vertical access trunks to connect the hull with the box. Design and operational difficulties associated with using these isolated spaces have resulted in designs that make relatively inefficient use of available hull volume when compared with monohull arrangements. In genera!, hull spaces in existing designs have been arranged for propulsion machinery, ship control machinery, pump rooms, and tankage only. Volume utilization inefficiencies such as those discussed above have resulted in designs that are less efficient than monohulls.

The twin-hull geometry also results in generic limitations. The larger wetted surface area results in greater frictional resistance. Therefore, a SWATH ship with the same amount of installed power as a monohull of equal displacement will have a maximum speed of approximately two knots less in calm water. The SWATH ship will, however, make better speed than the monohull in a seaway due to its improved motions characteristics which reduce added resistance in waves and voluntary speed reductions due to slamming, deck wetness, and poor ride quality.

The twin-hull configuration also leads to more skin plating and stiffening than used on a monohull. SWATH ships require additional structural detailing in locations such as the strut/cross-structure intersection to reduce high stress concentrations and prevent fatigue damage. Factors such as these cause them to have larger structural weight fractions than those of comparable monohulls.

As one might expect, SWATH ships must carry a heavier, more costly twin-shaft propulsion system for many missions performed by single-shaft monohulls. However, the propulsion system weight is similar to that of a comparable twin-screw monohull for a given type of transmission system.

The prime movers in small high-speed SWATH ships cannot be located in the lower hulls without adversely impacting powering characteristics due to increases in hull diameter for engine accommodation. Prime movers for such small ships are best located in the cross-structure. Mechanical Z-drive transmissions have been used on the *Suave Lino* and the *Seagull.* A key limitation of a Z-drive is the absence of a cross-connect capability, making it impractical to drive both the port and starboard propellers from one engine. This results in higher endurance fuel requirements, particularly when gas turbines are used. In addition, the Z-drive generally includes several pieces of machinery (e.g., bevel gear boxes) not normally used in monohull transmission systerns. Thus, the Z-drive system is heavier, more complex, and more costly. An alternative to the Z-drive is the electrical transmission system. However, currently, the weight of electrical transmission systems limits their applicability to larger SWATH ships of several thousand tons displacement and greater.

Mechanical transmission systems on ships with lower hulls large enough to house prime movers are similar to those currently used in monohulls. Shafting runs can be reduced resulting in reduced shafting weight. Engine access and maintenance are likely to be more difficult due to the small dimensions of struts and hulls.

Other subsystem weights are likely to be greater than those of a comparable monohull. There is more enclosed volume to be ventilated, heated, air-conditioned, and outfitted. The twin hulls require the duplication of subsystems such as propulsion and auxiliary machinery. The separation of buoyant volume and usable volume and the large beam result in longer runs for distributive systems. A ballast management system will also be required. Control surfaces are larger and more numerous than on monohulls. These and other similar factors contribute to making the lightship weight greater than that of a comparable monohull. SWATH lightship weight is likely to be 10-40 percent greater than that of a monohull, if the monohull is designed merely to carry the same payload and provide the same range and calm water speed. This leads to either a larger ship, or alternately, a ship with a smaller weight fraction available for fuel and payload for a given displacement. In addition, fuel on this equal-displacement SWATH ship will likely comprise a larger weight fraction than that for the monohull due to the higher calm water resistance. On the other hand, for those missions where ship motion effects on operability are important, a SWATH ship will generally be smaller than a monohull sized to provide the same operability. One recent Navy study concluded that a monohull would have to be 29 percent larger in displacement than a SWATH to provide equal operability under year round sea conditions.

The beam of a very large SWATH ship can restrict its passage through waterways such as the Panama Canal. Such large ships may also require special dry-docking facilities for construction and repair. Beam is not a major factor in most cases since existing dry-dock facilities are large enough to accommodate SWATH ships up to approximately 30,000 lton. The deeper draft can limit operations in coastal waters and in port, and the high deck edge freeboard may create difficulties when working side by side with smaller craft and in boarding and deboarding operations.

ATTRIBUTES IN A COMBATANT ROLE

The seakeeping superiority of the SWATH concept and its other attributes provide considerable improvement in the performance of naval combatant missions. One key benefit of improved seakeeping is the very small speed loss in a seaway. A SWATH ship can maintain higher speeds in moderately high sea states than a monohull of comparable displacement. The 350-lton *Seagull* [2] has demonstrated its ability to make a top speed of 24 knots through sea state 4 with less than a 2 percent loss of speed. Estimated speed loss through sea state 5 is only 5 percent for this small ship. In contrast to monohulls, the loss in speed of Seagull in high sea states is attributed to the increase in ship resistance and not to slowing down to limit deck wetness, slamming, or the undesirable effects of ship motions on personnel and equipment.

A 1983 survey of U.S. Navy ship operators [6] indicated that the seakeeping characteristics of today's monohulls result in a number of operational limitations that hamper the fulfillment of Navy missions. The survey concluded that Navy monohulls ranging in displacement from 2,700 to 11,300 lton could achieve full speed only through low sea state 5. The survey found that 400-ft monohull frigates could operate at full speed only 30 percent of the time during the winter in the North Atlantic. Similarly, 550-ft monohull destroyers or cruisers were found to be capable of full speed about 55 percent of the time in the same region. The percentages for full speed operations in the North Atlantic on a yearly basis were 45 percent for frigates and 70 percent for destroyers and cruisers. Operators stated that in nearly every case they slowed down to lessen the excessive slamming in an effort to minimize damage to the forecastle and to bow sonar domes. The survey found that *most* Navy operations (including helicopter, hull-mounted sonar, and replenishment-at-sea operations) could not be performed on conventional monohulls in sea conditions greater than low sea state 5. Helicopter operations on an FFG-7 class ship with a recovery assist secure and traverse (RAST) system, but without roll fin stabilizers, were limited to low sea state 5 because of the hazardous operating conditions on deck [7]. Sea state data [8] show that conditions of sea state 5 or greater occur 40 percent of the year in the North Atlantic (north of the equator). Therefore, conventional monohull operations are often restricted as a result of ship motion in regions of critical importance to the U.S. Navy.

The SWATH concept is well-adapted to air operations as a result of its excellent seakeeping characteristics. This was well-demonstrated on the SSP *Kaimalino* in 1976 with a LAMPS I helicopter and a USCG Sea King helicopter. More than 80 launches and landings were made on the nominal 200-lton SSP through sea state 4 conditions. One landing was made with the SSP dead in the water in a sea state 3. Participants in this test concluded that the motion in a seaway was comparable to that of an FF-1052 class ship in calm water, from a pilot's viewpoint. The lower deck motion also reduced the dynamic problems associated with rotor engagement and disengagement. Deck steadiness allowed helicopter operations in sea state 4 without a haul-down system. Finally, the effect of the helicopter landing on the SSP was generally imperceptible to the ship's crew.

Numerous design studies have been performed examining the SWATH concept as an air-capable combatant. These designs have ranged from 500 to 50,000 lton in displacement. A recent study for the USCG resulted in a 500-lton design as the smallest cutter capable of supporting helicopter operations. The larger ship designs were for short takeoff/vertical landing (STOVL) aircraft carriers and aircraft-capable cruisers. A study made for the Naval Studies Board compared SWATH and monohull concepts designed for the frigate mission. It was concluded that a SWATH ship to support the frigate mission with two JVX tilt-rotor STOVL aircraft would be smaller than the comparable monohull.

The hull form of a destroyer-size SWATH ship is amenable to locating conventional sonar transducers in the nose or on the keel of one of the lower hulls. Sonar performance in a seaway would be enhanced by the reduction in self-noise because the steadiness of the platform would result in fewer hull emersions. This steadiness is also likely to reduce damage to the sonar, thereby reducing maintenance needs, and permitting more time in operation. In addition, bubble-sweepdown problems will be reduced because motions at the bow are much lower than on a comparable monohull. The shape and deep submergence of SWATH hulls and their superior motion characteristics are expected to be most amenable to future conformal sonars.

Gun and missile system effectiveness would also be enhanced as a result of the steadiness of the SWATH ship. The effect of ship motion on a MK 32 5″/54 gun and MK 86 gun-fire-control system in 15-ft seas was studied analytically in 1981 [9]. The results showed that the probability of hitting a target was better than that for monohulls by 10-40 percent when averaged over all speeds, headings, and target bearings. The variation in probability is due to variations in modal wave period. The SWATH ship hit probability was also found to be more independent of heading than for the monohull by 10-40 percent. Improvements are also expected in missile system performance although a similar analysis has not been performed.

The geometry of the SWATH provides several other attributes for combatants. Trials aboard *Suave Lino* indicated that noise attenuation from the cross-structure to the water was very high. Part of this attenuation is due to the hull form and part to the structural configuration. The structural configuration is somewhat atypical of SWATH combatant structures, and the contributions of these two attenuation mechanisms has not been quantified. However, SWATH combatants with main propulsion machinery located in the cross-structure are expected to be quieter than present day monohulls. The reduced self-noise should have the secondary effect of improving the performance of hull-mounted sonars.

The lower hulls also are compatible with larger diameter propellers than those currently in use on monohull combatants. Larger diameter, slower turning propellers allow propeller loading to be reduced and raise the cavitation inception speed.

The twin-hull concept is advantageous from a vulnerability/survivability point of view, particularly in light of the threat from sea-skimmer missiles. Damage resulting from a sea-skimmer missile should be largely confined to one side of the ship, possibly preventing its loss. Also, twin-screw SWATH ships will likely retain propulsion capability on one side when the other half of the propulsion system is inoperable.

SWATH ships are highly adaptable to a number of combatant-related functions including aircraft and stores handling and multiple array towing as a result of their wide beam (transom). Aircraft maintenance facilities can often be located on the same level as the hangar deck due to their large beam. This arrangement eliminates the difficulties and inefficiencies inherent in the multideck shop facilities found on many monohull air-capable ships. The location of the cross-structure high above the water also permits downward venting of the exhaust from vertically launched missiles, thereby reducing the hazard of toxic gases to personnel. Finally, the higher freeboard and low motions provide a much drier deck for aircraft to be parked upon and operated from which should minimize washing, corrosion, and maintenance/repair.

LIMITATIONS IN A COMBATANT ROLE

Limitations of the SWATH concept in a combatant role result from its unique geometry. The topside arrangement of existing weapons and sensors is more difficult because the SWATH is much shorter than a monohull of comparable displacement. Radar, fire control, and communication equipment located topside on ships is arranged to reduce electromagnetic interference. This is done on monohulls by distributing the equipment along the entire length of the ship. Such a lengthwise distribution is not as effective on the shorter SWATH ships. Alternative arrangements must be devised to take full advantage of the larger beam.

A final geometry-related limitation is cross-structure depth. Frigate-size or smaller SWATH ships typically have only one deck in the cross-structure. This single deck is designed to be the minimum depth practical (usually about 10 ft) to reduce ship size. This often causes difficulty in arranging the ship to incorporate subsystems such as prime movers or generators, gun or missile systems with belowdeck magazines, and vertical-launch missile systems where the subsystem depth is greater than the deck height. Such subsystems must be accommodated by allowing them to extend above the weather deck into the superstructure or recessed below the box into the struts. The latter approach may result in asymmetric arcs of fire.

ATTRIBUTES IN A NONCOMBATANT ROLE

The SWATH is well suited for numerous naval and commercial noncombatant missions. For instance, the steadiness in a seaway combined with its station-keeping ability makes it very amenable to over-the-side work. This was demonstrated when the nominal 200-lton SSP successfully recovered floating equipment in a seaway after a 1000-lton monohull failed in several attempts [1]. Recently, the USCG demonstrated the ease of over-the-side work on a SWATH ship working side-by-side with a 1025-Lton USCG buoy tender [10]. The trials involved launching, retrieving, and handling a 2-ton buoy in up to 8-ft seas. Results of the trial indicated that buoy launching and recovery on the SSP could be performed more quickly and easily than on the monohull. The SSP's station-keeping combined with its low-speed maneuverability allowed the SSP to approach and recover the buoy from most headings while the monohull was restricted to head seas.

The USCG also performed small-boat launch and recovery trials on the SSP in 8 to 10-ft seas. The results of this trial indicated that such procedures could be performed without difficulty. These trials also demonstrated that over-the-side launch and recovery was preferred to over-the-stern from the viewpoint of personnel safety.

Other trials have demonstrated that small SWATH ships can perform many operations (e.g., search and rescue, boat and equipment recovery, remotely-controlled-vehicle operation, hydrographic survey, diver support, and oceanographic research [11]) in heavy weather more effectively than larger monohulls.

The *Seagull* has consistently demonstrated other attributes in a commercial role. The superior ride quality and ability to maintain speed in a seaway have been exploited to produce a commercially successful 400-passenger ferry. The *Seagull's* ability to maintain speed in a seaway allows it to run on schedule largely independent of weather. Its steadiness provides passenger comfort not available on monohulls which make the same run. In addition, the large deck area makes it possible to accommodate all of the passengers on a single deck level including their food service and baggage.

LIMITATIONS IN A NONCOMBATANT ROLE

The SWATH also has some limitations in performing noncombatant missions. It is not well-adapted to carrying and handling large, high-density, variable loads because of its sensitivity to weight and moment changes. It also may be somewhat more costly to operate as a result of its higher fuel consumption resulting from its higher calm water drag. This limitation may be offset by its lower added resistance in waves if sustained operations in high sea states are required.

The high freeboard makes passenger and cargo transfer, some aspects of over-the-side work, and coming alongside smaller, less steady vessels more difficult. For example, the USCG buoy-tending trials showed that the time required to hookup to the buoy was longer than that for the monohull because of the SSP's high freeboard. This difficulty was remedied by reducing freeboard by ballasting down. Difficulties with passenger egress from the SSP and the Suave *Lino* have also been encountered as a result of freeboard height incompatibility with existing facilities. These difficulties have been remedied by the use of longer gangways. Finally, the high freeboard also makes over-the-side launching of boats somewhat more difficult because of the greater distance to the water.

SUMMARY

SWATH ships are twin-hulled displacement ships that share many design and operational features with the familiar monohull. The trade-offs confronting an owner in selecting a SWATH rather than a monohull for a particular mission have been largely supported only by analytic studies, model tests, and intuition. At-sea operational experience will clarify the trade-offs in this competitive process. A worldwide experiment with SWATH has started. It began with small ships in Holland, the United States and Japan. Construction of small SWATH utility craft is continuing in the United States and the *Kaiyo* in Japan promises that this process will continue into larger sizes. The SWATH ship has survived its birth and is enjoying a robust infancy. The future still conceals the full potential of its maturity., but in the next section you will find a wide variety of emerging opportunities for SWATH *Current and Potential Applications.*

CURRENT AND POTENTIAL APPLICATIONS

As you will realize from reading this chapter, much has been learned about the state of SWATH ship design and technology. It is not a new or traditional concept. But it does represent change. Many tests have been conducted, feasibility studies completed, and technical papers written on the SWATH hull form. There is nearly universal agreement that SWATH ships are practical, and that they are not high-tech or high-risk ships. Although a few small SWATH ships have been in operation for several years, there is no experience base with a ship of a size which truly interests the U.S. Navy. This situation will change soon when the 3500-ton deep ocean support ship *Kaiyo* is delivered in May 1985, to the Japanese Marine Science and Technology Center [12]. Nevertheless, until a similar size ship is built for and operated by the U.S. Navy, SWATH development will be considered immature.

The principal determinant in judging mission suitability is often cost; and cost is probably the most difficult SWATH ship parameter with which to deal. For example, in the Navy, if it is important to have mission effectiveness in high sea states, then some cost factor must be added. Commercially, if passenger comfort is important, an added cost factor is necessary as well. Speed, displacement, range and endurance, etc., are also factors which have significance and they too must be included in the ultimate cost picture.

For a given mission and a given configuration, with seakeeping and ship motions as essential criteria, the cost of a SWATH ship may 'be quite competitive and may be the more cost effective alternative. But there is more to it than that! Seakeeping aside, the benefits of SWATH are considerable, and insofar as they are key to selecting missions, let's explore what it means operationally and what can be done with this type of ship.

The approach will be to bring forward from the previous section on *Special Attributes and Limitations* those features which appeal to an operator's sense of what is important when sailing in harm's way-both man-made and natural threats.

First, an operator, should be interested in the idea that SWATH ships contain "20-60 percent more volume" than a comparable monohull, even though some of that volume is in narrow struts and below in the hulls. In the smaller size ships those areas are not prime real estate as is that nice big box. But when bigger ships are eventually built, of 7-8000 or more tons displacement, there should be value in being able to spread out into the struts and hulls to disperse vital warfighting functions, or to add extra living, stowage. and recreational space for longer deployments. In these larger ships there should be ample space for wartime personnel berthing with gear and equipment stowage for embarked marines or soldiers. We have to make sure that the density of anything we add to these spaces is compatible with the ship's margin for weight growth, but we can discipline ourselves to manage these concerns properly. A potential mission for SWATH is the eventual replacement of the LPH class, where the emphasis is on handling, operating, maintaining and transporting aircraft (helos or VSTOL or STOVL) for the lift of combat equipped marines. This could be accomplished with a ship of between 20,000-25,000 tons. It just might be a winner, especially if a length, beam and draft combination can be found which will allow transiting the Panama Canal. A design study for this application is being pursued.

An operator might also be concerned with features such as "60-70 percent more draft," "25 percent more freeboard," apd "60 percent more wetted surface area." These features are of minor concern as naval architectual limitations, but they are very important attributes for a new cost effective ASW combatant with features uncommonly well suited to provide both the air capability and the sonar performance so vitally needed in the most hostile environments of the world where our ASW frigates and destroyers are currently operating with substantial limitations [6]. For example, the extra draft is good for keeping the propellers deep, and since SWATH ship motions are relatively benign. the propellers will not be racing near the surface nor will the bows be enveloped in so much green water, and bubbles. And the extra hull area, deeper below the waterline, should give the new "billboard" planar arrays plenty of "real estate" on both sides of the ship. And the extra freeboard means dryer decks which helps in many ways--helps keep deck machinery and aircraft from deteriorating, helps launch and recovery operations, and helps deck evolutions such as VERTREP or CONREP, and in foul winter weather up North minimizes ice buildup which can be a very limiting factor for some ships with vertical-center-of-gravity (VCG) problems, especially when their decks and "top hampers" are constantly being wetted with green water and freezing spray. Sending a working party out onto the weather decks to clear ice can be a most hazardous evolution. In peacetime, it is possible to slow down and change course or even abort the sortie, but in wartime, even the "small boys" will have to sail on, just as was done on the Murmansk run in WWII.

How about that "redundancy problem" which shows up as a "limitation" to those who compare a twin-screw SWATH to a single-screw monohull frigate? If cost *were the only factor,* one should buy the single-screw ship, but would that be the right choice for a small combatant which *needs* mission effectiveness and extra warfighting redundancy and survivability, especially in those hostile northern latitudes?

Such relationships must be carefully thought out and rationalized. If they are not, and the customer jumps simply to the bottom line-total price-without carefully analyzing what he is buying, SWATH may remain just a potentially "nice idea" on the shelf, another contribution to that growing list we call "available but underutilized technology."

As we continue to explore what can be done with this type of ship, one should keep in mind that monohulls (i.e., conventional ships) significantly larger and more expensive would be necessary to provide this same seakeeping capability. As can be imagined, there are many potential uses for any type of craft or ship which breaks that bond between sheer physical size and ability—seakeeping ability in this case. And, as a result, SWATH ship cost has recently been shown to be less than that of a conventional ship which has to be enlarged simply to achieve equivalence in seakeeping. Who can afford to send a frigate combat suite to sea in a cruiser-size hull?

Having watched the SSF' *Kaimalino* gain a solid reputation as a performer in tests, demonstrations, and range-support operations [I] in sea states as high as 6, the USCG is now moving forward with plans to construct their own SWATH ship, and we should take a moment to review their more recent activities whereby they have carried out several significant SWATH development efforts. Capitalizing upon the numerous technical and operational trials on both the Navy's SSP *Kaimalino* [1], [IO], and the privately owned, 50-ton SWATH craft, *Suave Lino* [2], the USCG sponsored a number of design studies at both the feasibility and concept levels. In 1983, a concept-level study was completed [13] for a new class of ship, the patrol cutter (WPC), which was intended to be the smallest SWATH ship capable of carrying and operating the new USCG helicopter. The result was a nominal 500-ton all-aluminum ship with a maximum speed of about 20 knots and an endurance of 10 days at a minimum cruise speed of 12 knots. The Coast Guard is carrying out its own preliminary and contract-level designs for this ship at a displacement of about 600 tons. As mentioned earlier, they anticipate awarding a contract in 1985 for detail design and construction.

So how can one be certain of SWATH's proper place in the U.S. Navy's future? How do we get there from here? This is a complex problem with no one right answer. In fact, a right idea today could be a wrong idea tomorrow. The complexity is due to many factors, some of which are time dependent.

Briefly, let's review the factors that are affecting these questions, from the top down. *First* there is the administration. If we are looking to put a lot of hulls in service as quickly as possible, with low to no risk, and with a minimal amount of controversy, then the thrust is for more of what we already have-more of the proven concepts now in production, conversion and modernization. The *second* factor is Navy requirements. If there is no naval requirement there can be no ship! True, a requirement can be "invented" to meet the capabilities of a con-

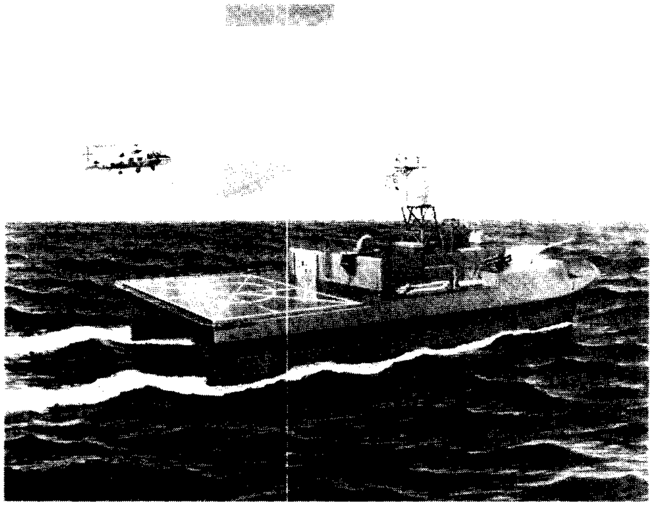

Figure 21. Notional FFX-Type SWATH Ship, Artist's Rendering.

ceptual ship, but this is the familiar technology "push" and is not currently a viable way of bringing a new system on line. A requirement "pull" must therefore be found from among the missions already developed or from those naval needs which have gone unfilled because they were perceived to be too hard or costly to satisfy.

The DOD acquisition system presents a third force with which to be reckoned, because the approval of an operational requirement can take years. Throughout the acquisition and PPBS (planning, programming, and budgeting system) processes there are reviews, boards, councils and further reviews, all exerting forces which can easily sidetrack the best of plans. Woven through this process are a *fourth* set of forces called "mind sets" carried by many decision makers who have preconceived opinions on any issue. When it comes to nonstandard hull forms, these mind sets have been particularly difficult to address because they are based largely on a lack of full understanding of how badly we need to introduce new hull, mechanical and electrical (H, M & E) system technologies into our ships as well as a lack of confidence in "the system" to deliver what is needed. We have too small a worldwide inventory of successful achievements at this time to provide confidence in, and acceptance of, these new technologies.

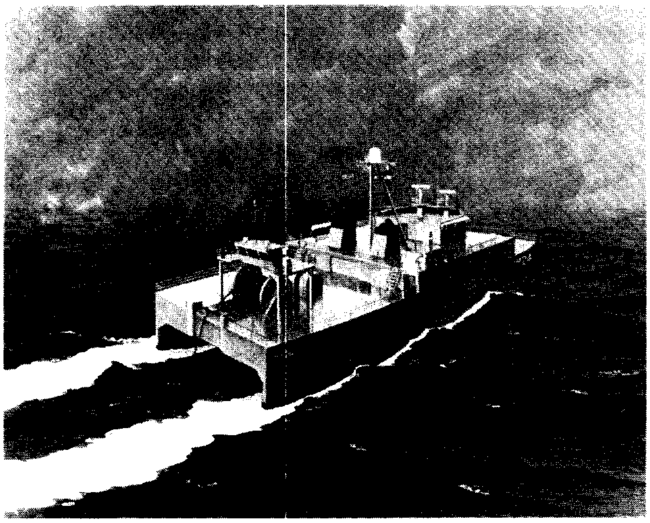

Figure 22. Notional SWATH Ship of the T-AGOS Type (AXX), Artist's Rendering.

Consequently, we must keep the first few steps realistic and affordable. The size of the first SWATH ought to be small but yet capable of carrying a military payload which not only satisfies an established requirement but fulfills a key naval need more cost effectively than any other hull form. The margins ought to be realistic and not enlarged in anticipation of unsubstantiated "problems." Sound engineering practices alone, not cumulative "ignorance factors," should be used to establish the margin policy to avoid misleading the decision maker who lacks in-depth knowledge of new technologies.

The U.S. Navy, always looking for the "right" platform to meet the requirements for specific missions, is now comparing the SWATH to other hull forms for applications which appear to be practical. Today SWATH is under active consideration as: an FF-1052 class replacement ship (FFX), Figure 21; an ocean surveillance ship (AGOS) Figure 22; an ocean survey ship (AGSX); an oceanographic research ship (AGOR); and a target drone for missiles. The Naval Studies Board, an arm of the National Research Council, recently reviewed SWATH ship technology and design experience for the Chief of Naval Operations and concluded that a SWATH of the AGOS/AGSX/AGOR size is practical and should be an immediate next step towards larger and more capable ships needed for combatant roles. The board, in their letter of 15 May 1984, encouraged the Navy to proceed in that direction and recommended that "a 2000-4000 SWATH of the AXX class should be built now." The studies done for the board reached the following conclusions with respect to a near-term, FFG-type combatant:

- On a calm water basis for the frigate ASW mission, SWATH costs 13 percent more than the monohull.
- However. on a seakeeping basis for the frigate ASW mission, SWATH costs 9 percent less than the monohull.
- Incremental improvements in seakeeping are more cost effective using a SWATH hull form.

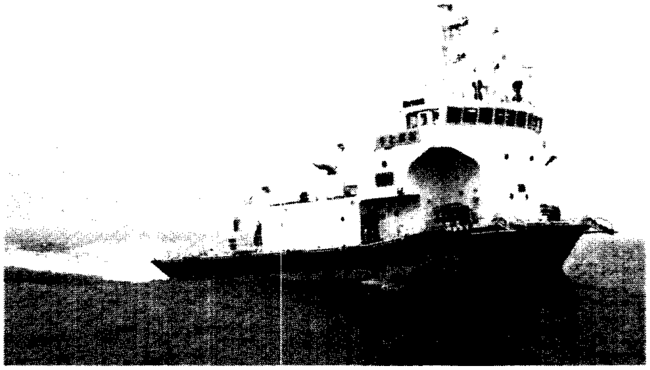

Figure 23. *Ohtori*, SWATH-Type Hydrographic Survey Vessel by Mitsubishi.

SWATH, in addition to being volume-oriented (i.e., has a bulky, light-density, load-carrying capability) with good seakeeping, instead of being volume limited, is attractive for several other reasons. Good coursekeeping or tracking and good maneuverability are inherent in this hull form. The twin propulsion plants, one in each of the widely separated hulls, enable the ship to rotate in its own length. The directional stability provided by the thin struts allows steaming in any direction at will without consideration of wave direction. In addition, the ability to tow and to hoist heavy objects on either side or between the hulls is a real advantage in heavy seas making this unique ship ideal for underwater research, underseas rescue and diving support, and oceanographic or hydrographic survey, Figure 23.

Of course, these operational attributes of good seakeeping, good coursekeeping, low ship motions, deeper draft and wide, dry decks, must be weighed against the lower tons-per-inch immersion and the somewhat more involved propulsion system. This would mean, for example, that a SWATH oiler would make little practical sense, since it is basically a bulk weight carrier-exactly what SWATH is not. A container ship or passenger ship, on the other hand, accommodates a large volume with less dense loads-perfect for SWATH.

Table 1 summarizes the naval roles which are typically assigned to various ship classes and shows where SWATH is recognized as being capable of carrying out these roles. Table 2 summarizes the pros and cons of generic SWATH and monohull ships. Table 3 provides, for comparison purposes, the key features of a generic monohull and SWATH in the 3000-9000-ton size range.

NATO recently completed a long term scientific study (LTSS) on advanced naval vehicles (ANV) and their combat systems (see Chapter I). At this writing, the results have not been officially promulgated, but there was agreement that the various advanced hull forms are not in competition with each other-each has its own place. For example, if the high calm-water speed ceases to be a requirement, if heavy weather is expected in the concept of operations, and if crew and equipment performance must be satisfactory *all* the time, then ***only*** the SWATH can fully satisfy the need. There also was no disagreement on the conclusion that seakeeping is important and that previous studies have not adequately addressed the true sea conditions prevalent in the North Atlantic.

The LTSS deliberated at great length about the need for combatant ships to operate in significant wave heights of at least 15 to 16 feet. Conventional ships, it was determined, would need to be over 8000 tons to operate at 25-30 knots in such seas with acceptable war fighting efficiency. Conventional frigates of 3000-6000 tons would inevitably suffer losses of speed and effectiveness under such conditions. So the SWATH is even more attractive as a multithousand ton alternative to the mono-

Table 1. Military SWATH Ship Utility.

SWATH SHIP CHARACTERISTICS	FRIGATE	AGOS	CARRIER	PATROL CRAFT	CRUISER	AGI	HCH	AHCH
Seakindliness and Drydecks	x	x	x	x	x	x	x	x
Maintenance of Speed in Seaway	x	x		x		x	x	x
Area and Volume for Operating A/C	x		x		x			x
Deep Underwater Hulls for Sonar	x			x	x			
Low Deck Motion for Handling Gear		x		x			x	x
Small Ship With Stability	x	x		x		x	x	x
Good Course Tracking		x					x	
Minimum Damage Vulnerability	x	x	x	x	x	x	x	x
Suitability for Signature Reduction	x	x		x		x	x	

The "x" indicates that the SWATH ship characteristic makes a significant contribution to carrying out the military role of the specific ship type.

Table 2. PROS AND CONS FOR SWATH AND MONOHULL

PRO
- SUPERIOR SEAKEEPING (< SEA STATE 8)
- DISPLACEMENT AND COST FOR ROUGH WATER MISSION LESS THAN MONOHULL
- MINIMUM SPEED LOSS IN HEAVY SEAS
- POTENTIAL FOR REDUCED ACOUSTIC SIGNATURE
- POTENTIAL AS ASW SHIP AND SENSOR PLATFORM IN HIGH SEAS IS UNIQUE
- DOLLARS PER TON SIMILAR TO MONOHULLS
- NO SIZE LIMITS FOR TECHNOLOGY

CON
- SLIGHTLY LOWER CALM WATER SPEED
- DISPLACEMENT AND COST GREATER THAN LEAST COST MONOHULL FOR CALM WATER REQUIREMENTS
- HIGHER FUEL CONSUMPTION
- PERCEIVED RISK GREATER THAN CONVENTIONAL HULL FORM-ACTUAL RISK IS VERY LOW
- DESIGN SENSITIVE TO UNANTICIPATED WEIGHT GROWTH
- DRAFT AND BEAM MAY CREATE LIMITS FOR LARGER SIZES ABOVE 10.000 TONS

hull because of the significant performance advantage it offers for comparatively little development and technical risk. An 8000-ton SWATH can probably carry six helicopters and an area defense missile system while maintaining fighting efficiency at about 30 knots in 15-foot seas. Smaller SWATH ships provide an interesting comparison with a conventional ASW frigate because the inherent beam allows four helicopters instead of two to be carried with little penalty. An analysis of emerging requirements suggests that the typical frigate of today will be forced to grow to maintain capability against the increasing threat and to provide the improved seakeeping required for the higher sea states. During this multinational exercise it was concluded that one could build a 3000-6000 ton ASW ocean escort ship ***now*** and a 6000-12,000 ton escort carrier in the not too distant future. Although the small aircraft carrier was judged extremely attractive, it is in the 12,000-24,000 ton size, and is considered too large to be built until more experience had been gained with SWATH architecture.

SUMMARY

The AXX initiative which the Naval Studies Board recommended for ship types such as AGOS, AGOR and AGSX SWATH ships are logical next steps which can be taken now by the U.S. Navy. When you build anything for the first time, much is learned that needs to be built into the next ship. The AGOS, AGOR, and AGSX initiatives would allow that learning process to be done on smaller, less expensive ships and thus provide that essential low-risk transition on our way to the larger more complex combatant ships which lie ahead.

SWATH is only now becoming a reality in world maritime service. As more experience and confidence are gained, the substantial capabilities of this form will sell

Table 3. Key Hull Features for SWATH and Monobull.

KEY FEATURES (3000-9000 TON SIZE)	MONOHULL	SWATH
* SPEED (KTS) CALM WATER	30+	30-
* SPEED (KTS) ROUGH WATER	MUST SLOW SIGNIFICANTLY	CAN MAINTAIN
• LIMITING SEA STATE (S/S)	S/S 5/6	S/S 7
• DECK SPACE:		
-DECK MACHINERY/EQUIPMENT ARRANGEMENT	POOR	GOOD
-MOTIONS	POOR	BEST
-WIND OVER DECK (IF AVIATION CAPABILITY DESIRED)	ADEQUATE (HEADING DEPENDENT)	BEST (LITTLE TO NO LIMIT)
. UNDERWATER SENSOR CAPABILITY	KNOWN TO BE LIMITED	BEST BUT MAY REQUIRE DEVELOPMENT OF SENSOR INTERFACE
• WEIGHT SENSITIVITY	BEST	POOR

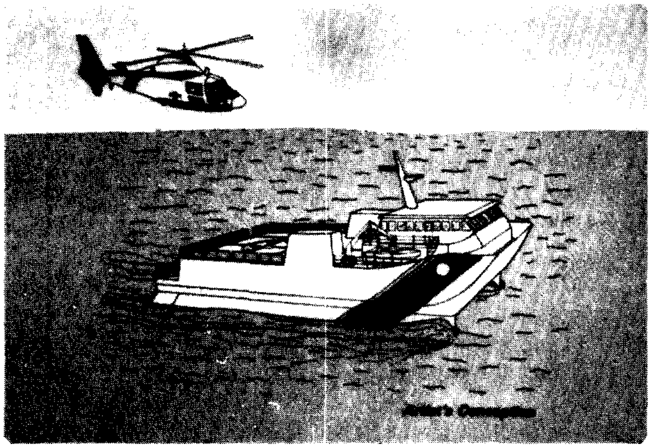

Figure 24. USCG SWATH WPC, Artist's Rendering.

themselves, and SWATH will become a common hull form for many commercial applications.

The next SWATH we will probably see in the U.S. will be the U.S. Coast Guard WPC, Figure 24—leading the way again! It will carry their new helicopter and will operate in some of the worst seas they patrol. It is only fitting that they should build another SWATH; after all, they built the first U.S. SWATH in 1973 at the Coast Guard Yard in Curtis Bay, Maryland. That's right, it was that Navy work boat called the SSP *Kaimalino*, and it must have left quite an impression!

STATE OF TECHNOLOGY

OVERVIEW

As you have discovered by now, a SWATH ship differs from the other types of modern ships and craft (except the advanced monohull) in that the ship weight is totally supported by buoyancy, rather than by hydrodynamic lift or aerostatic lift. From this perspective, it is *simply a conventional surface ship of unconventional geometry.* Indeed, experience to date has confirmed that the level of technology used for monohull design and performance estimation is also adequate for SWATH ships. However, there are some important differences between the technology suitable for SWATH ships and that for monohull surface ships. In most cases these differences are a direct result of the difference in overall geometry.

As embodied in the earlier terminology TRISEC, which preceded the acronym SWATH, there are three principal components of a SWATH ship: the lower hulls, the struts, and the upper box (or cross-structure). The geometry of each is, to a considerable degree, independent of the geometry of the others. Moreover, there is a wide range of possible configurations for each of the three components. This great range of possible configurations is intriguing to the technologist, but it presents a problem to the designer who needs to be able to quantify the effect of the choice of a particular geometry on some aspect of performance or ship size.

The effects of SWATH geometry on ship motions and motion control, structural loads and structural design, resistance and powering, a.s well as the other essential technologies, have been under investigation by the U.S. Navy since the late 1960s. The SSP *Kaimalino* [14] provided a wide variety of performance data [5], [15], and [16], and confirmed, through demonstrations and range-support operations carried out in sea conditions as high as sea state 6, that she could perform as advertised. In the commercial sector, SWATH development activity has been led by the Mitsui Engineering & Shipbuilding Company, Ltd., who began in 1970 to carry out model testing and design feasibility studies to define possible applications [17]. It will be shown in the remainder of this section that a substantial technology base is now available to support the design and construction of SWATH ships for naval applications, especially in sizes up to about 4000 tons.

MOTION AND MOTION CONTROL

The reduced waterplane area partially decouples the ship from wave action on the sea surface by greatly reducing the wave-induced forces and moments acting on the ship. Since the hydrostatic restoring forces and moments provided by the struts are also relatively small, SWATH ships respond to the sea with long natural periods in heave, pitch and roll. This combination of small wave *exciting forces* and *long* natural *periods* produces very *small* ship *motions* in stormy seas at most headings and speeds. This is the essence of the SWATH principle of operation.

Developing a full understanding of the factors which affect SWATH ship behavior has been a major focus of the Navy's development efforts. The most important early finding, in terms of the overall impact on design, was to confirm that *both* the total amount of waterplane area and the longitudinal metacentric height (GM,) have a significant effect on SWATH seakeeping. These two parameters, in turn, affect the overall ship design by determining its hull spacing and influencing the selection of waterline length. Another hydrostatic characteristic, the separation distance between the longitudinal center of buoyancy (LCB) and the longitudinal center of flotation (LCF), affects both seakeeping and resistance, so that the value selected will reflect a compromise between these two considerations.

A second important finding was that the SWATH concept is not viable for moderately high speed applications without stabilizing fins. The reason is the destabilizing "Munk" moment, which is caused by the longitudinally unsymmetrical pressure distribution on the two lower hulls. The magnitude of the Munk moment is proportional to the added mass in heave times the square of the forward velocity. For an unappended SWATH ship, the only force that counteracts the Munk moment is the hydrostatic pitch-restoring moment, which is equal to the ship displacement times the product of the GM, times the sine of the pitch angle. Because the GM, can be quite small, while the added mass in heave is roughly equal to the ship displacment, an unappended SWATH ship will

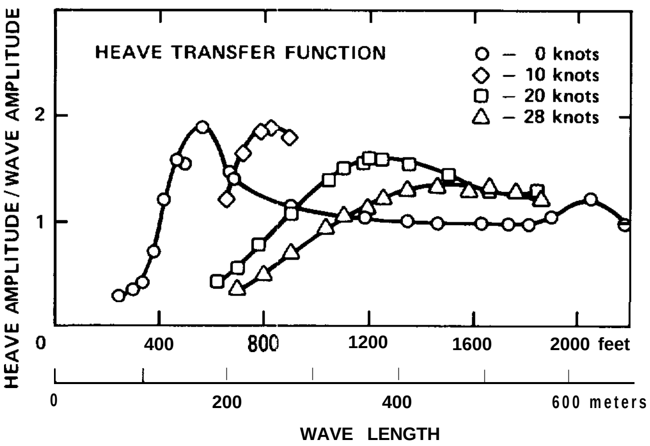

Figure 25. Nondimensional Heave Motion Responses for the SWATH 6A Model in Regular Head Seas.

become unstable in pitch above a certain speed. An approximate equation for determining the speed for onset of pitch instability was derived by Lee and Martin [18]. If the ship has fins located aft of the ship center of gravity, they will contribute a pitch-restoring moment which, like the Munk moment, increases in proportion to the square of the ship speed. As a result, the speed of onset of pitch instability can be raised beyond the practical range of operating speeds.

Another purpose served by the fins is to provide damping. Ship motions in waves are similar to simple spring-mass vibrations in that relatively large motion responses will occur at resonant excitation frequencies unless there is adequate motion damping. Resonant conditions for heave or pitch occur when the wave encounter period is approximately equal to the heave or pitch period. Since the thin vertical struts provide little wavemaking damping, and. since the amount of viscous (frictional) damping is also small, it is necessary to rely on the fins for adequate damping of heave and pitch motions. It has been found for some SWATH forms that, for a fixed total fin area, two sets of fins, one forward and the other aft, produce the greatest reduction in pitch motion. With such an arrangement the pitch moment from the forward fins is destabilizing, which means that the size of the aft fins must be increased sufficiently to provide an offsetting moment.

A third major finding was that SWATH ship seakeeping characteristics are highly speed dependent. This is partly due to the effects of the stabilizing fins, which increase at higher speeds. However, it is also caused by the effect of ship speed on the wave encounter periods in head and following seas. The experimentally measured effect of speed on heave motion responses of the DTNSRDC Model 6A in regular head waves is shown in Figure 25 [19]. When the 6A model is in waves 500 feet long full-scale, it experiences resonant heave motions at zero speed. At 20 knots, on the other hand, Figure 25 shows very little heave at the same wave length. This behavior is important because a wave length of 480 feet corresponds to a wave period of 9.7 seconds, which is the most probable modal wave period (period of maximum wave energy) for sea state 5 in the North Atlantic, [8].

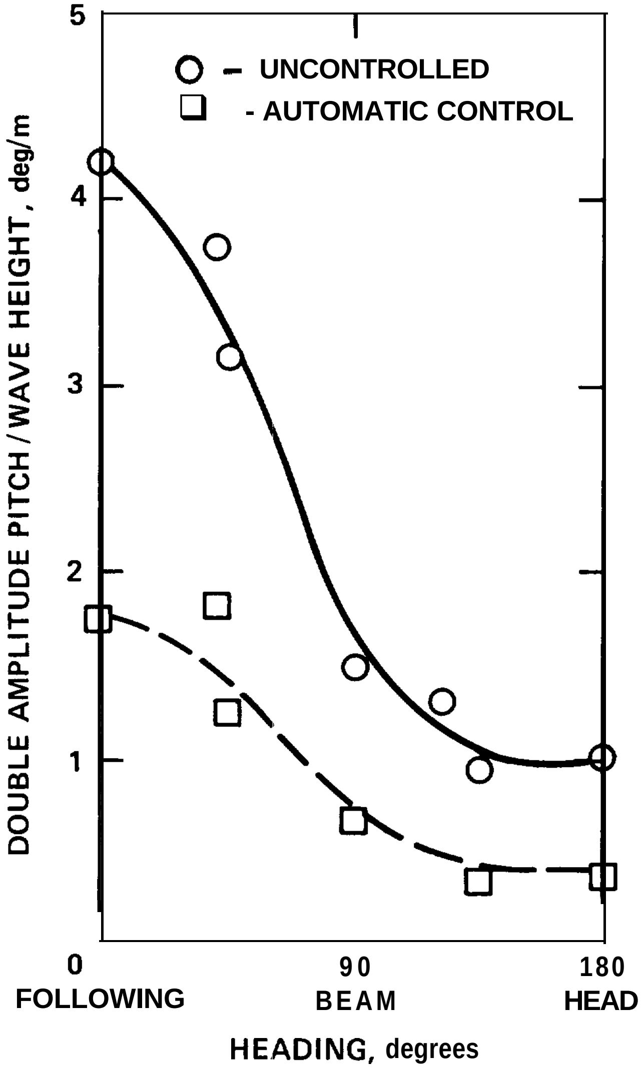

Figure 26. Measured Double-Amplitude Pitch Motions for *Kaimalino* Operating at 15.5 Knots in Sea State 5.

It is also possible to have sea state 5 conditions with some other modal wave period; the likely modal periods range from 7.2 seconds (265 feet) to 16.5 seconds (1395 feet) [8]. For a ship moving at 20 knots in head seas, the corresponding periods of encounter range from less than 4 seconds to about 12 seconds. Current thinking is that the zero-speed heave period of a SWATH ship larger than about 1000 tons, if designed for moderately high-speed operations, will be between 9 and 11 seconds. The pitch period will be at least 20 percent longer. Thus, the encounter periods for such a ship moving at 20 knots in the wave lengths of maximum energy in state 5 head seas usually will be considerably *shorter* than the ship heave and pitch periods. When the wave encounter periods are short relative to the heave and pitch periods, the ship will be platforming the waves, and there will be very little heave or pitch motion. Such will be the situation most of the time in sea states 5 and 6.

In following seas, on the other hand, *very long* periods of encounter frequently occur when a ship moves at moderately high speeds. This situation can occur in either of two ways: (a) with the ship going fast enough to overtake short waves, or (b) with longer waves that propagate fast enough to overtake the ship. One consequence of the low **GM,** of a SWATH ship is that the pitch motions in following seas are typically larger than for a monohull. The reason is that the very long ‘wave encounter periods present a quasistatic situation in which the ship is perched on the crest of a comparatively short wave. This induces a pitching moment, which is resisted principally by the ship hydrostatic pitch-restoring moment. Since this moment is much smaller for a SWATH, a ship without active control will experience more pitching in this circumstance than a monohull of equal size.

But there is no reason for concern over this behavior, because it has been determined that activating the aft set of fins is a very effective means of reducing pitch motions significantly in following seas. Figure 26 compares measured full-scale pitch motions for the SSP *Kuimalino,* with and without active control, for various headings at a speed of 15.5 knots [20]. There is a dramatic reduction in pitch motions in following seas.

Even though Figure 26 shows that active control produced a sizeable reduction in the pitch motions of the *Kaimalino* in head seas, this degree of motion reduction is the exception rather than the rule. More representative behavior is illustrated by Figure 27 [3], which shows the effect of active control on full-scale pitch motions for the 350-ton SWATH ferry *Seagull* at various headings in sea state 5. While active control produced a large reduction in the pitch motion in following seas, it made little difference in head seas. (Of course, the pitch motion was small to begin with in head seas). One reason for the difference in control system effectiveness between these two SWATH craft is that *Kaimalino,* which was designed much earlier, simply has a great deal more control surface area, relative to the amount. of strut waterplane area, than the more recent *Seagull.* This point is illustrated by Figure 28, which compares the ratio of these two areas for existing SWATH craft and the 6A model. The ratio of these two areas is a good measure of the probable effectiveness of the control system in reducing heave and pitch motion.

Although there is a lot of scatter in the data points, there is a discernible trend for the ratio of control surface area to waterplane area, which decreases as ship size increases. The band shown in Figure 28 is the current estimate of the required control surface area for SWATH ships. To some degree, the required fin area will vary with the design sea state of the ship.

In designing fins, the SWATH ship evaluation program (SSEP) developed by DTNSRDC is used to determine the optimum location and distribution of fin area. The SSEP computer program can predict motion responses for a given set of fins in irregular waves using strip theory [21]. Strip theory assumes that the flow at one transverse two-dimensional section of the ship is independent of the flow at another section. This approach has been used successfully to predict the motions of monohull displacement ships. However, SWATH ships present a somewhat more complex analysis problem in several ways. One difference is that interaction effects resulting from the closeness of the two hulls must be quantified even though they are ignored in predicting the vertical plane motions of monohull ships. The viscous components often dominate the potential flow components. Recently, semiempirical expressions have been developed and incorporated into the SSEP to model these viscous components. As a result, the correlation between predicted and experimental motion responses has been improved for the hull forms in the SWATH 6 series [22].

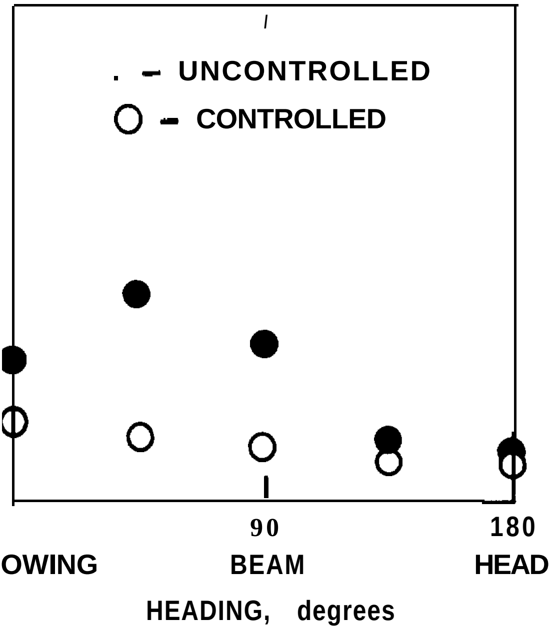

Figure 27. Measured Single-Amplitude Pitch Motions for Seagull at 24 Knots in Sea State 5.

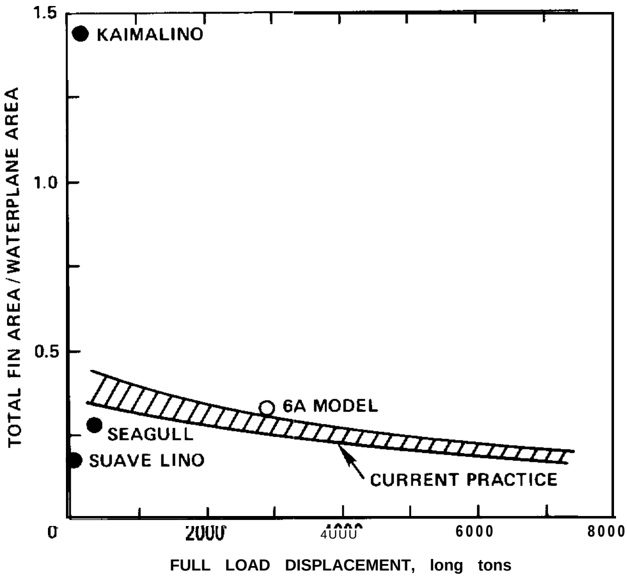

Figure 28. Comparison of the Available Control Surface Area for Existing SWATH Ships, the 6A Model, and Current Design Practice.

Incorporated in SSEP is an algorithm which selects the set of fixed stabilizing fins which provides vertical plane stability at the desired speed and which best reduces motion responses. Utilizing the predicted responses to various wave spectra, and a set of criteria for the motion response levels which limit ship operability, two types of seakeeping performance assessment are performed for each candidate fin area and location. The first is an operating index which gives the percent of the time the ship could operate without degradation of performance in the ocean region of interest. The second form of assessment available is the limiting significant wave height (average of the 1/3-highest waves) for which none of the limiting motions criteria is exceeded for any of the spectra which are considered within the specified confidence band of modal periods. The user can specify the relative importance of motion responses in head and following seas.

This fin selection algorithm has facilitated investigations of the effect of total fin area on seakeeping performance. In the past, the fin area on the 6A model was simply scaled up or down to determine the required fin area for a SWATH ship of a displacement other than 2900 tons. However, recent studies using the fin selection algorithm suggest that scaled 6A fins are unnecessarily large and are beyond the point of diminishing returns in providing increased operability. On the other hand, the fin area must be kept large enough to ensure that the forces generated are adequate to provide the required degree of motion reduction in extreme sea conditions. The required size can be minimized by selecting values for the waterplane area, GM, and LCB/LCF separation that will provide the ship with an inherent wave contouring capability at relatively low speeds in extreme head seas.

Once the size and location of the fins has been determined. the next step is to develop a control law for activating the fins. A computer program has been developed to determine optimal control laws for SWATH ships using linear quadratic control theory [23], [24]. The practical task for the control system designer using this approach is to select weighting factors which result in the operation of the control system within the imposed constraints (fin angle and fin rate), while achieving the maximum feasible reduction in pitch, heave, and roll. In order to facilitate such calculations, the SSEP has been modified to include the effects of active fins on the heave and pitch motions for any given set of control system gains. Current plans are to modify the SSEP further to include the effects of active fins on roll motion in stern quartering seas. These are the only headings where the amount of roll in sea state 6 can exceed the operability limits. Because the SSEP calculations are in the frequency domain, the consequences of using various weighting factors can be evaluated much more quickly than is possible with a time domain simulation.

STRUCTURAL LOADS AND DESIGN

Perhaps the first thing that needs to be pointed out is that all Navy SWATH ship designs to date have employed conventional plate-and-stiffener structure and standard Navy structural design practices. Moreover, the design allowable primary stresses assumed for the different materials are the same as those used for the Navy's monohull combatants. In 1972 the Navy's structural synthesis design program (SSDP) for monohull combatants [25] was adapted to provide rapid estimates of the weight of primary structure for typical SWATH configurations. This design tool incorporates all current Navy structural design criteria.

The SWATH version of SSDP and the results of some early weight sensitivity studies are described in Reference [26]. These studies showed that material selection can significantly affect structural weight. Moreover, an important and unexpected finding was that reducing the magnitude of the primary wave-induced load only moderately reduced structural weight. This implies that the scantlings for most of the structural members were driven by secondary loads or minimum thickness requirements. It has since been tentatively concluded that more *significant reductions in weight may be achievable* by developing more efficient structural arrangements and configurations.

Two issues are frequently raised concerning SWATH ship structure: (a) structural weight fraction and (b) ability to withstand wave-induced loads in extreme storm sea conditions. There is some basis for the first concern, since the configuration does require considerably more structural surface area to enclose a given amount of volume. Another contributing factor is that the geometry results in nonuniform distributions of primary stress. However, there is *no basis for the concern about catastrophic structural failure* in extreme seas. The reason is, basically, that the design and analysis tools are in hand for confidently predicting lifetime maximum loads and stresses. These tools can also be used to reduce structural weight, although they have not yet been sufficiently exercised for this purpose.

One of the principal thrusts of the Navy's development effort has been to determine the magnitude of the wave-induced loads and to develop a method for predicting the maximum lifetime loads on a SWATH ship of a particular configuration and displacement. A paper summarizing the results was presented as part of the 1983 ASNE Day program [27]. The most important wave load is the transverse bending moment, which is greatest with the ship at rest in beam seas. This conclusion has been drawn from seakeeping tests of 11 different models. Nine of these models had a single strut per hull and the other two had two struts per hull. Additional load data were obtained from sea trials of *Kaimalino*. These data validated the experimental model approach [28].

For convenience, the transverse bending moment of a SWATH is usually expressed as an equivalent transverse side force acting at middraft. The transverse bending moment is obtained by multiplying the side force by the lever arm from the middraft point to the structural section of interest. From load measurements taken during model seakeeping experiments, it has been found that, for a given wave height, the side load is maximum at wave lengths three to four times the underwater beam.

In the method described in [27], wave statistics were used with model side load response curves to predict the maximum lifetime side force for each single-strut configuration at displacements of 3000, 10000, and 30000 tons. The results were expressed in nondimensional form as side force per ton of displacement. It was determined that the maximum side load can vary by a factor of two depending on the particular ship configuration. It was also determined that there is a general trend for the maximum side load to decrease, as a fraction of displacement, as the displacement increases.

However, the most important finding concerning the seaway loads on a SWATH was that the expected maximum side load does not continue to increase without limit as the significant wave height increases. What happens, instead, is that the side load does increase fairly rapidly up to some significant wave height, but in seas above that wave height the side load levels off at the peak value or even decreases slightly. The underlying reasons are: (1) the wave length of maximum energy tends to increase as the significant wave height grows, while the peak side load unit response occurs in comparatively short waves; and (2) extreme wave conditions occur less frequently than moderate ones. Consequently, *there is no justification for concern about unexpectedly exceeding design loads for a SWATH ship in extreme storm seas.*

A simple method of estimating lifetime maximum side forces has been developed for concept design purposes. A two-dimensional analytical computer program for SWATH loads and motions [29] was employed to obtain the influence of parametric variations on the side load [27]. These data were used to devise a simple algorithm which is a function of the ship displacement, draft, lower hull length and diameter, and strut length. The hull spacing was found to have an insignificant effect on side load.

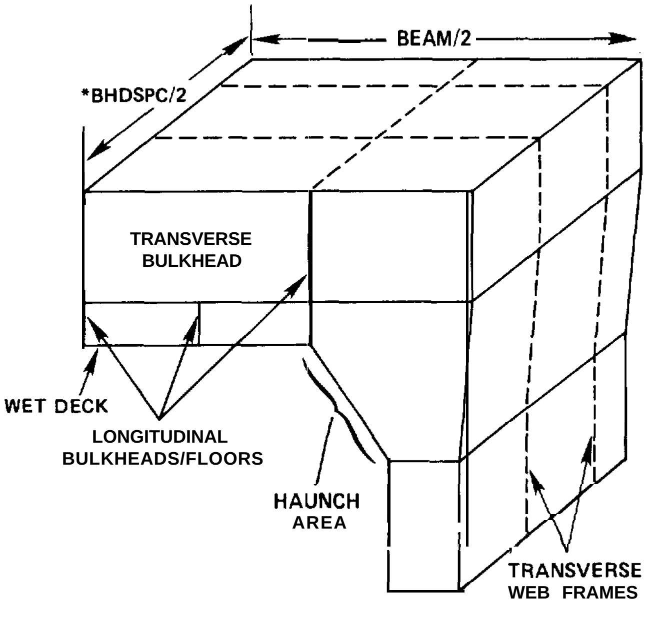

Figure 29. Representative Finite Element Model Half-Section.

Changes in draft were found to produce the greatest change in the side force, which is caused by wave action on the projected area of the ship profile below the waterline (approximately equal to draft times the effective length). One reason is that a one foot change in draft will produce a much greater percentage change in the projected area than a one foot change in effective length. An increase in draft also increases the lever arm for the transverse bending moment. A SWATH ship with a shallow draft is therefore preferable from side load considerations.

Generally, the minimum strut submergence will be governed by the need to avoid drawing an excessive amount of air into the propeller. Once the minimum submergence has been determined, an effective way to reduce the draft is to make the lower hulls elliptical in cross-section. It has been determined from mode1 experiments that the resistance with lower hulls of elliptical cross-section differs little from the resistance of an equivalent SWATH ship with circular lower hulls having the same cross-sectional area.

Finite element analysis has revealed that SWATH ship primary stresses produced by the wave induced side loading are not entirely calculable through strength of material idealizations. The shear stresses in the strut transverse bulkheads and the primary bending stresses at the cross-structure midspan can be calculated in this way. However, stresses in the haunch area at the intersection of the strut and cross structure (see Figure 29) may far exceed those calculated by ordinary methods. These stress concentrations can be alleviated by employing insert plates and introducing generous radii at the haunch intersections. High shear stresses also tend to develop in these areas at the intersections of longitudinal and transverse plating. The SSP *Kaimalino* used truss members which mitigated the transverse bulkhead stress concentrations. Innovations such as these require further exploration for the large SWATH ships.

In 1983 there was a significant increase in SWATH structural analysis capabilities within the Navy with the development of a data preprocessor for use with the NASTRAN finite element analysis program. Requiring only a modest amount of imput data, the preprocessor can discretize a section of a SWATH ship above the lower hulls that is half-beam in transverse extent and one half the transverse bulkhead spacing in longitudinal extent (Figure 29). Thus, finite element stress analyses can now be conducted much more rapidly than was previously achievable. This finite element capability, together with the SWATH structural synthesis program, can now be used to produce structural designs with confidence in the resulting structural weights, without fear that unexpectedly high stresses will occur in service. There is a need to exercise these tools further to study new structural concepts and to reduce SWATH structural weight.

A structural fatigue analysis capability has also been developed for SWATH ships [27]. This tool is based on linear cumulative damage theory. Inputs required are the stress spectrum and fatigue characterization data for the material under investigation. Properly employed, this capability can be used, together with the load and stress calculation technologies previously described, to produce designs with fatigue resistance levels equal to present monohull combatants. This is only strictly true, however, if a sufficient fatigue characterization data base exists for the material under consideration. Such a data base is now under development for HSLA-80, one of the commercial series of high-strength low-alloy steels.

Fatigue is not expected to be a problem for SWATH ships constructed of ordinary shipbuilding materials which have been in use for many years, if current design allowable stresses are used. Significant weight reductions may be possible without risking fatigue failure if current design allowables are relaxed somewhat, but further exploration is needed.

Economical weight savings may also be achieved through designs which incorporate hybrid structures with different materials applied to different parts of the ship. The HSLA series of steels, in particular, show promise for SWATH application. Since the structural weight fraction (ratio of structural weight to ship full-load displacement) increases as ship size decreases, at some point aluminum or fiber-reinforced plastics must be considered to satisfy range and payload demands on small SWATH ships.

In summary, the needed design and analysis tools exist to ensure SWATH ship structural integrity. These tools are now being employed to reduce structural weight and, consequently, ship size and cost. As Rains has pointed out, [30], structural weight reduction can significantly cut ship cost because it leads to weight reductions in other more expensive systems and the resulting increases in structural costs are small in comparison.

RESISTANCE AND POWERING

SWATH powering performance, like that of the traditional monohull ship, is derived from a combination of two distinct elements: resistance and propulsive efficiency. The traditional method for determining the powering performance of ships during preliminary and detailed design has been by means of model experiments; empirical systematic series data have been employed for early stage design studies. The 16 SWATH models which have been tested either at or for DTNSRDC constitute the Navy's SWATH ship resistance data base. With such a small data base, it is impossible to develop reliable empirical methods for predicting resistance, since *it takes approximately 12 major hull form parameters to describe the form of a SWATH ship.* Thus, it is fortunate that, due to the thin nature of SWATH struts and the slender nature of SWATH hulls, the classical thin-ship theory of wave-making resistance applies and, as a result, analytical procedures exist for predicting the wave resistance. These analytical tools are sufficiently accurate to apply to either parametric studies or early stage design.

Within the Navy there are two analytical tools which are commonly used for computing the wave resistance of SWATH ships. The first was developed by the late Bruce Chapman while he was working at NOSC [31]. The second was developed by DTNSRDC [32]. Both of these programs are based on the same theory. They differ chiefly in the manner they represent the geometry. The Chapman code computes the resistance of the ship as though it were in a canal whose width the user can vary, while the DTNSRDC code computes the wave resistance for a ship in an ocean of infinite horizontal extent. Comparison runs of both programs show good agreement at high Froude numbers; however, at low Froude numbers, the predictions of the two codes differ. Both codes predict a large number of rapid oscillations in wave resistance at low Froude numbers; such rapid oscillations are characteristic of the wave resistance predicted by thin-ship theory. The differences between the two codes at the lower Froude numbers are probably due to differences in the numerical integration schemes within the programs. At the present time, it is not possible to state which program is more correct in this speed regime, and the predictions from both programs for low Froude numbers are viewed with skepticism.

The viscous resistance of SWATH ships is accounted for by use of one of the traditional "friction coefficient lines" such as the ITTC 1957 model-ship correlation line. To this is generally added an empirical form drag to account for the three-dimensional aspects of the viscous flow about the ship which are not included in the essentially flat plate drag of the friction line. In coefficient form, the form drag is around 0.0005, based on comparisons with model data (normalized by the product of the dynamic pressure and the wetted surface area). The value of the form drag should not be confused with the final resistance component, the correlation allowance, which is added to full-scale predictions to account for the usually observed differences between model and full scale. The correlation allowance, again in coefficient form, is usually taken as 0.0005

Propulsive efficiency is dictated by the propeller efficiency and the hull-propeller interaction coefficients. Propeller technology is the same as that used on monohull ships. SWATH ships tend to perform best with propellers of about the same diameter as the hull. Operational considerations such as grounding and docking lead to reductions in the propeller diameter to about 90 percent of that of the hull. The resulting diameters are large compared to monohull standards. Cavitation inception considerations lead to propellers with reduced rotational speeds and higher torques, qualities which should lead to higher propeller efficiency and lower noise.

During the various stages of naval ship design a series of model experiments is normally performed. These experiments include propulsion tests with stock propellers and a wake survey, which provide the data needed to develop a set of design propellers. A propulsion test is then carried out with design propellers to ensure that they provide the desired propulsive efficiencies and the proper RPM at the design speed. In addition, a model of the design propeller is evaluated in a cavitation tunnel, in the simulated ship wake, to determine whether the cavitation inception speed is reasonable and whether the cavitation types and patterns are acceptable. Finally, after full-scale powering trials have been performed, correlation model experiments are run with the model at the same displacement and trim as that measured on the ship during the full-scale trials. These experiments are generally run on the first ship of a class, and serve to establish the correlation allowance for that class.

Prediction of the hull-propulsor interaction coefficients provides a much more perplexing problem than the prediction of resistance. The main reason is that the Navy has conducted propulsion experiments on only six SWATH models to date. All of these experiments have used stock propellers, so there is no knowledge of the propulsion characteristics of a SWATH ship with propellers that have been designed to meet realistic design constraints on diameter, RPM, and cavitation criteria. In addition, the Navy has performed only three wake surveys on SWATH models. and propulsion test data are available for only two of the three. Consequently, *at the present time it is not possible to make any definitive statement as to what propulsion performance should be attainable on SWATH ships.* Similarly, little can be said about what levels of cavitation performance are attainable since no cavitation experiment has been carried out with a design propeller. The lack of cavitation data is particularly important because of the wake deficit behind the struts; it is severe relative to that on most naval combatants.

When the U.S. Navy first began to develop the SWATH concept, it was conjectured that it would have a high propulsive efficiency because the lower hulls were bodies-of-revolution similar to modern submarines. However, the first experiments indicated that the propulsion characteristics were only slightly higher than those of a typical twin-screw combatant, and comparable with what might be achieved on a single-screw combatant, which can recover some of the wake from its skeg. *Only recently with the consideration of contrarotating propulsion, have dramatic improvements in propulsion characteristics been achieved.* Recent results for a model of an 11 ,OOO-ton SWATH ship with contra-rotating propellers have demonstrated that propulsion efficiencies in the high 80s to low 90s may be achievable. Determination of whether these efficiencies are truly achievable must await the planned evaluation of a set of design propellers on this model.

It is evident, after examining the powering performance of SWATH ships, that there are two significant performance regions: low Froude numbers and high Froude numbers. In the low Froude number region, the wave resistance is generally low and the hulls and struts are shorter so as to minimize the wetted surface and, thus, the frictional drag. Designs in the high Froude number region tend to have longer struts and hulls, so as to reduce wave resistance. These characteristics are exaggerated relative to a comparable monohull because a SWATH ship will tend to be considerably shorter, and thus operate at higher Froude numbers, than the equivalent monohull.

The wide variations in the residuary resistance coefficient with speed for a SWATH ship also have a significant effect on the hull-propulsor interaction coefficients. As the residuary resistance coefficient varies, the propeller thrust loading varies accordingly and the propulsive efficiency varies inversely. This means that for a low-speed design the propulsive efficiency is relatively constant. Conversely, for a high Froude number hull form, the propulsive efficiency will vary significantly and will usually have two local maxima and one local minimum. The differences in propulsion efficiency between these local maxima and minimum can be as much as 7 or 8 percent of the maximum propulsive efficiency. It is important for the designer to ensure that the cruise-speed Froude number, where the ship will spend most of its operating life, is in a low residuary resistance and, consequently, high propulsive efficiency region.

The absence of a correlation model experiment means that there is significant uncertainty as to the appropriate choice for the correlation allowance. The value currently used for the correlation allowance coefficient is 0.0005, and this can account for as much as 1.5 percent of the total predicted resistance. However, based on experience with monohull surface ships, the correlation allowance for a particular SWATH ship could vary by a factor of two in either direction from the currently assumed value. Thus, *there is a potentially large uncertainty in full-scale resistance predictions.* Realistic values for the correlation allowance can only be determined from several sets of reliable full-scale data for representative ship configurations and corresponding model experimental data for the same conditions as the full-scale trials.

PROPULSION MACHINERY

Prime mover options for a naval SWATH ship vary with the type of ship being designed. If it is a combatant there is only one candidate at present: the LM2500 gas turbine. For auxiliary ships the prime movers can be medium-speed diesels, high-speed diesels, small gas turbines, or some combination of these.

The geometry of a SWATH ship presents the propulsion system designer with a unique set of problems. One of the major decisions is whether to locate the propulsion engines in the lower hulls or upper hulls. There are advantages and disadvantages associated with either location, and these vary with t!he type of prime mover. Small craft are an exception, because their lower hulls are so small that the prime mover must be located in the upper box.

When the displacement reaches about 1000 tons, it becomes possible to put one high-speed diesel in each lower hull, but powering performance will be degraded because the hull diameter must be enlarged to accommodate the engine. At a displacement of 2000 tons, the hull diameter is naturally large enough for a high-speed diesel and there is no powering penalty. At about 3000 tons, there is sufficient room in each lower hull for one medium-speed diesel.

In 1978 the Naval Sea Systems Command completed a parametric study of the effect of various transmission systems on the size and powering performance of gas-turbine-powered SWATH combatant ships ranging from 4000 to 8000 tons [33]. As part of that study, arrangements were developed for each type of transmission, with different numbers of gas turbines. Based on those arrangements, conclusions were drawn and reported regarding the effect of increased installed power on the minimum lower hull diameter and strut thickness required for each transmission type. Subsequent investigations indicate that the minimum ship size that can accommodate two LM2500 engines is about 4000 tons, if one LM2500 is located in each lower hull. Epicyclic double-reduction gears provide the most compact arrangement. However, a SWATH as small as 2500 tons can accommodate the two LM2500 engines if they are located in the upper hull and right-angle bevel gear drives are used to transmit the power to the lower hulls.

The standard propulsion system for small conventional U.S. Navy escort ships is two LM2500 gas turbines driving a single propeller through a combining gearbox. This is a relatively efficient arrangement because one engine can drive the propeller at the cruise speed of 20 knots, at which speed the required power is typically less than 20 percent of the total installed power. With this arrangment, the single LM2500 runs at somewhat less than 40 percent of its rated power in the cruise operating mode and, as a result, the specific fuel consumption (SFC) is about 35 percent higher than at full power. Unfortunately, if a geared drive is used on a small SWATH escort ship, it is not possible to cross-connect the propeller on each hull so that both propellers can be driven by one LM2500 engine. If both engines are in operation when the ship is cruising at 20 knots, each engine will be running at as little as 20 percent of its rated power. As a result, in the cruise mode the SFC for the SWATH escort will be about 6.5 percent higher than at full power (and about 20 percent higher than the cruise SFC for the monohull escort). The difference in cruise SFC between gas turbine powered SWATH and monohull ships of frigate size translates into a considerable difference in the endurance fuel required. This is one of the factors that has made SWATH escort designs considerably bigger than the monohull alternative to carry a given payload. However, the inability to cross-connect does not penalize the fuel economy competitiveness of destroyer--size SWATH ships because existing twin-screw monohull destroyers have the same problem. Currently, trail-shaft operations are being used to partially alleviate this problem.

One solution to the problem of cross-connecting the two propellers is the advanced electric propulsion system now being developed for use on navy escort and destroyer-size ships. Current plans call for the development of geared AC-AC synchronous machines, with water-cooled stators and air-cooled rotors, suitable for single-turbine 30,000 hp-per-shaft installations as well as twin-turbine 50.000 hp-per-shaft installations. Land based testing of components for the 30,000 hp system may occur as early as 1987. As currently planned, these epicyclic gearboxes will be for single-rotation fixed-pitch propellers. However, it is within the current state of the art to design and build epicyclic gearboxes of 30,000 hp or 50,000 hp which would be suitable for contrarotating propellers. The use of contrarotating propellers, in combination with electric propulsion, would make the cruising fuel efficiency of a SWATH escort of destroyer size quite competitive with the comparable monohull ship. In addition, the cavitation inception speed would be raised and the ship radiated noise characteristics would be improved.

MANEUVERING

Understanding of the maneuvering performance of SWATH ships has advanced significantly in the last several years. It has been demonstrated by every existing craft that the use of differential thrust provides exceptional low-speed maneuverability. However, early model experiments indicated that, because the hull form possessed excellent directional stability, the maneuverability was poor at high speeds (Froude number > 0.30). This initial conclusion prompted a series of experimental investigations into the most effective rudder and hull configurations for improved maneuvering. The results of

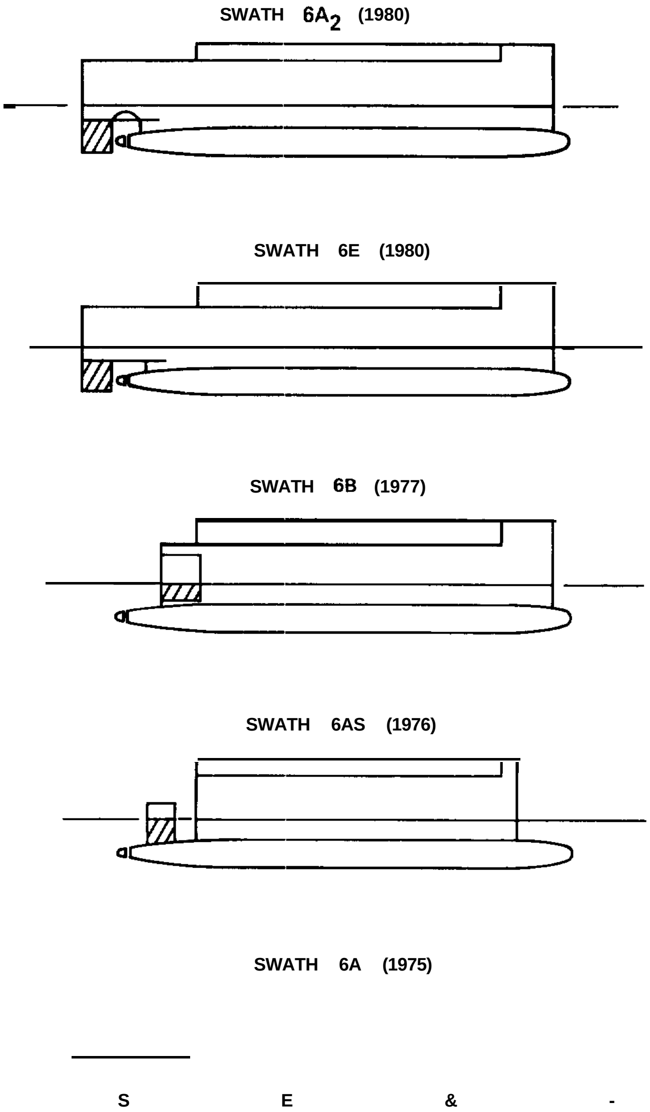

Figure 30. Strut Configurations and Rudder Locations for the Maneuvering Experiments With the SWATH 6 Model.

these experiments have brought the technology forward to the point where a SWATH ship can provide the same high-speed maneuverability as a comparably sized monohull. Recent research has been directed towards quantifying the effect of hull configuration on the stability and maneuverability so that these effects can be considered during the preliminary design process to minimize the size and weight of the rudders and associated machinery.

Captive model experiments have been conducted on a series of SWATH hull forms in the Rotating Arm Facility at DTNSRDC. An extensive series of experiments were carried out on the SWATH 6A model [34] and on a model of the *Kaimalino* [35] to develop a database for simulation and empirical studies [36]. The 6A model tests were conducted for two major rudder configurations having the same rudder area: (a) a surface-piercing strut rudder and (b) a surface-piercing spade rudder attached to the top of the lower hulls, between the aft end of the strut and the propeller. These results showed that the farther aft the rudder was located, the better the maneuverability at high speeds. Further experiments were carried out on an overhanging strut hull form designated the SWATH 6E design [37]. These experiments showed that an overhanging strut hull form with a conventional rudder behind the propeller provided the smallest steady-state turn radius at high Froude numbers. The rudder area was the same as that for the previous SWATH 6 hull designs.

The Canadian Defense Research Establishment Atlantic (DREA) and the Arctic Vessel and Marine Research Institute of Canada (AVMRI) have carried out free-running model experiments on a copy of the SWATH 6A design and a close cousin of the SWATH 6E. These results, reported in [38], verify the general effects of rudder location and hull configuration on stability and turning performance. The various configurations which have been tested in the United States and Canada are shown in Figure 30. A summary of the maneuvering performance of these designs is presented in Table 4.

While moving the rudder farther aft improves turning performance, it also increases directional stability. Unfortunately, the directional stability of a SWATH ship does not need to be improved; for many applications it would be more efficient to reduce the stability so that smaller rudders could be used. In Table 3 it can be seen that the DTNSRDC SWATH 6E and the Canadian SWATH 6A2 have slightly different stability characteristics. This is due to the increased strut length forward of the center of gravity on the SWATH 6E design. This additional strut area forward makes the 6E configuration less stable than the 6A2 and gives the 6E slightly better turning performance for the same rudder area and location.

The short strut designs are less stable than the overhanging strut designs and show better maneuverability at low speeds. However, the surface-piercing rudders used on these short strut ships do not perform well at high speed. These rudders, by the nature of their size and the general arrangement of the design, all come close to or extend above the calm water surface. At high speeds, ventilation causes a loss of wetted rudder area and an associated loss in their effectiveness. During the Canadian experiments on the 6A, an attempt was made to alleviate this by installing ventilation fences on the surface-piercing rudders. Although there was a slight improvement in performance, these fences did not correct the problem.

Another approach to improving the performance of short strut designs is to place the rudder away from the free surface. A promising concept involves using a pair of enlarged stabilizing fins with 20 to 30 degrees of dihedral in place of conventional rudders. This would eliminate the two sets of rudder actuator machinery normally required while retaining the actuators for the stabilizing fins, which must be included in the design anyway. However, this concept has not been studied sufficiently to assure maneuvering performance equivalent to any previous design or to the performance of conventional ships. Future efforts are being #directed towards providing the desired combination of good maneuverability and good directional stability in the most efficient way.

Table 4. Summary of Maneuvering Performance.

SWATH MODEL NUMBER	INDEX OF STABILITY *C	$\frac{\text{STRUT LENGTH}}{\text{HULL LENGTH}}$	TURN DIAMETER. IN FEET	
			Low Speed Froude No = 0.2	High Speed Froude No = 0.4
6A	0.00195	0.72	619	2886
6AS	0.00144	0.79	715	1551
6B	0.00195	0.87	619	3231
6A2	0.00254	1.03	1047	1397
6 E	0.00232	1.05	932	1080

$*C = Y_v'(N_r' - m'x_G') - N_v'(Y_r' - m') > 0$

SUMMARY

Over the past 15 years the U.S. Navy has developed a wide range of SWATH ship analysis and evaluation tools for all of the major technical disciplines relevant to the early stages of ship design. Some of these analytical tools have been described. Over 50 different model experiments have been carried out to validate these tools and determine the effect of a wide range of configurations on hydrodynamic performance and wave-induced loads. Considerable operational experience has also been gained with the seven existing SWATH craft (three in the U.S. and four in Japan). A fifth, the 3500-ton *Kaiyo*, which is the first ship-size SWATH, is scheduled to become operational in late May, 1985, about 15 years after Japanese interest in the concept began. It is believed that the U.S. Navy has developed an adequate technology base to permit a similar low-risk exploitation of the operational advantages of large ocean-going SWATH ships *now*.

PRODUCIBILITY AND SUPPORTABILITY

Having devoted earlier sections of this chapter to a discussion of the SWATH ship's strong and weak points, and given an effective match between technology and mission, we now stand at a point where the last major issue may hinge on commodity management among producers. A reader of *Shipyard Weekly, Maritime Reporter* and other periodicals of the trade, may develop a feeling that most of the U.S. shipbuilding industry is not interested in modern ships and craft — SWATH ships especially do not seem to be a part of their commodity future. The outlook of the producers does not seem to be optimistic because the ever increasing cost of their "commodity" seems to be a damper on the market.

Two recent examples do stand out as either anomalies or harbingers of a brighter future for U.S. Navy programs which have reached out to acquire newer technologies and ideas. The MSH (Minesweeper/Hunter) competition has stimulated the marriage of a U.S. conventional hull builder with Italian expertise in fabricating a "monocoque-type" structure with glass reinforced plastic (GRP) materials. Another MSH competitor is using a surface effect ship (SES) hull with a GRP material. The second example is the PBM (patrol boat, missile), now SWC-M (special warfare craft, medium), which, as a competitive effort, included SES in competition with the planing hull. We applaud such action within our shipbuilding community in exploiting new technology. But, we must remain skeptical of such new initiatives until there is visible activity in our bigger yards to exploit and apply new technology.

Commercially, the construction of the 50-ton *Suave Lino* by the Poole Boatyard in Chula Vista and a SWATH demonstrator of 60 tons by RMI, Inc., are small-scale examples of what could be happening with SWATH ships in the U.S. These ventures seem to have one major objective-to *provide the seakeeping and ride quality of a much larger vessel thereby providing the customer a lower cost alternative.*

Several members of the Naval Studies Board, chartered by the Chief of Naval Operations to look into SWATH, were senior executives with major shipbuilders. They all seemed genuinely interested in the potential of SWATH for U.S. Navy applications. Maybe they will soon come forward with answers to the following questions:

1) Would a mission comparable SWATH combatant cost more or less than a monohull — and why?
2) What about a mission comparable SWATH auxiliary?
3) What is different between construction of SWATH and monohull ships in terms of: (a) facilities, (b) tooling, (c) skilled labor, (d) time to build, (e) time to outfit, and (f) cost of each weight group?

To answer these three questions, a number of issues need to be addressed. For example:

- Are the modular aspects of the SWATH geometry exploitable to produce the ship more cheaply than a comparable monohull?
- What about the waterfront operation? If a SWATH is built in pieces and assembled on dry land. how does one launch it? Or, does one have to assemble it in a dry dock? What process and building sequence looks best for a SWATH and why'? How does that compare with the monohull?
- What about the detail design. the details of erecting the structure, the close out of each section? Are welding problems, surface cleaning, painting, wiring, HVAC installations, or ladders and accesses going to be problems and. if so, why? How does it compare with a monohull?
- What about engineering staff, and naval architects? Are they properly up to speed, or are they unfamiliar with these new ideas and technology?
- Is there a need for *anything* different than is now available, to bid and win a contract to build a SWATH ship, either commercial or naval?
- What about management? Is it prepared to debate or discuss the inevitable questions which will arise such as risk and schedule, cant-plus vs. fixed price contracts, and design margins'? Can a list be made of the factors in need of further investigation?

There should be less a feeling of concern about producibility than a feeling of expectation that, because the SWATH configuration lends itself to modular construction, it may offer an opportunity to one day produce ships for less than their monohull counterparts. U.S. industry can find ways to *shorten the time* required to build a SWATH. Getting that ship out of the yard faster should help bring costs down. Industry has known for sometime that modular construction can save money, through more efficient use of capital which is tied up in materials.

If any of these new ship concepts or new technologies have the potential to provide *any* customer with the performance he needs at lower cost, it could cause a resurgence in business. But who will take the first step? The U.S. Navy has invested over $1 billion in development and acquisition of modern ships and craft. Over $20 million of that was for SWATH with only the nominal 200-ton SSP *Kaimalino* as USN-owned and operated hardware to showcase the technology and operating potential.

Commodity management suggests that one develops all aspects of the marketplace to create a more competitive product in terms of performance, cost. user acceptance and customer satisfaction. Maintaining a place in this competitive business without introducing some of these fundamentally new ideas and technologies may suggest that the customer is satisfied with the monohull. Maybe the user community thinks their ships are “good enough.” In that case, we need the producers help even more to educate those who believe that operating ships which are naturally limited by their environment is all that can be achieved, because operator and producer should know by now that SWATH ships are viable alternatives at a very competitive price.

Perhaps part of the answer about that first step has already been provided by Mitsui Engineering and Shipbuilding Co., Ltd. In the early 1980s as they were developing *Mesa* 80, now *Seagull*, they changed their name from Mitsui Shipbuilding and Engineering Co., Ltd. It seems that engineering is where the emphasis needs to be placed to ensure that the shipbuilder becomes a visible force and an audible voice in the community of new ideas. How many shipbuilders have IR&D programs, and how much, as a percentage of sales, is being invested? Most, if not all, of the aerospace companies pursue signficant IR&D efforts and use the output to feed ideas and technology through the industry/government circuit. It would be interesting to see some comparative data on this question. The use of NICRAD agreements is another opportunity which allows technology to flow back and forth.

As for supportability, there is a need to document the effect of the change in length, beam and draft proportions on our waterfront operations. Will naval bases and shipyards be handicapped if they have to start accommodating more and more of these new shapes? We must take stock of such issues and make them part of a dialogue within the community-the sooner the better.

For maintenance, provisioning, repair and overhaul, there should be no surprises with SWATH. Any service that can operate and care for both surface ships and submarines should find SWATH straightforward. The one area which must be closely watched of course is weight growth. No SWATH can be allowed to be stuffed full of any and all “goodies” that the American sailor can move aboard. An occasional “strip ship” exercise may help keep that situation under control just as it did in Vietnam when our planing hulls became so burdened with extra gear that the hulls could not get up on “step” to reach their design speeds. Given a choice between loading down his ship with unauthorized “stuff’ vs. going to sea in a ship which does not cause his performance or his mission to be degraded in stormy seas, the sailor will choose the latter.

Modernization will require some preplanning and with the modularity now coming through the configuration-controlled interfaces of the SSES program (ship system engineering standards) for future combatants, the discipline and control needed for the preplanned product improvement over a SWATH ship’s lifetime should materialize in time for a SWATH FFX in the mid-1990s.

All in all, there do not *appear* to be any insurmountable problems of a producibility or supportability nature which should cause concern over the introduction of SWATH ships into widespread service. Even the extra freeboard and shorter LOA, which can cause misalignments between other ships or facilities alongside, should not be a serious problem. After all, there are significant differences in the freeboards, LOAs, and drafts of oilers and RO-RO Ships, of destroyers and carriers, of tuna clippers and draggers, of tug boats and submarines, of battleships and frigates. Port facilities are already flexible enough for current SWATH sizes of interest.

If they are not already doing so, it is hoped that this chapter on the SWATH ship will stimulate major U.S. shipbuilders to factor this ship configuration into their current thinking and planning for the future. It offers an exciting new capability for both commercial and naval ship applications which should be a significant factor in any future strategy.

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CHAPTER IV

PLANING CRAFT

THE EDITOR

Dr. Daniel Savitsky *is director of the Davidson Laboratory, Stevens Institute of Technology and has been intimately involved in planing hull research and hull design for over 25 years. He was a member of the Planing Craft Team of ANVCE and was awarded the SNAME Cochrane Award for research in planing hydrodynamics. Dr. Savitsky is a member of H-12 Planing Panel of SNAME and is chairman of the High Speed Marine Vehicle Committee of the ITTC. He is professor in the Civil and Ocean Engineering Department at Stevens.*

INTRODUCTION

The planing hull form is perhaps the oldest, simplest and most extensively employed member of the family of modern marine vehicles discussed in this special *Journal* edition. Appropriate application of modern technology has resulted in the development of planing hull forms which are devoid of the hydrodynamic problems that have stereotyped planing craft as underpowered rough-riding vehicles. Modern planing hulls are designed to avoid the so-called "hump problems," demonstrate good behavior in a seaway, have substantial useful load fractions, and have a potential for growth up to displacements which have established them as effective members of naval units.

As shown by Mazza [1], in the 1970-1983 period, 327 fast attack units and 1471 patrol craft have been constructed and exported world wide, thus establishing these smaller warships as "most popular" in the international market. Their excellent cost-effectiveness ratio, simplicity of operation, miniaturized electronics, and relatively heavy fire power have attracted the attention of many navies-particularly those operating in restricted waters as well as newly formed navies which consider the fast attack and patrol craft as their first ship in establishing an effective naval fleet.

The commercial usage of the planing form is primarily in the recreational area where, in the United States alone, annual production of recreational planing boats number in the thousands of units. In recent years the philosophy in designing these craft has moved from a preoccupation with high calm water speed to a serious effort to apply modern technology to substantially improve their seakeeping abilities. The modern planing hull now has surprisingly good seakeeping characteristics with little deterioration in calm water performance.

It is expected that the planing hull form will continue to find increasing utilization in military and commercial applications, particularly as research in this "traditional" hull form is continued. In this chapter we will describe the platform, discuss its special attributes and limitations, review the current and potential applications, summarize the state of technology, discuss the productivity and supportability and project future developments.

The material in this chapter is extracted from several sources such as presented in Reference [2] augmented by the generous contributions of many internationally recognized authorities in the technology of planing hulls. The editors wish to especially acknowledge the following individuals whose unselfish personal efforts contributed substantially to all aspects of this chapter:

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HISTORICAL EVOLUTION OF PLANING HULL FORM

Light displacement, high-speed, small combatant ships and ocean-capable patrol craft have been part of the world's navies since World War I. The Second World War brought substantial refinement and continued development which saw hard-chine hull forms evolving to equal status with the round-bilge forms so prevalent earlier. Great Britain, Germany, the United States and Russia, at this time, began to develop the early parentage of planing hull forms as we know them today.

To capitalize on the impressive German World War II E-Boat capabilities, two British prototypes called the *Bold* class were completed in 1948. *Pathfinder,* was produced in round bilge form, while its sister vessel had a planing hull with hard chines. *Pathfinder* was the last British round-bilge planing boat built, all successors being hard-chine designs.

A succession of follow-on efforts was undertaken by the British, and the early 1960s marked the real opening of the high performance gas turbine propulsion era with the *Brave* class which was designed for a 50-knot speed requirement, with a specific weapons payload identified.

When U.S. PT-boat (Patrol Torpedo Boat) needs became obvious in the early 1940s, the British Navy's Packard-engined, Thorneycroft-designed MTBs served as parent vehicles from which the 80-foot *Elco* and 79-foot Higgins PT-boats evolved through the war years. The U.S. Navy's post-World War II program was late starting and consisted of developing a new class of PTs. Capitalizing on both foreign and U.S. World War II experience, this program spawned a family of four 95-foot aluminum PT-boats which first saw service in the early 1950s. Each boat was different from the others but one had round bilge and the other three had hard chines. The speed capabilities of the three hard chine vee-bottom boats were nearly identical, ranging from 44 knots to 48 knots. The round bilge was slower at 38 knots but was more stable and easier riding in a seaway. All three hard chine boats exhibited varying degrees of pounding and directional instability at various headings in waves where the average of the one-third highest was 4.5 feet and higher.

In the mid 1960s. the British and U.S. navies achieved similar positions with respect to their high-performance patrol craft configurations. A similar evolution was occurring in Germany and the USSR. Their programs had produced the West Germany *Jaguar* class PTF, the USSR *Osa* class PTF(G), and *Nanuchka* class PGGP.

The 139-foot *Jaguar*, wnth a 23-foot beam and displacing 190 tons, has a round-bilge forward but becomes hard-chine in approximately the after one-third of the hull. Diesel propelled, this class achieved about 40 knots. The *Osa* class PTF(G) is a 127-foot hard-chine, 240-ton boat with a 22-foot beam and is estimated to be 4 knots slower than the *Jaguar* class. The *Nanuchka* class PGGP, at nearly 1000 tons with LOA of 198 feet and a 40-foot beam, is thought to be unique among the modern large high-performance craft in having a hard chine hull configuration.

In mid 1970, the U.S. Navy undertook an advanced planing hull research program aimed at improving seakeeping first while retaining as much speed as possible and at improving the lift-drag ratio of the hull through the mid-speed range of the speed envelope. This led to the development of a high length-beam ratio, high beam loading, double chine, moderate deadrise hull which met all the specified requirements of good seakeeping and good lifting efficiency. This prototype hull, identified as CPIC-X (Figure 7) became the U.S. "benchmark" design which met the conflicting demands for the best compromise of high speed and seakindliness in one hull form with minimum cost and complexity. The hull design features which achieved this performance are described in the technology section of this chapter.

The concept of a relatively small, fast, inexpensive carrier of a potent weapon at sea is not new, but a dramatic demonstration of this capability occurred on 21 October 1967. The event was the sinking of the Israeli *Eilat* by Styx missiles launched from an Egyptian *Komar* class patrol boat at a range of about 12 nm. The small boat concept has become most attractive to many of the smaller and newly-independent nations who are acquiring fast, heavily armed small combatants from Great Britain, France, Germany, the Scandinavian countries, the United States and the USSR. Furthermore, modern technology is now available to incorporate seakeeping and endurance with the speed, maneuverability, low profile, and low relative cost which are characteristic of these modern, very powerful vehicles.

Unfortunately, the aggressive and successful planing hull research program which was initiated by the U.S. in the 1970s subsided in the late 70s when the U.S. Navy decided to emphasize acquisition of large combatants capable of transiting the world's oceans.

DESCRIPTION OF THE PLANING HULL CONCEPT

The planing hull is designed specifically to achieve relatively high speed on the surface of the water. Although it is not essential to the concept of planing, rough water operation has become an important capability for most useful planing hulls, and this aspect of their design will be reviewed.

Speed on the water surface is closely related to the size of the vessel and the installed power. Length is the principal dimension used to define speed-size relationships at low speeds because the resistance of the hull to motion through the water is especially dependent upon the formation of surface waves which, of course, move at the speed of the hull. Surface waves have a fixed relation between their speed and their length. This is sometimes expressed, in English units, as the wave speed in knots divided by the square root of the wave length in feet and this ratio is always equal to 1.34 (except in very shallow water). The speed/length ratio of a displacement vessel is similarly defined as its speed in knots divided by the square root of the waterline length in feet. Therefore, when a vessel moves at a speed/length ratio ($V_k/\sqrt{L}$) of 1.34 it creates waves whose length is equal to the waterline length of the vessel. This critical speed is also stated in dimensionless form using the Froude number, $F_N = V/\sqrt{gL}$. Therefore, $V_K/\sqrt{L} = 3.36\ F_N$. The value of $V_K/\sqrt{L} = 1.34$ marks the upper limit of true displacement operation and the beginning of "high speed displacement" operation. The reasons for this are given in the next two paragraphs.

Below $V_K/\sqrt{L} = 1$ and as shown in Figure 1, marine craft span two or more waves (of their own bow wave train), the changes in draft and trim are small, and power requirements are modest. In this speed regime the hull is supported entirely by buoyant forces. Up to a $V_K/\sqrt{L}$ of 0.90 the drag is predominantly frictional. The hull is tapered at the stern and curved upward toward the waterline, to minimize flow separation which is another source

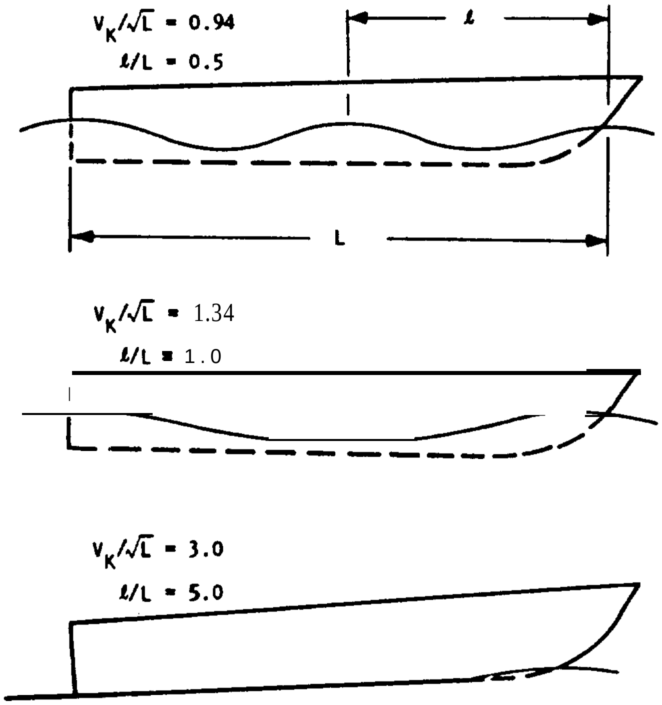

Figure 1. Wave Patterns vs. Speed-Length Ratio.

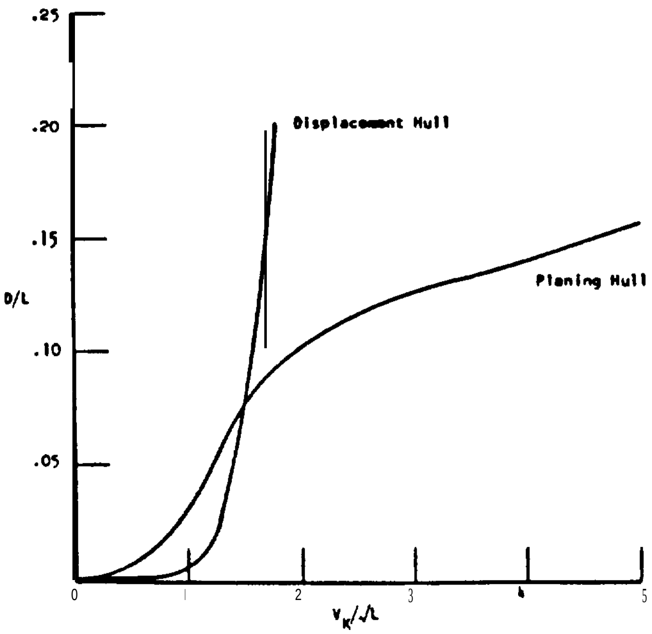

Figure 2. Typical Curves of Drag-Lift Ratio vs. Speed-Length Ratio.

of drag. This is typical of slow, heavy vessels as shown in Table 1. Above $V_K/\sqrt{L}$ = 0.90 the wavemaking drag becomes increasingly important. At about $V_K/\sqrt{L}$ = 1.20 it begins to increase at a very high rate. At about $V_K/4$ L = 1.34 wavemaking becomes a virtual barrier to further increases in speed for the true displacement hull form (Figure 2). This is because the increased local velocities caused by the rounded hull form result in negative pressures which cause the vessel to settle deeply and to trim down by the stern. The ship is literally climbing the back of its own bow wave.

Table 1 shows approximate representative ratios for the general type of vessel shown. This table shows typical values for Froude numbers and speed/length ratios as well as lift/drag ratios for a wide range of ships and craft. Note that low speed (low speed/length ratio) is generally associated with high lift/drag ratios whereas high speed craft tend to have much lower lift/drag ratios.

At $V_K/\sqrt{L}$ above 1.34 it is therefore necessary to depart from the "canoe stern" or "counter stern" of the low speed types and to make the buttock lines flatter terminating in a transom stern. This hull form avoids the negative pressures that occur when a true displacement hull is overdriven and causes the flow to separate cleanly at the stern, thus keeping the separation drag to a minimum. As the design speed of the vessel is further increased even straighter buttock lines are required and the transom must be broader and more deeply immersed (but round bilge sections may still be employed). This high speed displacement (or semiplaning) regime extends from $V_K/\sqrt{L}$ of about 1.3 to about 3.0. These speed regimes are depicted graphically in Figure 3.

A systematic series of high speed displacement hulls (Series 64) the parent form of which is shown in Figure 4a, was tested by Yeh [3] at speed-length ratios up to 5.0. In analyzing the results, Yeh makes the following statement regarding high speed displacement operation:

> "The dropping off of residuary, i.e. wavemaking, resistance coefficients and close spacing of R_r/Δ, i.e. wavemaking resistance per ton of displacement (proportional to D/L), contours between the speed/length ratios of 2.0

Table 1. Vessels Typical of Various Froude Numbers.

Length Froude Number F_N	Speed Length Ratio $V_K/\sqrt{L}$	Drag-Lift Ratio D/L	Lift-Drag Ratio L/D	Type of Vessel
0.15	0.5	0.001	1,000	Slow Cargo Vessels
0.24	0.8	0.002	500	LST, Tankers
0.30	1.0	0.005	200	Amphibious Cargo Ships, Transports
0.33	1.1	0.008	125	Aircraft Carriers
0.39	1.3	0.02	50	Light Cruisers. Ocean Escorts
0.45	1.5	0.03	33	Frigates
0.54	1.8	0.05	20	Destroyers, etc.
0.98	3.3	0.10	10	PG (Patrol Gunboat)
1.34	4.5	0.14	7	CPIC-X (Coastal Patrol and Interdiction Craft, Experimental)

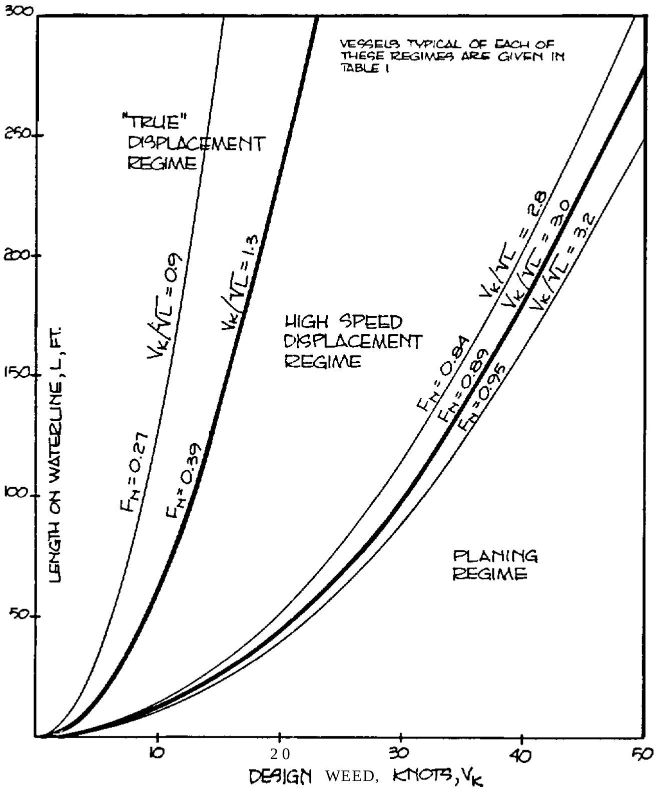

Figure 3. Speed Regimes.

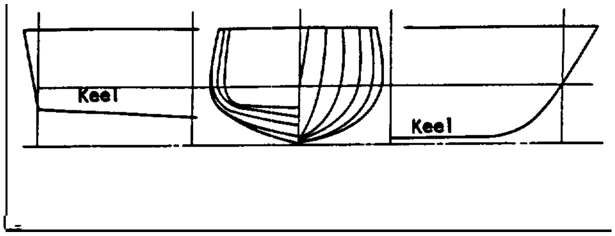

Figure 4a. Typical High Speed Hull Forms.

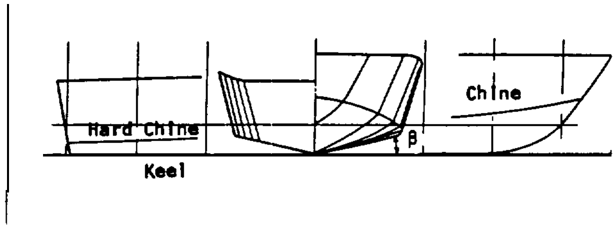

Figure 4h. Typical High Speed Hull Forms.

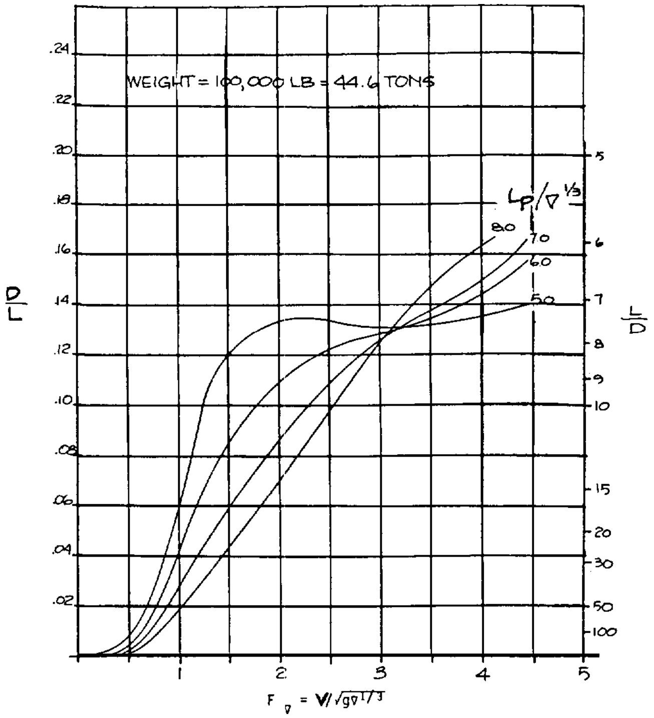

Figure 5. Drag/Lift Contours for Efficient Planing Hulls as a Function of Volume Froude Number and Slenderness Ratio.

(F_N = 0.5) and 3.0 (F_N = 0.9) mean that a small increase in horsepower will bring a higher return in speed in this speed range than in any other speed range, except at the very low speeds. The leveling off of the residuary resistance coefficients and their magnitudes after the speed/length ratio of 3.0 (F_N = 0.9) indicate that the wave resistance is no longer an important factor. The frictional resistance, however, remains the dominant factor, and its magnitude is about twice as large as the form drag

Therefore, for ships designed to operate at speed/length ratios over 3.0 (F_N = 0.9), it is highly desirable to keep the wetted surface to a minimum."

It is precisely this factor that makes the planing type of hull, shown in Figure 4b, desirable at high speeds. The manner in which it generates lift (discussed below) causes it to rise bodily above its static flotation level and to trim up by the bow thereby reducing the wetted surface significantly.

Since the formation of waves is less significant and not primarily influenced by hull length above semiplaning speeds, the length Froude number is no longer very useful as a measure of the speed-size relationship and the volume (or displacement) Froude number $F_\nabla = V/\sqrt{g\nabla^{1/3}}$ is frequently used. Figure 5 shows a plot of drag/lift ratio against Froude number for several slenderness ratios ($L_p/\nabla^{1/3}$). The curves represent the state of the art for efficient planing hulls at their design speeds and do not represent any one hull throughout the speed range. It can be seen that the curves all cross in a small area around F_∇ = 3.3, indicating that slenderness ratio, and hence the length, has little effect on the specific resistance at this Froude number. At lower speeds longer hulls have a great advantage over shorter ones and (from other data) high speed displacement or semiplaning configurations have an advantage over full planing configurations, to be described below.

At higher speeds, as noted above, the planing type of hull is required. These facts are illustrated dimensionally in Figure 6, where the line marked "Upper Bound Displacement Hulls" represents F_∇ = 3.3, the limit of speed

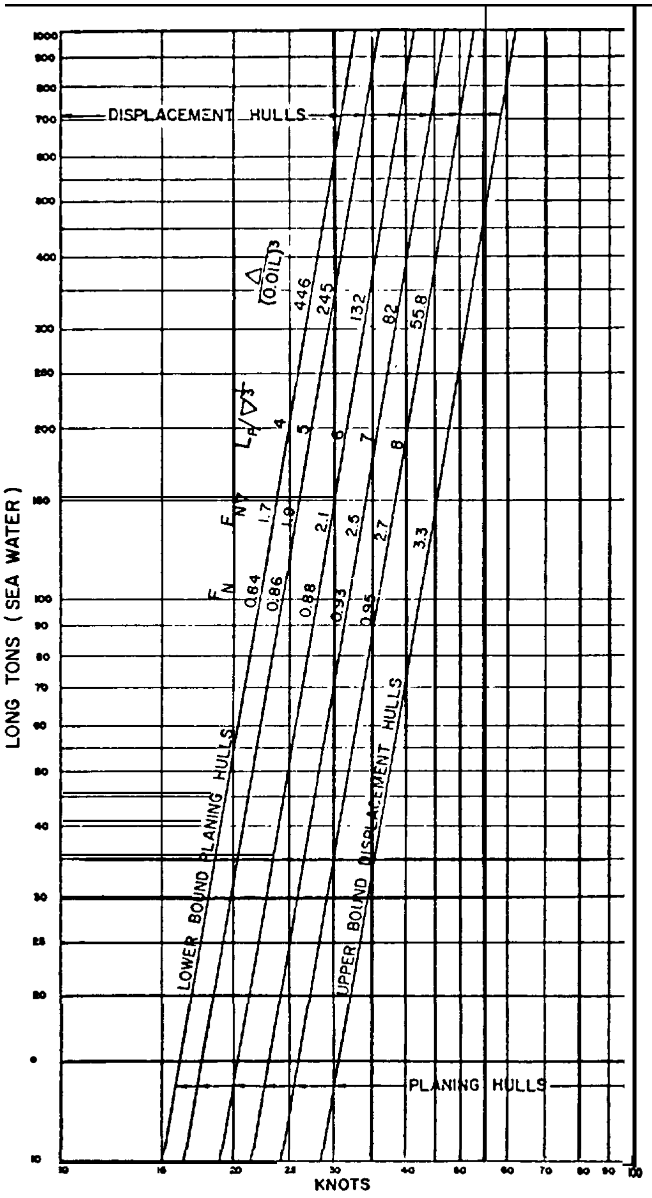

Figure 6. Ranges Application: Displacement-Planing.

above which the high speed displacement type hull form may be more efficient depending on the length and weight (slenderness ratio) of the vessel. The shorter the hull, at constant weight (the lower the slenderness ratio), the lower the speed at which the planing type hull can be considered. This range of lower limits, shown in Figure 6 as the family of curves labeled "Lower Bound Planing Hulls," corresponds to a range of length Froude numbers from 0.84 to 1.10. This range is also shown in Figure 3.

The chief characteristic of the planing hull is effective flow separation, not only at the transom as in the high speed displacement ship, but also at the sides. Effective flow separation is necessary to prevent the formation of negative pressure areas on the bottom of the hull. This is usually accomplished with a hard chine configuration, one type of which (Series 62) [4] is shown in Figure 4. Greater deadrise and/or more rounded transverse sections can be used if effective flow separation is achieved by proper placement of spray rails. The longitudinal shape (buttock lines) must have no convexity aft of the bow sections. This basic rule may be violated occasionally when local longitudinal convexity (rocker) is added in the transom area-particularly in high speed recreational craft. The negative pressures developed by this "rocker" geometry provides a bow up trim moment to the craft and thus prevents the craft from running "too flat" at high speeds.

Figure 7. A High Length/Beam Double-Chine Planing Hull.

When a planing hull is driven beyond the displacement speed range it initially trims down by the stern like the other types, but because it is a "lifting surface" it develops positive hydrodynamic pressures as speed increases thus generating dynamic lift. As the hydrodynamic lift increases with increasing speed the amount of hydrostatic (buoyant) lift decreases so that the total lift remains constant and is equal to the craft weight. At full planing speeds, $V_K/\sqrt{L} > 3.0$, the wavemaking resistance, which effectively becomes a speed barrier for a displacement ship, actually decreases for a planing craft as the speed increases.

Although primarily adapted to high speed operation, useful planing hulls, with few exceptions, must be able to operate successfully in the high speed displacement (semiplaning) and low speed (true displacement) regimes, and importantly in rough water as well. The hull form which best meets these requirements has a relatively high length-beam ratio (greater than 5) to reduce impact accelerations at high speed and to reduce trim and therefore resistance in the transition speed range. The high slenderness ratios associated with these proportions produce low resistance at low speeds. A good planing hull will also have moderate deadrise (about 15 degrees) aft increasing to high deadrise (about 45 degrees) forward combined with fine lines in the bow. These characteristics further reduce slamming at all speeds, and minimize rough water resistance. The only disadvantage that must be accepted is a small increase in resistance at low displacement speeds and at full planing speeds compared to hulls optimized for either of these speeds. This is an acceptable penalty considering the all around good performance that is achieved, particularly the ability to run with good efficiency throughout the entire speed range.

The theoretical and analytical considerations just described permit definitive model testing with dependable scaling, with high confidence in both the hull form and its full scale performance prediction. The way is then open to intelligent selection of hull material, construction techniques, and choices of scantlings and propulsion components.

Hull construction can be of welded steel with light alloy superstructures (particularly for the larger sizes); of all-aluminum welded structures, of glass fiber reinforced plastic (particularly for the smaller sizes), or of wood.

The vast majority of conventional planing hulls are powered by diesel engines driving fixed pitch propellers via reversible reduction gears. More recent high performance designs use gas turbine power plants for high speed operation and separate diesel engines for slow speed and maneuvering economy. Commercially available subcavitating propellers with high blade area ratio are used in the speed range up to approximately 35 knots. At higher speeds, special so-called "transcavitating" propellers are required. Transcavitating propellers combine features of both conventional and supercavitating propellers, giving good efficiency over the entire speed range. All these features will be discussed in greater detail in the following sections of this chapter.

SPECIAL ATTRIBUTES AND LIMITATIONS

The modern planing hull is a relatively inexpensive high speed platform capable of carrying potent military payloads. Development and eventual utilization of large size planing vessels can be achieved at a substantially reduced cost as compared to other types of advanced naval vehicle concepts.

ATTRIBUTES

Principal capabilities of a planing hull from the technological viewpoint are listed below.

- The basic smooth and rough water hull hydrodynamic technology is sufficiently advanced to enable reliable preliminary performance predictions to be made.
- Model-prototype performance correlation is sufficiently well-documented to establish model testing as a reliable design and evaluation procedure.
- Planing hulls generically do not have serious navigational draft limitations.
- The hard chine planing hull has more inherent roll damping, particularly underway, than a round bilge hull, which effectively reduces roll motions in a seaway. Active roll fin stabilizers are easily added to the vessel to further reduce roll motions in the displacement speed range. This allows for comfortable long-term operation at these speeds.
- Planing vessels properly designed for seakeeping can retain a large portion of their calm water operational speed capability in moderate to severe sea conditions. For instance, at a speed of 37 knots, a 100-foot planing hull was able to perform its mission in waves of significant height up to five feet.
- Hull construction can follow normal shipyard practice and will not require aircraft-type fabrication techniques.
- Much of the required structural technology is in hand and no unresolvable structural design problems are envisioned.
- The large useful load fraction (approximately 40 percent) of a well-designed planing ship provides sufficient fuel for long transiting capabilities at low speed without refueling and at medium speeds with refueling enroute.

LIMITATIONS

Principal limitations of a planing hull from the technology viewpoint are listed below:

- The lift-drag ratio at very high speeds ($V_K/\sqrt{L} > 4.0$) is less than comparably size hydrofoils and SES craft.
- The seakeeping performance in high sea states will never be the equal of hydrofoil craft but is nonetheless quite acceptable for reasonable operating periods.
- The planing hull has been traditionally stigmatized as a small boat with small payload and no rough water capability. Although recent technology advances in planing hull design have negated these perceived limitations, some time will be required for general acceptance of these possible improvements.
- Commercial and state user agencies tend to buy off-the-shelf recreational boats and modify them to meet their needs. Unfortunately the best and latest hull technology is usually not incorporated into these available hulls.

CURRENT APPLICATIONS

U.S. NAVY

In the last 4 to 5 years the combat role of planing craft has been deemphasized. This is mainly due to the great expanse of ocean over which the United States is required to make its presence known. Earlier experience with small fast warships has caused the U.S. Navy to decide that these ships pose too many restrictions considering long-term open-ocean seakeeping and weapons carrying capability. The U.S. philosophy today is to build combatants capable of transiting any of the world's oceans and carrying a vast assortment of weapon systems. Unfortunately, with this philosophy, problems can arise when it is necessary to engage in limited warfare in areas where the larger ships cannot operate close to shore or in the inner harbors or rivers. The primary uses today of planing craft within the U.S. Navy are as patrol craft, insertion craft, riverine craft and ships' boats.

Patrol Craft

Limited patrol in shallow waters and around islands as well as some coastal patrol is undertaken by Navy small boat groups. These missions are usually performed to intercept terrorists and drug runners or to ensure safe passage of personnel going from ship to shore. Currently the Navy's primary patrol boat for this mission is a 65-foot PB.

Insertion Craft

These craft are used for operations which require the insertion of advance troops such as commandos, guerilla operatives, or other special forces. They are required to be of low profile, fast, seaworthy, and capable of being davit-launched at sea. At present the Navy uses various inflatable craft and a specially designed 36-foot fiberglass hull for such applications.

Riverine Craft

Riverine craft were used during the Vietnam War to patrol the delta and many rivers of South Vietnam. The enormous numbers of boats in this region required the Navy to modify or build boats to interdict this traffic. Craft used included the 31-foot PBR, 50-foot PCF, 95-foot Osprey and many converted LCM-6 and LCM-8 landing craft. Other riverine craft were used to provide firepower and landing capability during the many assaults. These craft included the ASPB, LCM-6 Monitor, 36-foot Mini ATC and any other small craft capable of supporting a small caliber weapon.

Ships' Boats

Tests are presently being conducted and prototypes built of a light-weight inflatable craft with a rigid V-hull made of fiberglass. This craft is officially known as a rigid inflatable boat (RIB) and will be deployed on combatant ships, such as frigates and cruisers. It was originally designed in England for the Lifeboat Service to transit the surf zone and proceed at high speed through rough seas. They have a conventional fiberglass deep V-hull with a larger diameter inflatable tube around the gunwale. This has proven to be a very seaworthy and stable design. As an example, these craft have been davit launched at 12 knots in a sea state 3. They will be used for boarding, search and rescue, and personnel and supply transport.

With the present U.S. Navy philosophy, the future does not look promising for further planing craft development beyond the present inventory with the exception of one or two larger craft for special missions. Those missions which could be handled by planing craft will probably be accomplished by more sophisticated and expensive vessel types such as the SES and hydrofoil.

FOREIGN MILITARY

The present and future applications of planing craft in foreign navies are distinctly more positive than in the U.S. Navy. Foreign navies have placed great emphasis on the use of small naval combatants, as attractive alternatives to larger ships. This is due to the escalation of shipbuilding costs, the institution of the 200-mile territorial limit, and the entry of "third world" nations into modest naval programs.

The emphasis on small ships has resulted in an impressive number of these high speed vessels in foreign service [5]. Reported characteristics in 1979 indicate over 2,700 vessels under 200 feet LOA in active service worldwide with the following distribution:

LOA, ft	Percent
61-70	11
71-90	19
91-110	7
111-130	44
131-150	11
151-170	4
171-190	2
191+	2
	100

The largest concentrations by overall length are 127 feet (30%) and 87 feet (16 percent).

It is also interesting to examine the distribution as a function of speed shown in the following table:

Speed, knots	Percent
≤20	1
21-30	32
31-40	35
41-50	25
51+	7
	100

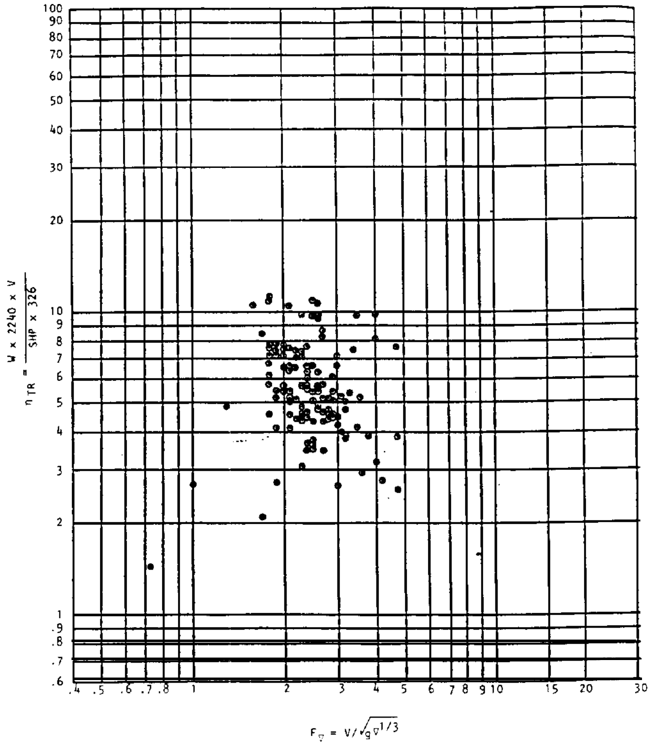

Figure 8. Smooth Water Performance.

The smooth water performance characteristics of the craft reported were used to calculate transportation efficiencies and a dimensionless speed (F_∇) from which representative data were plotted in Figure 8. The greatest number of craft have maximum speeds above the "planing hump speed" of $F_\nabla = 1.5$ with a high concentration in the semiplaning region of $1.5 < F_\nabla < 3.0$. There are also an impressive number of "pure planing" craft operating at $F_\nabla > 3.0$. This is important in identifying the trends of hull form as they change with increasing F_∇.

As discussed by Mazza [I], the international market for small warships has grown explosively between 1970 and 1983. It became a multibillion dollar annual market in the 70s. Many factors contributed to this surge in interest. Typical are:

- The rapid development of new generations of weapons systems which caused significant changes in naval tactics that highlighted the use of small combatants.
- The creation and expansion of completely new navies, particularly in the evolving countries.
- Depressed shipyards, pressed by the world wide decline in orders for merchant ships which turned their attention to the international market for small combatants.
- The growing importance of offshore resources and the consequent creation of the 200 mile EEZ (Exclusive Economic Zones) thereby creating new surveillance requirements.

During this period, the average displacement of warships has *decreased* from 1,100 tons in the 60s to 800 tons in the 70s mainly as a consequence of the fast attack craft's development and diffusion. There is indeed an international trend towards greater utilization of smaller surface vessels. The European industries dominate the export business with the German and French yards being the leaders, and the most popular size fast attack craft is in the 250-300 ton range.

U.S. COAST GUARD

The U.S. Coast Guard is a unique branch of the armed services in that it has well defined roles and missions in maritime safety, search and rescue, aids to navigation, environmental protection and law enforcement under the Department of Transportation in times of peace, while maintaining a state of military readiness to function under the Department of the Navy in times of war. The Coast Guard currently uses a variety of planing hull boats in carrying out these missions.

The largest number of boats are classified as light utility boats (UTL). These are nonstandard, less than 25 feet in length, purchased from the boating industry by district commanders to meet the specific needs of the individual Coast Guard districts. There are over 1,000 UTLs of various types, and the overwhelming majority of them are planing hulls. These boats are used for short range search and rescue, law enforcement, port and environmental safety, marine environmental response, recreational boating safety, and the servicing of short range aids to navigation. Wartime missions for them will remain essentially the same. but one would expect some change in emphasis. For example, the number of harbor patrols for port safety will probably increase.

A clearer picture of the current use of planing boats may be obtained by reviewing some of those in service. Five examples will be considered: Two multimission boats, two specific mission boats and a new ship's boat.

The 30-foot utility boat MkIII (UTM) is of fiberglass and is used for search and rescue, and law enforcement, in moderate sea states. It has an overall length of 30 feet, a IO-foot 7-inch beam and a 2-foot IO-inch draft at an operating displacement of 6 tons. The 30-foot UTM is powered by a single 270-horsepower Cummins VT 8-370M, or 280-horsepower Cummins UT6-250M, diesel engine. It has a maximum speed of 25 knots. There are 365 of these boats in service.

The 41-foot utility boat (UTB) is built of aluminum and is also used for search and rescue and law enforcement in moderate sea states. It has an overall length of 40 feet 8 inches, a 13-foot 6-inch beam, and a 4-foot draft at an operating displacement of 12.8 tons. It is powered by a pair of either 280-horsepower Cummins V903M, or 320-horsepower Cummins VT903M diesel engines. The maximum speed is between 22 and 26 knots. There are 201 of these boats in service.

The 30-foot surf rescue boat (SRB) is of fiberglass and is used for search and rescue in moderately heavy seas and surf. This boat was designed to have a faster transit speed than more traditional surf rescue boats. It has an overall length of 30 feet 4 inches, a beam of 9 feet 4 inches and a draft of 3 feet 7 inches at an operating displacement of 4.6 tons. It is powered by a General Motors 375 horsepower 6V92T diesel engine and has a maximum speed of 28 knots.

The 55-foot aids-to-navigation boat (ANB) is aluminum and is used to provide quick response servicing of lightweight aids to navigation. This is a work boat with length overall of 58 feet, a 17-foot beam and a 5-foot draft at an operating displacement of 28.8 tons. It is powered by a 540-horsepower General Motors 12V-71 TI diesel engine and has a maximum speed of 22 knots. There are 20 of these boats in service.

The Coast Guard is in the process of equipping each of its cutters with an Avon d-meter rigid hull inflatable boat (RHIB). The 6-meter RHIB has a fiberglass, deep-vee planing hull to which is attached a synthetic rubber, inflatable flotation collar. It is powered by a pair of 70 horsepower outboard motors. It can carry from two to ten persons and has a maximum speed of 25 to 35 knots. The boat can be launched and recovered from a cutter while underway using a single point davit. There will be 124 of them in service.

The Coast Guard has a fleet of 26 "Cape" class, 95-foot patrol boats (WPB), and 53 "Point" class, 82-foot patrol boats (WPB) in commission. They have conventional patrol boat displacement hulls and are capable of operating in the high speed displacement regime, i.e., speed/length ratios of from 2.0 to 2.5. The 95-foot WPBs were built from 1953 through 1959. The 82-foot WPBs were built from 1960 through 1970. These boats should start to be replaced at the end of this decade.

Federal guidelines for major acquisitions require the consideration of alternative system designs for the replacement of the present WPB capability. This means a consideration of various types of advanced marine vehicles. Speed, the ability to maintain speed in a seaway, and seakeeping will be major factors in evaluating any vessel that meets the basic range and endurance requirements. Good seakeeping qualities may lead to the consideration of deep-vee, or double chine planing hulls.

The Coast Guard cannot predict the outcome of the acquisition process that is being undertaken for the replacement of their present WPB capability. However, it is difficult to envision a replacement fleet that does not contain some planing hulls. Planing hull boats have two strong points in their favor: A proven record of performance throughout the world in war and peace, and a low initial cost.

In the foreseeable future, district commanders will continue to purchase planing hull UTLs, and planing hull boats are likely candidates for the WPB replacement programs. There does appear to be a definite role for the planing hull in the Coast Guard of the future.

COMMERCIAL PLANING HULLS

Commercial applications of planing hulls fall into three basic categories: Yachts and recreational boats, work boats, and patrol boats.

Yachts and recreational boats represent the major current and potential commercial usage of planing hulls. In the United States it would be fair to estimate that 95 percent of the planing boats built annually are designed and used for recreational purposes. Recreational planing craft range from 10 to 100 feet in length and from 250 lbs to over 100 tons in displacement. The majority are in the 16-foot to 30-foot size range. Annual production in this size range numbers in the thousands of units. Quantities in sizes over 30 feet decrease with increased length with less than 10 boats per year in the 90 to 100 foot category.

Recreational boat types are:

- Runabouts. mostly 16 to 2.5 feet, maximum 60 feet
- Sportfishing boats, inland and coastal water sizes 16 to 45 feet, and offshore sizes 25 to 80 feet
- Cruising boats, from 25 feet to 100 feet
- Sports racing, from 16 feet to 60 feet

The fact that a high percentage of total planing boat production in the U.S. and elsewhere is for recreational purposes is quite understandable based upon economic and technical reasons. It is essential for a successful planing craft to have relatively light weight for a given size. Inasmuch as return on investment, significant payload capacity, and endurance are not generally overriding concerns for recreational craft, i.e. they do not have to "earn a living", they can generally be lighter and thus more easily powered for attainment of planing speeds. On the other hand some boats, although designed for planing, are often operated at speeds representing semiplaning conditions due to overweight or to avoid exorbitant fuel consumption.

The future of the recreational boat business and planing craft production as the major part of it, depends largely on basic national economic conditions. Purchase, maintenance, and operating costs for recreational craft fall into the category of discretionary expenses and require a healthy economy to be sustained. Another aspect of the recreational boat market is that it is not large enough or mature enough to support development and production of engines designed and built primarily as marine propulsion units. Almost all marine propulsion engines are built as a spin-off of automotive or industrial engines. Therefore, the availability of marine propulsion engines at prices low enough to be affordable for recreational boats requires that there be some other larger commercial need for such engines so as to provide the manufacturer with the incentive to produce the basic engines for conversion to marine applications. For instance, many recreational boats use gasoline engines in the 380- to 425-cubic-inch range. As Detroit down-sizes automobiles, these engines may become unavailable for marine use because the underlying automotive market will no longer have a need for them. Most commercial planing boats are designed around existing power plants and the type and quantity of boats built is a function of the availability of engines at reasonable prices.

Work boat applications are the second most numerous application for planing craft. The following are typical of the various applications:

- Offshore oil rig crew boats, 50 to 120 feet
- Commercial fishing boats, 25 to 50 feet
- Charter fishing boats, 36 to 60 feet
- Pilot boats, 35 to 60 feet
- Fire boats, 30 to 80 feet
- Oil spill clean-up boats, 16 to 50 feet
- Hydrographic survey boats, 25 to 50 feet
- Landing craft type cargo boats, 25 to 50 feet

Crew boats are probably the most significant of the non-recreational types used today in the U.S. Planing craft are suitable for this service inasmuch as speed is important, payloads are not excessive, and endurance requirements are reasonable. Production, which fluctuates with the fortunes of the offshore oil drilling business, is currently low, but it has been significant over the past 20 years and can be expected to continue to be a major application of planing boats.

Other applications as listed above hardly represent a major industry, but they do represent a variety of different usages each with its own special needs. The requirements of these other usages are such that they can often be satisfied by less expensive and/or more durable displacement type craft. However, in those instances where craft size is not too large, thus permitting planing speeds with the available lightweight power plants, or where high speed is essential to the mission, planing craft are employed. Generally their use is suitable where payloads are moderate and endurance requirements are low as in the case where runs are short allowing frequent refueling.

Patrol bouts are a quasi-commercial type of planing craft. Users include various local, state and federal government agencies such as harbor police, fisheries enforcement, customs, parks and recreation, etc. In the United States patrol boats are generally small, 25 to 50 feet in length. Missions which would require larger craft are usually handled by U.S. Coast Guard vessels of a displacement or semidisplacement type.

In the U.S. most patrol boats are adaptations of boats originally designed to be recreational boats and are built to recreational boat standards. As a consequence they are often not ideally configured for this application and are not as durable as their military patrol boat counterparts. On the other hand, they are relatively inexpensive.

In Europe and Asia one sees more harbor police launches than in the U.S. and they are generally custom-designed and built for patrol use. They are recognizably different in configuration from recreational boats and have a no-nonsense appearance. Some of the most technically advanced are built in Italy using hull forms and other technology closely akin to those of offshore racing boats.

Patrol boat requirements can be expected to increase in the future as governments continue to increase their involvement in various water oriented activities. Such applications should employ the best and latest technology and provide an impetus for advancing the art. However, if recent experience continues to be the norm, such will not be the case. Most nonfederal agencies do not have the expertise to design or prepare suitable specifications to obtain the best in the way of patrol boats. So long as patrol boats are purchased by the user agencies the same way they purchase typewriters, agencies will continue to get off-the-shelf recreational boats not ideally suited for patrol boat applications.

POTENTIAL APPLICATIONS

The design of high speed craft has recently become one of the most active areas of naval architecture. The 200-mile fishing limit, recognized since 1 January 1977 by virtually all nations, imposes national jurisdiction over nearly 10 percent of the world's ocean areas. These areas have become the Exclusive Economic Zone of the coastal states who wish to protect and exploit their potential offshore wealth, which includes fishing as well as oil and other natural resources. It has been estimated that 90 percent of both living and natural resources in and under the sea are within the 200 mile limit and that world demand for patrolling coastlines could require up to 600 additional high speed vessels. Such factors when coupled with mounting aspirations of emerging nations, have given rise to a world-wide interest in planing craft capable of acceptable operations in a seaway.

From a totally military point of view, high speed planing hulls armed with powerful surface-to-surface missiles, self-protected with surface-to-air missiles and close-in defensive weapons and countermeasures, and fitted with modern electronics systems will be entering service in the world's navies in ever increasing numbers. As noted earlier this enthusiastic interest in the use of small, fast, patrol craft with devastatingly capable missile systems was in part precipitated by the sinking of the Israeli destroyer ***E'ilat*** in 1967. Since that time, second generation antiship missile systems have appeared which operate from lightweight fixed launchers. In addition, gun armaments have experienced rapid developments with the introduction of effective and accurate fire control, increasing rates of fire, and high precision munitions. Various caliber guns are available which can be effective even against aircraft and incoming missiles and which are compatible with planing hulls.

As discussed by Dorey [27], sensors, computation and display facilities, and electronic warfare systems now form an integral part of the weapon outfit of any warship, and their availability in forms compact and light enough to be installed in high speed planing craft can make this class an effective warship.

Developments now in the technology pipeline using microminiaturization for all forms of electronics equipments will have a dramatic effect on the "packing factor" of the black boxes which comprise the weapons systems of today. When the effects of such change are ultimately felt in all facets of the combat system design for small warships, the day of the multimission small warship truly will have arrived.

It is further expected that the demands of commercial and recreational markets will continue to expand. Further, with greater needs for good seakeeping performance, modern technology will be applied to develop hull forms which will satisfy this demand.

STATE OF TECHNOLOGY

SMOOTH WATER PERFORMANCE

Planing craft hydrodynamic technology is based primarily upon experimental data obtained from tests of prismatic planing surfaces such as those reported by Savitsky [6] and results of hull series tests such as illustrated by Series 62 reported by Clement and Blount [4]. This technology has been synthesized into simplified empirical equations which are easily used in design. The following discussion of the smooth water characteristics of planing craft is based upon analytic considerations, model test results, and full scale data.

Hydrodynamic Lift

The lift on the planing surface is attributed to two separate effects. One is the positive dynamic reaction of the fluid against the moving planing bottom, and the second is the so-called buoyant contribution which is associated with the static pressures corresponding to a given draft and hull trim. At very low speeds, the buoyant lift predominates, while at high speed, the dynamic contribution predominates. A plot of lift coefficient as a function of mean wetted length/beam ratio for a range of speed coefficients is given in Figure 9 for a zero deadrise surface. The correction for deadrise is given in Figure 10. The important hydrodynamic characteristics demonstrated are:

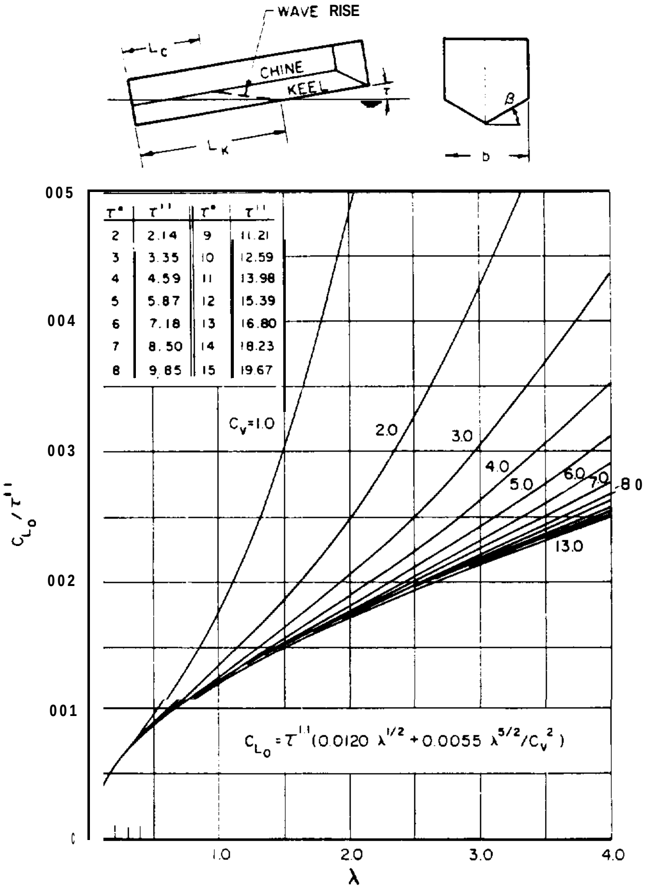

Figure 9. Lift Coefficient of a Flat Planing Surface; β = 0”

The lift coefficient, C,, increases as the exponential power of trim angle and as the square root of the mean wetted length/beam ratio. according to the following equation (for zero deadrise surface):

$$C_{LO} = \tau^{1.1}(0.0120\lambda^{1/2} + 0.0055\lambda^{5/2}/C_v^2)$$

where: $C_{LO} = \Delta/\tfrac{1}{2}\rho V^2 b^2$
τ = trim angle, degrees
λ = mean wetted length beam ratio
C_v = speed coefficient = $V/\sqrt{gb}$
V = speed, ft/sec
h = beam of planing surface, ft
g = acceleration of gravity, ft/sec^2

- All other parameters being constant, the hydrodynamic lift varies as the square of the beam.
- The planing lift is predominately due to dynamic bottom pressures when the speed coefficient C_v, a Froude number defined above, is greater than 10.
- The effect of deadrise angle is to reduce the lift coefficient, all other factors being equal.

Hydrodynamic Drag

The hydrodynamic drag of the bare hull is composed of pressure drag due to lift forces acting normal to the bottom, and to viscous drag acting tangential to the bottom in both the pressure area and in the spray area which is located immediately forward of the pressure area. These drag components, at full planing speed, are best illustrated in Figure 11. It has been found that these drag/lift ratios are only slightly dependent upon speed (except as speed influences trim) and mean wetted-length/beam ratio. These are the hydrodynamic characteristics illustrated:

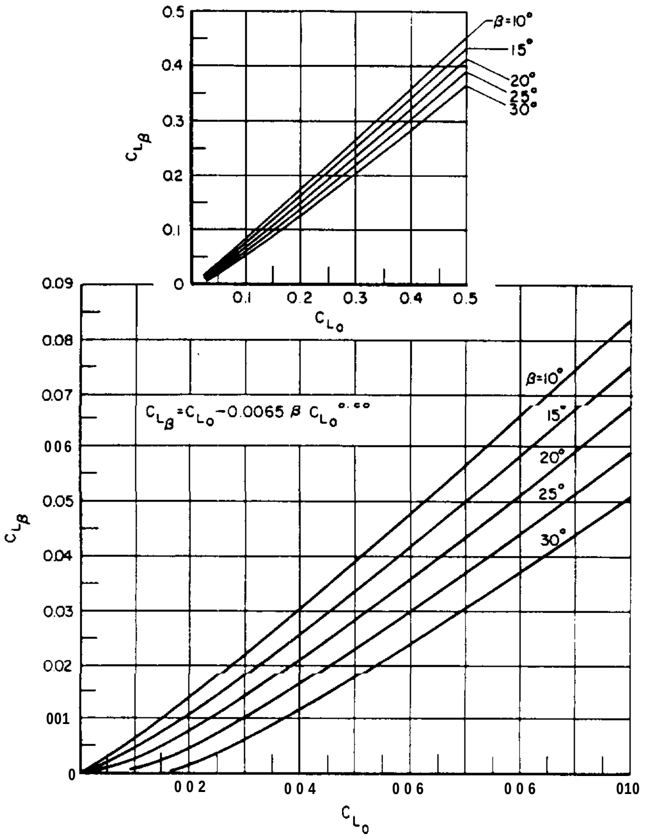

Figure 10. Lift Coefficient of a Deadrise Planing Surface.

1) The drag/lift ratio is primarily dependent upon trim angle with the optimum trim at approximately 4 degrees.
2) At trim angles of less than 4 degrees, the viscous drag due to bottom friction dominates, while at larger trims, pressure drag due to dynamic lift generation dominates. For typical hull forms, low trim angles will also immerse the bow, further adding to the total resistance.
3) The drag/lift ratio increases significantly with increasing bottom deadrise—especially at low trim angles.
4) For trim angles less than 4 degrees, the drag/lift ratio decreases with increasing trim angle. This is a beneficial feature that reduces the drag penalty due to overloading since, all other parameters being equal, planing hull trim angles increase with increased loading.
5) If the sole design requirement was to provide minimum power at high speed in smooth water, then it would be concluded, from Figure 11 that a flat-bottom hull planing at a trim angle of approximately 4 degrees would be the ideal combination of hull form and trim attitude. Unfortunately, this selection would be unacceptable for several practical reasons:
    a) At high speed, the combination of β = 0 degrees and τ = 4 degrees most likely will result in longitudinal instability-“porpoising.”

b) When operating in a seaway, the flat bottom hull will develop severe wave-impact accelerations (as discussed in a subsequent section on seakeeping).

c) Trim angles less than 4 degrees are desirable to reduce wave-impact accelerations (as discussed in a subsequent section on seakeeping).

6) Early planing hull designs were guided almost entirely by the requirement for high speed in calm water so that low hull deadrise angles were used and loaded to attain optimum trim angle. Modern planing hull design is so dominated by seakeeping considerations that reasonable compromises in smooth water performance are not only tolerated but sought. Consequently, good planing hull forms will have moderate deadrise at the stern (approximately 15 degrees) increasing to high deadrise (approximately 50 degrees) at the bow. To achieve the desirable low trim angles in rough water, provision is made to shift ballast or fuel into bow tanks. If this design feature is not possible, then transom flaps are installed to reduce the trim as necessary. These trim control techniques allow for setting the optimum trim angles in both calm and rough water. Design procedures for selecting the size and deflection of trim flaps are given by Savirsky and Brown [7].

The results of systematic series tests (Series 62 and 65) have been synthesized into the results given in Figure 5 which show the drag/lift ratio for efficient planing hulls as a function of speed for various slenderness or displacement/length ratios. The curves, which are for a displacement of 100,000 lbs, represent the state of the art for efficient planing hulls and do not represent any one hull over the entire speed range. At $F_\nabla \leqslant 2.0$, corresponding to the cruise speed range for most naval craft, the longer hulls have substantially less resistance than the shorter ones. There is only a small effect of slenderness ratio at $F_\nabla = 3.0$ and a moderate increase in resistance with increasing slenderness ratio for $F_\nabla \geqslant 3.0$. It can also be seen that the long hulls have little or no hump drag but do have greater resistance at high speed.

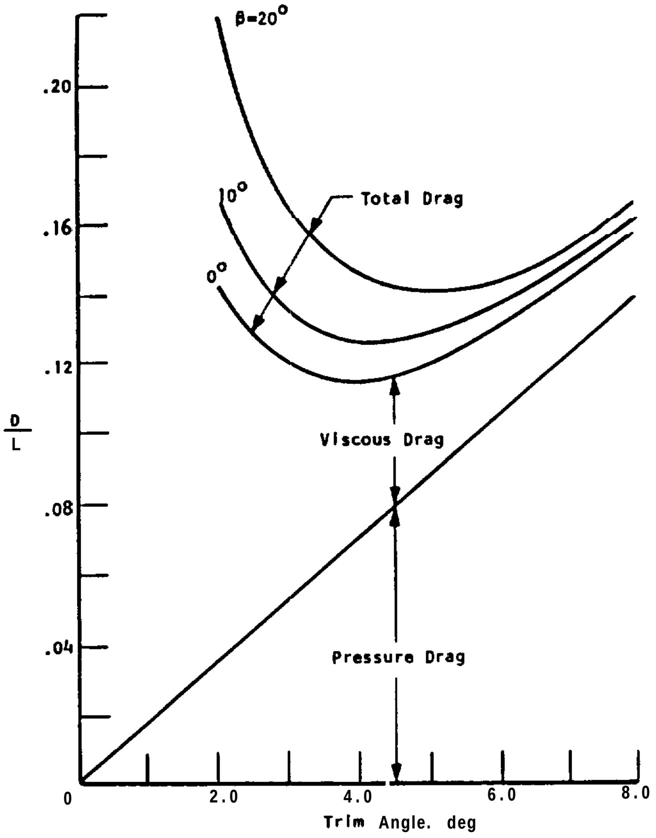

Figure 11. Variation of Drag-Lift Ratio for Prismatic Planing Surfaces.

Center of Pressure and Trim

Because trim angle is such a critical planing parameter, as discussed above under lift and drag, trim control devices such as transom flaps or longitudinal transfer of fuel or ballast are used to achieve the desired running attitude. For example, low trim reduces impact accelerations at high speed in head seas, high trim is required for maximum speed in smooth water and for operating in following seas.

The center of pressure of planing hulls is calculated by means of a semiempirical equation given in Figure 12. It shows a variation in center of pressure from 33 percent of the mean wetted length forward of the transom at low speed to 75 percent forward at high speed.

Equilibrium Conditions

For a planing hull having a specified length, beam, deadrise, displacement, center of gravity, and thrust line, there is a relation between running trim angle and speed at which the hull is in equilibrium. This equilibrium trim angle is easily computed using the basic hull technology just described and determines the drag/lift ratio of the boat as plotted in Figure 11. Typical curves of trim and resistance as a function of speed for conventional planing craft are demonstrated in Figure 13 for hulls of various length/beam ratios. It is seen that, as speed increases, the craft trim and resistance increase to a so-called "hump" value and then decrease as the speed is further increased. The hump trim and resistance decrease with increasing length/beam ratio and are barely noticeable at high length/beam ratios.

It is interesting to observe that, at volume Froude numbers (F_∇) between 2.5 and 3.5, the drag is essentially constant and independent of length/beam ratio so that increases in installed power will result in relatively large increases in speed. At volume Froude numbers greater than 3.5 to 4.0, the drag will moderately increase as the length/beam ratio increases.

Simply stated, when given a fixed displacement, the designer should attempt to configure the planing bottom to be as long and as narrow as possible-consistent with the requirements of internal arrangements and transverse stability. Fortunately (as will be shown) a high length/beam ratio hull is also very desirable for good performance in a seaway.

A review of proportions of past planing hull designs indicates that the preponderance of constructed boats had length/beam ratios between 3 and 5, with large numbers of commercial and recreational craft being in the ranges between 3 and 4. It is these craft which experience pronounced hump trim and high resistance characteristics—a performance pattern which even nautically-oriented observers so typically associate with planing boats. In recent years, the design trend has been to length/beam ratios in excess of 5.0—even at the expense of compromising the internal arrangements. This results in a substantial reduction or even elimination of the “hump” problem, as well as a substantial reduction in drag in the preplaning speed range.

ROUGH WATER PERFORMANCE

Perhaps the greatest demand imposed on today’s designers of planing hulls is to develop hull forms with good operational capability in a seaway.

Traditionally, planing hulls have been characterized as small boats with no rough water capability. It should be recognized however, that such hulls were designed almost entirely for high speed in calm water-culminating in a hull form and loading combination which resulted in unacceptable seakeeping qualities in even moderate sea states.

Recent research in planing hull seakeeping technology have quantified the relations between hull form, loading, speed/length ratio, sea state and the expected added resistance, motions, and, most importantly, wave impact accelerations [7]. In fact, the designer now has the tools to optimize the planing hull for specified operational requirements in both smooth and rough water. An example of such an optimization was given by Savitsky, Roper, and Benen [8].

A brief summary of the most important seakeeping technology and its effects upon planing hull design is given below.

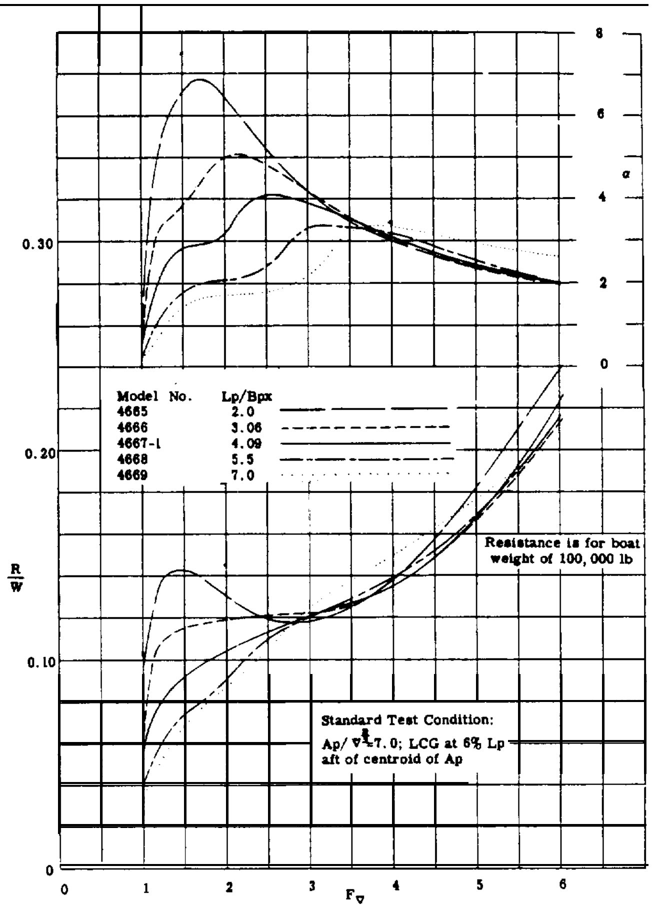

Figure 13. Drag/Lift Ratio and Angle of Attack Versus Froude Number for Five Models of Series 62.

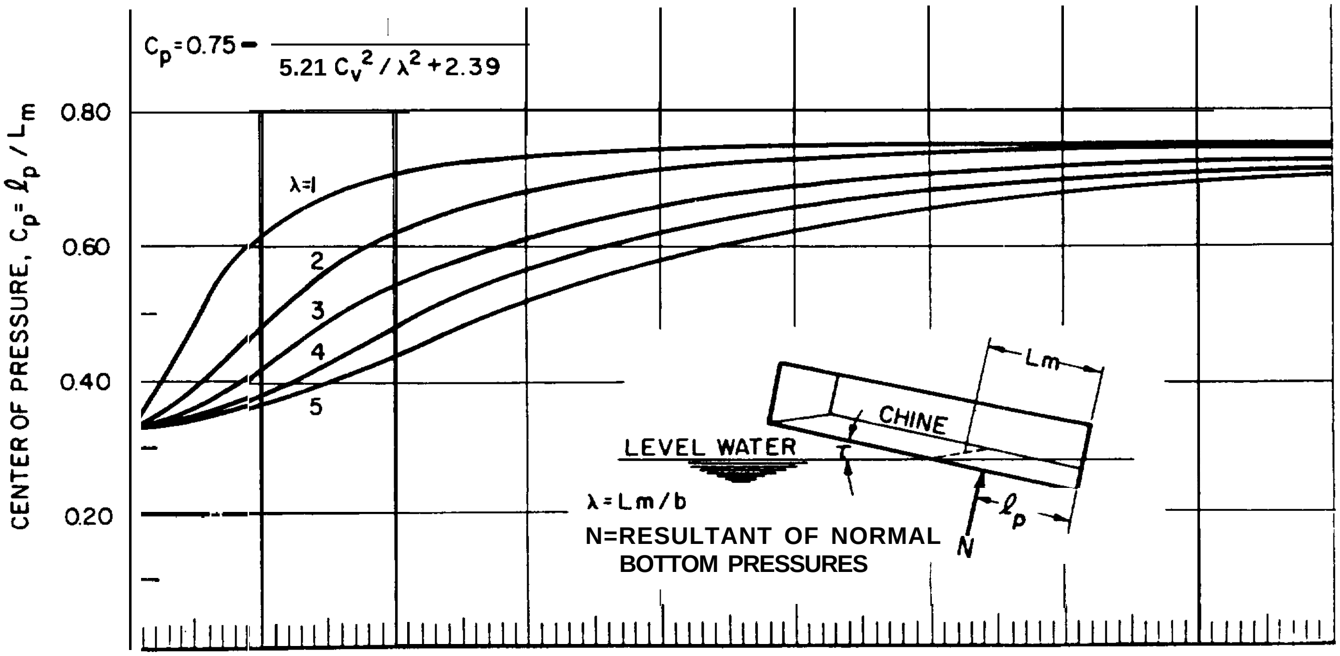

Figure 12. Center of Pressure of Planing Surfaces.

Wave Impact Acceleration

The accelerations from impacts in waves are not linearly dependent upon wave height. As a consequence, the linear superposition techniques developed for seakeeping analysis of displacement ships are not applicable to planing hulls at high speeds. Model tests must therefore be carried out in irregular seas. Based on Fridsma's analysis of model tests in irregular waves. the average impact acceleration at the center of gravity of a planing hull operating in irregular head seas having a Pierson-Moskowitz spectrum, can be represented by the following empirical equation [7]:

$$\bar{n}_{CG} = 0.0104(H_{1/3}/b + 0.084)\tau/4(5/3 - \beta/30)(V_K/\sqrt{L})^2(L/b)/C_\Delta$$

where:

$\bar{n}_{CG}$ = average center of gravity acceleration, g's
$H_{1/3}$ = significant wave height. ft., (average of $\frac{1}{3}$ highest waves)
τ = equilibrium trim angle, deg
β = deadrise angle. deg
V_K = speed, knots
L = load waterline length. ft
b = beam, ft
C_Δ = beam loading coefficient, Δ/wb^3
w = weight density of water. lbs/ft^3

The average 1/Nth highest acceleration. $\bar{n}_{1/N}$, is related to the average acceleration $\bar{n}$:

$$\bar{n}_{1/N} = \bar{n}(1 + \log_e N)$$

Therefore, the 1/3 highest and the 1/10 highest are, respectively 2.1 and 3.3 times the average acceleration.

The limits of applicability of these empirical equations are identified in Reference [7].

Several interesting and useful design conclusions result from an examination of the impact acceleration equation. All other conditions being equal:

1) The impact accelerations are linearly dependent upon equilibrium trim angle. Hence, they are easily reduced by a reduction in trim angle through the use of ballast transfer or trim flaps.
2) The impact accelerations for equal trim angles are inversely proportional to the deadrise angle-large increases in deadrise result in large decreases in impact acceleration.
3) The impact accelerations vary inversely with beam loading coefficient $C_\Delta = \Delta/wb^3$ or as the cube of the beam. Thus, even a 10-percent decrease in the beam is expected to reduce the accelerations by nearly 30 percent. A recent planing hull design incorporated a double chine hull as shown in Figure 14. The upper chine provided the beam necessary for roll stability at low speed and the lower chine, which caused flow separation during the impact process, provided the narrower beam desirable for reduction of wave impact loads. Full scale test results for the hull form were presented by Blount and Hankley [10].
4) Although it appears from the impact equation that acceleration increase with increasing L/b, the ultimate effect is to reduce the accelerations. Increasing L/b for a given hull displacement leads to a reduction in beam which, in turn. increases C_Δ by the cube of increasing L/b, thus resulting in a reduction in impact loads.
5) Accelerations are proportional to the significant wave height in irregular seas and increase as the speed squared

Figure 15 presents a graphical representation of the trim and deadrise effects upon the 1/10-highest impact accelerations expected to be experienced by a 200-foot planing hull running at 50 knots in seas of 10-foot significant wave height. If a reduction in impact acceleration were the only operational consideration, a planing hull would be designed with high deadrise; a longitudinal weight distribution such that the craft would run at a very low trim angle; and a narrow beam to obtain a high beam loading. Unfortunately, while this combination of design and operating parameters would indeed yield small im-

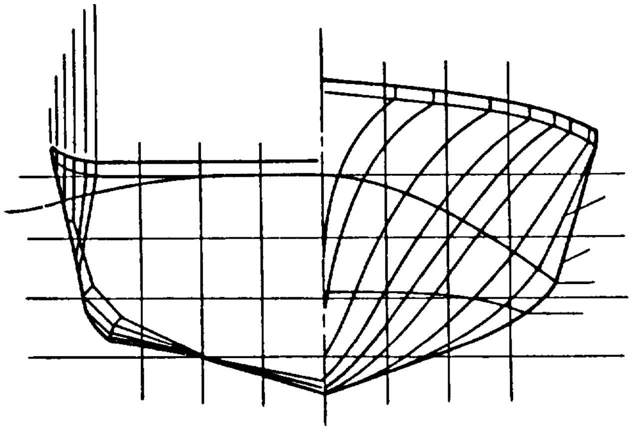

Figure 14. Body Plan for Modern Double-Chine Planing Hull.

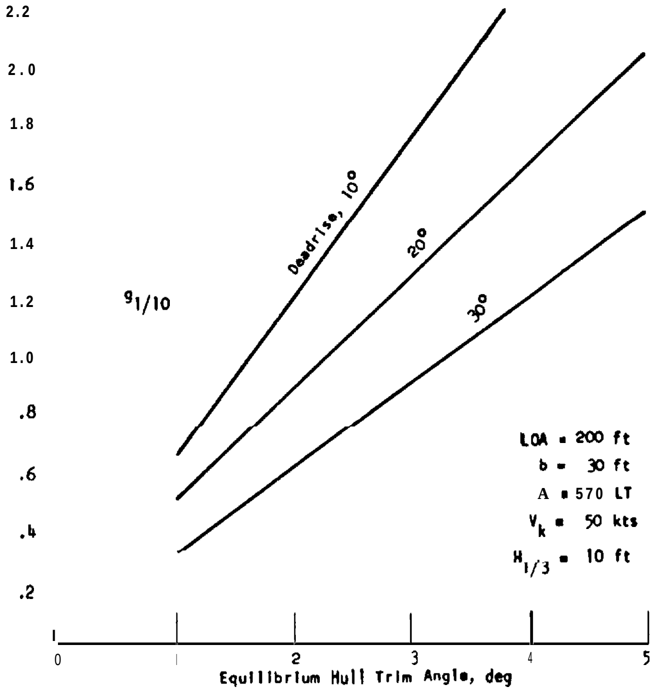

Figure 15. CG Impact Acceleration in Head Seas.

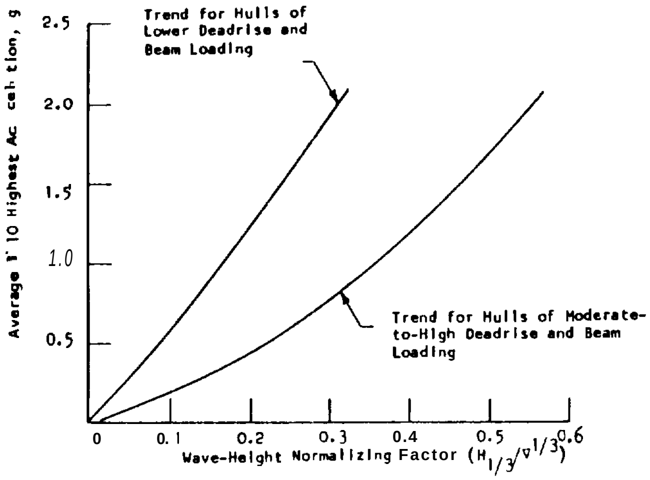

Figure 16. Typical CG Accelerations for Planing Hulls $F_\nabla \approx 3.0$

pact accelerations, it will also develop large hydrodynamic resistance and have reduced internal volume. An acceptable design must establish the best compromise between resistance, impact acceleration, and total useful volume. The technology for developing a design philosophy for such effective trade-offs is in hand.

The actual average l/IO-highest acceleration levels as a function of non-dimensional wave height obtained in full-scale trials of planing hulls operating at $F_\nabla = 3$ is shown in Figure 16. The upper curve is representative of hulls with lower deadrise and beam loading-typical of planing craft designed a decade ago. The lower curve shows the trend for modern, more useful planing hulls designed with moderate to high deadrise and beam loading. It is seen that recent hull designs experience less than one-half the acceleration levels measured on earlier planing forms. For the 20-degree-deadrise hull specified on Figure 15, $H_{1/3\nabla}^{1/3} = 0.37$ and, from Figure 16 it is expected that at 50 knots, the l/IO-highest CG acceleration will be approximately lg-a rather modest load for a 50-knot speed capability. Future seakeeping research should result in additional reductions in "g" loadings while still maintaining practical hull form.

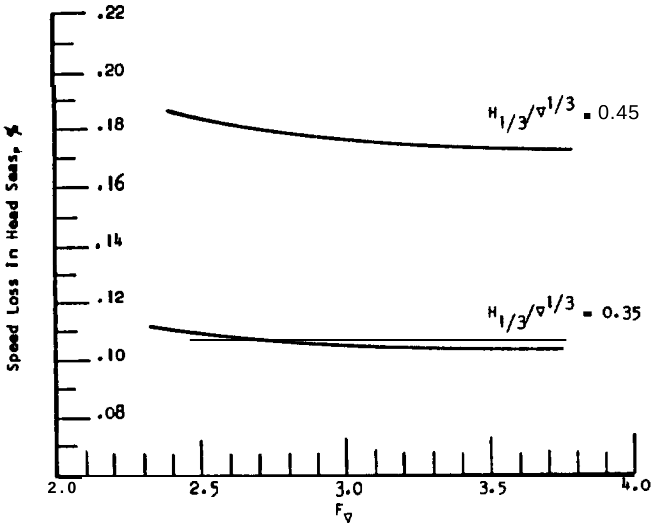

Figure 17. Speed Loss in a Seaway for Typical High L/B Planing Hull (at Constant Power).

Speed Loss in a Seaway

In addition to demonstrating reduced impact accelerations, it is also essential that the speed loss in waves be acceptably small. The results of recent model tests, of a hull form such as shown in Figure 14, have indicated only modest resistance increases in irregular seas. These data have been used to predict the speed loss in waves at constant power and the results are shown in Figure 17. It is seen that, for $H_{1/3}/\nabla^{1/3} = 0.35$ (corresponding to a 10-foot wave for the 200-foot planing hull in Figure 15), the speed loss is approximately 17 percent. Although Figure 17 indicates only a small reduction in speed loss with increasing F_∇, there are other combinations of hull loading and form which result in larger speed losses when F_∇ is increased. However, for most high length/beam ratio planing hulls with moderate deadrise, the speed loss in a seaway is primarily dependent upon significant wave height, and to a much smaller extent, upon planing speed.

Relative to the effect of geometric form, it has been found from model tests that the speed loss in waves increases with decreasing deadrise angle and/or decreasing trim angle-particularly if substantial bow immersion is associated with low trim.

Pitch und Heave Motions in a Seaway

The pitch and heave motions in a seaway are usually largest in the displacement speed range when the wave encounter period equal to the natural period in heave and/or pitch. At planing speeds, the motions are essentially constant with speed, being approximately one-half those in the displacement speed range. For high length/beam

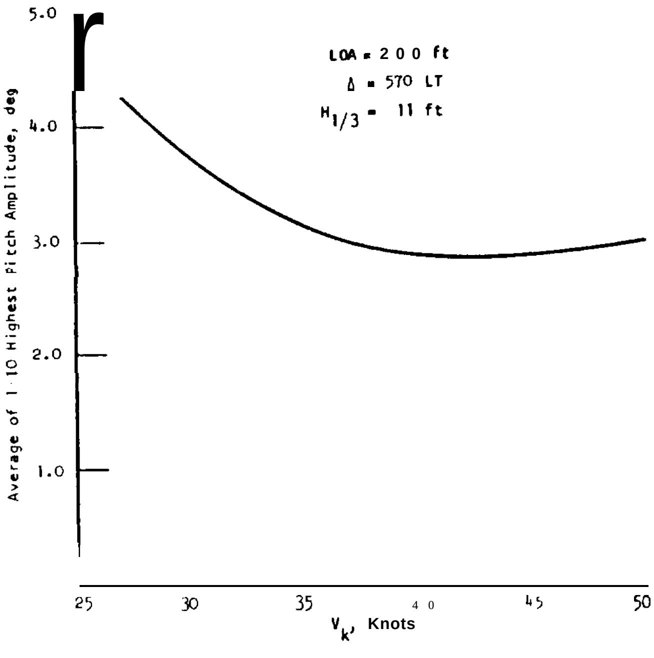

Figure 18. Pitch Motions of a High Length-Beam Ratio Planing Hull in Head Seas.

ratio hull forms, the pitch motions are expected to be tolerably small. Figure 18 shows the expected 1/10-highest pitch amplitude as a function of speed for a 200-foot planing hull operating in seas with an 11-foot significant wave height. These plots are based on the results of recent model and full scale tests scaled to a 200-foot planing craft [10]. It is seen that, for speeds in excess of 35 knots, the 1/10-highest pitch amplitude is only about ± 3 degrees.

Roll Motions in a Seaway

Recently, attention has been paid to reducing the rolling motions of a planing craft in the preplaning range in order to provide a more stable platform for military systems and to improve habitability. The problem has been to increase the hydrodynamic roll damping which is inherently small even for hard chine planing hulls. Active roll-fin-stabilized systems have been used with good success at speeds in excess of 10 knots when roll stabilization was necessary. The effectiveness of active roll fins, whose area was approximately 1 percent of the hull waterplane area, is demonstrated in Figure 19. These results are based on recent full-scale trials for a ratio $H_{1/3}/\nabla^{1/3} = 0.50$. It is seen that, in beam seas, the roll motions were reduced by a factor of 2, in stern quartering seas by a factor of 2.2, and in bow quartering seas by a factor of 4. Such large attenuations in roll improve the mission effectiveness and the crew's efficiency. The speed loss due to the added drag of the roll fins is easily accepted in light of the added stabilization and comfort they provide. Also, at planing speeds, the fins can be retracted to eliminate this appendage drag.

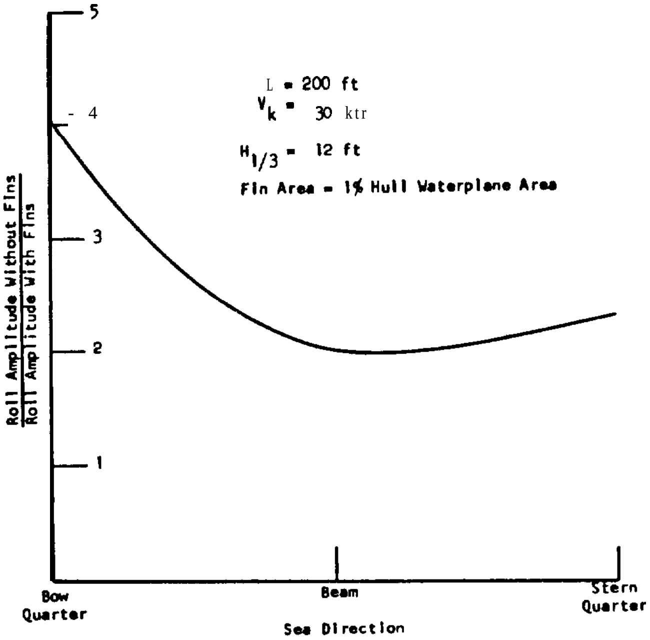

Figure 19. Effect of Activated Roll-Fin Stabilization.

Habitability

Criteria for evaluating the effect of ride quality on the performance effectiveness of crew members in high speed marine vehicles continue to be reviewed but, as yet, there is no agreement on any one standard. For the purposes of this paper, reference is made to the International Standards Organization standard reported in MIL-STD-1422B and by Von Gierke. This criterion uses vertical accelerations and frequencies of occurrence as a measure of human tolerance. Criteria are shown in Figure 20 where curves of 1/3-octave RMS g's are plotted against center frequency of the 1/3-octave bands for tolerance levels corresponding to 1, 2.5, 4 and 8-hour durations. The ISO standard is for center frequencies greater than 1 Hz and corresponds to levels of fatigue-decreased proficiency. Von Gierke's criterion is for center frequencies less than 1 Hz and corresponds to 15-percent motion sickness incidence.

Superposed on this curve are measured acceleration levels for a high length/beam planing hull of moderate deadrise operating at speed/length ratios of approximately 2, 3, and 4 in an irregular wave having a significant wave height of approximately 30 percent of the hull beam. It is seen that, using these criteria, the accelerations encountered at high speed indicate a tolerable ride up to 4 hours duration. This evaluation is substantiated by personnel aboard even though observers not on the boat felt the visual appearance including the flying spray indicated a rough ride.

DIRECTIONAL STABILITY/MANEUVERABILITY/CONTROL

Directional stability, maneuverability, and control have received little research attention during the entire period of planing hull development. There have been rotating arm tests on specific hulls to enable performance

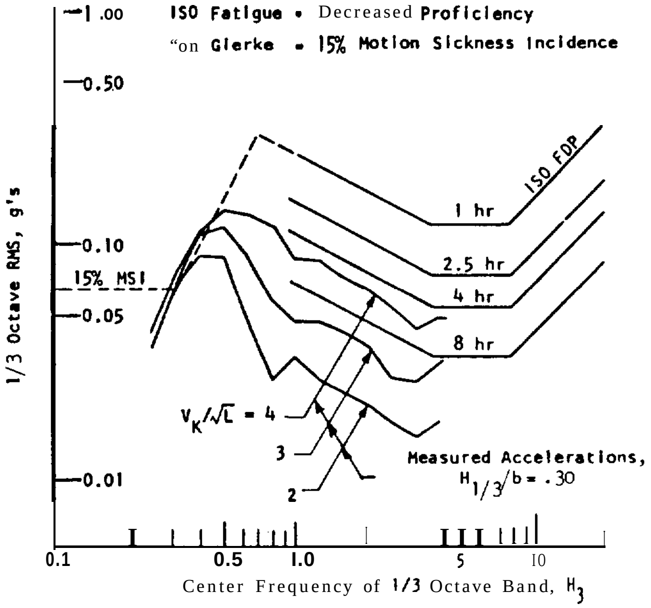

Figure 20. Limits of Human Tolerance to Vertical Accelerations.

predictions to be made, but, there is currently no published procedure for estimating the hydrodynamic derivatives required for a reliable prediction of coursekeeping stability, longitudinal stability, and turning.

In the low speed range, the craft may be statically unstable on course because the bow has not yet trimmed up. However, with active rudder control, it can be made dynamically stable. In the planing speed range, when the craft has positive trim, it usually has static and dynamic stability. If instability does exist at planing speeds, it is easily eliminated by increasing the skeg area at the expense of a minor increase in drag.

At very high planing speeds the trim decreases so that portions of the convex bow become exposed to high water velocities. If the convex geometry of the bow (both transverse and longitudinal) is severe, large negative pressures will develop and possibly result in roll and/or yaw instabilities. In some instances the judicious placement of longitudinal "spray" strips may correct the problem, but this is not always the case.

Directional control rudders, either mounted flush under the hull bottom or stern-mounted in a surface-piercing position, are of such size and vertical location as to develop adequate coupled yaw and roll moments to cause the boat to heel into the turn and are located in the wake of the propellers whenever possible. High speed turning diameters are in the order of 10 times the boat length and are mainly dependent on the rudder characteristics. In the displacement speed range, the turning diameters are considerably less-especially for twin propeller installations where asymmetric thrust can be used to assist turning. An important hydrodynamic consideration in rudder design is the avoidance of cavitation and ventilation of these control surfaces if high speed tight turns are to be achieved. Chord-wise fences on the stern-mounted rudders can prevent ventilation. Cavitation inception is delayed to higher speeds by the traditional means of reducing rudder thickness and lift coefficient.

Because of the usual roll-yaw moment coupling, a roll bias due to unbalanced engine torque on narrow beam planing hulls can require some rudder deflection in order to keep the boat on straight course. The addition of a fixed trailing edge tab on the outboard edge of the transom will provide a roll moment to counter this engine torque, avoiding the necessity for rudder deflection to maintain a straight course.

Longitudinal instability (porpoising) has not been a serious problem. If it does occur, it can be corrected by means of trim flaps which reduce boat trim or forward movement of the center of gravity which also causes the boat trim to decrease.

PROPULSORS

Given the option to select an optimum thruster, one will find a preponderance of fixed-pitch conventional-section propellers on most craft operating up to speeds of 3.5 knots. However, above speeds of 30 knots the trend is to use cambered section blades with transition to supercavitation sections at about 40 knots and above. The majority of applicants utilize these fixed pitch propellers on inclined shafts with maximum shaft angles of 15 degrees in low speeds and 10 to 12 degrees at 40 knots. Some newer designs of very high speed craft utilize right angle (inboard/outboard) drives or surface propellers. Many of the right angle drive units are installed so as to permit the propeller to operate in a surface mode. Experimental data indicate that above 30 knots, a 10 to 15 percent increase in speed is normal by changing from a submerged propeller to a surface propeller with no other changes. It can be projected that surface propellers will become commonplace as the drive system mechanism becomes more reliable.

Although a number of other propulsor types (i.e. ventilated propellers, partially-submerged propellers, waterjets, etc.), do offer some promising performance features, their application to planing craft has been limited so that operational experence is also limited.

Subcavitating Propellers

Conventional subcavitating propellers of commercial manufacture are most commonly used on planing craft up to speeds of approximately 30 knots. Above 30 knots, these propellers have had serious erosion problems. Through custom design and close tolerance manufacturing the useful speed of these propellers may be increased to approximately 35 knots

Propeller characteristics are obtained from standard series propeller charts, such as the Gawn-Burrill series [11]. This series covers a range of blade area ratios and pitch-diameter ratios for a series of cavitation numbers. The developed blade outlines are of elliptical shape and the sections are ogive (flat face, circular-arc back. and sharp leading and trailing edges). While demonstrating good performance characteristics in the fully wetted condition, these sections sustain serious thrust breakdown and losses in efficiency when cavitation occurs. Figure 21 demonstrates the thrust breakdown for expanded blade-area ratios of 0.50 and 0.80 for cavitation numbers down to 1.0 (28 knots). It is seen that large propeller diameters and large blade-area ratios are required to reduce the propeller loading (K-r) and, hence, delay thrust breakdown at high speeds. This is an impractical solution for the designer since struts, low RPM, and large reduction gears are required, especially if a gas turbine power plant is used.

The Gawn-Burrill series test data do not extend to design speeds beyond 38 knots. However, as indicated by DuCane, it is believed that, even for the highest blade-area ratios, cavitation will no longer be avoidable and severe thrust and torque breakdown accompanied by efficiency losses will occur, spreading gradually to higher advance ratios (lighter propeller loadings) with reduced propeller cavitation numbers.

Fully-Cavitating Propellers

Since planing hulls often operate at speeds in excess of 35 knots, propeller cavitation will be unavoidable. For-

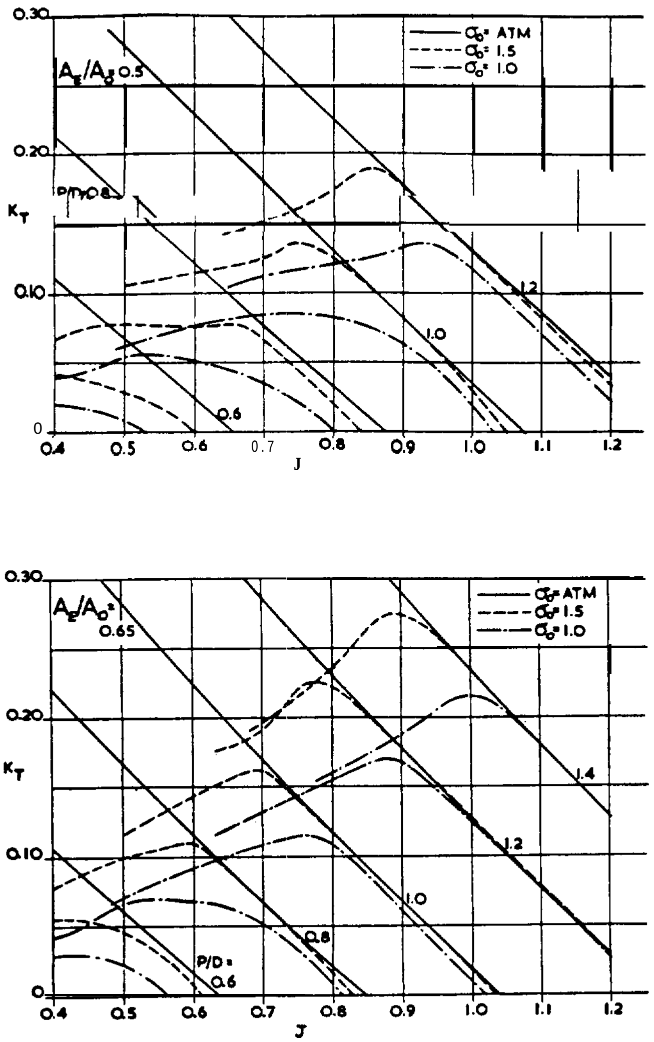

Figure 21. Cavitation Characteristics of Gawn-Burrill Propeller.

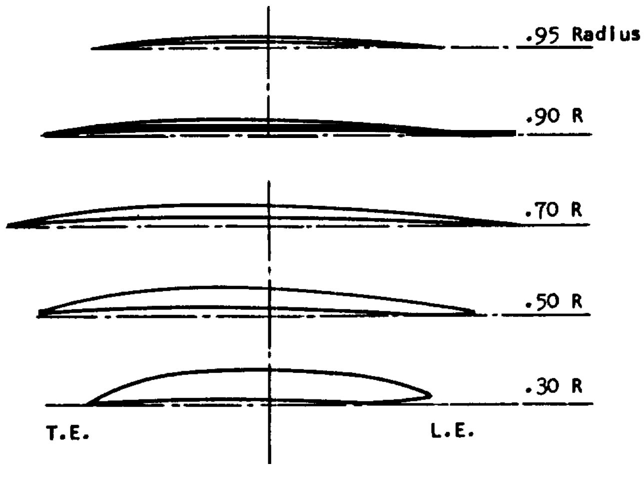

Figure 22. Blade Sections for Newton-Rader Fully Cavitated Propeller.

tunately, there is a propeller series available which is designed to accommodate cavitation without the serious performance deterioration associated with the ogive propeller. This is the Newton-Rader [13] propeller which has cambered sections such as shown in Figure 22. For typical advance ratios at design speed, the propeller develops a cavity which extends over more than 85 percent of the blade surface and beyond the trailing edge. They are frequently referred to as "fully-cavitating" or "transcavitating" as distinct from the supercavitating propellers. Figure 23 compares the efficiencies of the Gawn-Burrill and Newton-Rader propellers at a cavitation number of 0.50. At the usual design values of advance coefficient 0.7 ≤ J ≤ 1.0, the shaded area represents the gain in efficiency associated with the Newton-Rader propeller. At J = 0.80, for example, there is a 22-percent gain in efficiency even though the blade-area ratio of the Newton-Rader propeller is only two-thirds that of the Gawn-Burrill propeller. Further, there is no significant compromise in efficiencies at low speeds when the propeller is fully wetted.

The use of a fully-cavitating propeller permits an increase in loading, resulting in smaller propeller diameters and higher RPM. Although this usually causes a reduction in propeller efficiency, the overall propulsive coefficient (OPC) may actually increase due to the reduction in appendage drag associated with reduced shaft angle and shorter strut lengths. In addition, there should be a weight reduction associated with smaller reduction gears, propellers, shafts, etc.

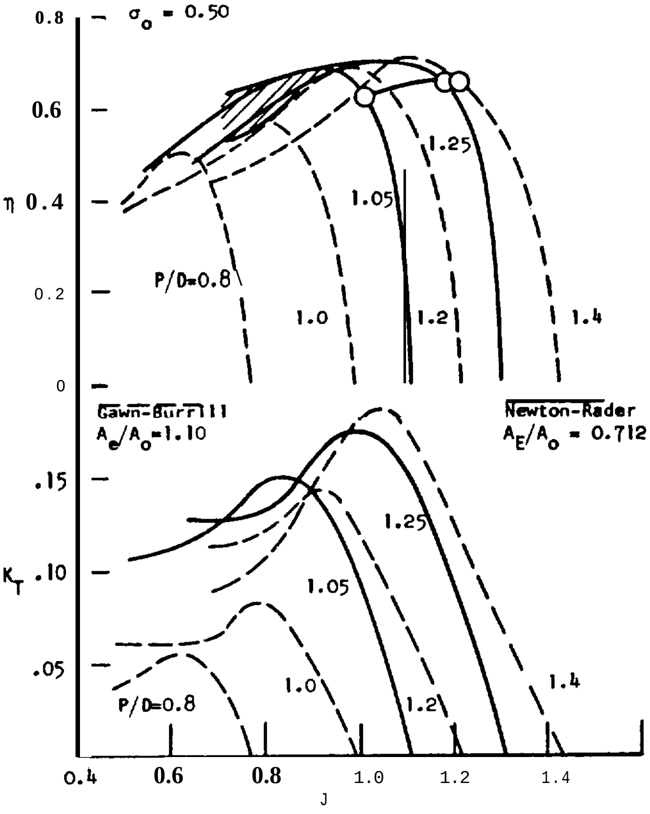

Figure 23. Comparison of Gawn-Burrill and Newton-Rader Propellers at Low Cavitation Number.

Most Newton-Rader propellers installed on fast patrol boats have been constructed of high-tensile, nickel-aluminum bronze; have had blade-area ratios of approximately 0.7; and a working stress level of less than 15,000 psi. This compares with 80,000 psi ultimate tensile strength of the material. Blade erosion has been minimal even for extended service at speeds up to 55 knots. The American Bureau of Shipping has certified a Newton-Rader propeller designed for a high speed planing yacht. These propellers have been fabricated by foundries that normally produce small boat propellers in large quantities. The price has been very modest. Design procedures useful in selecting the optimum Newton-Rader propeller are given by Blount and Hankely [10].

Propulsive Coefficients

Propulsive data, the transfer functions which describe hull-thrust interrelations, are essential for accurate speed-power predictions. Hadler and Hubble [14] developed and presented analytical models for propulsive data for single, twin, and four screw planing craft as a function of shaft angle. These data agree very well with a collection of model and full-scale experimental propulsive data reported by Blount and Fox [15].

Reference [15] relates to conditions of minimal propeller cavitation. The quantitative effects of cavitation on propulsive data are ill-defined although it has been observed that for cavitation numbers less than 1.7, cavitation effects are important modifiers of propulsive data and correlation factors so that full-scale speed-power performance will be less than predicted when neglecting cavitation. For the cavitated case, the required power should be calculated by the methods described by Blount and Fox [15] along with correlation experience reported by Blount and Hankley [IO].

HULL SHAPE DETAILS

Having described the effect of major hull proportions, loading. speed. etc., on the planing craft behavior, it is now of some interest to discuss hull shape details and their evolution over the years.

When planing speeds became possible around the turn of the century, due to the introduction of higher horsepower lighter weight engines, the hull form of the typical small launch evolved quickly from that of a rowing or sailing craft toward one with a broad stern and straight after buttocks. These characteristics kept the stern from "squatting," making higher speeds possible. But spray was a problem because a sheet of water would run well up the side before separating from the hull. For many years this was not only accepted but considered smart; more than one advertiser proudly pictured his craft racing along "with a bone in her teeth." The disadvantages of this phenomenon, i.e. deck wetness, increased resistance, and instability (in roll, pitch and yaw). were occasionally recognized over the years and attempts were made, sometimes successfully, to solve them by the application of spray rails. Correctly placed spray rails are indispensable in the design of high speed round bottom boats because they provide for the flow separation which is necessary at the boundaries of a planing surface.

In parallel with the development of the high speed round-bottom boat was the development of the high speed vee-bottom boat. The vee configuration, especially in the favored form with rather low deadrise and hollow sections, inherently provided for flow separation and good lift, **but** the characteristics which provided good lift in smooth water provided a hard, pounding ride in rough water.

Both round bottom and vee bottom boats retained a high length/beam ratio into the twenties. However, starting in the thirties there was an accelerating trend toward greater beam, primarily for reasons of increased internal volume and greater stability to carry the tophamper associated with increased cruising accommodations. Typical round bottom and vee bottom hull forms of the fifties are shown in Figures 24 and 25 respectively.

In due course many other hull forms were tried; for example, inverted vee, inverted vee with beveled chines, a W-shaped bottom, inverted bell sections, the so-called cathedral hulls, and many complex variations. Examples of all these are still being built. However, it is interesting to note that those designers and builders who observed

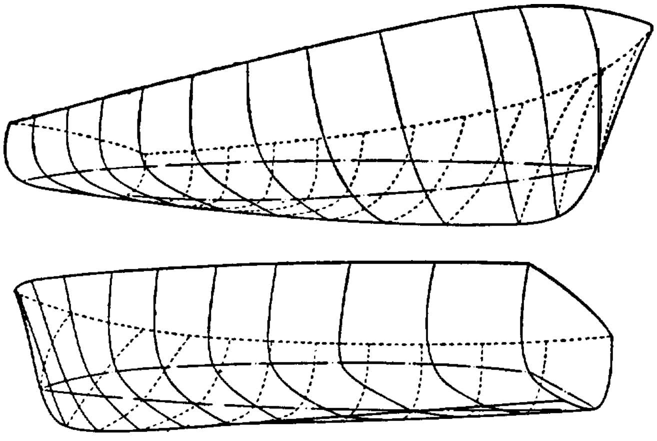

Figure 24. Round Bottom Sections.

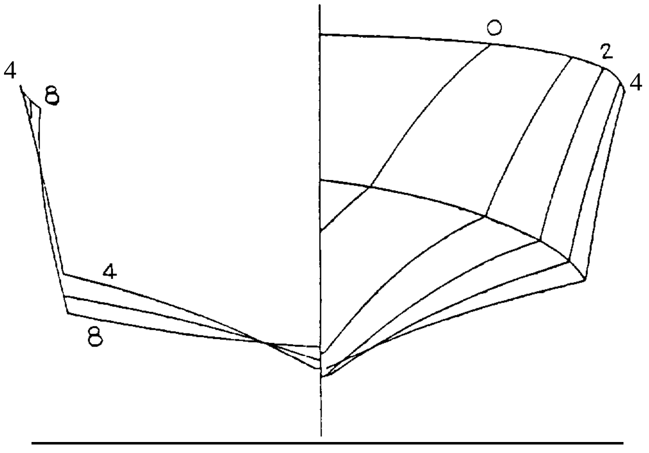

Figure 25. Concave Sections.

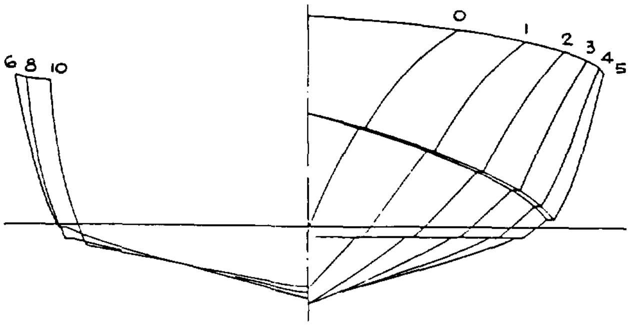

Figure 26. Recommended Chine Shape. (Please note that in the forebody this is virtually a round boat).

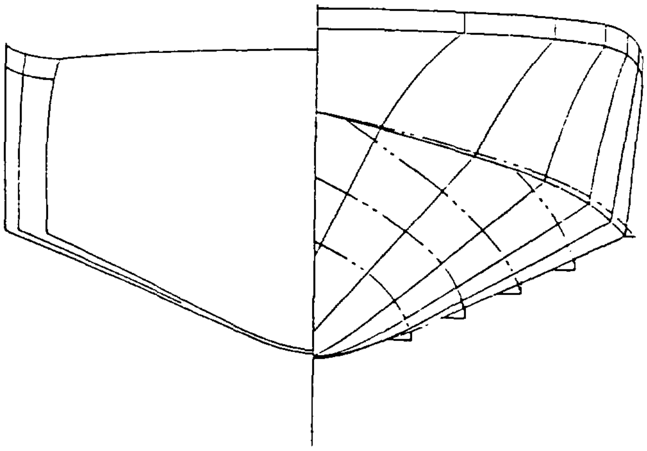

Figure 27. Deep V Section With Spray Strips.

their designs carefully and made improvements with each successive model are developing their designs along converging lines. As round bottom hulls were developed for greater speed and as vee bottom and cathedral hulls were developed for better seakeeping, they all tended to converge toward the same general hull shape, an example of which is shown in Figure 26, depicting a design of the sixties.

The incorporation of high deadrise was a major breakthrough in planing boat design. This took place in the 1950s when the first "deep vee" was built. An approximation to the body plan of this boat is shown in Figure 27. Prior to this, designers generally believed a boat had to be flat to plane although sea plane model data to the contrary had been available for decades. Another belief then current and still held by many is that, for good planing efficiency, the deadrise should be constant, that is, the hull should be a monohedron. Indeed, the "breakthrough" boat shown in Figure 27 is a monohedron. But, any monohedron can be improved because, for good seakeeping and handling, the amount of deadrise desirable in the bow is greater than that required at the stern, and the resistance penalty for a moderate amount of warp in the bottom is small, if any. In addition, too much deadrise at the stern reduces transverse stability. both at rest and when planing.

When comparing the relative merits of round and vee bottom boats it should be noted that some well-known studies have come to false conclusions because they compared a good design of one type with a poor design of the other type. It is important to point out that with proper sections and with spray rails for effective flow separation, a round bottom boat can be designed for both good rough water performance *and* good planing performance. In the same way, when the sections of a vee bottom boat are developed for good seakeeping and spray rails are located for good flow separation, it will be very similar to the highly developed round bilge boat. In particular, one type does not necessarily need more deadrise than the other.

Design Techniques

Although the design of planing hulls rests on a preponderance of science it still requires some intuition. A good example is the calculation of hydrodynamic performance in smooth water. The optimum planing surface to carry a given load at a given speed can easily be calculated. The problem for the designer is that the lowest resistance planing surface is always too wide for its length to be practical, and too small to be either useful or stable. The utilization of very efficient planing surfaces requires the use of more than one such surface per vehicle, spread out either laterally for roll stability as in the catamaran, or longitudinally for pitch stability as in the stepped boat, or both. The higher the speed the more specialized the design must be. Currently the ultimate seems to be a modern development of the hydroplane (invented many years ago) which rides on small areas of its sponsons and is balanced in pitch by riding on the propeller. At top speeds of over 1.50 mph and frequently over 200 mph, aerodynamic forces aggravate the already severe stability problems. Rough water operation is out of the question. In the design of boats of this type intuition coupled with experience predominates, but it is only in these extreme designs that highly efficient planing surfaces can be utilized. In some cases, efficient planing surfaces can be further improved by cambering their trailing edges. Cambering, which is amenable to calculation, increases the average pressure under the surface and thereby reduces the wetted area.

The point here is that boats (usually monohulls) which are intended for purposes other than racing must be artfully designed with greater length and beam than would be possible with the optimum planing bottom. This usually causes them to run at lower trim angles and have greater wetted areas than optimum. Whereas a perfectly flat surface is most efficient, some deadrise is required to provide good banking in turns, and a great deal more is required for good rough water ability. The way in which the intended service of the craft influences the choice of hull characteristics, and hence the possible technological advancement, will now be discussed:

Craft Types, Their Limitutions and Capabilities

Each craft type. taken here in the four broad categories of pleasure cruisers, ocean racers, crew boats, and patrol boats, has certain limitations that define the state of the art. Principal among these is rough water capability. In the case of ***pleasure cruisers*** the conflicting requirements among which a compromise must be reached are these: it is necessary to maximize the accommodations (volume) for a given length. This dictates a wide, deep boat, and many pleasure boats tend in this direction. But, for good seakeeping the hull should be long and narrow and because of stability requirements, the narrowness dictates that the boat must be low. For reasons such as this the cruising types, however comfortable and/or profitable they may be, do not define the state of technology for planing hulls.

Ocean racers seem to be locked into a single type of deep vee hull with virtually constant deadrise. However, they have brought about great advances in the design, construction, and installation of equipment and fittings suitable for use in such a rugged, high "g" environment. The limitation now seems to be the amount of punishment the crew is willing or able to take.

The hull form of ***crew*** boats has likewise become quite standardized. It is usually an approximately developable shape with moderate deadrise and somewhat more variation of deadrise with length than seen in ocean racers. Practical considerations such as cost of acquisition and operation limit the size (power) of engines and hence the speed of the boat. In most cases the actual speed of operation is about 25 knots and it is seldom over 30 knots. Therefore, crew boats do not define the state of technology for planing hulls.

The most significant advances in the hull form of planing boats have been made in the design of ***naval patrol bouts.*** These applications require moderately high speeds (although not as high as those of ocean racers) and the ability to maintain these speeds in water rough enough to cause the postponement of an ocean race. The hull form that was considered best for this purpose in the 1970s was simply a logical extension of the trends described in the history given earlier. This design, shown in Figure 14, incorporates features of both Figure 26 and Figure 27. The double chine, evident in the afterbody, is not an essential feature of the concept but facilitates the incorporation of several other features. This design has excellent seakeeping characteristics and good resistance characteristics. Recently a hull has been designed and model tested which not only has low vertical accelerations in rough water but which also has low resistance over the speed range. This is shown on Figure 28.

The model test revealed one area in which improvements can be made. It was observed that the exceedingly fine bow knifed into the water so easily that wave impact occurred, not on the bottom but under the topside flare. The fineness of the bow also necessitates greater freeboard than normally expected. The obvious development is to make the sections a little fuller so that when pitching into a wave there will be two light impacts rather than one larger one (even though in this design the single larger impact is much less than that experienced by the average planing boat). The question is whether or not these changes can be made without impairing the resistance characteristics which are probably due to the fine bow.

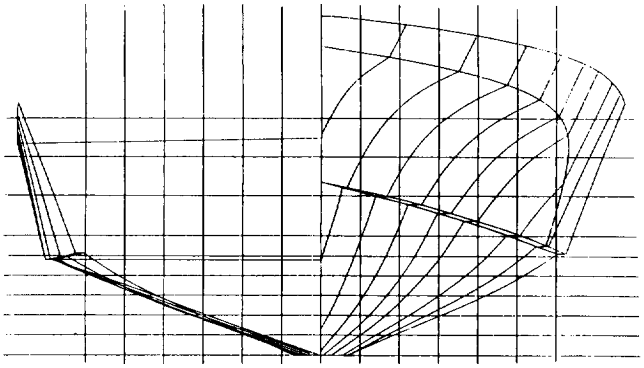

Figure 28. Recent hull design with both low vertical accelerations in rough water and low resistance over the speed range.

Hull Form Development

The concomitant characteristics of a fine bow and a relatively far aft location of the center of gravity brings up a problem with planing boat stability which is not yet fully understood. There seem to be two distinct cases. One, involving only transverse stability, was encountered as early as the 1950s. The other, which has only come to light in the last decade (except for some round bottom boats), involves both transverse and longitudinal stability. It is exhibited, as far as is known, by boats with centers of gravity unusually far forward and which have, consequently, very full waterlines and large longitudinal buttock curvature at the bow.

The former case seems to involve too much deadrise at the stern and too high a center of gravity. When a boat becomes unstable in this mode it usually just lies over until it planes stably on one side of the bottom.

The latter case is more serious because a boat, apparently planing stably in a normal attitude, can unexpectedly drop its bow to about zero trim and then, just as suddenly, roll over on its side and/or develop a yaw. At this writing the phenomenon seems to be due. at least in part, to extreme convexity of the waterlines and buttock profiles at the bow. Because so little is known about this problem it will only be said that this is a fertile field for experimentation and research.

STRUCTURE

Structural Loads

The most severe loads on a planing boat are the loads on the hull bottom due to the combined effects of the advance of the boat into waves and the heaving and pitching motions. The resultant pressures are called impact pressues. The maximum pressure of each impact exists only momentarily and over a small portion of the hull bottom. The location on the hull, the size of the area affected and the magnitude of maximum impact pressure vary with each wave encounter. A typical impact pressure distribution on a hull bottom is shown in Figure 29-note the very large peak pressure and the small area over which it acts. Thus, the average pressure over large areas

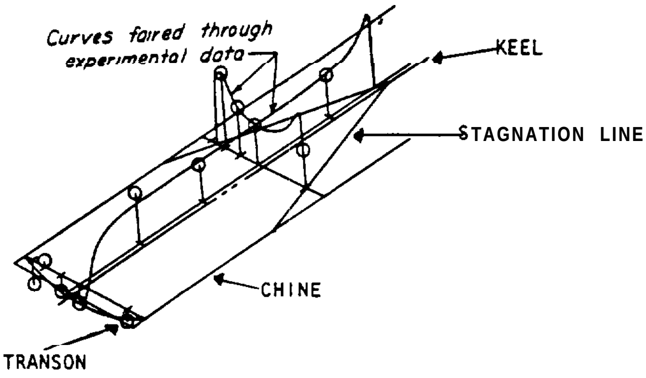

Figure 29. Typical Pressure Distribution During Impact of 30” Deadrise Hull.

of the bottom is substantially smaller than the average pressure over small local areas. As a consequence structural components such as plating and longitudinals must be designed for higher average pressures than transverse frames which support a greater area.

In general maximum impact pressures are encountered in the area from approximately 0.3L to 0.5L aft of the bow and reduce to approximately 50 percent of their maximum at the bow and 25 percent at the stern.

Several well-proven methods are available to predict the bottom loads on planing craft. The work of Heller-Jasper [16] and Allen-Jones [17] yield bottom design pressures based on known craft impact accelerations. Spencer’s [18] work, which deals exclusively with aluminum crew boats, gives bottom design pressures based on typical crew boat performance and dimensions. These local bottom loads are more critical in design than overall bending loads. Longitudinal hull bending moments can be estimated using the work of Heller-Jasper. Design loadings for the remainder of the structure (hull sides, decks, bulkheads, superstructures, etc.) are normally based on hydrostatic heads. Spencer’s work provides a useful summary of these loadings. U.S. Coast Guard Navigation and Vessel Inspection Circular No. 11-80, provides guidelines for loadings on aluminum passenger vessels having deep-vee hull forms, lengths from 60 to 130 feet. and speeds up to about 25 knots.

Classification societies’ procedures are not based on loadings for the specific craft and usually result in heavier structures when compared with the “tailored” design procedures described above.

It is not to be concluded that there is universal agreement on the magnitude and distribution of pressures to design planing hull structure-components. Most designers tend to use methods with which they have had success. It appears, however, that the Heller-Jasper method is the most favored.

Structural Design

The structural design of planing craft is a very straightforward procedure. Suitable materials are available, design tools are at hand, and successful examples abound. It remains for the designer to determine loads, select materials, and apply good engineering practice.

A conventional planing craft can be constructed successfully from any of the recognized structural materials (aluminum, steel, wood, composites). Ideally, the special qualities of the material selected should match the special requirements of the craft in question. Since most planing hulls are designed by the builder, the selection of material is heavily influenced by the builder’s facilities and capabilities.

Once design loads are determined, the analysis of the structure of a planing craft is a matter of recognizing the limitations of the selected material and using good engineering practice. It is important to consider all loads, identify all load paths and check the associated stresses and deflections to ensure that the structure is adequate but not overdesigned. When determining the characteristics of the major structural units (bottom, side, deck, bulkheads, superstructure) it is important to consider the structure as a whole and to provide structural continuity so that loads and stresses are transmitted and distributed smoothly throughout. In the process. it is often possible to simplify the structure by reducing the variety of structural components and by spacing them uniformly. This makes it easier to order materials and prevents many construction mistakes.

Since local loadings are usually more critical for planing craft than overall bending loads, it would appear that structural weight can be reduced by using small panels and thin plating. Such an approach can lead to a complex structure with many parts which is expensive to fabricate. This trade-off between cost and weight is difficult to evaluate accurately. It is usually resolved by considering shipyard capabilities and designing the lightest structure which the builder(s) involved can fabricate using existing techniques.

A comparison of structural weight versus overall length as a function of hull material was made by Sharples [26] where it was shown that the steel hulls are substantially heavier than aluminum hulls. Their use is, of course, justified based on lower cost and their fire-resistant qualities.

Based upon a survey of existing boats, it appears that the methods for selecting design loads and the materials used in construction are related to the displacement and speed of the craft. Figure 30 provides some empirical boundaries. It is seen that, for relatively low displacements, the GRP material is most commonly used. For displacements between approximately 45 and 100 LT and less and speeds in excess of 25 knots, aluminum is the preferred material. For larger displacements, steel is the most common material.

It is important, in the early stages of any design, to coordinate the structural arrangement and the general arrangement of the craft. This minimizes structural weight and enhances structural continuity by incorporating the main propulsion and armament foundations as well as tank bulkheads into the primary structure of the craft. It also reduces the number of non-structural bulkheads. It is also important to minimize the total enclosed volume

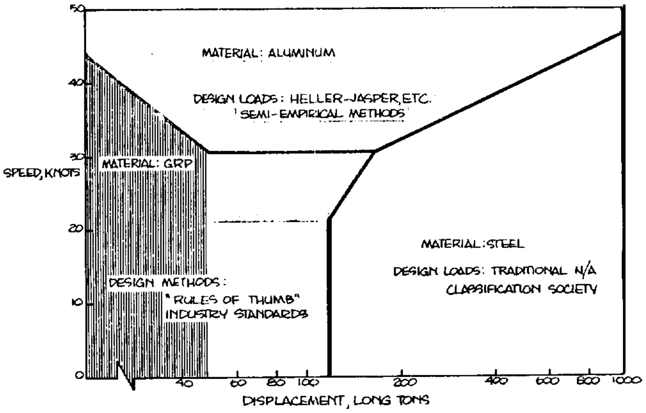

Figure 30. Methods Used to Select Design Loads and Scantlings.

within the limits of space and subdivision requirements. This helps to reduce not only structural weight but also the weight of other systems (piping, wiring, HVAC, etc) which are volume related.

While adequate methods for estimating design loads are available, it would be of great value to have a method of predicting design pressure distributions which takes into consideration the local geometry of the craft. As planing craft become larger (L/B increases) overall bending loads will become more critical. More data are needed to help evaluate the loads. Advances in composite materials, particularly for non-cored materials, offer opportunities for significant structural weight reductions. The challenge here will be to effect these improvements at reasonable cost.

As to the loadings commonly used, the smaller craft generally use "rules of thumb" which have been developed empirically over the years to the point where the number of failures has reached an acceptable level and must be considered good design for the craft to which they are applicable. The high speed boats must rely more on experimental data and empirical design methods such as Heller-Jasper, Jones-Allen and Spencer. These methods should produce good-to-excellent results. For the higher length and tonnage. standard naval architectural practices such as those of the classification societies will be adequate as long as high speed (30 + knots) and severe structural weight fraction restrictions are not required. Otherwise use must be made of experimental data and analytical methods.

USEFUL LOAD FRACTIONS

The trends for useful load fraction as well as weight fractions for structure, machinery, and other fixed weights for four existing planing hulls are shown in Figure 31. The term useful load includes military payload, ship fuel, potable water, ship's complement and effects, and stores. It is seen that useful load fraction increases with displacement so that, extrapolating to 600 tons, the useful load can be as large as 45 percent of the full load displacement.

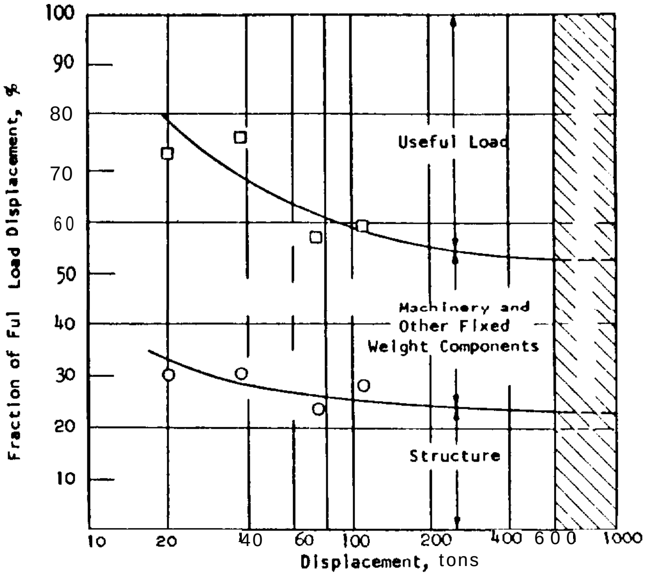

Figure 31. ‘D-ends for Various Load Fractions for Four Military Planing Hulls.

SURVIVABILITY

Survivability of planing craft can best be described as the capability of the boat to endure and remain afloat after exposure to a variety of predictable perilous situations such as extreme sea states, damage by fire, hostile action, underwater explosion and structural damage.

The features of hull design which influence seakeeping have already been discussed and model tests are an accepted method for evaluating survivability in extreme seas. Weapons attack includes missiles, medium and small caliber projectiles and. in the case of riverine craft, small arms fire. Damage can also come from blast bombs and underwater explosions.

As previously stated, the design of high performance craft is usually governed by operational considerations of power, speed, range and payload. Naval architects and designers are faced with having to choose power plants and propulsors as close to model test and calculated results as possible. This means that power margins of 35 to 50 percent used in big ship design are not feasible for high performance craft. Therefore, in many cases, survivability considerations become secondary. Nevertheless, a hazard analysis should be conducted as part of the design effort with trade-offs and compromises documented.

Specific features which contribute to the survival of craft are:

a) arrangement of vital systems
b) structural protection
c) damage control
d) compartmentation
e) ordnance stowage

Arrangement of vital equipment and systems should be such that parallel equipment is located in compartments as far from one another as practical to preclude the possibility of flooding adjacent compartments and destroying an entire system when the craft is hit by weapons fire or underwater explosion. If separation is not possible and an armor material can be used, then the equipment should be centralized. This centralized compartment should be sheltered behind as much armor and non-vital equipment as possible.

Structural protection would require the use of heavy ballistic armor, watertight and fire resistant bulkheads and damage tolerant primary structures. Ballistic protection against large weapons would be prohibitive because of the weight penalty, but watertight and fire resistant bulkheads are usually part of the design from the beginning and are therefore available for structural protection.

Damage control is designed into the craft with the use of systems such as damage repair equipment and stowage; shock mounting of equipment; bilge pumps; fire detection and extinguishing; and counterflooding. Normal practice by the U S Navy in small craft design has been to provide damage control equipment and stowage according to set rules. Delicate equipment is shock mounted according to equipment manufacturers instructions. Fire detection and extinguishing systems are sized and installed in conjunction with compartment use and size, with Halon being the most prevalent extinguishing agent. Flooding capability is usually limited to the forepeak and compartments with longitudinal watertight bulkheads.

Compartmentation is used to meet stability criteria and as part of damage control. Present criteria set a two-compartment standard of subdivision which requires that the floodable length be great enough to allow any two adjacent compartments to be flooded without loss of the craft due to foundering, and, in addition, that the craft retain sufficient stability in the damaged condition to keep the final hull trim angle within defined limits.

Ordnance stowage should be in compartments below the waterline as far as practicable. This becomes more difficult the smaller the craft becomes.

In conclusion, adequate survivability is difficult to design into small, fast combatant craft. All of the factors should be weighed and as much as possible should be incorporated into the design from the beginning. These craft will not accept heavy weight penalties. therefore, it challenges the naval architect and designers to incorporate innovative ideas to ensure survivability.

PRODUCIBILITY AND SUPPORTABILITY

The technology for constructing metal and fiber reinforced plastic planing hulls is well advanced and has been successfully applied. A summary of some of these construction techniques and the supportability of crafts constructed of these materials is discussed below:

ALUMINUM HULL CONSTRUCTION

Aluminum is an ideal material from which to construct fast patrol craft because it is readily available and easily fabricated into strong, lightweight structures without the need for exotic assembly techniques. Aluminum is homogenous, has omnidirectional strength characteristics, is highly corrosion resistant, is easily formed and joined, and can be assembled into hulls without the necessity for expensive tooling. If production volume warrants, very effective labor-saving techniques and equipment are available which can greatly decrease the manhour content of the end product. In sheet or plate it can easily and quickly cover large hull surfaces. The internal stiffening structure may be varied in size and location depending on craft configuration and service. Because of its formability, weldability, and easy handling properties, very complex hull forms can be produced.

Welding is one thing; welding aluminum is something else again, and welding an aluminum boat is an art and skill strictly unto itself. A great deal of training is necessary if one is to become a skilled aluminum shipyard welder. The availability of reliable, compact welding equipment was, more than any other factor, responsible for the growth of the aluminum boatbuilding industry. Welding has now reached a very high level of development. The latest “pulsed arc” equipment enables high quality welds on lighter gage sheets than had been possible previously. As technology proceeds at its present rapid pace, it is expected that even more efficient welding methods will be used. High frequency and electron beam welding processes are two which are presently being developed.

By far the most reliable method of inspecting welds is by x-raying (radiography). Just to say that a weld shall be “x-ray quality” is meaningless; the standards to which the x-rays are to be inspected must be clearly specified. The classification societies all publish such standards.

Where x-raying is not feasible, dye penetrant inspection may be used for surface defects. A dye is brushed over the welded area, then the excess wiped off. The dye is usually a fluorescent color or is visible under “black light,” readily revealing surface irregularities and cracks. A major problem with dye penetrant inspection is that all traces of the dye must be removed before any subsequent welding is done, and it will bleed through paint.

A skilled weld inspector can tell by the visual appearance of welds whether any of the common superficial defects exist, such as undercuts, cracks, arc strikes, craters, cold laps and surface porosity. Welds should be regular, uniform and have proper crown or contour.

The aluminum companies and welding equipment suppliers are valuable sources of information and guidance which should not be overlooked by those involved in aluminum design. fabrication, and maintenance. The vast array of alloys, hardnesses, sheet and plate thickness and widths and special extrusions which were offered by the aluminum companies just a few years ago are no longer economical to produce. The industry in the U.S.A. has basically standardized on alloy 5086 sheet and plate for marine applications.

The basic methods of cutting aluminum are shearing, sawing, and plasma cutting. Shearing and sawing are normally employed by shipyards of all sizes with well known procedures and equipment.

The plasma cutting process was developed in 1955, but has come into widespread use only recently. Plasma arc cutting heads for "electric eye" burning machines can cut stainless steel and other metals as well as aluminum. Far more exotic cutting machines with multiple-head torches, controlled by numerical tapes developed from computerized lofting, are also becoming very widely used in boatbuilding. Using plasma arc with numerical control, burning speeds on the order of 180 to 240 inches per minute (4½ to 6 meters/minute) are possible, and an excellent quality of cut is obtained.

The basic forming processes employed in boat construction include rolling, progressive bending, flanging, and forming or straightening shell plates or panel assemblies on a bumping or forming press.

For commercial and military craft, the longitudinal framing system is most often used. Here, the principal shell stiffeners are disposed longitudinally and are supported by transverse web frames and bulkheads. Longitudinal framing usually results in a stronger, fairer hull which requires fewer manhours to build than does one which is transversely framed.

Some builders use the floating frame system, where the transverse web frames do not directly contact the shell plating. instead supporting the shell longitudinals only. Other builders favor the "deep web" system, where the web frames are notched to pass the longitudinals, or the longitudinals are intercostal to the webs. For simplicity in fabrication, uniform web frame space is generally used.

Aluminum boats normally incorporate two types of longitudinal framing: primary shell stiffeners and deep longitudinal girders which (a) support the loads of main propulsion engines, fuel tanks and strut legs, and (b) afford additional hull girder stiffness.

Longitudinal shell stiffeners may either continue through watertight bulkheads and/or frames or may be intercostal. The effort required to fair a longitudinally framed hull where the longitudinals pass through the bulkheads is considerably less than with intercostal longitudinal framing, and there is no chance of misalignment on opposite sides of the bulkhead or web frame. However, many yards find it easier to form and handle the shorter intercostals.

Shell plating can be installed in single sheets from keel to chine and chine to shear for smaller craft, but straking is necessary in the larger sizes. Aluminum plate is economically available in the U.S. in widths up to about 96 inches. Beyond that, there are considerable delays in rolling and shipping, and premium prices must be paid.

Inverted Construction

It is most efficient to construct an aluminum hull through the shell plating stage in the upside-down position. In this way, transverse and longitudinal framing can be set up and shell plating can be wrapped around the hull unobstructed by supporting structure. Gravity will help with the plating job, external shell seams can be welded flat, and there is far less accumulation of debris inside the hull.

Once the hull is welded, either before or after installation of the deck, it can be rolled over to an upright position using either trunnions welded or bolted to the ends of the hull or nylon straps or cables wrapped around it.

There are several systems of supporting the hull structure in a jig during fabrication. These include:

Ladder Jig: Transverse frames are clamped or bolted to steel uprights which accurately locate the web frames and bulkheads and (in some cases) longitudinal girders. The jig uprights normally support the frame floors and horizontal cross bars support the upper ends of the frames near the sheer. The jig is arranged so that adequate clearance is provided between the sheer of the boat and the shop floor to permit easy access of workmen. A disadvantage of this fabrication technique is that considerable overhead clearance is required to lift the hull clear of the jig.

Grid Jig: A variation on the ladder jig which consists of a series of flat bars standing on edge and spaced at the transverse frame spacing of the hull. Extensions of the transverse frames above the sheer, or separate temporary extensions welded to the frames, are then bolted to the flat bars, after they have been aligned on the vertical and longitudinal reference centerlines. If the hull has a sheer bar and a straight sheer, the jig can be even simpler; just a large flat platen.

Deck Jig: Another very practical jig consists of an inverted framework to support the vessel's deck: either a series of transverses or longitudinals set at the proper camber and sheer, or both. Deck plating is first welded together (using automatic equipment if available), then trimmed to the plan of the deck. Deck stiffeners are installed, then the transverse bulkheads and web frames are erected on the deck itself. Temporary bracing is used to hold frames plumb and in the correct lateral alignment.

Combinations and Variations: In a production setup, it may be most efficient to employ separate jigs for the construction of decks. After the hull is turned over, the deck assemply is mated to the hull.

Upright Construction

Some builders have successfully employed upright construction whereby a bottom frame grillage subassembly is constructed, then dropped into the shell plating which is supported by a female or pin jig. With a shallow hull where the bottom can be a separate subassembly this method may have merit.

Subassemblies

The higher the production rate, the greater the demand for breaking work down into small units. It is desirable to shop-fabricate as many hull components as possible into modules or subassemblies and then bring them together at the point of assembly. Items which lend themselves to shop or bench fabrication include struts, shaft logs, transverse frames, bulkheads, engine foundations, transoms, keels/stems, skegs, deck fittings, deckhouses, consoles, boarding platforms, tanks and the like. Economies effected by these means generally are reflected in greater values to the buyer.

There is very little justification for building aluminum hulls in more than one module except in the much larger sizes, i.e., above 150 feet.

FIBERGLASS REINFORCED PLASTIC (FRP)

Fiberglass, or more specifically fiberglass reinforced plastic (FRP), is the most popular material for planing boats today. FRP offers ease of construction by semiskilled labor, durability (including complete resistance to corrosion), relatively light weight. and reasonably low material cost.

The most common *materials* for FRP construction are:

- **Reinforcement** — Fiberglass mat consisting of randomly oriented short glass fibers rolled together in a felt-like mat, weight is specified in ounces per square foot and common weights are 1 oz psf, 1½ oz psf and 2 oz psf; fiberglass roving which is a coarse woven material using flat bundles of glass fiber strands for both warp and fill, weight is specified in ounces per square yard and common weights are 18 oz psy and 24 oz psy.
- **Laminating resin** — ‘The most common are isothalic and orthothalic polyester resins pre-pregnated with copper napthanate and catalyzed with methyl ethyl ketone peroxide. Most commercial construction employs general purpose (non fire-retardant) resin whereas military and commercial hulls subject to USCG inspection use fire-retardant resins. Fire-retardant resins cost approximately 1.5 times that of general purpose resins.
- **Core materials** — The most common are polyurethane foam, polyvinyl chloride foam, end grain balsa wood and douglas fir plywood. Densities used vary from 6 pcf to *30* pcf.

There are some materials less commonly used but gaining acceptance to reduce weight and/or to increase strength. Usage is limited to date because they are considerably more expensive and less understood. These include:

- **Vinylester laminating resins** — Provide considerably greater strength after prolonged immersion in water and are therefore attractive for use in the submerged portion of hulls. Its use permits reduction in scantlings therefore reducing weight. Cost is less than 2.5 times that of non-fire-retardant general purpose polyester resin.
- **Non-woven reinforcement materials** — Provide higher reinforcement content inasmuch as the bundles of fibers are not woven together, and there is less space per ply to be filled with resin yielding low resin content ratio laminates. Some non-woven reinforcement materials are unidirectional and are used where strength is required in only one direction thus saving the weight of the unneeded fill yarns of a woven material. Multidirectional non-woven material is available in what is known as triaxial configuration consisting of three plies of unidirectional material typically with one central ply oriented with the strands parallel to the length of the roll sandwiched between plies with strands oriented plus 45 degrees and minus 45 degrees to the central ply.
- **Aramid fibers (Dupont trade name Kevlar)** — These fibers are much lighter than glass for the same strength, i.e., much stronger in tension; minor flexural strength increase. but weaker than FRP in compression. Fiber weight is approximately 43 percent lighter than the equivalent glass and laminate weight is approximately 33 percent lighter than conventional FRP. Vinylester resin is recommended for use with aramid fibers. Aramid fiber costs approximately 7 times more per pound than fiberglass.
- **S-Glass-Conventional** fiberglass is made of so-called E-Glass. So-called S-Glass is stonger but not generally available and is more expensive.
- **Carbon fibers** — These fibers are much lighter than glass for the same strength. Laminate weight reduction can be SO percent or greater compared to conventional FRP. Carbon fiber costs are 30 times more per pound than fiberglass.

A very limited number of planing craft hulls have been built using these so called high technology materials. Some boats have used them throughout the entire structure, but more frequently they are used only for highly stressed portions. Their use not only increases material costs but also in some instances dictates more costly fabrication methods. Usage is thus limited primarily to recreational racing craft where cost is not an overriding consideration.

Construction Methods

Boat building with fiberglass is accomplished by a variety of techniques. The most popular procedure today is hand layup where workers apply and saturate layers of fiberglass material to a pre-gel-coated open female mold. Some smaller craft builders in the high volume commercial industry use chopper guns to apply a thickness of resin mixed with randomly chopped glass fibers to the same type of molds. This method relies heavily on the skill of the machine operator to maintain consistent skin thickness eliminating alternating thin spots or excessive buildup. “Chopped” hulls are not as sound or strong as those made of layered woven material. More sophisticated procedures than hand layup include resin injection molding and resin transfer molding where reinforcement is captured in closed molds and resins are injected under pressure. These techniques require more extensive and highly stiffened closed tooling or matched molds to maintain shape during resin injection. They are cost effective only when considering volumes of hundreds of parts per year. Resulting parts are usually lighter, often“ stronger, and tighter tolerances can be maintained.

Tooling for the more popular open mold technique is usually a female version of the part to be molded. The mold is stiffened with external ribs, frames, and often cored skins. Large hull and deck molds can be mounted in pits in the ground which allow workers to climb inside or they can be mounted in giant rollers, facilitating rotation, so workers may lay up one side at a time while standing on the floor. Costs of such special tooling run about 25 to 50 percent more than typical fixed tooling, excluding plug. Plug costs could be two to four times more than part cost, depending on construction technique. Some manufacturers use one-off techniques to build plugs and incorporate the tooling into a vessel, recovering the one-time expense.

Fiberglass reinforced plastic as a construction material lends itself to compound curves and complex shapes. Simple open molds require draft of 1.5 to 2.0 degrees to prevent capture of parts in the mold. Sharp corners are not practical in simple molding procedures where a minimum of 1/8-inch radius is required to allow forming reinforcement material during layup. The more exotic procedures achieve sharp corners with great expense. When parts to be built require closed sides or return curvature, as does a hull with tumble home, split molds or multipiece molds are used. These molds have bolting flanges built into mating surfaces which uncouple to allow part release.

Common lay up procedures use precut "dry" material layed in molds by hand then saturated with resin using spray guns and hand rollers. Builders of larger vessels (70 to 100 feet) make use of resin impregnators which saturate the reinforcement as it comes off the roll which is suspended over the mold. Hand work is still required to affix and deaerate the material. After saturated material is positioned in the mold, some manufacturers cover the uncured composite with a plastic sheet or "bag," seal the perimeter and draw a vacuum on the plastic. This forces air and excess resin out of the laminate. Vacuum is held until curing is complete. The disdvantage of this method is that it requires saturated material and the vacuum-bag to be in place while the resin is still in a liquid state, normally only 45 to 60 minutes. However, for a single critical layer like core material the procedure is ideal to guarantee a complete bond.

Relatively recent plastics technology includes the development of a presaturated reinforcement material which allows unlimited working time. This material, however, must be refrigerated until its use. After all laminate layers are cut and positioned in the mold, a vacuum is drawn, and the whole apparatus is wheeled into an oven or autoclave where curing begins when heat is applied. This procedure requires a sophisticated facility and materials are expensive to purchase and store.

The proper amount of heat is required for complete curing of even conventionally saturated material. Normally, multilayered laminates generate adequate heat or exotherm during the chemical reaction to effect cure. In cases where there are many layers of material (more than about six) or when a coring material is incorporated, layup must proceed in stages, allowing intermittent catalytic reaction or "kicking" to take place and exotherm to dissipate. Core material insulates and traps the heat against the mold surface. Extreme heat will accelerate the reaction in spots causing shrinkage, laminate distortion, and possible stress concentration.

Builders must be cognizant of materials and procedures and plan cycle times carefully to maintain consistent quality and homogeneous integrity. Material suppliers are familiar with their products and can aid builders in proper use and procedures.

For more information on fiberglass construction techniques, see References [19] through [26].

Economics

The variety of fiberglass planing craft for commercial service is almost endless. For one-off custom configurations fiberglass lends itself to piecewise assembly and finish work. However, this approach is costly-perhaps 20 percent to 100 percent more from a labor standpoint than the premolding of parts. A rule of thumb of molding is that break-even amortization of tooling and mold occurs at six production units. Production fiberglass planing craft hulls cost between $3 and $4 per pound to produce. Approximately half the cost is material, when conventional products are used, and half is labor. Customized production can sometimes double the labor figure, not including engineering and overhead requirements to support such efforts. Conventional materials would include general purpose resins and E-type glass fiber material. Special purpose products such as fire-retardant resins, vinylester and epoxy resins, S-type glass, unidirectional weaves and aramid fibers cost more.

Data requirements for military small craft are voluminous but comprehensive, even by today's information-hungry standards. This practice provides the customer with a complete package which is not privileged information to a unique contractor. This ultimately benefits both contractor and government, standardizing products and methods. However, depending on the completeness of the basic design provided by the Navy, at least 500 hours and as many as 2000 hours are required per contract for engineering support and drafting services to comply with specifications for drawing packages.

Small commercial vessels, intended to carry passengers for hire, normally require U.S. Coast Guard certification. Modest data requirements prior to construction and intermittent inspection procedures raise contract costs by increasing labor usage and overhead and interrupting production. Engineering support in these cases is usually less than 500 hours. Customized commercial vessels not requiring certification can often be adapted from existing designs and molds with much lower support requirements. Depending on the manufacturing facility and methods used, learning curves for fiberglass craft are approximately 85 percent. Fabricator labor is generally non-union and semiskilled. A large percentage of the work force may be in training, provided that key personnel are experienced.

Operating costs for fiberglass boats include annual antifoulant replacement, cosmetic refurbishment, and the routine machinery maintenance found on other craft. Typical costs for painting and refurbishment are generally less than routine preventative maintenance costs for steel or aluminum vessels. This includes two coats of bottom paint and one coat of paint on hull topsides, deck and superstructure. However, only the harshest service would require yearly recoating of above-water surfaces. Normally, gel-coated or epoxy coated surfaces merely require periodic polishing and waxing to remove oxidation and maintain their high-gloss finish.

Facilities

Facilities for fiberglass boat construction must meet a mixture of legal and practical environmental requirements. Legally, facilities must comply with safety and ventilation regulations set down by OSHA. Noxious styrene monomers are critical to plastic resin workability but must be purged from layup buildings by some sort of forced ventilation. Environmentally controlled areas, avoiding temperature extremes and high humidity, produce the best and most consistent results. Also, the cleaner the area, the lower the likelihood of material contamination and the better the cosmetics of the end product. A well-lighted facility is essential but direct ultraviolet rays may sporadically accelerate resin cure and upset the hardening process. High volume builders need high ceilings to allow separation of parts from molds without requiring mold movement from the layup area. Also, large doors allow access and egress of large fiberglass parts.

Supportability

Fiberglass reinforced plastic is a common enough medium today in boat building to provide the vessel owner and the designer adequate assurance of longevity and service. Adequate repair of FRP craft can be performed with semiskilled labor, rudimentary tools and a few key yet readily available materials. However, a professional service facility or a production plant will attain greater efficiency and cosmetic perfection with more proficient personnel, sophisticated tooling and elaborate techniques. For example, resin, fiberglass and gel-coats may be applied by hand with a simple paint brush and finished with grinder and sandpaper. The professional will utilize spray equipment, forms and fixtures, and more exotic finishing tools to accotnplish a better looking product'in half the time. Ultimately structural integrity could be equivalent between both fixes. Navships Document 0982-0190-0010, "Manual for Major Repairs to Glass Reinforced Plastic Boats" is one source of information about field repair published by the Navy.

STEEL

High tensile steel has a strength-weight ratio similar to typical marine aluminum alloys. Because of minimum gage constraints, however, it may not be attractive for small craft since it will result in heavier hulls relative to other materials. Recent studies by R. Allen of DTNSRDC indicate that high tensile steel may indeed by attractive for large, high-speed planing hulls with displacements in excess of 500 tons. Because minimum gage, and not strength., is the governing consideration for small hulls, mild steel is used primarily for these hulls. Relative to cost considerations, it appears that, although heavier, steel hulls will be cheaper than aluminum. Planing hulls built of steel are more widely available abroad-particularly for speeds less than approximately 35 knots.

The construction techniques for steel hulls are well-known and will not be discussed in this chapter. It would appear that, world-wide, there is more boat building and repair capability for steel than for other construction materials.

CONCLUSIONS

There is an expanding international interest in the use of fast patrol boats particularly as the nucleus of naval units in developing new nations. In addition, the introduction of the Exclusive Economic Zone of coastal states has required the acquisition of large numbers of these high speed craft to protect and patrol their off-shore wealth. The commercial and recreational utilization of planing hulls expands each year.

Fortunately, the recent developments in planing hull technology have demonstrated that high speed hulls can now be developed and constructed with the following characteristics:

- Impressive seakeeping characteristics in comparison with the older designs, when hull form proportions and loadings are properly selected for the sea state and speed of interest.
- Structural weight fractions as low as 22 percent of full load displacement.
- Useful load fractions approaching 45 percent of full load displacement.
- Elimination of the traditional "hump" trim and resistance penalties.
- Simplicity of design which permits ease of fabrication, the use of available propulsion systems, readily available engines, and proven propellers capable of speeds up to 50 knots.
- Avoidance of special control systems.
- Various choices of construction materials.
- Well-established design, construction and repair techniques available world wide.

Quantitative projections of costs of planing hulls are impossible to discuss in these inflationary times. However, there are major considerations which should reduce the cost of planing craft relative to other members of the advanced vehicle family. These are:

a) The number of shipyards (world wide) which are capable of building planing hulls is relatively large and continues to increase. This should result in more competitive bids and a favorable price to the customer. In contrast, there are only limited numbers of manufacturers capable of constructing ACV, SES, hydrofoil, etc.
b) The required structural technology is in hand and hull construction can follow normal shipyard practice. In fact, many of the traditional builders of displacement ships are easily expanding into the fast patrol boat market.
c) There are no special control or operational systems nor special support or maintenance procedures required in planing hulls.
d) With the elimination of "hump" speed characteristics through proper hull design, it appears that constant pitch, fully cavitated propellers can be used throughout

the speed range. These propellers are easily fabricated in existing foundries.

e) The absence of "hump" will also enable economical slow speed operation on one relatively small engine and, with the ability to bring on line (in sequence) multiple engines, the result will be an operating profile where engines can be set to run at their best fuel rate.

The final decision on cost will be dependent upon careful analysis to establish trade-offs between capital costs, operating costs, maintenance costs, and value of the mission to be performed. A reduction in maximum speed, for instance, can result in a reduction in the number of engines required, and this decision will have a significant impact on cost, especially if high powered expensive gas turbines are being considered.

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CHAPTER V

HYDROFOILS

THE EDITOR

Capt. Robert J. Johnston, USNR (Ret.) *began his professional career as an engineering officer in the U.S. Navy. His last assignment before leaving the Navy in 1954 was hydrofoil program officer in the Office of Naval Research. In 1954 he joined Miami Shipbuilding Corporation, later becoming that company's president. Miami Shipbuilding was heavily involved in a number of hydrofoil development programs including the hydrofoil landing craft* Halobates. *In 1960, he joined the Grumman Corporation where he ultimately became director of marine programs. At Grumman, he was responsible for a number of major projects including* H.S. Denison, *for the Maritime Administration; the Navy hydrofoils* Plainview *(AGEH-1) and* Flagstaff, *(PGH-I): and the Grumman passenger hydrofoil* Dolphin.

In 1973, he returned to government service as a civilian in the position of technical manager of hydrofoil development at the Naval Ship R&D Center For his work in this role he received the Navy Superior Civilian Service Award in 1981. He retired in 1982 and founded Advanced Marine Systems Associates, Inc., a firm of which he is president. AMSA only recently completed a worldwide study of high-speed waterborne transportation for the Urban Mass Transportation Agency.

INTRODUCTION

In the family of modern ships and craft, the hydrofoil ship is a well-developed concept whose maturity has been demonstrated through many successful commercial and military applications. Military applications have been the primary incentive for the development of the hydrofoil ship both in foreign countries and the United States. At the same time their commercial value has been demonstrated in many countries throughout the world. This chapter will identify some of the principal hydrofoils that have marked the progress of development along with current operational, commercial and military vehicles. Future prospects for the use of hydrofoils with developing concepts based on the present state of technology provide a look at what one may expect in the next generation.

This chapter has been prepared by a team of experts who have gained knowledge and experience by being directly and intimately involved in the development of the hydrofoil. They have also contributed to the difficult step of turning a design concept into a vehicle that is practicable to build, operate, and maintain. A brief identification of this team in alphabetical order and their areas of expertise are provided below.

Cdr. Peter J. Boyd, U.S. Coast Guard, while a relative newcomer to the field of hydrofoils, has in the past few years brought a fresh viewpoint to the utilization of modern ships in the Coast Guard. His expertise in naval architecture and marine engineering coupled with at-sea command experience is reflected in a practical approach to the use of hydrofoils.

Charles S. Coffey, one of several Boeing Marine Systems contributors, has been involved with hydrofoil design and development for over 25 years. Twenty-three years of his effort have been with Boeing which includes the design of various hydrofoil propulsion and foil systems, the management of the preliminary design activities and chief engineer for the Jetfoil program. Mr. Coffey is currently manager for Jetfoil Product Development and Advanced Marine Vehicle Concepts.

Michael C. Eames, assistant to the technical director of the Canadian Defense Research Establishment, Atlantic, needs no introduction. His wealth of experience with modern ships has been previously described in the section entitled "Views from the Bridge." Like several of the hydrofoil contributors, Mr. Eames' expertise and interest in modern ships includes other platforms and concepts. Also, like others whose roots were in the development of the hydrofoil, having seen the hydrofoils go from experimental gadgets to seagoing vessels, he retains enthusiasm for the concept. This chapter was fortunate to have Mr. Eames as a contributor.

James H. King, who is a naval architect in the Systems Integration Department of the David W. Taylor Naval Ship Research and Development Center (DTNSRDC), is another individual with capabilities in modern ships other than hydrofoils. He has conducted a number of hydrofoil studies and designs including a recent patrol boat design for the U.S. Coast Guard. His assignments have also included those of consultant to the Office of the Chief of Naval Operations and consultant to the Director of the NATO ASW Research Center.

Capt. John W. King, USN, (Ret.) has had a long career as a line naval officer, ten years of which were in the management of research, development and acquisition of advanced marine vehicles. He was responsible to the Chief of Naval Operations for the direction of the NATO/PHM program from its inception as a concept in NATO to the launching of the USS Pegasus (PHM-1). Since retirement from active duty, he has been a consultant with emphasis on modern ships and craft. He is currently manager of Advanced Marine Systems Associates, Washington, D.C. office.

Roy E. Lawton is also from Boeing Marine Systems with expertise in maintenance engineering. For the past eleven years he has been involved with the maintainability programs for the PHM and Jetfoil. Prior to joining Boeing he spent 12 years as a naval officer in billets at sea and ashore. He is currently a senior engineer with Boeing's hydrofoil logistics support program.

John R. Meyer, Jr. is another contributor with broad engineering and design experience. For the past eight years he has been one of the principal engineers in the hydrofoil program at DTNSRDC. He is now the manager of hydrofoil technology at the Center. In his capacity he has directed several design studies including the effort on the extended performance hydrofoil. Mr. Meyer's background prior to joining the Center was in the aerospace industry in research and development and in engineering management positions.

David S. Olling is the current Boeing Marine Systems' manager for PHM product development. He joined the hydrofoil program in 1967 with a background in tooling and electronics and has had a wide variety of hydrofoil experience including structural and auxiliary systems design, test, and craft refurbishment.

William C. O'Neill is one of the outstanding hydrofoil experts of the U.S. Navy. He has spent the last 24 years working on the development of hydrofoils and their technology. He brought to the U.S. Navy an expertise as a controls engineer and has been instrumental in improving and developing the automatic control systems for hydrofoils including the digital autopilot. Moreover, his expertise is quite broad including many other aspects of modern ship technology. He currently is a senior research engineer and technical advisor at DTNSRDC.

Charles G. Pieroth, who is the director of Grumman Aerospace Corporation's Naval Ship Systems, is a contributor with 25 years experience in the design of hydrofoils and other modern ships. He began his hydrofoil design career as a naval architect on the *Denison* and was also the principal naval architect for the design of the Grumman *Dolphin* and *Flagstaff* (PGH-1). As head of the preliminary design section, his efforts were the basis for the Israeli Navy's *Shimrit* class. His most recent hydrofoil contributions have been to utilize recent advances in technology to develop advanced lift and propulsion systern concepts.

W. Alfred Smith, who recently retired from Boeing Marine Systems assisted in the final editorial process. Mr. Smith's expertise results from 34 years with Boeing of which 26 years were associated with the development of the hydrofoil and its utilization. His efforts in improving the content and flow of the chapter were significant. Recognition is also given to Rodriquez Cantiere Navale of Messina, Italy, who supplied information and pictures of their commercial hydrofoils.

HYDROFOIL SHIP DESCRIPTION

The basic principle of the hydrofoil concept is simply to lift a ship's hull out of the water and dynamically support it on wing-like lifting surfaces, i.e, hydrofoils, in order to reduce the effect of waves on the ship and to reduce the power required to attain modestly high speeds.

Engineers and naval architects have been intrigued with the possibilities envisioned by this concept for many years. A United States patent for a hydrofoil was defined in the late 1880s, about the same time as the early airplane and airfoil patents. The earliest record of a successful hydrofoil flight is 1894 when the Meacham brothers demonstrated their 14-foot test craft at Chicago, Illinois. This compares with the Wright brothers' first airplane flight in 1903. The early attempts to exploit the hydrofoil concept were frustrated by lack of suitable structural materials and power plants. However, advancement in these areas, much of it stemming from aircraft developments, have permitted development over the past 30-40 years of the technology necessary to achieve and demonstrate reliable and effective hydrofoil ships for both military and commercial applications. History of early developments and later U.S. Navy programs is detailed in References [1] to [4].

HYDROFOIL. CONFIGURATION

Hydrofoil configurations can be divided into two general classifications. surface piercing and submerged, which describe how the lifting surfaces are arranged and operate. In the surface-piercing concept, portions of the foils are designed to extend through the air/sea interface when operating. Struts connect the foils to the hull of the ship with sufficient length to support the hull free of the water surface when operating at design speeds. A typical example is shown in Figure 1. As speed is increased, the lifting force generated by the water flow over the submerged portion of the foils increases causing the ship to rise and the submerged area of the foils to decrease. For a given speed the ship will rise until the lifting force equals the weight carried by the foils. When the ship encounters a wave, more or less of the foil will be submerged, and the ship will pitch or heave up or down to bring the weight and lift again into balance. Since these force changes occur automatically, a properly designed surface-piercing hydrofoil system is self-stabilizing requiring no active controls for height, longitudinal or roll stability. While reaction of a surfacing-piercing hydrofoil

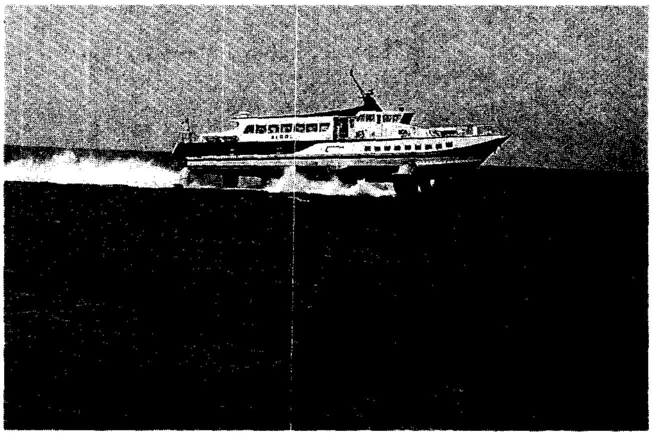


Figure 1. RHS 160

Figure 2. U.S. Navy Patrol Hydrofoil, Missile (PHM)

to waves is substantially less than for a high-speed displacement or planing ship of the same size, the requirement for ship motion to balance the disturbing forces caused by the waves coupled with geometric limits to a practical design restricts the sea states in which high-speed operation can be [considered acceptable. For this reason, modern surface-piercing hydrofoils augment their stability by electrohydraulic control systems.

As indicated by the terminology, the foils of the submerged concept are designed to operate at all times under the water surface. The struts which connect the foils to the hull and support it when the ship is foilborne generally do not contribute to the total hydrofoil system lifting force. In this configuration, the hydrofoil system is not self-stabilizing, Means must be provided to vary the effective angle of attack of the foils to vary the lifting force to counter changing conditions of ship speed and weight and the continually changing apparent angle of attack of the water in rough sea conditions. This is generally provided by angular changes of the entire foil or trailing-edge flaps driven by hydraulic actuators and controlled by an automatic control system. An example of a hydrofoil ship with a fully submerged foil system is the U.S. Navy PHM shown in Figure 2.

The principal and unique operational capability of submerged hydrofoil ships is the ability to uncouple the ship to a substantial degree from the effect of waves. This permits a relatively small hydrofoil ship to operate foilborne at high speed in practically any sea conditions normally encountered while maintaining a comfortable motion environment for the crew and passengers and permitting effective employment of military equipment. It is this desirable characteristic which has caused the hydrofoil ship development in the United States to concentrate on the fully-submerged foil concept.

For the fully-submerged hydrofoil ship the primary consideration in selection of the foil and strut configuration must be the resultant behavior of the ship while foilborne in the unpredictable environment of heavy seas. The factors involved are:

1) Maintenance of directional and roll stability at all times.
2) Stable recovery when a foil comes out of the water (broaches).
3) Graceful deterioration of performance in the severe seas occasionally encountered, and
4) Safety.

The basic choices in foil, and strut configuration are:

1) Canard or conventional arrangement. The names are derived from aircraft terminology and typical arrangements are illustrated in Figure 3. Generally ships are considered conventional or canard if 65% or more of the weight is supported on the front or aft foil respectively. If the weight were distributed relatively evenly on the fore and aft foils, the configuration would be described as tandem.
2) Variable lift control by trailing-edge flaps or variable incidence of the entire foil. This alternative is illustrated in Figure 4. (Note: These are the control methods normally used to date. Other methods are discussed in the technology section.)
3) Rudder aft or forward, and

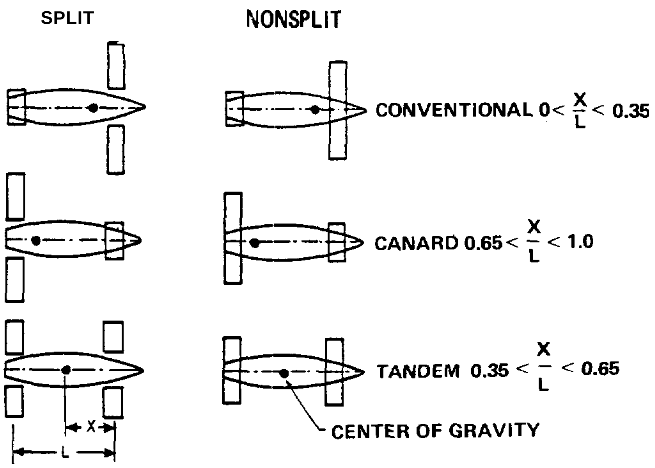


Figure 3. Hydrofoil Ship Configuration

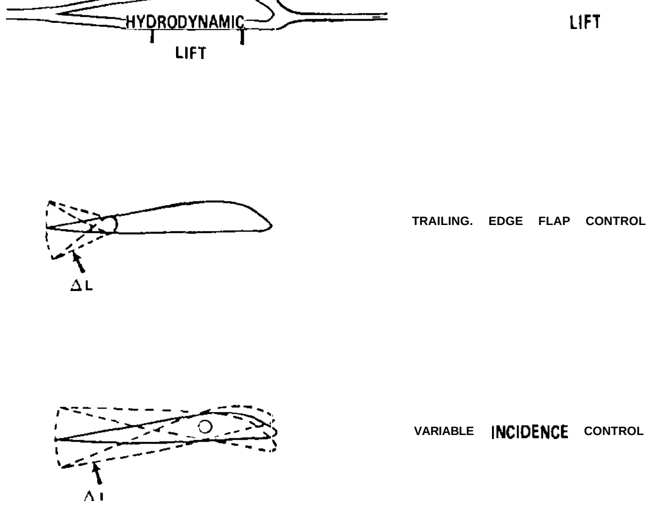


Figure 4. Hydrodynamic Force Control

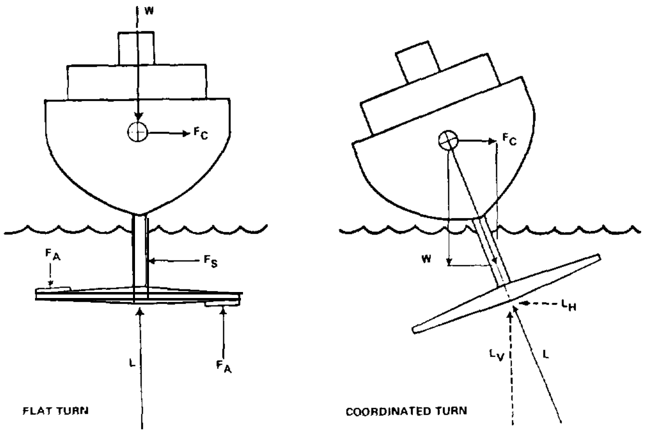


Figure 5. Turning Force Schematic

4) Banked, fully coordinated turns or flat turns. This option and the necessary Forces on the foil and strut in each case are illustrated in Figure 5. As noted, lateral forces are not required to be maintained by the struts during banked, coordinated turns. This is advantageous for control because a strut piercing the water surface is unreliable as a force generator due to varying wave heights and unstable ventilation characteristics.

Before considering the merits of the foregoing configuration choices, it is desirable to recognize the different reactions to a water surface disturbance or ship roll of the fully-submerged hydrofoil compared to a displacement ship or surface-piercing hydrofoil. In Figure 6 it is apparent that a wave, as in a beam sea, will result in a shift of the center of buoyancy (CB) of the displacement ship or the center of pressure (CP) of a surface-piercing foil system causing a rolling moment as indicated. No significant force change is generated on the fully-submerged hydrofoil. If the ship rolls. a similar shift in the center of buoyancy of the displacement ship and center of lift in the surface-piercing hydrofoil will produce a roll-righting moment to return the ship to vertical as indicated in Figure 7. However a shift in center of lift does not occur in the submerged foil ship. Thus, control action is required to produce the necessary roll-righting moment The control action is provided by the automatic control system (ACS). When the ship roll is sensed by the ACS vertical gyro, the control system moves the foil control surfaces to create the roll-righting moment as indicated in Figure 7.

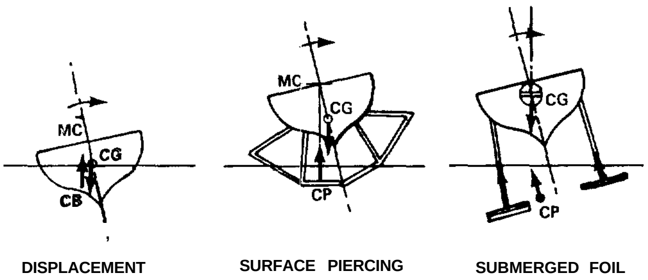


Figure 7. Roll Correction

Now, to consider the performance of hydrofoil ships in rough seas, it is necessary to recognize that seas will be encountered where wave heights will exceed the length of the struts. Therefore, the forward foil will at times fly out of the wave, which is referred to as "broaching." By way of definition, a broached foil is one that has either broken the water surface or come close enough to the surface to completely ventilate the upper surface to atmospheric pressure. In either case the hydrodynamic lift is essentially lost. Extensive operational experience has shown it is always the forward foils which may broach in high seas. It is mandatory that the hydrofoil configuration should enhance stability and controllability with special emphasis on prompt, safe recovery from forward foil broaching without loss of roll control or directional stability.

Typical foil lift curves as a function of angle of attack and flap angle are shown in Figure 8. Variable incidence control in which required change in lift force is achieved by changing the angle of attack of the entire foil is represented by the curve for δ = 0. With flap control, change in lift force is obtained by changing the angle of the trailing-edge flap and, to a limited extent, the pitch angle of the ship. Of particular significance is the loss of lift capability which occurs when the upper surface is ventilated. A broached or ventilated foil cannot supply neces-

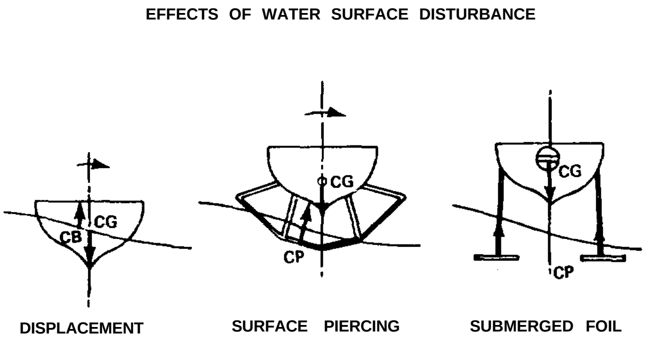


Figure 6, Effects of Water Surface Disturbance

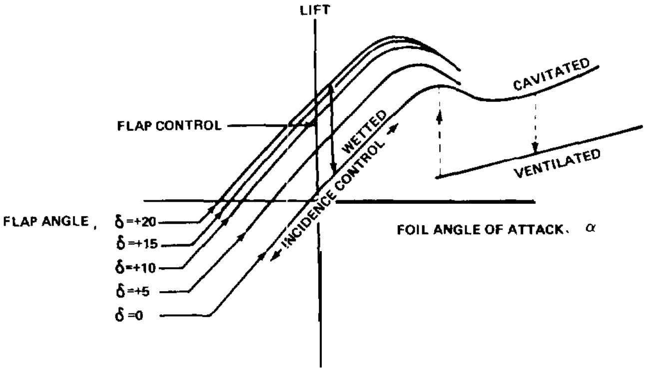


Figure 8. Foil Lift Curves

sary control or stabilizing forces. Also, a broached foil does not rewet immediately upon reentering the water at high angles of attack.

Foils with trailing-edge flap control have demonstrated superior recovery characteristics from a forward foil broach compared to variable incidence foils [5]. To overcome this difficulty, variable incidence foils have successfully used broach recovery devices. Such devices sense an impending broach and preset the broaching foil to a low angle of attack. The affects lift recovery when the foil reenters the water. The longitudinal location of roll control is not particularly significant for operations in which the foils are always submerged and fully wetted. In these cases a roll-righting moment is generated for either canard or conventional configuration by differential control surface movement as previously discussed. However, in the case of a forward foil broach, the difference in response between canard and a split-foil conventional configuration can be dramatic. When the forward foil broaches on a canard configuration, no rolling moment results. The ship merely pitches down as the foil reenters the water and recovers lift.

A rolling moment will not be generated by broach of the forward foils of a conventional configuration if both foils broach simultaneously. However for split forward foil configurations, the more frequent occurrence is for one of the forward foils to broach. The off-center loss in lift results in a combined roll and downward pitch in the direction of the broached foil. Therefore the single forward foil of the canard configuration has been found to be the best configuration for recovery from a foil broach.

To be directionally stable without control augmentation, the lateral center of pressure of the underwater surfaces of the struts must be aft of the center of gravity. However, hydrofoil ships operating in rough water encounter large changes in water height, and, thus, side force generation capability. between forward and aft struts. Consider the case of encountering an oncoming wave with the forward strut. The lateral CP will shift forward and may even become statically unstable. The forward rudder of a canard configuration, however, will provide increased controllability, particularly if the entire forward strut rotates as in the U.S. Navy PHM. The situation is similar during recovery from a forward foil broach.

As hydrofoils increase in size, the complexity of rotatable forward struts increases. Such struts must have bearings which can support the lift of the forward foil and still allow strut rotation. It is expected that large hydrofoils will use a tandem configuration with either strut flaps or rotatable strut fairings for directional control.

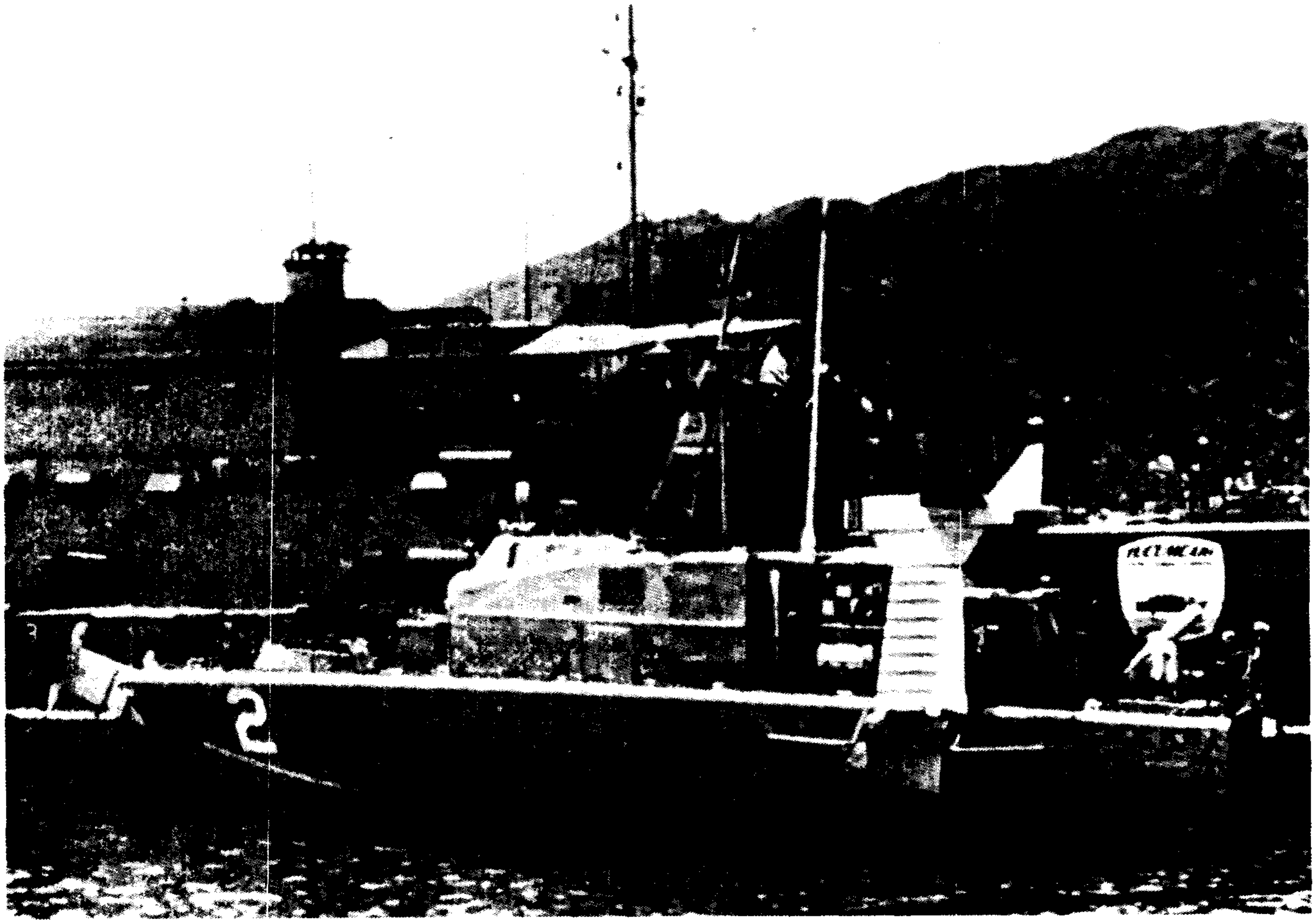


Figure 9. PGH-2 *Tucumcari* Foil System (Retracted)

OTHER FOIL AND STRUT CONSIDERATIONS

The length of the hydrofoil struts is a function of the desired sea state performance. The fully-submerged hydrofoil ships designed for smooth operation in high sea states have struts generally longer than the design wave height. The resultant draft with the foils extended is significantly greater than normal for an equivalent size displacement ship; for example, 7.1 meters for the 240-ton PHM. This consideration has led to installation of the capability to retract the foils for draft reduction when entering harbors and moorages. Retraction also provides improved capability for maintenance of the foils and struts. Figure 9 shows a PHM with foils retracted.

The foils and struts are highly loaded structures and are generally constructed from a high-strength steel material. However, solid 6061 aluminum foils have been used on the *USN Flagstaff* and Israeli *Shimrit,* both designed and constructed by Grumman.

CONTROL SYSTEMS

As noted earlier, surface-piercing hydrofoil configurations are self-stabilizing in both pitch and roll and thus do not require an automatic control system. However, to reduce the inherent reaction to rough seas, a number of ships have added trailing-edge flaps to the surface-piercing foils and have used autopilots for ride improvement.

In the United States, full automatic control of submerged foils has been deemed necessary to attain the seaway performance desired for ocean going hydrofoil ships. This design philosophy has been verified by outstanding rough water performance of U.S. designed hydrofoil ships. Typically, control is accomplished by positioning trailing-edge flaps on the forward and after foils and by rotating the swiveled forward strut (rudder) or by positioning the entire foil surface and by positioning the power driven aft strut as a rudder. Figure IO. The control surfaces are positioned by means of conventional electrohydraulic servos. The control system motion sensors consist of:

1) A vertical gyro which measures craft pitch and roll angular motion.
2) A rate gyro which measures craft yaw rate.
3) Three vertical accelerometers, one accelerometer being located approximately on top of each strut. The two aft accelerations work differently to provide roll angular acceleration feedback, and they work in unison to provide pitch and heave acceleration feedback.
4) A height sensor which measures the height of the bow above the water surface.

The manual inputs consist of a foil depth command, which the helmsman uses to select any desired foil depth (or flying height), and the helm, which introduces the craft turning commands.

The ACS provides continuous control during takeoff, landing, and all foilborne operation. The pitch, roll, and height feedback loops provide automatic stabilization of the craft. The craft is automatically trimmed in pitch by the pitch feedback, and roll trim is accomplished by helm inputs. To steer the ship, the helmsman simply turns the helm, and the ACS automatically maintains a coordinated turn, with turn rate being proportional to helm deflection. ACS system requirements and operation are discussed in detail in References [6], [7], and [8].

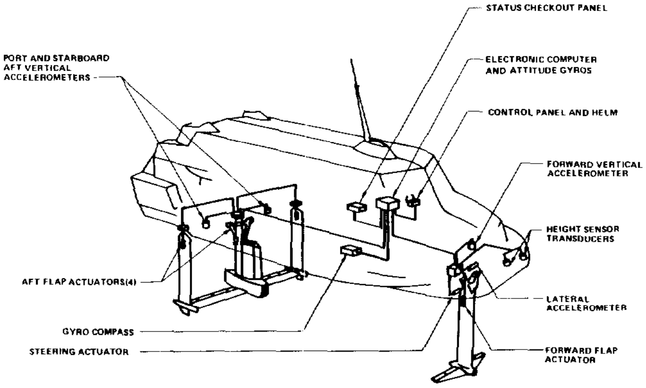


Figure 10. Typical Automatic Control System

PROPULSION

Effective modern hydrofoil ships have been made possible by the development of lightweight diesel engines and marinized gas turbine engines.

Most of the European commercial ships using fixed surface-piercing foil systems have also used lightweight diesel engines driving subcavitating propellers by means of an angled shaft power transmission system. This combination provides simplified construction, relative ease of maintenance and low cost. However, the comparatively high specific weight (6-8 pounds per horsepower) of the diesel engines and higher overall drag have resulted in practical design speeds of these ships of about 35 to 40 knots.

Existing aircraft gas turbine engines slightly modified for operation in a marine environment and coupled with specially designed free-power turbines are available in sizes with power ratings up to about 30,000 horsepower and specific weights of around 0.5 pounds per horsepower. The newer large engines employing blade cooling techniques have specific fuel consumption rates at their design power about equal to diesel engines. Gas turbine engines have been used in all major U.S. military and commercial hydrofoil ships permitting practical design speeds greater than 40 knots.

Propellers are the most efficient propulsion device available for operating over the subcavitating speed range of current hydrofoil ships. The power transmission systems required when using fully-submerged foil systems consist of right angle bevel gears, flexible shafts and possibly a speed reduction gearbox in the propeller transmission pod. See Figure 11.

Problems encountered with gear transmission systems in early hydrofoil ships led to interest in waterjet propulsion systems. While not entirely eliminating the need for gearboxes, these systems consist of underwater inlets,

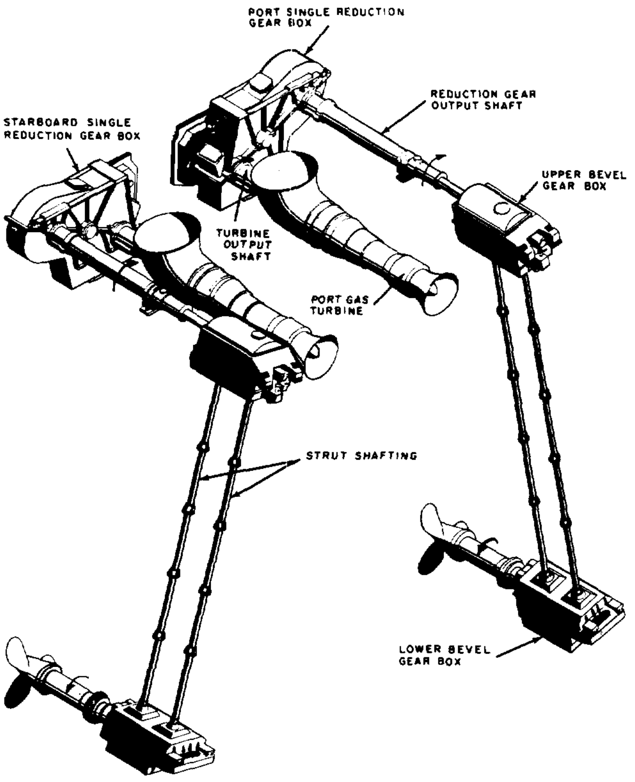


Figure 11. AG(EH) Foilborne Transmission System

water ducts in the struts, a pump located in the machinery spaces and an above-water exhaust nozzle. The U.S. Navy's PGH-2 waterjet system is shown on Figure 12. The price paid to achieve these less complex waterjet systems is a decrease in propulsive efficiency of about 20% at 45-50 knots and considerably more at takeoff speeds along with an increase in propulsion system weight due to the water carried in the system.

Commercial hydrofoil, ships normally operate foilborne except when docking. Military ships on the other hand typically spend a substantial portion of their underway time operating at low speed and use their high-speed capability for rapid transits, reaction to a distant threat, evasive maneuvering, etc. Typically, the power required at normal hullborne speed is 5% or less of that required at design foilborne speed. Specific fuel consumption of gas turbine engines is very poor when operating at low power. Therefore, military hydrofoil ships generally have a separate propulsion system for low-speed hullborne operation. Diesel engines have often been used for hullborne propulsion because of their lower first cost and higher efficiency over a wide power range compared to small gas turbines. However, with lighter weight and improvement in fuel consumption, small gas turbines are becoming more competitive for this role.

HULL CONFIGURATION

The development of a satisfactory hull form for hydrofoil application represents a significant challenge to the designer. The hull should perform well in the hullborne mode but also during takeoff and during foilborne operation where impacts with waves are involved. In addition, the hull configuration of a hydrofoil ship must satisfy all of the requirements for strength, freeboard and intact and damaged stability of any other ship.

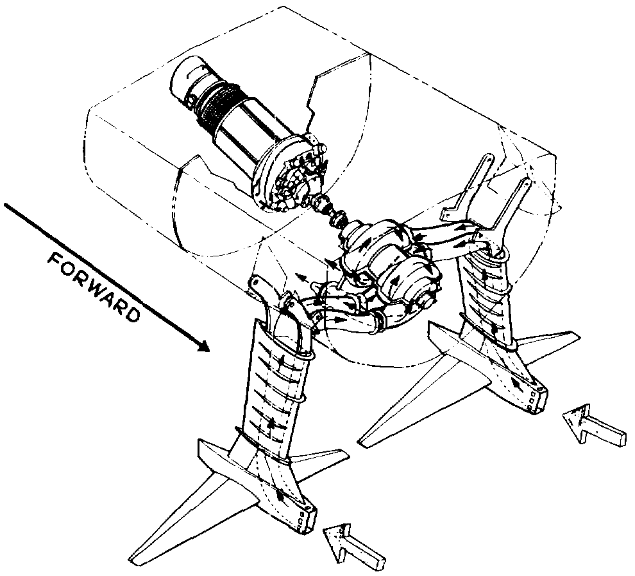


Figure 12. *Tucumcari* Propulsion System

Relatively high power requirements for high-speed operation, in common with other high-performance systems, pay a high performance dividend for achieving a minimum weight structure. Therefore, hydrofoil ship hulls are generally constructed using high-grade aluminum alloys, 5000 series weldable alloy being typical. Structurally, the hull must have the strength to resist wave impact at high speed as well as distribute the concentrated load at the strut attachment points. Since operation at high speed in rough seas will routinely result in occasionally driving through the top of waves, the bow will normally be fine and the bottom will have high dead rise to reduce impact loadings.

Although hydrofoil hulls may appear quite conventional, the required compromises are more complex than for a monohull because of the many operating modes of the ship.

ATTRIBUTES AND LIMITATIONS

The principle advantages of hydrofoil ships, over all other monohull or alternative ship types are: (1) the ability of a ship. which is small by conventional ship standards, to operate effectively in nearly all sea environments, and (2) an attractive ratio of power to displacement in the 30 to 50 knot speed range permitting economical operation at these higher speeds.

The submerged-foil ship can maintain its speed and maneuverability in heavy seas while simultaneously providing a comfortable working environment for the crew. Figure 13. This successful operation is essentially the result of the mutual interworking of the submerged foils with the ship's automatic control system (ACS) The ACS provides continuous dynamic control of the ship during takeoff, landing, and all foilborne operation. In addition to providing ship roll and pitch stability, the ACS controls the hull height above the water surface, causes banking in turns and all but eliminates ship motions caused by the orbital particle motion of waves. The ship hull operates above the effects of surface waves. The foils that provide lift and control forces operate below the water surface where wave effects diminish with depth. Foilborne operations only become limited as the wave heights exceed the hydrofoil strut length. The result is an exceptionally smooth operating environment for crew and combat system equipment.

Figure 14 shows operating data points for three submerged-foil hydrofoil ships in actual sea conditions. The data clearly show only a modest reduction in speed as wave heights increase. A hypothetical operating envelope is drawn to represent hydrofoils designed to have a 50-knot speed capability in calm water.

The greatest single influence on the seakeeping ability of a conventional ship is its size as characterized by its length. A measure of seakeeping is the speed the ship can sustain in rough seas without severe slamming and deck wetting. "Good practice" is considered no more than one slam or deck wetting per minute. Figure 15 shows the "good practice" rough-water speed of a number of conventional U.S. Navy and U.S.S.R. ships as a function of their lengths, [9]. Three hydrofoil ships are also shown for comparison. The ability of the hydrofoil ships to maintain speeds over 40 knots in rough seas is unmatched by much larger conventional ships.

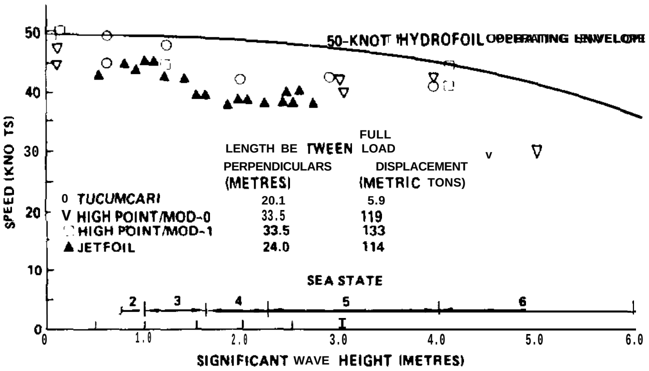


Figure 14. Effect of Sea State on Hydrofoil Ship Speed.

While the hydrofoil has a modest speed advantage in calm seas over the conventional ship with equivalent power, the speed advantage is as much as two to four times in rough seas.

Figure 13. PHM-1 Pegasus in Rough Water

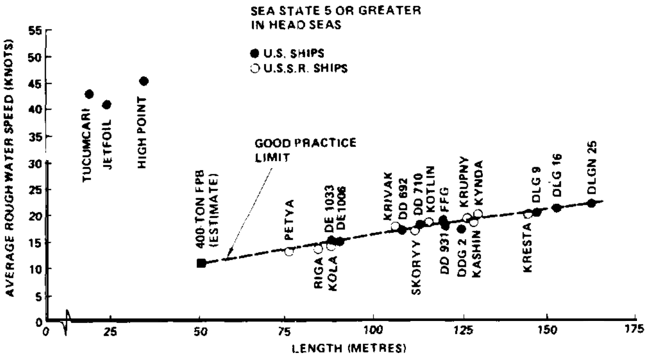


Figure 15. Effect of Length on Rough Water Speed in Head Seas

Military hydrofoil ships are designed to operate in severe sea environments. Figure 16 compares the all-season wave height distribution of three typical seas and the North Atlantic, [10]. For example, it is seen that significant wave heights less than 3.0 meters are experienced 80 percent of the time on an annual basis in the North Atlantic, 90 percent in the North Sea, 95 percent in the Mediterranean, and about 99 percent in the middle Baltic. The wave height distributions do not take into account all the characteristics of the sea affecting ship performance. The difference between wave and swell (wave period) and the directional characteristics are also important. Wave height, however, is the dominant factor and is the most convenient representation of sea severity for comparing ship performance.

Analytical studies verified by sea trials and extensive operations have been made on ship motions and their significant impact on crew proficiency, passenger comfort and combat system effectiveness [11).

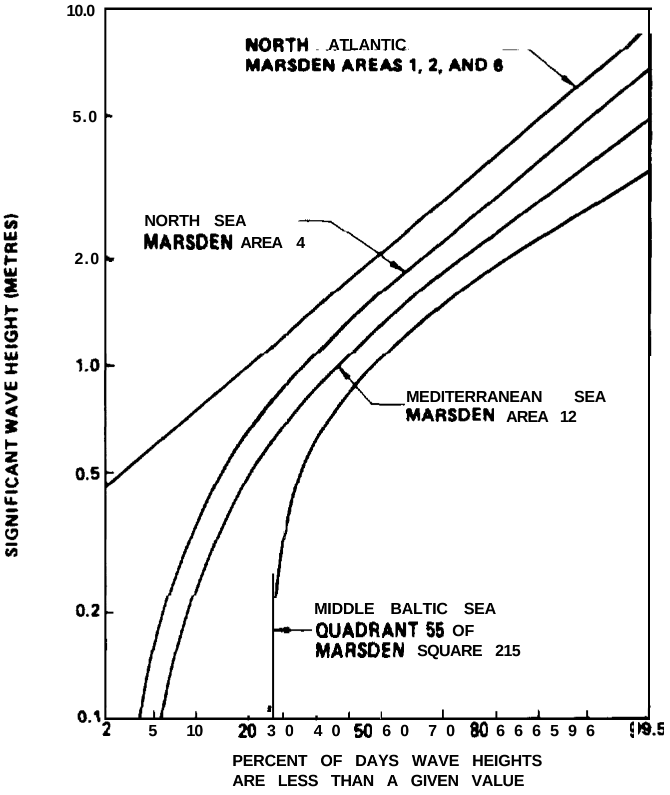


Figure 16. Long-Term Wave Height Distributions (All seasons)

The effect of motion and, in particular, vibration on the human has been the subject of much study in recent years [12]. The individual's response is dependent on the direction, magnitude and frequency of the vibration. In ships, vertical motion is the primary known cause of motion sickness, while both vertical and lateral acceleration are major contributors to fatigue. The magnitude and frequency content of the vibration determines how long the human can tolerate a given level before becoming sick (severe discomfort) or before proficiency is impaired by fatigue. For a naval vessel, the "fatigue decreased proficiency boundary" is of most interest since the crew will be "seasoned." Figure 17 shows the data base for human response to vertical acceleration in terms of frequency and exposure time.

Hydrofoils operating at 40 knots or over in head to bow seas will encounter waves every I to 2 seconds depending on the wave period. The commander of a conventional ship, unwilling to subject his ship or his crew to the punishment of the rough seas, will slow down to the "good practice" limit of one slam per minute (0.017 Hz), a wave encounter frequency below the data base. For comparison purposes, however, an acceptable vertical acceleration level must be selected for determining crew proficiency. The acceleration levels for proficiency at 1 .0 Hz are considered reasonable values for the hydrofoil at or above 40 knots. A lower allowable acceleration should apply to the conventional ship. For comparison purposes, however, the levels at 1.0 Hz are also selected for the conventional ship.

The rough water behavior (ride quality) in terms of vertical acceleration at the steering station for the fully-submerged foil hydrofoil and for several classes of conventional ships operating in the North Sea is shown in Figure 18. Note how much better the ride of the hydrofoil is than that of the fast patrol boat (FPB), even if the FPB slows to 10 knots. The IO-knot speed for the 400-ton FPB and the 16-knot speed for the 3,000-ton frigate (125 meters long) are reasonably "good practice limits" in rough water.

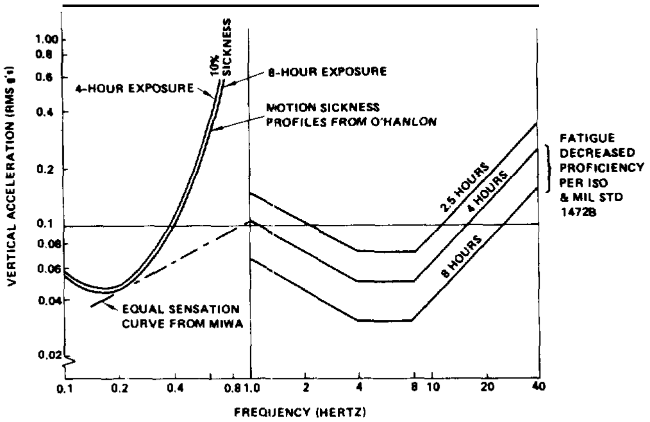


Figure 17. Data Base for Human Response to Vertical Accelerations

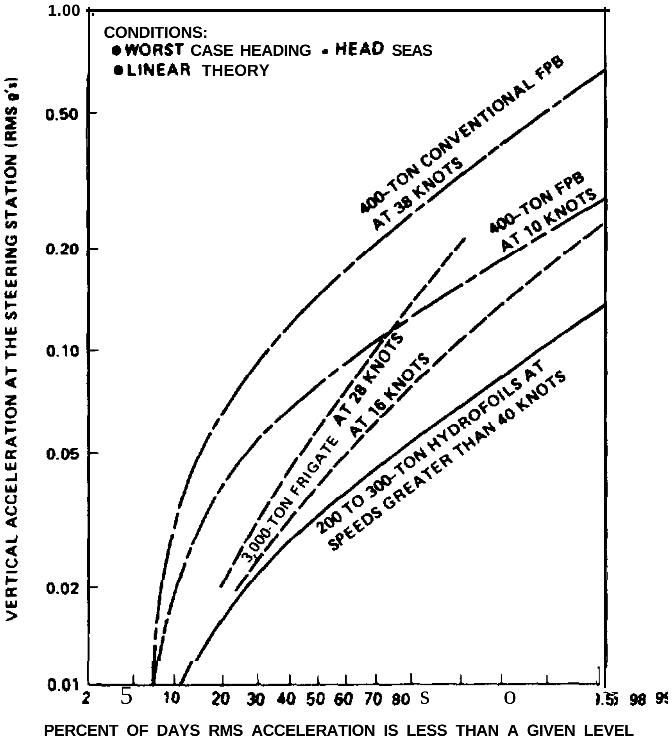


Figure 18. Long-Term Vertical Acceleration Distributions in the North Sea.

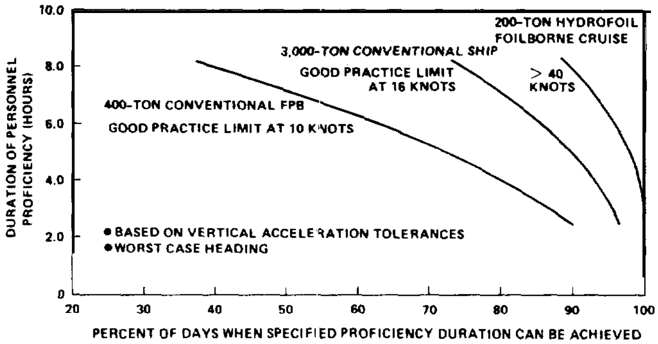


Figure 19. North Sea Working Environment (All Seasons)

Figure 19 compares the percent of the days that personnel can be expected to remain proficient at a duty station for a stated number of hours in the North Sea on hydrofoils. on a 400-ton FPB, and on a 3 ,000-ton conventional ship. This figure combines vertical acceleration data with the acceptable levels and time limits at 1.0 Hz. For a normal watch of 4 hours, it is seen that the crew member can expect to remain proficient 99 percent of the days aboard the foilborne hydrofoil at speeds over 40 knots, compared to 80 percent of the days aboard the conventional fast patrol boat often operating at only 10 knots.

The foregoing, while specifically addressing the foilborne performance of submerged-foil hydrofoil ships in rough seas, is applicable to a degree to surface-piercing

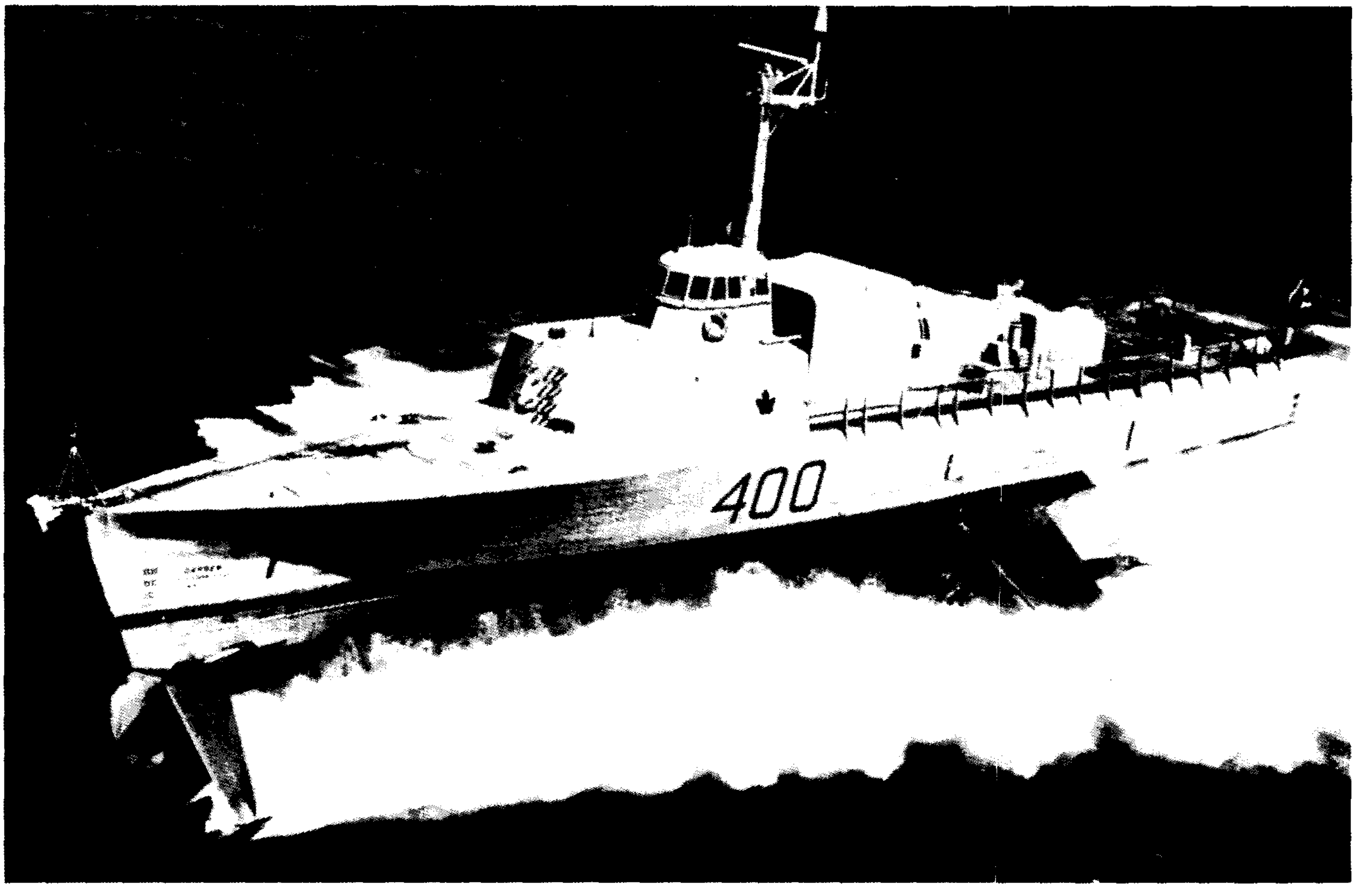


Figure 20. Canadian *Bras d'Or*

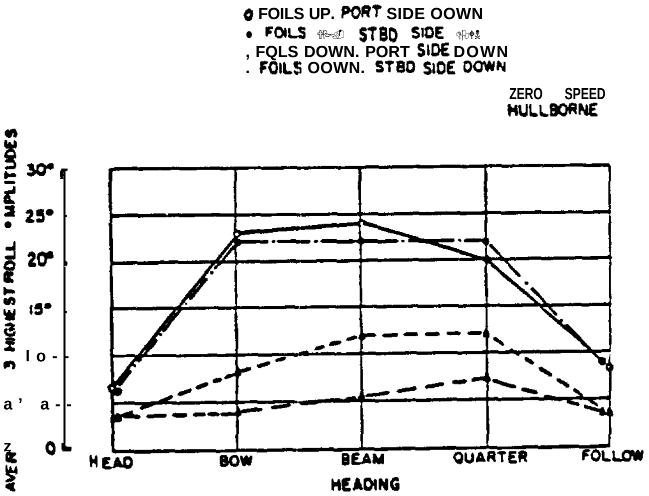


Figure 21. The Predicted Hullborne Roll of AGEH-12 in State 7 Seas Based on 5-Foot Model Tests

hydrofoil ships. Some of the latter have used an automatic stability augmentation system. This technique substantially improves their ride quality, providing much better performance than displacement or planing ships of similar size, but poorer than fully submerged systems. A hydrofoil ship with surface-piercing foils exhibiting excellent rough sea performance was the 200-ton Canadian Bras *d'Or*, Figure 20. However, its motion in a seaway is higher by a factor of two than motions for a comparable size submerged foil ship such as the PHM, Figure 13.

Reference [13] reports measured motions of the Italian passenger hydrofoil RHS-200, a surface-piercing hydrofoil with a stability augmentation system. These motions are considerably lower than the Bras *d'Or* showing the improvement resulting from the use of such a control system.

The extensive operations of commercial and military hydrofoil ships to date has brought general recognition of their exceptional seaway performance when foilborne. Less well realized is the major contribution of the foil systems to motion reduction when hullborne. The foils, acting as mass dampers. significantly reduce motions in both the roll and pitch modes, graphically illustrated in Figure 21, [14]. Thus, the strut/foil system gives hydrofoil ships hullborne motion characteristics equal or better than those of much larger displacement ships. For example, the 200-ton ***Bras d'Or,*** Figure 20, demonstrated hullborne pitching and rolling motions less than those of a 4,000-ton conventional ship, Reference [15], simply through the damping action of the foils. This characteristic applies both to ships with fixed or retractable foils since at sea the foils will always be extended. The excellent seakeeping characteristic hullborne is particularly important for military ships which for some missions may spend the greater proportion of operating time in the hullborne mode.

In the 30 to 50 knot speed range, hydrofoils are more efficient than other types of sea craft. Thus, for a given ship size and installed power, a higher maximum speed may be obtained, Figure 22. The combination of excellent seakeeping and relatively efficient high-speed performance is now being exploited militarily in the United States, Italy and Russia with squadron level operations of hydrofoil ships in sizes from 60 to 300 tons. However. the great majority of hydrofoil craft in service today utilize this speed advantage in the passenger ferry role. Prime examples are those developed by Supramar and Rodrigues and the many hydrofoil craft plying the waters of the major Russian rivers, lakes and coastal waters. The Russian commercial craft use minimum draft, nonretractable foil systems suitable for the relatively calm waters found in those areas. In addition to the greater transport efficiency, these hydrofoils take advantage of the fact that while foilborne a hydrofoil's wake is orders of magnitude less than for a similar size displacement or planing ship at the same speed.

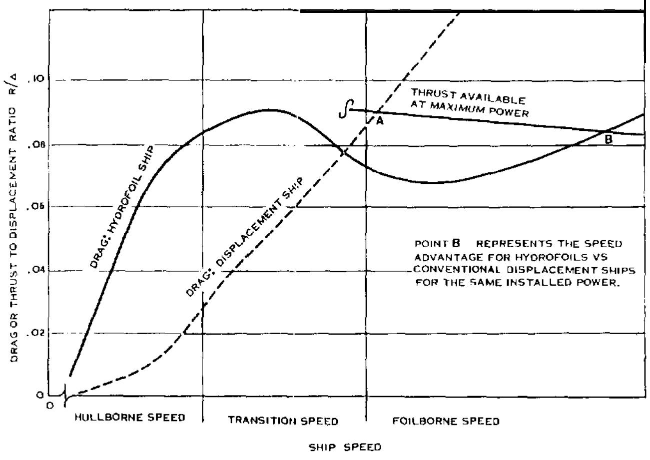


Figure 22. Ship Drag-Thrust-Speed Curves

Besides a significant speed advantage, hydrofoils are more maneuverable and provide a more stable platform than conventional ships. Foilborne turns are accomplished in a banked (coordinated) fashion, Figure 23. This causes the centrifugal force required in turns to be provided predominantly by the reliable lift capability of the submerged foils rather than by the unpredictable side forces from the surface-piercing struts. Turn coordination enhances crew comfort during high-rate turns because the accelerations due to turning are felt primarily as slightly greater vertical forces rather than lateral forces. For example, a 0.4g turn is felt as only 0.08g vertical acceleration increase while the lateral acceleration is zero. Therefore, hydrofoil ships have design turn rates of 6 to 12 degrees per second, two to four times those of conventional ships, and they can maintain these rates in both calm and rough seas, Figure 24. This makes the hydrofoil ship a more difficult target for enemy missiles, guns, or torpedoes. The exceptional stability of the hydrofoil ship makes it a superior platform in which to mount surveillance equipment and weapons while maintaining crew comfort and proficiency.

Another naval attribute of hydrofoils is their radically different pressure and acoustic signatures while foilborne compared with displacement hulls. This difference in signatures coupled with the demonstrated capability of foil systems to withstand underwater explosions make the hydrofoil of interest in mine warfare.

From the naval viewpoint, the essential merit of the hydrofoil principle is that it offers the only reliable prospect of a comparatively small ship capable of matching the speed and seakeeping capabilities of major combatants. In this respect it offers the future analogy of the World War II corvette-the smallest and least costly vehicle capable of all-weather operation in the open ocean.

In essence, the combination of foils and hull provides the designer with scope to optimize the characteristics most valuable for a particular application, such as seakeeping ability, low power, and high maneuverability, either at foilborne or at hullborne speeds. A craft designed to takeoff in harbor and transport passengers in comfort at a constant high speed to a known destination at minimum cost will differ radically from a naval craft spending the majority of its time on hullborne patrol in the open ocean, but able to sprint at high speed regardless of sea conditions or able to operate over a wide range of intermediate speeds to escort or shadow other naval forces.

These advantages do not come cheaply. Though requiring less power than conventional ships of the same size and speed, power requirements are still high. Therefore, in common with other high performance systems, weight of structures, propulsion and auxiliary systems must be carefully controlled to attain the useful load weight fractions necessary for effective military or commercial ships. To obtain the outstanding rough water behavior demands a foil system with relatively complex strut, foil and flap structures, automatic control systems and high power hydraulic actuation systems. Therefore, the cost-per-ton of a hydrofoil ship will always exceed that of conventional ships. It is the problem of the designer to properly balance the cost of weight reduction and complexity with the resultant performance improvement to attain a cost effective ship for the planned end use. When appropriately designed for military and commercial roles which take advantage of the unique operational capabilities the hydrofoil offers, a hydrofoil ship can cost less when measured in dollars or per unit of applicable performance than conventional ships for the same role.

In the early naval development of hydrofoils, speeds of 60 to 100 knots were considered. Current military requirements discuss sprint speeds of more than 50 knots. Present operational hydrofoils are all based on foils and strut sections designed to avoid or at least minimize cavitation. The speed available for ships designed with subcavitating sections is limited to about 55 knots. Higher speeds can be achieved with supercavitating foils, but one is faced with high development and construction costs and a major increase in specific power requirements. In addition, operational analyses of potential naval missions have generally indicated a diminishing increment of effectiveness for speeds above about 50 knots.

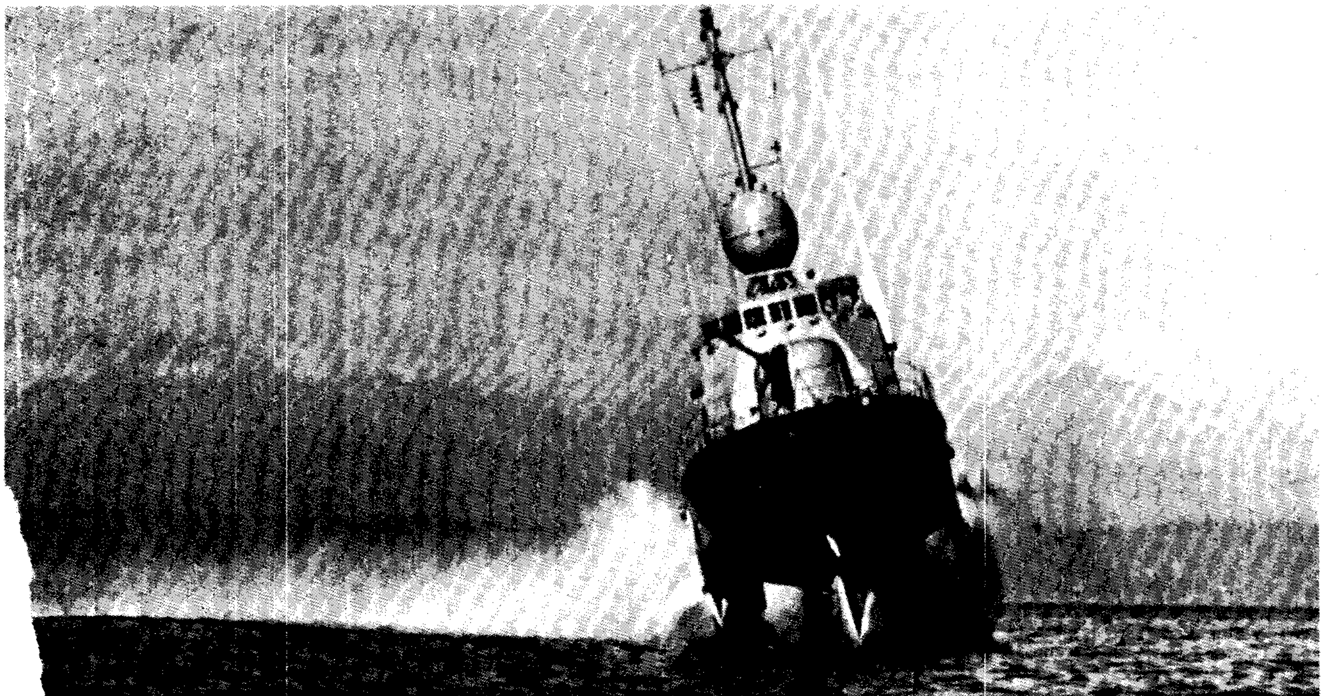


Figure 23. PHM Banked Turn

These factors narrow the field of potentially useful applications to the point that development of the higher speed capability may not be warranted.

In establishing the requirements for a vehicle, either commercial or military, careful attention should be placed on the specified speed. If a 35-knot vessel will accomplish the mission, rather than a 50-knot, procurement and operational cost savings can be realized.

A hydrofoil ship will become foilborne at about 50% of its design foilborne speed and will operate in a stable manner in rough water over the upper third of its speed range. It also has the characteristic, unusual compared to displacement ships, that maximum foilborne range will occur at about 90% of the design speed and will not vary more than about 10 to 15% over the entire stable foilborne speed range.

A military hydrofoil ship may spend a substantial portion of its underway time at lower speed and, if so, will generally have a separate propulsion system for efficient operation in the low-speed operational mode. When operating in this hullborne mode, the ship is similar to any other displacement ship from a powering standpoint only having the extra friction drag of the foil system. For efficient overall design, the hullborne propulsion system will normally provide a design hullborne speed corresponding to a hull speed-to-length ratio of 1 .O to 1.4.

These two characteristics. efficient operation at low speed or high speed, have resulted in viewing hydrofoils as having an operational "speed gap." Actually, there is no appreciable speed gap since the main propulsion system can be used to provide stable hullborne speeds above that provided by the "hullborne" propulsion system when operationally required.

The main point is that operation either at lower speed or high speed is more efficient than at intermediate speeds. Maintaining an average speed by alternative high- and low-speed operations (sometimes referred to as sprint and drift) is more efficient than maintaining a constant intermediate speed. Therefore, constant intermediate speed operation will normally only be utilized when some specific operational consideration demands it. A prime example is underway replenishment which is often accomplished at speeds greater than available from the hullborne propulsion system of the present operational hydrofoil ships. Also, as future hydrofoil ships grow in size the design hullborne speed can be expected to increase to match the typical speed of naval formations.

One of the questions frequently asked of hydrofoil designers is, "How big can they be built?" Two appropriate answers to such a question would be, "To do what?" or "Big enough to do an effective job for many naval or commercial roles in any sea environment." Nevertheless, the largest operational hydrofoil in the free world is the U.S. Navy's *Plainview* (AGEH-I), a 320-ton ship. Reports have been received of larger hydrofoils in Russia. Design studies conducted on hydrofoil ships with displacements greater than 2,000 tons indicate their feasibility.

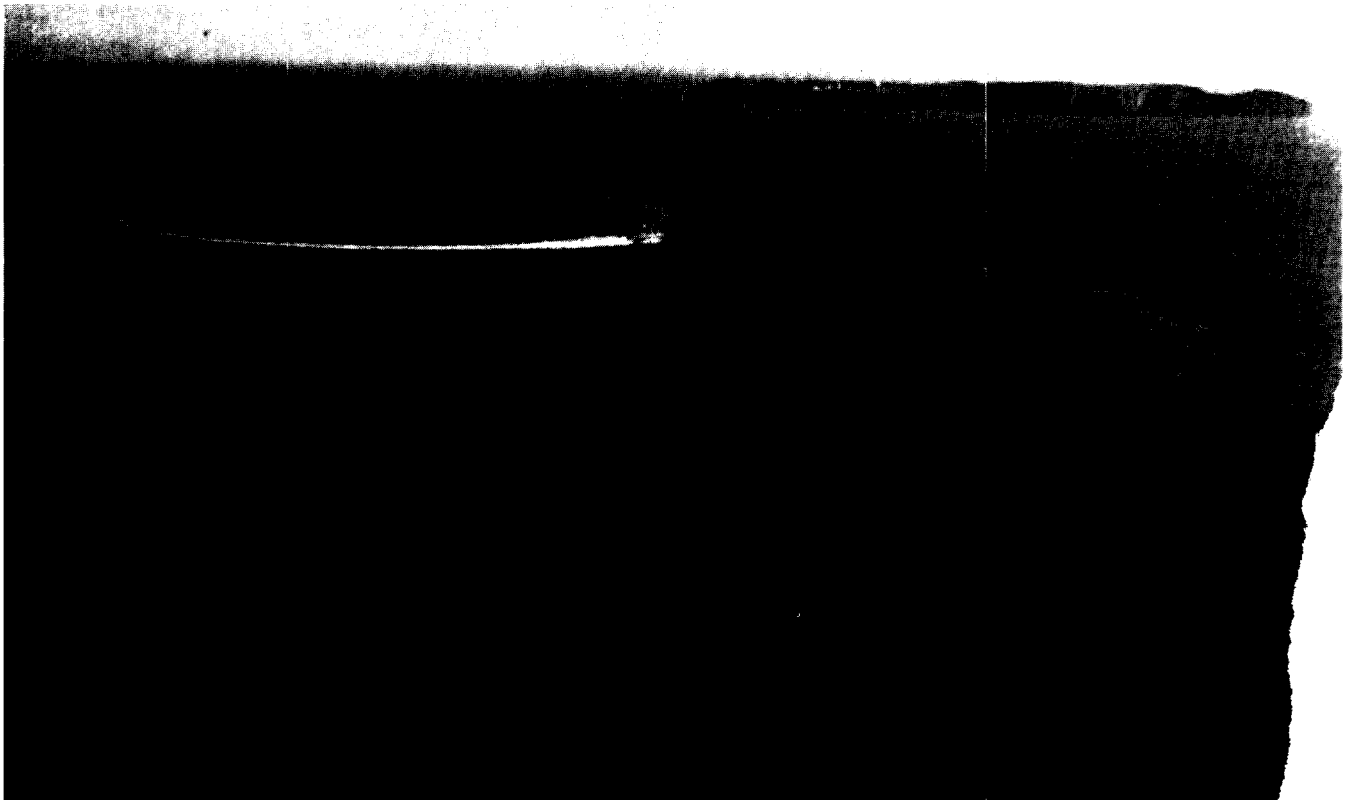


Figure 24. Hydrofoil Maneuver Capability

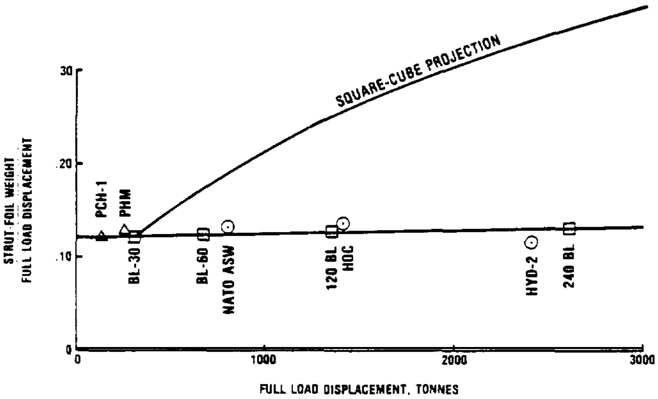


Figure 25. Foil System Weight Trend

A fundamental limitation is imposed by the so-called "square-cube" law, which impacts the growth potential of hydrofoil ships. Because the lift developed by the foils is proportional to their wing area (the square of a linear dimension), whereas the weight to be supported is proportional to volume (the cube of a linear dimension), it follows that as size is increased, the foils tend to outgrow the hull. Aircraft solve this problem by increasing speed and wing loading as size is increased, but practical hydrofoil speeds are limited by cavitation. In the early period of hydrofoil develoment it was felt that increase in the foil and strut weight fraction by direct application of the square-cube law would inherently limit hydrofoil size. More detailed design studies show that foil system weight fractions increase only slightly with displacement, Figure 25. The principal reasons why the weight fraction does not increase as might be expected is that required strut length varies with design sea state, not ship size, and larger foils are structurally more efficient.

For hydrodynamic efficiency, it is desirable to use as high a foil aspect ratio (span/chord) as possible. The PHM aft foil extends almost 10 feet on either side of the hull. Thus, a camel is normally used to hold the ship away from the pier for mooring. When no camel is available the ship must be moored across the end of a pier or the transom of a larger ship with the stern overhanging. PHMs have occasionally nested bow-to-stern. As ship size increases and foils grow relative to the hull and in actual dimension, practical considerations dictate efforts to limit the foil span. The trend will be to move toward tandem foil configurations to divide the weight more evenly between the forward and aft foils. Figure 26 shows this configuration for a typical larger hydrofoil design.

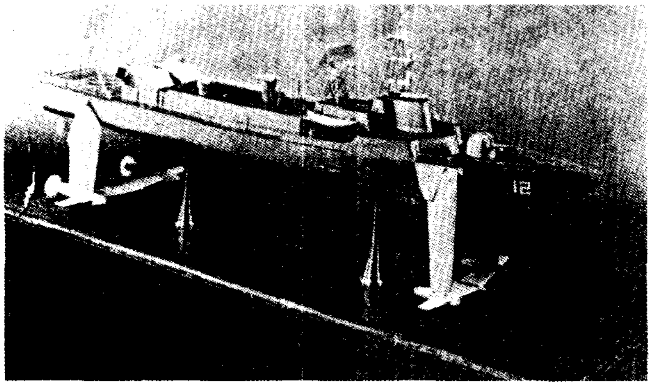


Figure 26. Typical Large Hydrofoil Design

Although the foil system weight and the strut length do not grow to the extent predicted earlier, retracting the foils becomes increasingly difficult as ship size increases. In larger ships, making the foil system nonretractable could save considerable weight and complexity, but the required draft would restrict the harbors available and increase drydocking problems.

Another possible size limitation suggested in the 1970s was that imposed by hydroelastic instability (divergence and flutter). This problem was addressed in a detailed hydroelastic analysis of the aft strut-foil system of the 2,400-ton HYD-2 design. Although the speed of inception of hydroelastic instability tends to decrease with increase in ship size, it was still in excess of 180% of design speed of HYD-2 which gave more than an adequate margin of safety.

Another limitation suggested in the 1970s was the large increase in wave drag, particularly in the vicinity of takeoff speed, due to the decrease in Froude number based on increased chord length. Tests at low Froude numbers (0.8 to 2.0) made at DTNSRDC showed the wave drag does become a more dominant factor for large (3,000-ton) hydrofoils. For propeller driven ships an adequate margin in takeoff thrust is still available to assure takeoff in a seaway. For larger hydrofoils driven by waterjets, wave drag at takeoff speeds will pose serious problems because of the relatively lower thrust available at takeoff.

Hydrofoils up to 3,000 tons, are affected by practical engineering limits in the propulsion drive train. Based on a series of designs done at DTNSRDC on the hydrofoil analysis and design computer program (HANDE), the propulsive power needed for 40-knot and 50-knot designs as a function of full-load weight is shown in Figure 27. Assuming that practical hydrofoils will be limited to two power struts, each strut must transmit half the total power shown in this figure. Gas turbines come in discrete sizes up to about 40,000 hp and multiple engines per side can be used: therefore prime movers pose no serious limit to the size of a hydrofoil. The power from the prime movers is transmitted to the propeller through two right angle bevel gear boxes to the propulsion pod and thence through a planetary gear box to the propeller. It is in this transmission system that we first encounter practical engineering limits.

The present state of the art in transmission systems limits the power per strut to 25,000 to 30,000 horsepower which in turn limits the size of hydrofoils to between 1,250 to 1,950 tons, depending on the design speed, Figure 27.

Waterjets would circumvent the need for mechanical transmissions, but their weight, inherently lower efficiency and relatively low thrust at takeoff, tend to reduce their practicality for larger hydrofoils as indicated in Figure 28.

In the future, with improvements in bevel gear design or the advent of superconducting and water-cooled elec-

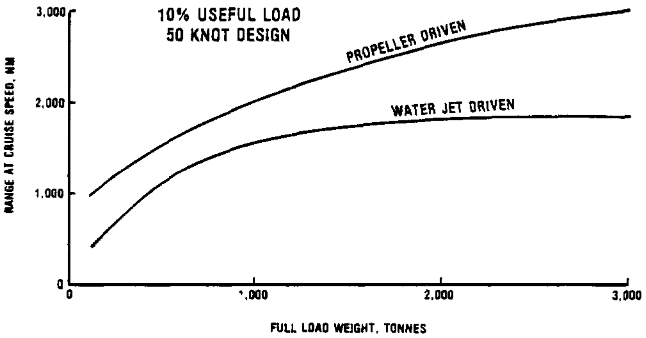


Figure 27. Range as a Function of Full Load Weight

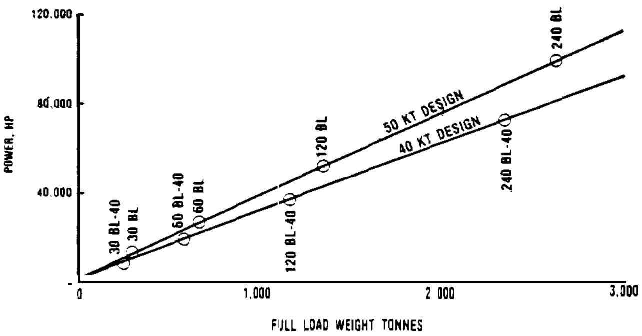


Figure 28. Power as a Function of Full Load Weight

tric drive, hydrofoil ships of 2,500 to 3,000 tons would become possible. Electric drive could have the further advantage of improving arrangement flexibility and simplifying the problems associated with transmission system compatibility with foil retraction mechanisms.

From the foregoing it can be concluded that hydrofoil ships of sizes to 3,000 tons can be foreseen as technically feasible. However, serious mission considerations and cost tradeoffs with other modern ships are necessary before a hydrofoil this size should be selected for development. Certainly if the requirement can be justified, the technology is available to develop a 1,000- to 2,000-ton hydrofoil ship.

Hydrofoil technology has reached that stage of maturity where it is possible to define attributes and limitations with confidence, and where designs can be optimized for a given requirement. The current regime of the naval hydrofoil ship lies in sizes up to about 1,000 tons, and in maximum rough water design speeds of 35-50 knots.

HYDROFOIL APPLICATIONS

MILITARY MISSIONS

Historically, military applications of hydrofoils have been consistent with the relatively small displacements of early versions as the technology was developing. In World War II, the Germans started an ambitious hydrofoil program that became heavily impeded by the exigencies of the war but did produce the first hydrofoils to see action. These were a group of five, 20-ton, surface-piercing hydrofoils that were used in the Norwegian campaign for coastal surveillance. Three larger, 60-ton, craft were also built, but were lost during bombing raids while the first craft was in the sea trial phase and the other two were still on the building ways. These hydrofoils were intended as high-speed logistics transports, each to carry a tank across the Mediterranean to Rommel's forces in North Africa.

After World War II, Dr. Vanevar Bush conceived the hydrofoil ship as a way to provide high-speed, transocean, logistics transport. Submarine development during World War II had led the way for the true submersible, which culminated in the nuclear submarine with a very high submerged speed compared with the diesel boats that had ravaged the Atlantic and the Pacific. Dr. Bush was impressed by the potential of the hydrofoil as a surface ship that could keep out of the path of a hostile submarine. Although the Navy initially supported Dr. Bush's objective, it was proven to be unrealistic at that time, and the project was abandoned.

Starting in the early 1960s, the U.S. Navy moved from experimental craft to the construction and testing of operational hydrofoils. The first Navy operational hydrofoil was *High Point* (PCH-1) (Figure 29). The initial design of *High Point* was done by the Bureau of Ships, and the ship was built by Boeing. The principal characteristics were:

	High Point (PCH-I)
LOA	115.75 feet
Beam	31.28 feet
Draft	
Foils Retracted	6.5 feet
Foils Extended	17.0 feet
Full Load Displacement	112 tons
Manning	1 Officer and 14 Enlisted

High Point was originally intended for off-shore ASW. The concept was to use the PCH as a small, high-speed, sonar platform, equipped with ASW torpedoes to sortie from harbors in advance of a convoy. Using its speed to move quickly over a larger area, the PCH could protect the departing convoy and its larger ASW escorts at its origin when they are most vulnerable. However, development of a sonar suitable for effective utilization of the ship's unique capabilities was never prosecuted.

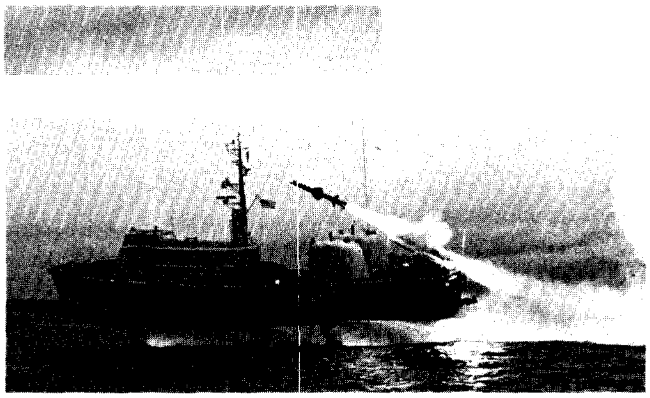


Figure 29. *Highpoint* (PCH-1)

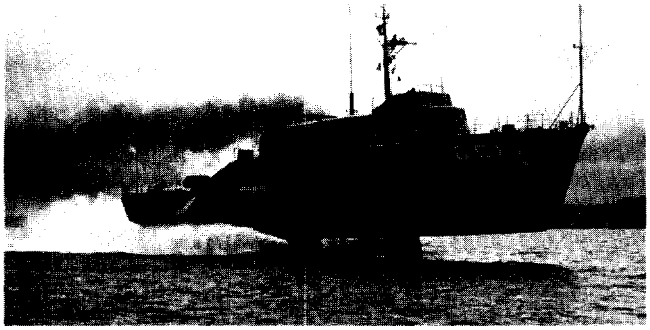


Figure 30. ***Plainview*** **(AGEH-1)**

The ship was initially delivered in 1963. Operational problems encountered during initial operations indicated a need for further development, and *High Point* became the workhorse of the Navy's R&D community. In 1974 the foil system was modified and the full load displacement increased to 126 tons.

During the period that *High Point* was under construction, the Navy contracted for the design of *Plainview* (AGEH-I), (Figure 30), with The Grumman Corporation. The ship was built by Lockheed Shipbuilding and delivered to the Navy in 1969. *Plainview* was originally planned as an ASW ship. However, since it was at that time the largest hydrofoil in operation and sonar development had not occurred, it also was turned over to the R&D sector of the Navy. The principal characteristics were:

	Plainview (AGEH-I)
LOA	211.73 feet
Beam	70.79 feet
Draft	
Foils Retracted	6.2 feet
Foils Extended	26.0 feet
Full Load Displacement	320 tons
Manning	4 Officers and 16 Enlisted

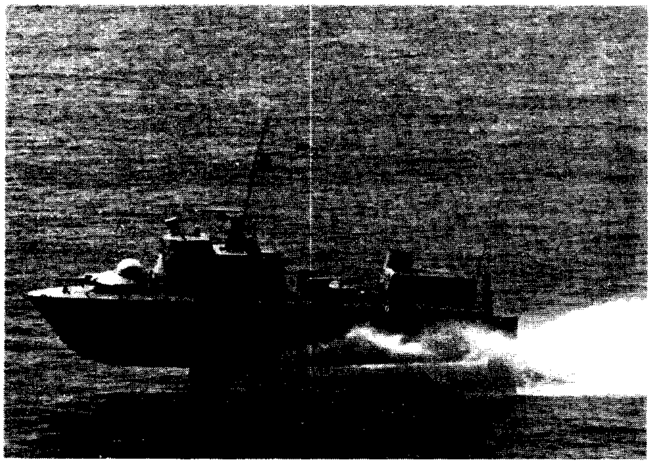


Figure 31. Flagstaff (PGH-1)

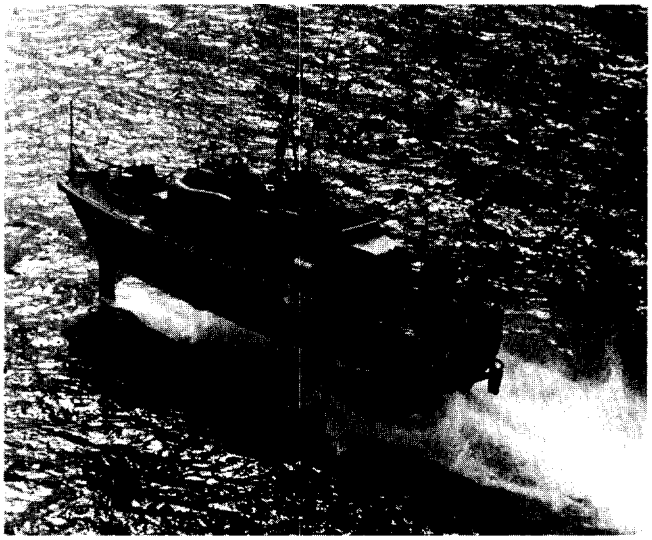


Figure *32. Tucumcari* **(PGH-2)**

The first U.S. Navy operational hydrofoils that were delivered to the fleet were the patrol gunboat hydrofoils (PGHs). Two PGHs were built, one by Grumman, *Flagstaff* (PGH-1), (Figure 31) and one by Boeing, *Tucumcari* (PGH-2), (Figure 32). Although designed and built to the same performance specifications, their configurations were substantially different. PGH-1 was propeller driven and had a conventional foil distribution. PGH-2 was waterjet propelled and had a canard foil system. Delivered to the Navy in 1968, they both saw service in Vietnam, making them the first U.S. Navy hydrofoils in combat. The characteristics of the two craft are:

	PGH-1	PGH-2
LOA	74.0 feet	71.8 feet
Beam	37.08 feet	35.3 feet
Draft		
Foils Retracted	4.20 feet	4.50 feet
Foils Extended	13.50 feet	13.90 feet
Full Load Displacement	68.59 tons	57.40 tons
Manning	4 Officers and 12 Enlisted	1 Officer and 12 Enlisted

The PGHs were designed and operated as patrol craft to support special operations of the amphibious force which may include (1) surveillance of coastal areas of interest and interdiction of high interest shipping or infiltrators, (2) delivery and retrieval of special force personnel, and (3) deception and decoy of hostile forces. The operational experience gained from these hydrofoil ships, particularly *Tucumcari,* provided the confidence necessary to proceed to the PHM program.

By 1984 all of these hydrofoils with the exception of *High Point* had been retired from service. They are included in this introduction to bring some perspective to the progress of U.S. Navy hydrofoils and as a basis for future reference in this article.

The concept for the PHMs, Figure 33, developed from the need to find an effective counter for the Soviet *Osa*

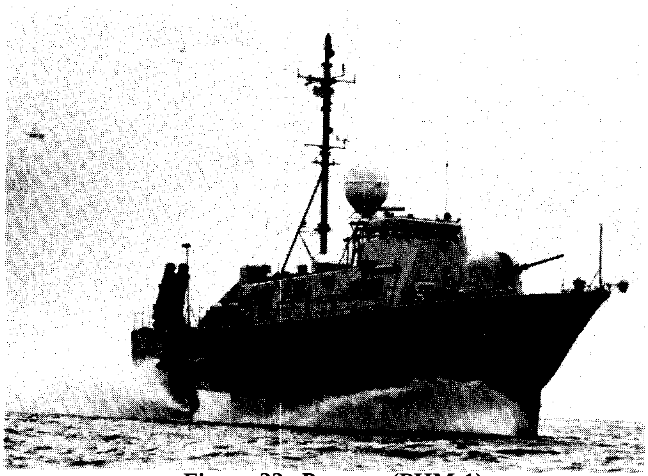
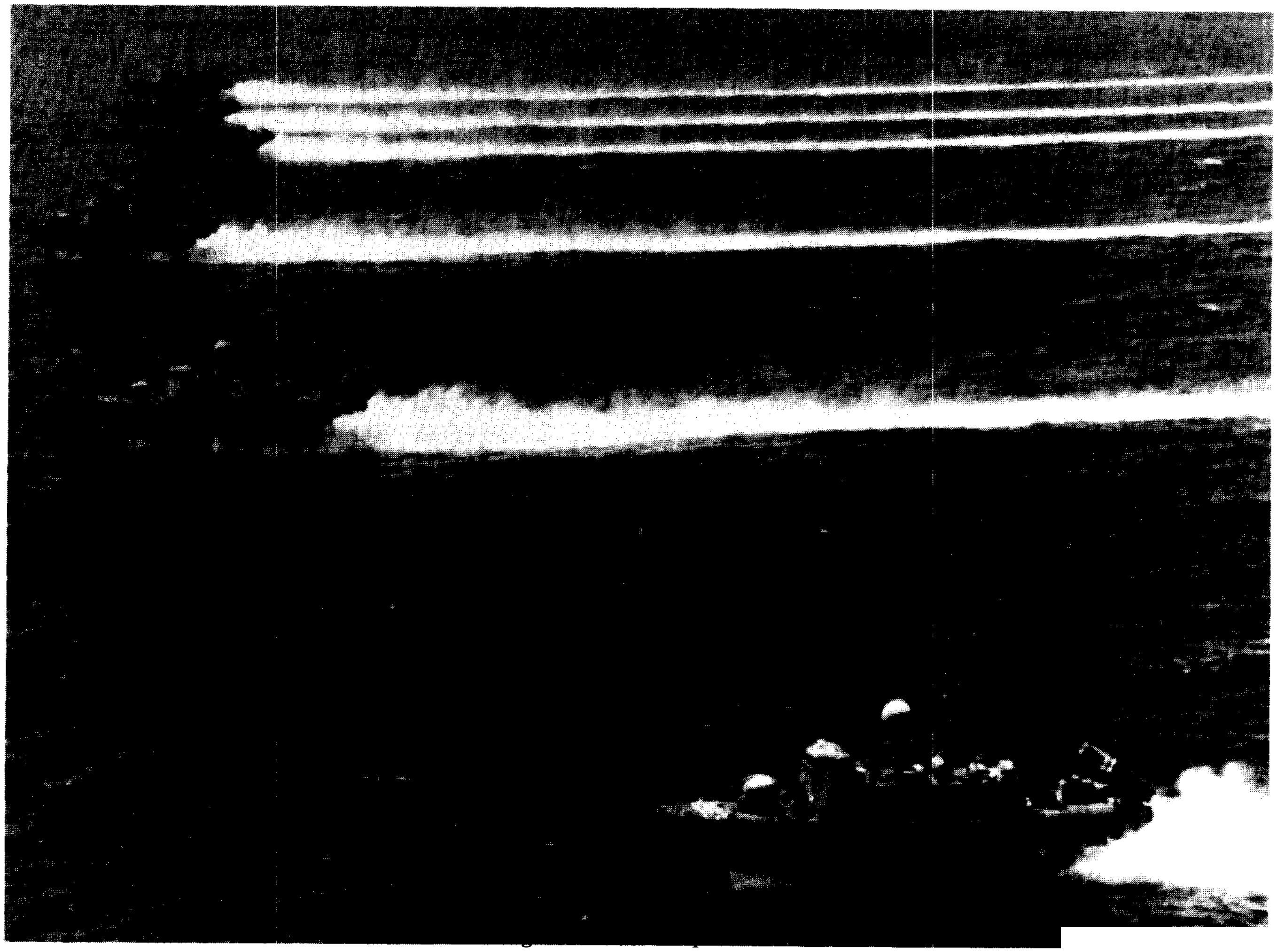


Figure 33. *Pegasus* (PHM-1)

Komar missile boats in NATO's Mediterranean waters. The NATO group that subsequently drafted the military requirements for the NATO PHM was quick to realize that a modern hydrofoil, when equipped with antiship missiles became, by itself, a formidable surface combatant with unique capabilities for high-speed all-weather operations over distances and mission durations consistent with operations of their more conventional fast patrol boats. While high costs and political considerations eventually resulted in the committed NATO nations withdrawing from the PHM building program, the PHMs were nevertheless designed and built to meet military requirements aimed at operations in NATO waters. The PHM is described in detail later in this section.

Operational military hydrofoils are in service or under construction in the free world today in the United States, Italy, Israel and Indonesia. These are all under 250 tons in displacement. Their primary mission can be summarized to be the attack and destruction of larger surface ships with antiship missiles and/or guns. Secondary missions include:

Surveillance of coastal areas, especially choke points
High technology naval presence
Special operations which include:
  Delivery and retrieval of commando-type special force units,
  Trailing and shadowing of high interest shipping, and
  Deception and decoy of hostile faces.
Quasimilitary operations which may include:
  Surveillance and protection of fishing and off-shore oil zones.
  Antismuggling, and
  Search and rescue.



In the United States, the squadron of 240-ton PHMs operating from Key West, Florida, is extending these roles to operations with and support of major fleet units of the U.S. Navy, Figure 34.

VAdm. John D. Johnson, Jr., Commander of the Naval Surface Forces, Atlantic, praised the PHM for its characteristics of speed, seakeeping capabilities, agility, survivability, a weapons system which can provide mission kill on large combatants, and its relatively low cost, [16]. In the final paragraph of Reference [15] he said, "The advantages of the PHM are a terrific punch for a very small ship. A difficult ship to kill, a high-speed ship. Those are strong advantages, and I believe naval planners and tacticians will increasingly value them when we prove the concept and deploy PHM to the right places." Admiral Johnson's statements were made prior to arrival of the full squadron of six PHMs at Key West. Subsequently his expectations have been demonstrated by operations and exercises including close surveillance and tattletaling, surveillance and patrol of choke points, combined patrol and barrier operations with FFGs, surface warfare support of carrier battle groups and rapid response, pursuit, search and seizure operations in cooperation with the U.S. Coast Guard for ships suspected of illicit activity, [17, 18].

Operations have also included long-range deployments to and from Hawaii and transits from Puget Sound to Key West. These operations have routinely included underway refueling in calm and very rough seas, Figure 35

Much of the activity of the present operational, military hydrofoil ships is devoted to development of optimum tactics to capitalize on the unique operational characteristics of submerged foil ships when combined with effective modern weapons. For example, even though effective modern missiles are capable of being launched over-the-horizon. it is necessary to know what is being targeted. To assure missiles fired will attack high-value units of an opposing force, it may be necessary to close to relatively short range. Tactics which take advantage of the speed, maneuverability and small radar cross section of hydrofoil ships in such an attack role are described in References [19 and 20].

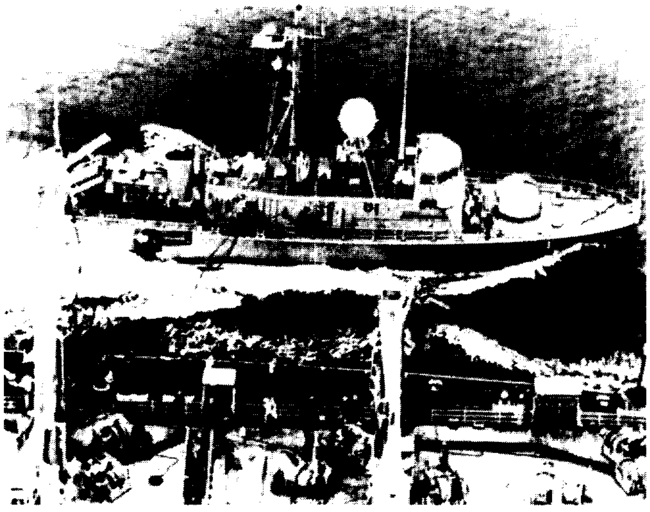


Figure 35. PHM Underway Refueling

It may be observed that none of above mission discussion includes ASW, while Soviet hydrofoils of the *Turya* and *Babochka* classes include ASW armament and sensors. Other missing naval warfare areas include antiair and mine warfare. While elements of both ASW and mine warfare and some AAW defense capabilities have been demonstrated in U.S. Navy hydrofoils, few military planners have included them. A possible explanation for this is the relatively small size of the available weapon payload in the present ships and, in the case of ASW, the technological lack of an optimum ASW sensor at foilborne speeds.

Some defense planners have held the opinion that because hydrofoil ships can operate effectively at speeds above 30 knots, their application to ASW must await development of reasonably long-range "high-speed sensors." Others have argued that, in view of the few high performance ships available or presently planned, there is insufficient priority to support spending scarce R&D monies for development of such sensors. In addition to this circular "Catch 22" situation, the physiology of the environment makes development of the high-speed sensor capability, for other than short ranges, extremely difficult, if not impossible. These factors have to date frustrated those hydrofoil ship proponents who believe the unique capabilities of submerged foil ships can and should be exploited to increase ASW capabilities of navies in coastal waters for the near term and the open ocean in the future.

A unique capability of hydrofoil ships, often not understood and presently not exploited, is the ability to deploy and operate ASW sensors at low speed where their sensing capability is greatest and then to move rapidly to another location for redeployment of the sensor or for attack. The speed capability of the ships is sufficiently high to permit average speeds consistent with screening and attack when using present technology sensors in this intermittent-search operational technique. The development required for this application is the engineering adaptation of present sensors and equipment, not specific sensor development. The Canadian Navy's *Bras d'Or*, Figure 20, was originally planned to be an open-ocean ASW hydrofoil ship using a variable depth sonar in such an intermittent-search mode. The foil system was specifically designed with this role in mind, particularly to achieve riding comfortably hullborne in ocean seas while searching. The *Bras d'Or* program was discontinued after initial sea trials primarily because of a policy change in the role of the Canadian Navy and secondarily due to correctable technical problems. However, through a joint U.S./Canadian research effort, the VDS built for that program has been tested to foilborne speeds towed by the USN *High Point*. This demonstrates the feasibility of searching at modest speed and sprinting at high speed without the need for extensive dead time otherwise associated with recovering the sonar before going foilborne.

Suitable adaptation of present ASW equipment could permit present hydrofoil ships to operate effectively in ASW or mine warfare roles. Adaptation is necessary because systems designed for use on large surface ships are generally too heavy to be directly applied to the present relatively small hydrofoil ships.

Few, if any, weapons systems have been specifically developed for employment on hydrofoil ships. Conceivably this fact-of-life restriction can be eased or eliminated in the larger oceangoing hydrofoil of 1,000 or more tons. While eliminating unnecessary weight will always pay off, the range of naval missions available for such a large hydrofoil virtually becomes limited only by the imagination of the naval planner. Not only could they fulfill the surface combatant roles of today's hydrofoils, but such ships could also be capable of performing AAW, ASW or mine warfare missions. Such a ship could take its place as a highly versatile ship of the line with one important new characteristic-that of an all-weather speed advantage over conventional ships and submarines.

Following are sections providing details of the present military and commercial hydrofoil ships and recent analytical and research efforts.

PATROL HYDROFOIL SHIP (PHM) DEVELOPMENT

In 1970, a NATO group, composed of representatives of eleven NATO nations, decided that a hydrofoil with fully submerged foils was the answer to the operational requirements for a common fast patrol boat carrying surface-to-surface missiles. The NATO group studied different concepts of vehicles, but the final choice of the group was a ship configuration based on the design of the United States Navy hydrofoil *Tucumcari,* which was to become the prototype for future fast patrol boats. The original concept called for an operational displacement of about 140 tons.

In 1972 the governments of the United States, Germany and Italy formally agreed to proceed with the joint development of a patrol hydrofoil ship. A contract was awarded to The Boeing Company for the feasibility study and the design and construction of two PHMs. While the initial contract called for two lead ships, program cost growth forced suspension of work on the second ship in August 1974. Its completion was later incorporated into the production program.

The U.S. acquisition process historically requires about a 7-year development cycle for the definition, design and first unit construction of a new ship platform. As the schedule of major events shows, Figure 36, nearly six years elapsed from the signing of the contract for the design and construction of the lead ship and its commissioning.

The NATO patrol missile hydrofoil (PHM) was the first U.S. Navy ship program to complete all aspects of design, construction, technical evaluation and independent operational evaluation as required by DOD Instruction 5000.1 which sets forth the "fly-before-buy" policies required of selected DOD system acquisition programs. The extensive predelivery test and evaluation program including problem resolution and corrective actions account for the more than 2% year time span from launch to delivery. The PHM test program planning, execution and results through the completion of technical evaluation, including conclusions regarding the overall concept of exhaustive prototype testing prior to entering a production program, are reported in Reference [21].

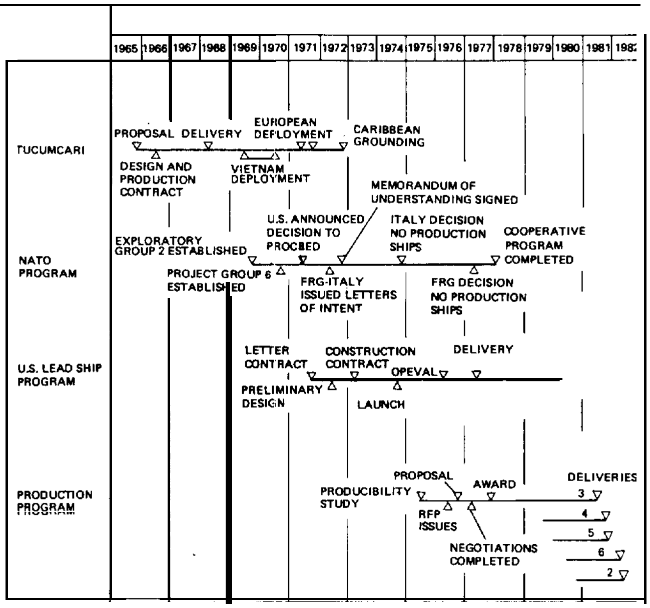


Figure 36. Major Events Schedule for the PHM Development

The earlier examination of ship alternatives and configuration choices required two more years. Again, referring to the major events chart, Figure 36, over ten years elapsed between the start of the lead ship program and the completion of the five production ships which, together with the lead ship, make up a six-ship squadron.

An immediate task in late 1971-early 1972 was to determine the feasibility of designing a hydrofoil to meet the performance goals of the three participating governments. The objective was examined from the standpoint of three alternative mission suites, in particular the surface-to-surface missiles. The feasibility baseline design and parametric studies were to provide the data and alternatives which would allow the participating governments to knowledgeably select the primary performance and major configuration characteristics to be incorporated into a standard design. Baseline ship cost estimates were also developed to provide information on the effect of configuration choices on cost.

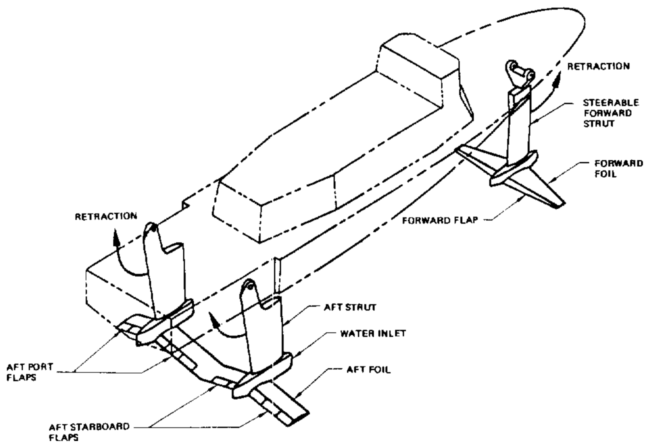


Figure 37. Foil System Arrangement

The initial effort determined that the performance goals could be attained with any of the three mission suites, but the displacement in each case was greater than a target value which had become 170 tons. In fact, by the time the feasibility baseline design was completed in April 1972, the design full load displacement was established at 228 metric tons including a 9.5 metric ton margin for growth during the service life.

Another major task in the first days of the hydrofoil contract was to study the feasibility of designing and constructing the ship using metric units in order to achieve the objectives of a cooperative design in the most cost-effective manner. The approach involved review of each major element of the design specifying metric units for new elements and using imperial units for elements already developed in those units. The initial cost impact was estimated to be about five percent on design, five percent on procurement and an initial ten percent impact on maintenance and support items. The decision to "go metric" can now be viewed as very favorable. The engineering designers had no problem in changing their thinking to metric equivalents. This represented a significant first in U.S. shipbuilding experience.

The hull lines were developed to satisfy considerations related to accommodations, weight. intact and damaged stability, a two-compartment flooding criteria, seakeeping. hullborne resistance, takeoff resistance, and foilborne wave impacts. The hull was designed as an all-welded structure fabricated primarily from 5456 aluminum alloy.

The use of a canard foil system, Figure 37, was established at the outset of the program. The forward foil/strut system has a steerable tee configuration which stows ahead of the bow in the retracted position. The aft foil system was configured as a structural bent. This resulted in greater structural and hydrodynamic efficiency but necessitated retracting the system rearward behind the transom for shallow-water, hullborne operation. These retraction constraints along with the strut length requirements dictated by sea state, determined the location of the foils relative to the hull. The final distribution of foil area, fore and aft, was then determined by the ship center of gravity location. The length of the struts was chosen to allow foilborne operation in 5-meter maximum height waves. The basic material chosen for the foils and struts was a martensitic, precipitation-hardening corrosion resistant steel, 17-4PH.

The propulsion plant went through more of an evolutionary process during the feasibility baseline design period than any other major system. The foilborne system was initially conceived as two double-impeller centrifugal waterjet pumps driven through two combining reduction gearboxes by four General Electric LM500 gas turbines. The hullborne system consisted of a single AVCO TF25A gas turbine engine driving a controllable, reversible-pitch propeller through a veebox.

Since the foiiborne propulsion system has a major cost impact on the ship, its selection was of primary importance. The hullborne system was of secondary importance and was largely dictated by the foilborne system. Criteria used in the selection process were many, but the important considerations included risk, availability, cost, arrangement/access, other commercial and military applications, and performance.

The LM500 engine was not a qualified marine engine at the outset of the hydrofoil development program, and it was estimated that appreciable cost would be required to accomplish its qualification. Other engines considered at the time were the LM1500 and LM2500. Both resulted in heavier ships, increased machinery weights, larger machinery spaces, larger intake and exhaust ducts, and higher per-engine costs. The LM1500 was a first generation turbine which GE planned to phase out of its production. On the other hand, the LM2500, while more costly, was a second generation engine with a substantially higher compression ratio and turbine inlet temperature resulting in much lower fuel consumption, even when operated at lower power levels. The decision to select a single LM2500 engine was based upon the desire to standardize gas turbines in use by the U.S. Navy since LM2500 engines are used in the FFG and DD-963 classes. The LM2500 engine is rated at considerably higher power output than necessary for a ship sized to meet the PHM specification. The engine fuel control was therefore modified to limit the output to the 17,000 horsepower needed to meet the specification performance, and the propulsor and gearbox were designed for the reduced power.

For the foilborne propulsor the choice of the single engine, mounted on the ship centerline. narrowed the selection of waterjet pump to a single or a twin-pump consideration. The twin-pump system required a complex power train system which included gearboxes, flexible couplings and shafting spanning the beam of the ship. This twin configuration was initially adopted as the feasibility baseline design. However, complexity and technical risk caused the later selection of a single pump with integral gearbox. direct-driven by the engine, with the inlet ducting (water) spanning the ship. Either a single centrifugal or a mixed-flow pump could have satisfied this configuration decision. Three companies responded to the pump requirement specification.

One company proposed a mixed-flow, single-stage pump; the second proposed a mixed-flow, two-stage pump; and the third (the *Tucumcari* supplier), proposed a

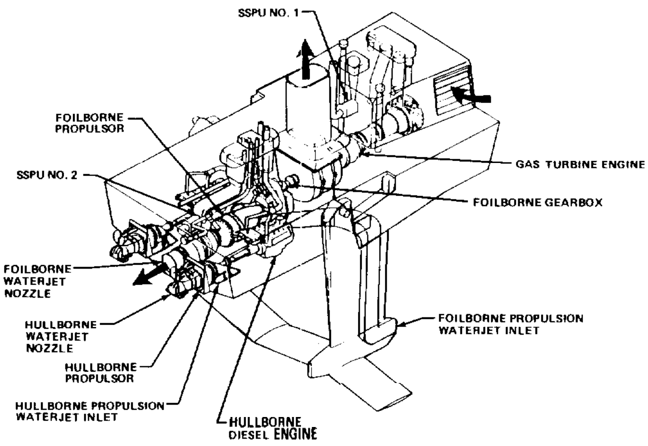


Figure 38. PHM Propulsion System Configuration

double-impeller, centrifugal pump. After consideration of risk, cost and performance, the second proposal was chosen. The foilborne propulsor has been very successful with no changes in performance but with some changes in materials and fabrication techniques between lead ship and the production ship. The PHM propulsion configuration is shown in Figure 38.

The foilborne gearbox on the lead ship experienced some problems early in testing. These problems were analyzed, and corrections were made. The production ship design accounted for these corrections, and the following design modifications were made: 1) capability was increased from 16,200 to 17,000 metric horsepower with a battle override rating of 19,680 metric horsepower, 2) rolling element bearings were changed to journal bearings, 3) increased geartooth strength resulted in decreased tooth bending and contact stresses, and 4) all main gear elements were made integral with their shafts.

After the selection of the single foilborne propulsor, the hullborne propulsion system became a twin system. Twelve candidate hullborne systems were quickly reduced to three. They were: two ST6J-77 turbines and controllable-pitch propellers; two MTU (Motoren-und Turbinen-Union) MB 8V331TC80 diesels and controllable-pitch propellers; and two MB 8V331TC80 diesels and waterjets. The MTU diesels were selected due to lower cost, low specific fuel consumption and good availability. The diesels also had excellent cold start and response time capability, a desired attribute for cold weather operations. Also, early in the program, there was a desire to find some potential FRG equipment suppliers to increase the European content in the ship. The choice of diesel has proven to be excellent. The only changes from lead ship to production have been a change in designator, MB 8V331TC81, and a very minor increase in continuous power from 750 to 815 metric horsepower.

The choice of hullborne waterjet propulsor over CP propeller was based on least cost, best availability, simplicity, direct access for maintenance, and very low underwater damage vulnerability.

The electrical system feasibility baseline design called for two redundant gas turbine driven generator sets of 200-kW each. Power would be 120/208-volt, three-phase, 400-Hertz a.c. The required 450-volt, 60-Hz a.c. power; the 120-volt, three-phase, 60-Hz a.c. power; and the 28-volt d.c. power would be obtained through power conversion equipment. An auxiliary power unit would provide 60-kW of 400-Hz a.c. power for in-port use, battery charging, and emergency supply to navigation and radio equipment.

The selection of the voltage and frequency for the a.c. power system involved a long and arduous process to meet differing standards of the three countries. Boeing's airplane experience favored the four-wire "Wye" system at 1201208 volts. Also, 400-Hz frequency resulted in lighter, higher speed motors and generators. All aircraft equipment is qualified to this type of system. U.S. Navy ship experience, on the other hand, has all been three-wire "Delta", 450-volt, 60-Hz. The final system chosen for the lead ship and for production was a "Delta" three-wire, 450-volt, 400-Hz system.

The 400-Hz equipment is smaller and lighter than comparable 60-Hz equipment. The two Westinghouse 200-kW (250-kVA) 450-volt, 3-phase, 400-Hz generators have proven to be very reliable. Problems occurred in the lead ship in attaining the reliability goals in some of the 400-Hz equipment, e.g., the centrifugal pumps in the seawater distribution system. The production ship's system accounted for these problems. Another problem area was the solid-state frequency converters which are used to convert 400-Hz to 60-Hz. On the lead ship, frequency converter failures necessitated removal of the entire unit for repair. These units weigh over 400 pounds and are cumbersome to remove. On the production ships, a significant effort was made to improve frequency converter reliability. and the units were redesigned to enable fault detection and maintenance actions to be made at the "card" level.

The hydraulic and automatic control systems are worthy of mention because: 1) they have proven reliable and functionally well-suited for a hydrofoil ship, 2) they combine proven aircraft system equipment applications with unique hydrofoil equipment applications, and 3) they are essential to all operations; foilborne, hullborne and docking.

The hydraulic systems operate at a standard 3,000 psi (20.68 MN/m^2) constant pressure. Proven aircraft hardware, mostly from the Boeing 747 aircraft, was used where possible. The hydraulic pumps, tube fittings, tubing material, and filters are all taken directly from the 747.

Because the hydraulic systems are crucial to both foilborne and hullborne operation the design employs multiple levels of redundancy to assure continued operation in the event of system failures. Four separate systems supply the required power to the various hydraulic equipment users which include the foilborne and hullborne control actuators, strut retraction and lock actuators, bow thruster, anchor windlass, and emergency fuel pump. Systems No. 1 and No. 2 supply hydraulics to the forward part of the ship while systems No. 3 and No. 4 supply the aft part. Two separate supply systems feed each user, with provisions included to transfer (shuttle) the user from its primary supply to its alternate supply in the event of loss of primary supply pressure.

In the case of the foilborne control and hullborne steering actuators, an automatic shuttle valve was specifically developed for the hydrofoil program which rapidly transfers the user actuator from a failed supply to the alternate, thus assuring continued safe foilborne operation.

The hydrofoil program pioneered the use of a new hydraulic fluid, a synthetic hydrocarbon. This new fluid provides a much greater resistance to fire and explosion than its predecessor. At the same time it overcomes the serious shortcomings of phosphate ester-base fluids which have proven to be incompatible with the saltwater environment.

The hydraulic actuators on the patrol hydrofoil were for the most part specifically designed and developed for this program. The four foilborne control actuators, the hullborne steering actuator, two hullborne thrust reverser actuators and the strut retraction actuators all were designed, manufactured and qualified to military specifications including rigorous environmental and life testing.

While the automatic control system (ACS) derived much of its basic approach from the earlier *Tucumcari* and *High Point* designs, major technology advances as well as considerable electronic equipment obsolescence had occurred during the intervening years. At the same time. current performance and equipment requirements were considerably more extensive and stringent than for the previous programs. Therefore, the foilborne control system and hullborne steering systems were designed and developed specifically for the PHM program.

Functionally, the foilborne control system provides continuous automatic control of the ship during takeoff, landing, and all foilborne operation. Pitch, roll, and height feedback loops provide automatic stabilization. The ship is automatically trimmed in pitch over the entire operating envelope,and roll trim is accomplished by helm inputs. To steer the ship the helmsman simply turns the helm. and the ACS automatically provides a coordinated turn with turn rate being proportional to the helm angle. The ship employs a fully-swiveled forward strut for foilborne steering and an inverted "W" foil aft which enhances directional stability and maneuverability. Trailing-edge flaps on all the foils are actuated by hydraulic actuators to provide the necessary control force.

In order to meet the stringent ride quality requirements, acceleration feedback is provided to the forward and aft flap actuators. A heading hold system was developed to satisfy long-term steering and navigation relief requirements. Dual sensors, power supplies, electronics and hydraulic actuators were incorporated to meet the foilborne safety requirements. An automatic failure detection system and an auto land system were incorporated for the same safety reasons. Dual tandem actuators were incorporated for the aft flap actuation to eliminate the possibility of a failure resulting in a hard-over roll command.

The control system consists of 31 separate assemblies that are distributed throughout the ship. These assemblies include gyroscopes, accelerometers, height sensors, power supplies, computer assemblies, hydraulic servo actuators and pilothouse control and display panels. Where possible off-the-shelf qualified equipment was selected. Gyros, accelerometers, and some power conditioning equipment fell in this category. The remaining assemblies were designed specifically for the hydrofoil program. The electronics systems employ all solid-state equipment with frequent use of integrated circuit modules such as operational amplifiers and multipliers.

Only one significant development problem arose after installation of the ACS on the ship, that being the coupling of electromagnetic noise and shipboard accoustical noises into the height sensors. These problems were solved by minor redesign in the height sensors which effectively isolated the sensor from the noise sources.

To most observers. the configuration of the follow-on series production ships, which began with the third hull, looks identical to the lead ship. Except for structural simplifications achieved during the producibility study, which will be described later, and the following internal rearrangement, the configuration is essentially the same. The command and surveillance equipment items and operator stations in the CIC were rearranged, the wardroom was eliminated allowing enlargement of the crew messroom, and the head facilities were combined eliminating one head and creating a crew storeroom. Table 1 lists the general characteristics and principal subsystems of the production ship. Table 2 lists the mission equipment. Figure 39, the deck plan and inboard profile of the series production ships, shows the assigned uses of the compartments and the location of the primary equipment.

Table 1. Production Series General Characteristics

Dimensions:	Length overall, foils down 40.5 m
	Beam, main deck 8.6 m
	Overal aft foil span 14.5 m
	Draft. foils up 1.9 m
	Draft, foils down 7.1 m
	Height of bridge. hullborne 6.8 m
	Height of bridge, foilborne 11.1 m
	Full-load displacement 241.3 metric tons
Foilborne propulsion:	(1) General Electric LM2500 gas turbine engine (1) Aerojet Liquid Rocket Company waterjet propulsor
Hullborne propulsion	(2) Motoren-und Turbinen-Union (MTU) MB8V331TC81 diesel engines (2) Aerojet Liquid Rocket Company waterjet propulsors with nozzle steering and reverser assemblies
Electrical:	(2) AiResearch ME831-800 gas turbine engines. each driving one generator rated at 200-kW (250-kVA), 400-Hz 450-V. three phase.
Fuel:	Diesel oil per MJL-F 16884 (NATO F-76) or JP-5 per MIL-J-5624 (NATO F-44)
Hull:	Welded 5456 aluminum
Foils and struts:	Welded 17-4PH corrosion-resistant steel
Accommodations:	24 berths
Complement:	23 officers and enlisted personnel
Provisions:	5 days

HYDROFOIL APPLICATION IN THE U. S COAST GUARD

The Coast Guard patrol boat (WPB) fleet will reach obsolescence by the end of this decade. The hydrofoil is a candidate replacement craft for the WPB capability. The hydrofoil offers attractive performance characteristics that have great potential for future WPB application in several mission areas. The major hydrofoil attributes that could enhance typical Coast Guard operations include: high speed, high speed in adverse weather, and superior seakeeping in adverse weather.

Other advanced or high performance vessels also offer significant improvements in these areas, but the hydrofoil offers the best performance when foilborne in moderate

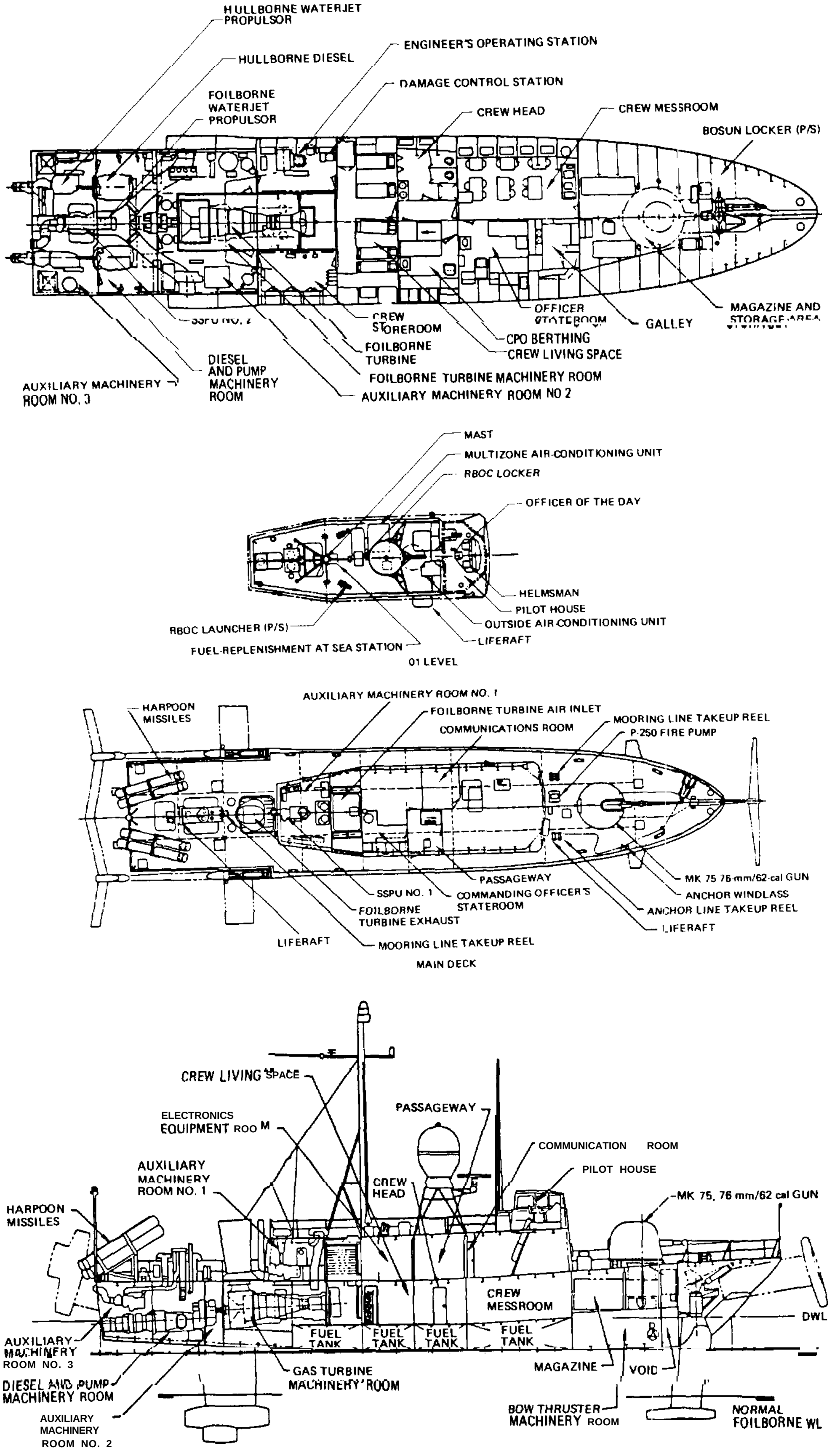


Figure 39. Production Series Deck Plan and Inboard Profile

Table 2. PHM Equipment

Armament:		(1) 76-mm/62-cal OTO Melara gun (2) Surface-to-surface missile canister launchers (2) 4.4-m Rapid Blooming off board chaff (RBOC) launchers
Ammunition:		(400) 76-mm rounds (8) Surface-to-surface missiles (24) Chaff cartridges Small arms, ammunition, and pyrotechnics
Command and surveillance:		
	Command and control:	(2) Radar repeater displays
	Navigation:	(1) OMEGA (1) SMA 3TM20-H radar (1) PL41E gyrocompass and vertical reference (1) UL-100-3 underwater log (1) DE-723D depth sounder (1) Windspeed and direction system (type F) Dead-reckoning tracer
	Interior communications:	(1) MCS 2000 intercom, announcing, and alarm system
	Exterior communications:	(1) VHF transceiver (2) UHF transceivers (2) HF transceivers (1) Radio teletype system
	Surveillance:	(1) IFF system
	Countermeasures:	Rapid blooming offboard chaff ESM (weight, space, power reservations)
	Fire control:	Gun fire-control system Surface-to-surface missile ship command-launch control set

to high sea states. Having experienced sea state 5 in the ultimate comfort of the USS *Gemini* (PHM-6) at 40 knots, the Coast Guard (CG) envisions a comparatively unsophisticated hydrofoil design with current commercial reliability as a logical contender for their next patrol boat. There are two evolutionary trends that are surfacing and may make the relatively expensive hydrofoil attracive. The first is the continued improvement of long-range sensors and intelligence collection. The second trend is the improvement in the reliability, maintainability, and availability being demonstrated by the present generation of hydrofoils.

Too often the hydrofoil is thought of as a single-purpose vessel and incapable of meeting multimission CG requirements. A hydrofoil design, with a moderate high-speed capability that can be combined with an economical cruise speed, can meet CG patrol boat multimission requirements, especially if particular attention is paid to the needed small boat launch/retrieval and towing arrangements. Without a need for high-powered armament and excessive payload, a WPB hydrofoil could also provide the required range and endurance necessary for typical CG WPB missions. Fleetwide application of hydrofoil technology is probably not cost-effective. However, the high speed and stability that the hydrofoil offers in moderate to high sea states has to be considered in making future fleet-mix decisions. No other craft can offer high speed and a relatively stable platform in high seas.

Table 3 lists the characteristics of a conceptual WPB hydrofoil design that were generated from the information contained in the draft report "Hydrofoil Concepts for U.S. Coast Guard Mission." This report is a product of the Advanced Hydrofoil Systems Office of DTNSRDC. This design is representative of a hydrofoil which could be produced to satisfy WPB mission requirements, and it gives an indication of possible performance.

Table 3. U.S. Coast Guard WPB Hydrofoil Characteristics

Length	111.3 Feet
Beam	22.1 Feet
Foil Span	38.3 Feet
Draft	
Hullborne, Foils Down	16.4 Feet
Displacement	
Light Ship	108.0 LTONs
Full Load	141.2 LTONS
Speed	
Foilborne	35 KTs
Hullborne	15 KTS
Range	
Foilborne	1079 NM
Hullborne	1000 MN
Propulsion	CODOG
Crew	16

The most important feature of this design is that maximum speed was compromised for increased range and endurance. This compromise was necessary to meet existing WPB mission requirements. An iteration on this basic design could relax range and endurance requirements and allow speed to increase. There are specific applications within the CG where the potential benefit is likely to overwhelm both technological and economic risk.

Several of the original Coast Guard patrol boats are now over thirty years old. The traditional search and rescue (SAR) mission continues with the goal of minimizing loss of life. personal injury, and property damage on the high seas and waters subject to U.S. jurisdiction. However, less than 20% of WPB operational time is involved with SAR. The major mission for CG patrol boats is now enforcement of laws and treaties (ELT). The simplified goals of this mission are to detect and deter illegal operations involving drugs, fish. and immigrants. This mission involves 60-70% of WPB operational time of which drug enforcement is the primary contributor. Replacement vessels will most likely be a mix of vessels with a multimission capability which incorporate state-of-the-art technology to improve overall WPB mission effectiveness. WPB mission needs are challenging in that a vessel must have high speed and also be able to tow effectively. Mobility. a combination of range and endurance, is probably the single most important criterion for the replacement WPB to meet. A five-day endurance with a range requirement that allows operation for four days at a cruise speed of 10 knots and operation at a higher speed for one day are essential. This "mixed-mode" mission requirement of cruise and maximum speed fits well with the hydrofoil hullborne and foilborne speeds. Assuming the mobility requirement is met-then speed, the ability to maintain speed in a seaway, and seakeeping become major factors in evaluating potential WPB replacement vessels.

The Coast Guard and Navy have been working together in drug interdiction operations. Joint USCG/USN operations have combined a small group of CG personnel (Law Enforcement Detachments or LEDETs) with hydrofoil technology (PHM and crew) to detect and deter the illicit seaborne trafficking of drugs. The PHM/LEDET combination has been in operation since October 1982 and has resulted in several successful drug busts.

The detection, chase, interception and boarding of suspect vessels is fairly realistic training for the PHM squadron wartime tasking. The Coast Guard normally will request the PHM when some detailed intelligence suggests that a fast reaction resource is needed.

The CG has not identified this quick-reaction, high-speed, limited-endurance activity as necessary for the major WPB mission. The current WPB mission dictates a greater range and endurance than the PHM presently meets. Assuming the mission remains the same, a hydrofoil design similar to the WPB hydrofoil is a potentially good compromise that will provide a relatively high-speed interception capability with an economical cruising speed for long patrols.

Current and future operations of the PHM with CG LEDETs onboard may uncover the need for a specialized high-speed, low-endurance vessel within the CG inventory. Recent analysis performed by the Coast Guard indicates that the acquisition cost for a hydrofoil of 130 tons displacement will be significantly higher than that of a comparable planing hull. However, the life cycle cost of the hydrofoil is competitive assuming that the increase in effectiveness is worth the initial cost.

FOREIGN MILITARY APPLICATIONS

Foreign countries have demonstrated an interest in applying hydrofoils to military missions. Italy has been developing its class of fully submerged hydrofoils since the early 1970s. Israel contracted for its first hydrofoil in 1977. The Soviet Union leads the world with active hydrofoil development beginning shortly after the end of the Second World War. Today, the USSR has the largest number of hydrofoils, civilian and military, in the world. In 1980 the United Kingdom acquired a military variant of Boeing's commercial Jetfoil as did Indonesia in 1982. These applications of the hydrofoil in naval missions are discussed by country in the following sections.

Italy

The Italian *Sparviero* is the prototype of a six-ship class of hydrofoils designated the *Nibbio* class. Figure 40 shows two of this class operating foilborne. The design of these hydrofoils is based on that of the *Tucumcari* (PGH-2). More detailed information than presented here can be found in Reference [22]

Sparviero (P-420) was built over the period 1970 to 1974 by Alinavi, S.p.A. Although most of the basic technology of *Tucumcari* was carried over to *Sparviero*, the ships differ in many ways, some obvious and others not so obvious. This is due partly to the advance of technology in the intervening period between the construction of the two ships. More significantly, the Italian boats have a very different mission.

Tucumcari was designed as a patrol gunboat. It carried a crew of 13 and was to operate on missions of several days' duration. *Sparviero* and the *Nibbio* class boats, however, are fast attack craft. Their missions are expected to last only 10 to 12 hours. The U.S. Navy mission included a large amount of time at low, hullborne speeds,

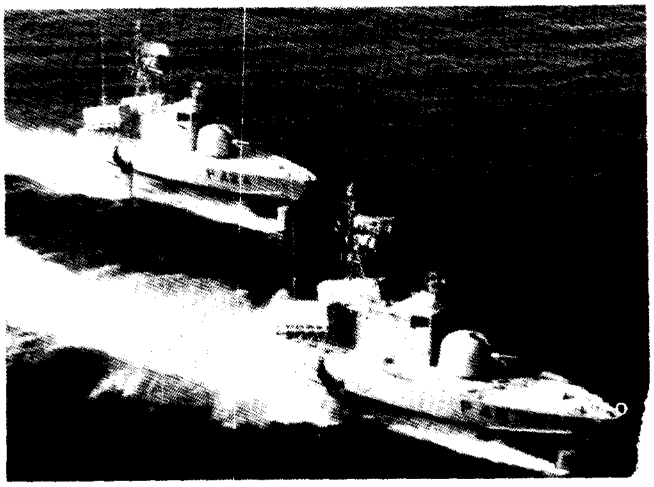


Figure 40. ***Astore and Grifone*, Two of the Italian Navy's *Nibbio* Class Hydrofoils**

while the Italian boats will perform almost exclusively foilborne missions. *Tucumcari* was relatively lightly armed. The newer boats are among the more highly armed craft of their size in the world.

After extensive trials on *Sparviero* and considerable reengineering, the *Nibbio* class production began at the Muggiano shipyard of Cantieri Navale Riunite. A large number of changes were incorporated in the production boats. Deficiencies were corrected. Some US-supplied equipments were replaced by equipments from Italy and other European nations. Light ship weight was reduced.

The arrangements of the *Sparviero* and *Nibbio* are obviously very different from those of *Tucumcari.* The Italian boats are dominated by the 76mm OTO Melara gun. The large combat operations center and the Otomat missiles are also very prominent.

The Italian boats are true “day-boats.” The sparse accommodations on the *Tucumcari* allowed for crew bunks. The ten crew members on the Italian boats are not supplied with bunks for their short missions. Crew support provision is virtually nonexistent on the Italian boats.

The *Sparviero* also has a much larger beam than *Tucumcuri.* This provides increased volume, but, more importantly, larger transverse inertia, particularly at large heel angles. This is needed to provide adequate stability with the very heavy combat system. The reduced length-to-beam ratio is justified by the relatively limited hullborne operations.

The relatively limited structural loadings imposed by the weapons on *Tucumcari* resulted in a structural design based on sea impact and deck loads. The structure of the Italian boats is heavily influenced by the loading imposed by the gun, especially in its rapid-fire mode. The structure must not only stand up under these loads but must minimize the transmission of the vibration through the ship. Considerable effort was directed toward improving this aspect in the production boats relative to the prototype along with reducing weight.

These boats have a single-engine, waterjet foilborne propulsion system. Gas turbines are the foilborne prime movers. The waterjet hullborne propulsion of *Tucumcari* was replaced by rotatable propeller outdrives for better efficiency and lighter weight. However, like *Tucumcari,* the Italian boats are powered by diesels in the hullborne mode. The use of the outdrives permitted elimination of the bow thruster designed into *Tucumcari.*

Although not included in *Sparviero,* the production boats have water-injection gas turbines. This feature permits a 400 kw increase in power for short periods. The boat can takeoff with a fuel overload for increased range or increased speed in a burst mode. Either capability could be important when the ship is engaged in combat with another high-speed unit. Because water injection increases engine wear it must be used sparingly.

Other engineering improvements were incorporated in the production boats. Italian waterjets and diesels were substituted for the U.S. units in *Sparviero.*

Tucumcari had 400-Hz electrical power supplied by one gas turbine and one diesel. The gas turbine contributed to reduced weight, and the diesel afforded good fuel efficiency. Low fuel consumption was important for the patrol mission. The Italian boats retained the 400-Hz system but use exclusively gas turbine power. This saves weight. Because the electrical power production consumes a small fraction of the fuel consumed by the Italian boats in their foilborne, high-power mission, the relative inefficiency of the gas turbine is acceptable.

Many of the auxiliaries in the Italian boats are similar to those on *Tucumcari.* Of particular note, 3,000 psi hydraulics were retained to save weight. Some auxiliary system deficiencies were corrected, and some changes were made to make these boats more consistent with Italian naval practices.

The Italian hydrofoils use a canard foil system as did *Tucumcari.* This means that a majority of their dynamic lift is produced by foils near the stern. Trailing-edge flaps are used for control. The foils are completely retractable and are constructed of 17-4 PH stainless steel.

Sparviero incorporated a self-lubricated kingpost bearing for the steerable forward strut; however, this suffered rapid wear and failure. This was replaced on the production boats by a ceramic bearing with an increased bearing surface. Some strut construction problems on the prototype were corrected on the production boats.

The automatic control system is vital to a fully-submerged hydrofoil. The Italian boats use a system built by Sepa but which follows the same basic design used on *Tucumcari.* Inputs are provided by two sonic height sensors in the bow, a vertical gyro, a yaw rate gyro, three vertical accelerometers, and the helm. Trailing-edge flaps control the depth, pitch, and roll of the boat. The *Nibbios* bank to steer and possess excellent maneuverability.

The Italian hydrofoils have a very sophisticated electronics suite consistent with their complex mission. *Tucumcuri,* on the other hand, as a prototype multifunction special warfare ship had only locally controlled weapons and a relative simple electronics suite.

The very extensive weapons suite on the Italian hydrofoils is most impressive for a ship of this size. Each craft has a 76mm Oto Melara rapid-fire gun similar to that on the U.S. PHM-1 and FFG-7 class ships. The primary surface-warfare weapons are two Otomat antiship missiles.

Six *Nibbio* class hydrofoils have been produced. The first was delivered in August of 1981, and the last was delivered in November 1983. They are designed to be operated from small harbors or similar facilities and to be supported by mobile maintenance units. To date, operations have been most successful.

Israel

The *Shimrit,* Figure 41, was designed and constructed by the Grumman Aerospace Corporation. It is the first of the *Flagstaff* Mark II series, a follow-on to the *Flagstaff* (PGH-1). *Flagstaff* was designed to the same performance specifications as *Tucumcari. Flagstaff,* however, had propeller foilborne propulsion and airplane-configured foils. Grumman had developed the Mark II design as an

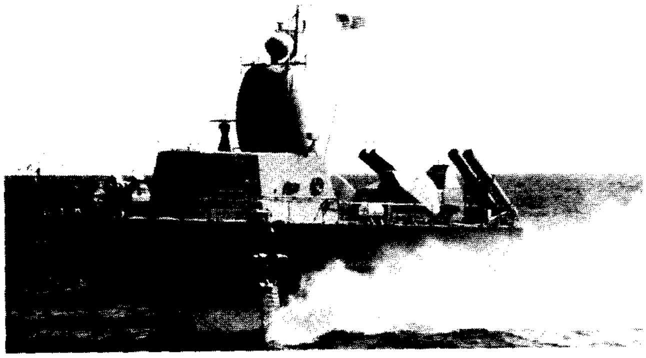


Figure 41. Israel's *Shimrit*

outgrowth of their previous efforts. Israel adopted this basic design approach with some modifications, and production began in early 1978. *Shimrit*, the lead ship, was built in Florida. The second ship. *Livnit*, was built in Israel with some critical components produced in the U.S. Reference [23] provides more information on these ships.

Like *Sparviero*, *Shimrit* is a very powerfully-armed, strike vessel. Its operation as a "day-boat" has had a significant influence on the choice of ship systems and arrangements. Crew comforts take second place in this ship. Primary emphasis is on command, control and engineering.

In general. *Shirnrit* is arranged much like *Flagstaff*. It has two inverted tee-foils forward and one inverted tee-foil aft. These are all retractable. Its profile is dominated by the large Radome mounted atop the house. Its Gabriel and Harpoon missile launchers are also prominent.

The hull form of the Mark II boats is very similar to that of *Flagstaff* but the hull flare has been increased at the sides. The hull is larger to accommodate an increase in full-load weight of about 52%.

The hulls of the Israel hydrofoils are of welded 5456-H111 aluminum using 5356 filler rods. Extruded planks with integral stiffeners were used for most of the hull structure. This reduced the amount of welding and permitted a large proportion of the welding to be done automatically. Seven transverse bulkheads, two longitudinal bulkheads, and 33 transverse stiffeners were used in the design. The forward deckhouse is of riveted 6061-T6 aluminum. The aft deckhouse is of welded 5456 aluminum.

Foilborne power is supplied by an Allison 501-KF gas turbine which produced 5,400 hp at 14,500 rpm. The propeller-driven propulsion system requires the use of a Z-drive. This includes a hull-mounted reduction gear. two bevel gears to transmit the power to the underwater pod. and a planetary reduction gear in the pod. The foilborne propeller is a four-bladed, controllable-pitch unit. Its diameter is 52 inches. It operates in a trans-cavitating mode at high speed.

Hullborne operation is minimized. The hullborne propulsion system is intended for harbor operations and emergency use in the event that the foilborne system fails. The two transom-mounted stern drives are driven hydraulically. Each unit develops 80 hp through 26-inch, three-bladed propellers that are steerable. These drives are retracted behind the transom during foilborne operation.

The hydraulic system on *Shimrit* is most notable. The hydraulically driven hullborne propulsion plus the demands of the control system and other functions requires a very large hydraulic system. The 3,000 psi power is supplied by two gas turbine auxiliary power units (APU). Emergency power is supplied by a pump mounted on the foilborne propulsion system gear box. The APUs also power AC and DC generators. The two 200 kw ac generators are also mounted on the foilborne propulsion system gearbox.

The struts and foils of Shimrit are scaled up from those of *Flagstaff*. This is a fully-submerged system of the airplane type. Approximately 70% of the weight is carried on the forward foils. Incidence control is used for all of the foils.

The struts are all made of welded HY 130 steel. Each foil is machined from a single 601-T-652 forging.

In keeping with the small crew and size of this vessel, considerable emphasis has been directed toward command and control. The automatic control system (ACS) and engineering monitoring and control system (EMCS) are particularly notable.

The digital ACS controls the ship in both the foilborne and hullborne modes. In the hullborne case, it actively reduces pitch and roll. Its foilborne function is much like that of other fully-submerged hydrofoils except that it has antibroach logic based on seawater pressure at the forward struts. The ACS also permits the foilborne ship to operate in a platforming mode in smaller sea states and a contouring mode in the higher states. The ACS uses inputs from two radar height sensors in the bow along with an accelerometer and gyros.

The EMCS is a microcomputer-based, distributed processing system which controls 22 of the ship's systems and subsystems. A single engineer controls and monitors all of these systems from one station. This station is connected to six remote terminals which perform monitoring and control functions that are programmed into them.

The combat system of *Shimrit* is extremely powerful for a small combatant. It has a twin Emerlec 30mm gun forward. A combination of two Gabriel missiles and four Harpoon missiles are mounted aft.

Shimrit construction began in September 1978 in Lantana, Florida, and the ship was launched in early 1981. Sea trials were completed in June 1982. The second hydrofoil of the class, *Livnit*, was built at the Israeli Shipyards, Limited. Many of its equipments and subsystems were supplied by Grumman. Israel is believed to be considering the construction of ten additional vessels.

Although no details about the operational employment of *Shimrit* and *Livnit* are available, they are believed to be active in Israel's defense.

Soviet Union

The Soviet Union is the world's leader in the use of hydrofoils. Their civil and military programs are very closely related, Development began with captured German hydrofoils and personnel shortly after the end of the Second World War. Emphasis has been on surface-piercing hydrofoils and ships that have a single lifting foil forward, called "tail-draggers." Their hydrofoils are diesel powered with inclined propeller shafts connected by conventional vee-drives. Currently, Soviet hydrofoil developers are expanding into the fully-submerged systems with zee-drives and propellers for foilborne propulsion.

The *Turya* and *Matka* classes are "tail-draggers." Surface-piercing foils are used to lift their bows, while their sterns plane. The *Turyas* are employed in ASW while the *Matkas* will probably replace the ***Osas,*** which are fast planing hull ships, in surface warfare.

Sarancha and ***Bubochka*** are the largest operational hydrofoils in the world. According to Jane's *Surface* ***Skimmers*** the ***Babochku*** displaces about 400 tons and *Sarancha* 330 tons. Both are reported to have speeds in excess of 50 knots. ***Babochku*** uses three gas turbines and has a surface-piercing foil system. It appears to be intended for ASW. *Sarancha* has a fully-submerged foil system forward with surface-piercing augmentation. Its aft foil system is fully submerged. This ship is also gas turbine powered and has a zee-drive propulsion system. It appears to be intended for surface warfare.

Although Soviet hydrofoil technology has lagged that of the U.S. and other western nations, it is gaining rapidly. The appearance of *Sarancha* and ***Babochka*** demonstrate that virtually all of the key technologies have been mastered by the Soviets and that their state of the art permits large hydrofoils to be built.

United Kingdom

Later in this discussion the development of the Boeing commercial Jetfoil and its military variant will be described. This 90-foot long craft with a displacement of 115 tons has been readily adapted to military applications. The first such craft was HMS ***Speedy,*** Figure 42, a fisheries protection vessel delivered to the U.K. Royal Navy in 1980. This Jetfoil variant has enlarged fuel tankage, a diesel-waterjet hullborne propulsion system, modified superstructure, naval navigation and accommodations for a crew of seventeen. This craft performed fisheries protection missions in the North Sea for approximately two years until it was laid up when budget considerations forced a major reduction in the size of the Royal Navy surface fleet.

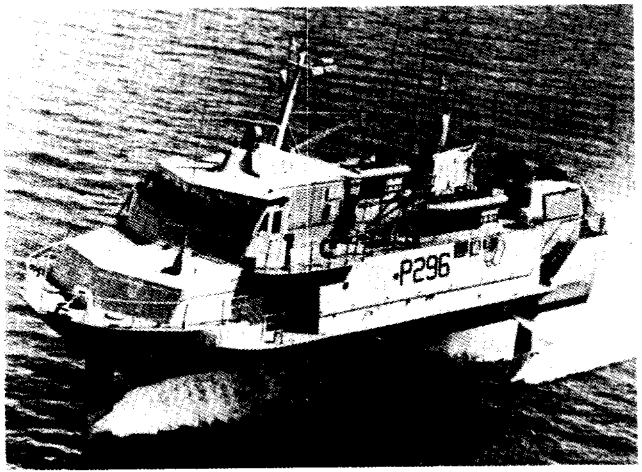


Figure 42. HMS *Speedy*

Indonesia

The second military Jetfoil variant is the ***Bimu*** *Sumadera* 1, delivered to Indonesia in 1982. It has enlarged fuel tankage and naval navigation and communications. The ship was employed throughout Indonesia by the government services in crew training and passenger ferry service demonstrations and by the Indonesian Navy in patrol, fisheries protection, search and rescue. and troop transport missions. This experience led to a major Indonesian program with a firm contract for four additional Jetfoil variants and options for six additional craft to be provided through a joint Boeing-P.T. Pal (an Indonesian government shipyard) coproduction program.

FUTURE NAVY CONCEPTS

The history of hydrofoil development in the United States has been one categorized by cyclical periods of brief bursts of significant technology advancements followed by sustained periods of assessment and retrenchment. In 1977 this pattern 'seemed to have been broken as both major industrial suppliers of hydrofoil technology to the U.S. Navy initiated, for the first time, serial ship production programs. In October 1977. The Boeing Company was awarded a production contract by the U.S. Navy for five patrol hydrofoil, missile (PHM) ships and in December of the same year Grumman Aerospace Corporation initiated the production of two lead hydrofoil ships for the Israeli Navy. Both awards, to Boeing and Grumman, were for hydrofoil ship designs based upon proven prototypes as discussed in the preceding paragraphs.

With this background of renewed optimism, investigations were initiated into means of advancing the proven technology base. One initiative undertaken by Grumman was to investigate the technical feasibility of developing an advanced technology lift and propulsion system (AT-LAPS) for hydrofoil craft. This development, if implemented, could offer significant improvements over the operational capabilities of hydrofoil ships in the 250-metric-ton class. These performance improvements result in reduced fuel consumption, thereby improving range and/or military payload capabilities of a given hydrofoil platform.

Another initiative was the study of hybrid hydrofoils. One concept combined the employment of buoyancy lift with dynamic lift from the foils and is called the extended performance hydrofoil (EPH). This concept could offer range improvements and lower minimum foilborne speeds.

A third naval concept is the militarized Jetfoil. This vehicle is an outgrowth of the Boeing commercial Jetfoil program. The militarized Jetfoil is smaller than other

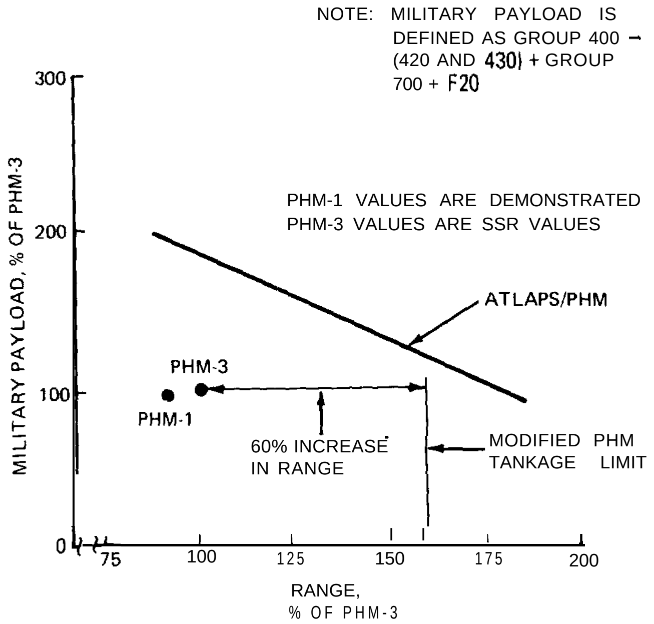


Figure 43. Range and Payload Enhancement

naval concepts covered. However, with the smaller size comes lower cost of acquisition and considerable versatility, making it suitable for many of the navies of smaller countries in the world.

These three initiatives are discussed in the following paragraphs.

Advanced Technology Lift and Propulsion System (ATLAPS)

A principal objective of the ATLAPS concept is to blend hardware elements of both the PHM and *Shimrit* programs into an advanced development program which offers significant operational enhancement for hydrofoil ships in the 250-metric-ton class. The approach, based upon a foundation of proven technology, is considered to be a feasible, low risk, and minimum cost undertaking.

Implementation of the ATLAPS concept can be viewed as consisting of two parts: development of a new, advanced technology lift and propulsion system components, and modification to the PHM class hydrofoil to demonstrate at sea the above mentioned lift and propulsion system.

The most significant advantage offered by this design is a predicted improvement in foilborne and hullborne range for hydrofoil ships in the 250-metric-ton class as shown in Figure 43. This figure compares the foilborne range and military payload capability of an ATLAPS modified PHM-3 with the PHM-3 specification requirements.

The ATLAPS foils were sized using a procedure developed by Grumman whereby the drag polar for any given hydrofoil ship can be expressed as a function of the total foil area and total dynamic lift. The drag polar presents the hydrodynamic characteristics of the craft, and, with the specification of a foil area, the cruise general drag polar characterizes the craft/propulsion system for the ship. The procedure for deriving the drag polar for any vehicle is presented in Reference [24.]

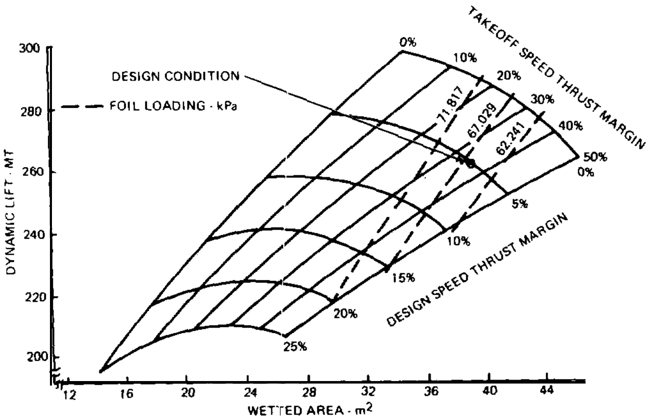
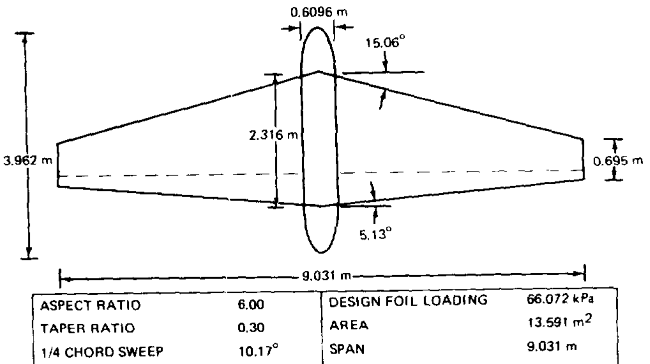


Figure 44. Effect of Thrust Margin on Dynamic Lift and Port Area

The resulting procedure for sizing the foils is based on the philosophy that the optimum hydrofoil design is one which utilizes all of the available thrust at the takeoff and design speed conditions by sizing the foils to produce the maximum lift-to-drag ratio at design speed. For a given propulsion system, this technique also maximizes the dynamic lift of the hydrofoil. This process is identified as the "two point power limited design" in the Grumman generalized performance analysis.

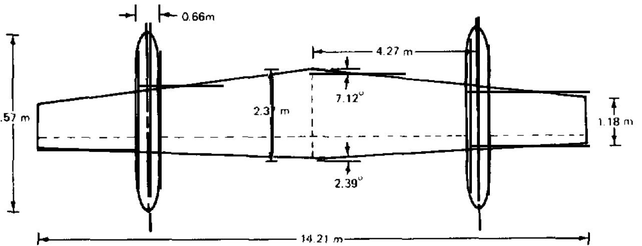
For the ATLAPS design, with selected 1.37mm diameter KaMeWa-type propellers and an overall transmission gear ratio of 10 to 1, the total thrusts available at the takeoff and design speed conditions are incorporated into two point power limited equations. By varying the thrust margins at takeoff and design speed, it is possible to construct a matrix of dynamic lift versus total foil area, Figure 44.

The forward and aft strut/foil arrays selected by this procedure are presented in Figures 45 and 46, and the pertinent planform parameters are tabulated on the figures. As the figures indicate, the hydrofoil configuration selected for the design consists of a single tee-foil for-



ASPECT RATIO	6.00	DESIGN FOIL LOADING	66.072 kPa
TAPER RATIO	0.30	AREA	13.591 m^2
1/4 CHORD SWEEP	10.17°	SPAN	9.031 m
L. E. SWEEP	15.06°	ROOT CHORD	2.316 m
T. E. SWEEP	−5.13°	TIP CHORD	0.695 m
SECTION	NACA 16-308	AVERAGE CHORD	1.505 m
		MHC	1.650 m

Figure 45. Forward Foil Geometry



ASPECT RATIO	8.0	DESIGN FOIL LOADING	66.075 kPa
TAPER RATIO	0.5	AREA	25.24 m²
1/4 CHORD SWEEP	4.76°	SPAN	14.210 m
L. E. SWEEP	7.12°	ROOT CHORD	2.368 m
T. E. SWEEP	-2.39°	TIP CHORD	1.184 m
SECTION	NACA 16-308	AVERAGE CHORD	1.776 m
		MHC	1.842 m

Figure 46. Aft Foil Geometry

ward for supporting 35 percent of the vehicle weight, and a pi-foil assembly aft supporting 65 percent of the vehicle weight. The aft assembly consists of a foil, two struts, two pods housing the flap control mechanism and the power transmission, and two controllable-pitch KaMeWa-type propellers located at the aft end of the pods. The forward assembly consists of a foil. one steerable strut, and one pod housing the flap control mechanism.

The foil section is identical forward and aft (NACA 16-308). The planform parameters, aspect ratio, taper ratio, quarter-chord sweep angle and leading edge sweep angle were all determined using various optimization analyses developed by Grumman as part of the corporate generalized performance analysis. The forward and aft foils both have 25 percent chord flaps with an envelope of approximately + 25” to – 15° for control. All of the struts are NACA 16 series sections with a constant chord (1.52 m forward and 2.29 m aft) over their length. The thickness-to-chord ratios at the strut/pod intersections are 0.10 and at the baseline 0.15. Suitability of these values, based on cavitation considerations, was confirmed by operation of the PGH-1 *Flagstaff.* The strut length provided allows platforming operation in the design sea state with an acceptable frequency of hull impact.

The ATLAPS foilborne propulsion system consists of two Allison 570-KA gas turbine engines, each driving a KaMeWa-type 4-bladed, controllable-pitch, supercavitating propeller by means of a right angle Z-type mechanical transmission system.

Propeller performance is based on data supplied by KaMeWa confirmed by model tests and full-scale application of a 4-bladed, supercavitating controllable-pitch propeller. The propeller design. in turn, was derived from the successful 3-bladed supercavitating propeller used for over ten years on *Flagstaff.*

TYPE	SUPERCAVITATING, CONTROLLABLE PITCH, PUSHER INSTALLATION
NO. OF BLADES	4
DIAMETER	1.4 m
EXPANDED BLADE AREA RATIO. EAR	0.65
HUB DIAMETER RATIO, d_h/D_o	0.35
DESIGN PITCH RATIO, $P_{.7}/D_o$ (DESIGN)	1.5
PITCH RATIO @ TAKEOFF, $P_{.7}/D_o$ (TAKEOFF)	PROGRAMMED FOR 1100 RPM

Figure 47. Foilborne Propeller Characteristics

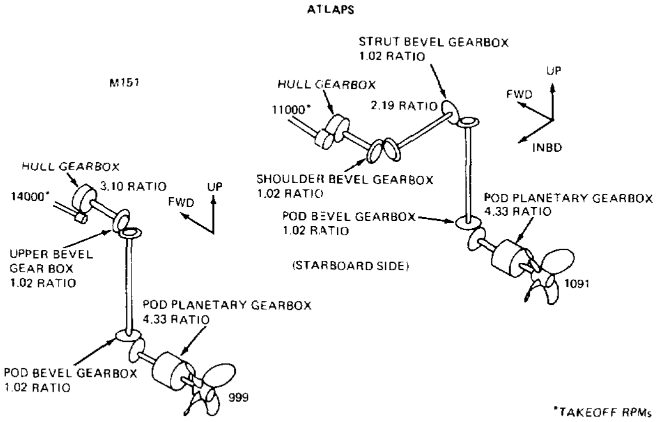


Figure 48. Transmission Systems

Propeller design characteristics are summarized in Figure 47. A 4-bladed propeller was selected to avoid simultaneous passage of blades through wake lobes and thus reduce the torsional excitation forces.

The transmission for the ATLAPS propulsion system is based on the technology developed for the Grumman model M-151 transmission for the MARK II hydrofoil program. The Ml51 transmission was described in Reference [20]. The ATLAPS transmission utilizes the M-151 spiral bevel and modified pod planetary gearset with a new hull-mounted spur gearbox designed to match the Allison 570-KA engine. Use of the existing component designs will considerably reduce development risk and evaluation time. Schematics of the ATLAPS and M-151 transmissions are shown in Figure 48 (the starboard side of the ATLAPS transmission is shown).

The original material considered for the fabrication of the ATLAPS struts and foils was HY-130 alloy steel. This material and welding and manufacturing procedures for fabrication of HY-130 lift structures, developed at Grumman, were used successfully in manufacturing and delivering to the U.S. Navy an aft strut for *Plainview* in February 1976. However, Navy personnel expressed reservations regarding the usage of HY-130 for structures which are subjected to fatigue loadings, such as the struts and foils for this design. After completion of a comparative analysis of HY-100 alloy steel in lieu of HY-130, the decision was made to proceed with the lift system structural design using HY-100.

The preliminary fatigue properties and design curves derived for HY-100 steel apply to a base metal “in air.” Use of the material requires that the external strut and foil structure be completely and effectively coated with a NAVSEA approved coating system. The “Magna” system as manufactured by the Midland Division of Dexter Corporation consists of a teflon-filled polyurethane topcoat over an epoxy primer and is a candidate coating. Internal surfaces would be protected by a corrosion preventive compound such as specified in MIL-C-16173.

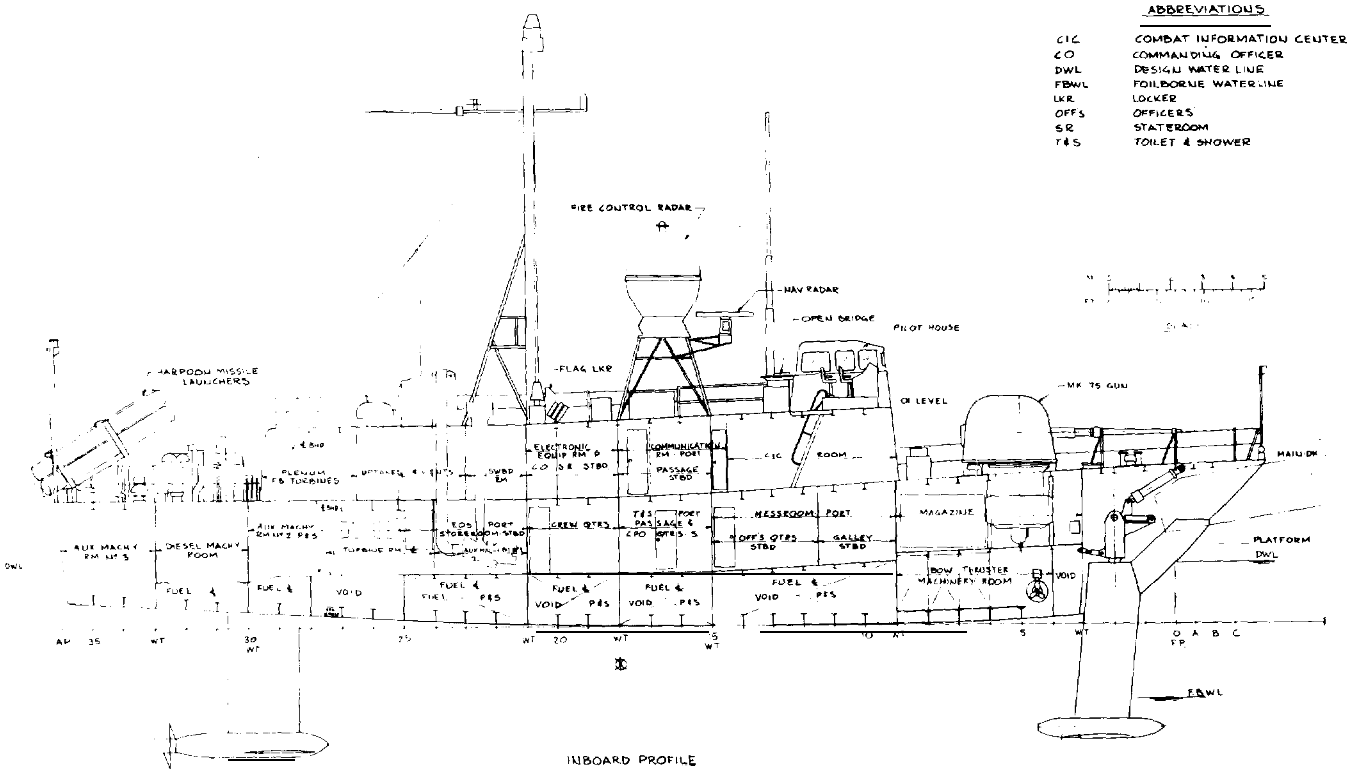


Figure 49. ATLAPS Design.

The general arrangements and key dimensions of an ATLAPS modified PHM design are shown in Figure 49. Selected principal characteristics are as follows:

Length Overall (foils retracted)	44.70 m
Length Overall (hull)	39.30 m
Length Between Perpendiculars	36.00 m
Breadth Extreme (over foils)	14.51 m
Breadth Extreme (hull)	8.40 m
Depth, Molded, Amidships	4.16 m
Draft, Mid-Keel to DWL at Max Section	1.833
Light Ship Displacement	183.2 MT
Full Load Displacement (with 64.3 MT fuel)	266.2 MT

The general arrangement remains identical to that of the PHM-3 series throughout those compartments forward of frame 21. Aft of frame 21, in the machinery spaces, major changes are necessary consistent with the requirements of the ATLAPS propulsion and transmission system.

As one of the predicted advantages of ATLAPS is the potential for increased range, a study of the craft compartmentation was made to ascertain those areas which would be best suited for carrying additional fuel. To retain a lift distribution of approximately 35-65 percent on the foil system, it is imperative that the additional fuel be carried in the aft portion of the ship.

That area occupied by the foilborne propulsor on the centerline of the PHM-3 series between frames 28 and 33 lends itself ideally to the installation of new fuel tanks inasmuch as there are neither major components nor a significant amount of ship system piping located between the side keelsons.

Additional tankage can also be incorporated into the fuel systems by conversion of the outboard bilge areas between frames 21 and 25 into fuel tanks.

The capacity of usable fuel in the proposed additional tankage would be:

Frame 21-25 Port	3.99 Metric Tons
Frame 21-25 Starboard	3.99 Metric Tons
Frame 28-30 Centerline	4.65 Metric Tons
Frame 30-33 Centerline	4.44 Metric Tons
Total	17.07 Metric Tons

To accommodate the air inlet and exhaust requirements of the 570-KA gas turbine, which are in reversed positions from those of the LM2500, it becomes necessary to extend the aft end of the deckhouse. With the removal of the LM2500 gas turbine and the associated waterjet propulsion components ample space is made available for the installation of the ATLAPS.

The two 570-KA gas turbines are installed within a foreshortened main engine compartment. However, to retain the longitudinal bulkheads in their current locations,

SWBS GROUP	PHM-3	ATLAPS MODIFIED PHM
100 - HULL STRUCTURE	47.38 MT	50.27 MT
200 - PROPULSION	24.83	20.99
300 - ELECTRIC PLANT	7.53	7.53
400 - COMMUNICATIONS AND CONTROL	10.53	10.53
500 - AUXILIARY SYSTEMS	19.85	19.85
567 - HYDROFOIL LIFT SYSTEMS	32.28	34.38
600 - OUTFIT AND FURNISHINGS	14.60	14.60
700 - ARMAMENT	9.52	9.52
LIGHTSHIP WEIGHT - LESS MARGIN	166.52	167.67
MARGINS:		
DETAIL DESIGN AND CONSTRUCTION	2.46	2.46
PRELIMINARY DESIGN	—	6.61
NAVSEA	6.45	6.45
LIGHTSHIP WEIGHT	175.43	183.19
LOADS:		
SHIPS FORCE	2.63	2.63
ORDNANCE	15.04	15.04
POTABLE WATER	1.00	1.00
FUEL (USABLE)	47.20	47.20
FULL LOAD	241.30	249.06
WATERJET WATER	8.43	0.00
FULL LOAD	249.73	249.06
EXTRA PAYLOAD		17.07
FULL LOAD		266.13

Figure 50. SWBS Group Weight Comparison

it would be necessary to modify the recommended air inlet and exhaust configurations.

The area made available by the removal of the existing PHM-3 class waterjet propulsor in the diesel engine room becomes suited for the installation of the transmission lube oil storage tanks and other components of the transmission lube oil system, which would be mounted on the extended tank top. The recommended arrangement permits the main engine to be removed with a minimum of disturbance to other components.

The weight summary is presented in Figure 50; also included is a SWBS group weight comparison with the PHM-3. The only SWBS weight groups which differ significantly from the PHM-3 are Groups 100 (Hull Structure), 200 (Propulsion) and Group 567 (Lift System).

The last of the production PHM-3 class hydrofoils has entered service with the first U.S. Navy operational hydrofoil squadron. As the merits of these ships are demonstrated, military planners will identify additional roles and missions for them. These alternate uses will likely demand greater performance from the hydrofoil platform. The ATLAPS concept, based upon proven technology, will offer significant options to Navy planners for enhanced hydrofoil performance for ships of PHM-3 size to meet these future mission requirements.

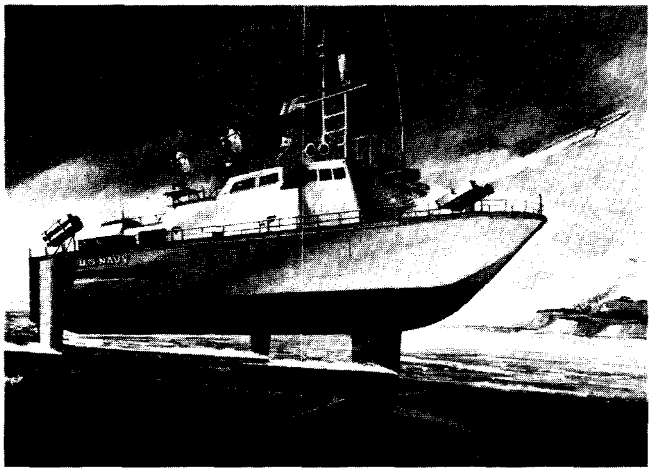


Figure 51. Extended Performance Hydrofoil Concept

Extended Performance Hydrofoil

The extended performance hydrofoil (EPH) concept is illustrated in Figure 51. It is one variation of a hybrid hydrofoil employing buoyancy enhancement. Buoyant lift. in the form of a long, slender, submerged body, is combined with the dynamic lift of a fully-submerged foil and strut system. Investigations of the EPH concept reported by References [26] and [27] show that the EPH, with a buoyancy/fuel (B/F) tank providing about 50% of the total foilborne lift, had a range potential well beyond that possible from a comparable conventional hydrofoil. Range improvement, which increases with ship size, results basically from an increased fuel weight fraction and higher weight-to-drag ratios, particularly at reduced design foilborne speeds. The lower end of the foilborne speed spectrum can be efficiently extended down to 20 to 25 knots, thus permitting foilborne operations with existing ships.

Hydrofoils with and without B/F tanks were investigated to determine the relative performance merits of the EPH design option as a function of size. Payload and crew size were fixed within each of four size categories ranging from 200 to 4,000 tons [27]. In most cases, the design speed was 40 knots in sea state 3. However, in all cases, strut lengths were sufficient for foilborne operation in sea state 6. The designs can be used to determine trends of range with lightship weight and speed. Lightship weight was selected as a key characteristic since acquisition cost is directly related.

If one incorporates various size tanks in the several size categories, it becomes evident that those designs having buoyancy (together with foil/strut system buoyancy) of about one half of full-load weight are the most practical. This observation is illustrated in Figure 52 where the solid line for 40-knot design speed "small" conventional hydrofoils is generated by varying dynamic lift. Here maximum foilborne range is taken at an optimal foilborne speed. A somewhat arbitrary parent ship is se-

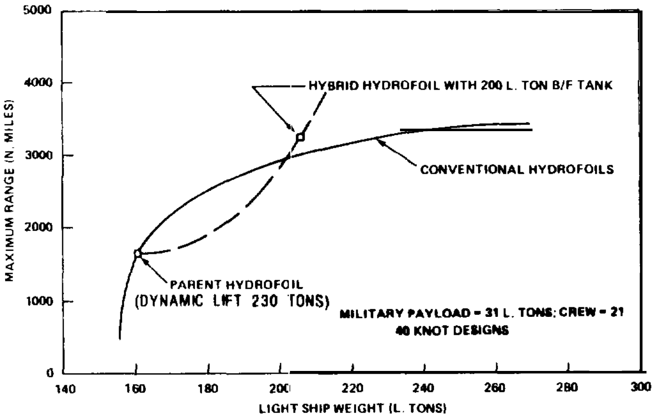


Figure 52. Maximum Foillborne Range at Optimal Speeds as a Function of Light-Ship Weight for Small Small Ships.

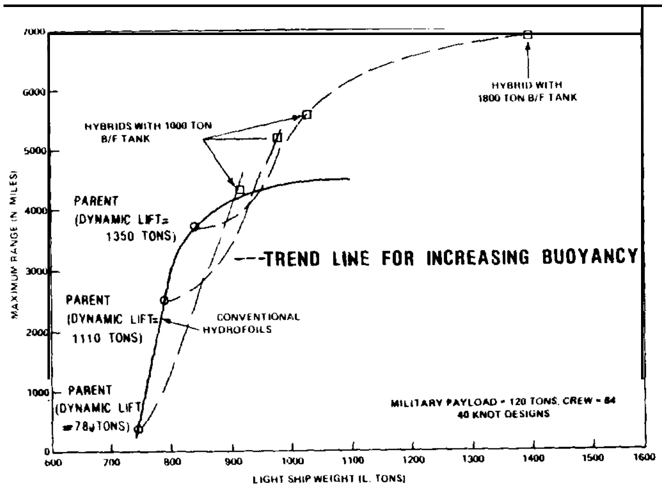


Figure 53. The dashed trend line for EPH.

lected at 160 tons lightship weight (dynamic lift of 230 tons). The dashed line shows the trend for increasing buoyancy or B/F tank size. A 200-ton displacement tank, which approaches 50% of the full-load ship weight, is marked on the trend line. It is evident from this plot that the addition of a B/F tank smaller than 200 tons can impact adversely on maximum foilborne range. The trend for tanks larger than 200 tons is shown.

Some insight into the shape of the dashed trend line for EPH with larger B/F tanks can be obtained from Figure 53. Here a relatively large number of 40-knot "medium" size designs is shown, all with a payload of 120 tons and a crew of 84. It is evident that just as undersized B/F tanks are undesirable, so too are excessively large tanks. The latter is exemplified by the 1,800-ton B/F tank on a parent hydrofoil having a dynamic lift of 1,350 tons and a lightship weight of 850 tons. The dashed trend line in Figure 53 bends over because of fixed ballast requirements and the rapid growth in propulsion and foil/strut weight.

Figure 52 displays another important characteristic of the EPH concept when compared to a conventional hydrofoil. This characteristic is the slope of the curves for maximum foilborne range as a function of lightship weight in the region of relatively high range values (crossover of solid and dashed lines). This slope is a measure of the increase in maximum range attainable (for a given military payload and crew) by the designer from an increase in lightship weight and corresponding change in dynamic lift. For instance, the EPH (developed from the 160-ton lightship weight parent) in the region of 2,250 n. miles (or 205 tons lightship weight) has a slope about 7 times that of a comparable (same lightship weight) conventional hydrofoil. This means that to obtain a given range increase, the EPH requires only 1/7th the increase in lightship weight compared to a conventional hydrofoil. Note in Figure 52 that the slope of the curve for this EPH is about the same as the slope of the curve at the parent ship design point. So the EPH designer has, with the appropriate proportions of buoyancy and dynamic lift, the same range improvement leverage as the hydrofoil designer had previously but now at a greater maximum range level (in the small size case, about 1,500 n. miles greater). This characteristic of EPH is typical of all ship sizes (2.5, 26].

A series of experiments were performed on a 1/20-scale model of a small hydrofoil with a buoyancy/fuel tank. A lower hull (B/F tank) was designed, attached to the 1/20-scale hydrofoil model strut-foil system and mounted on a force-measuring apparatus and run as a captured model. In terms of full scale, the tank would produce about 200 tons of buoyant lift compared to 235 tons of dynamic lift from the foil system. A series of tests was carried out first with the B/F tank alone. then with the tank and hydrofoils, and finally with tank, hydrofoils, and struts.

Upon completion of the captured model tests, the 1/20-scale hydrofoil model was modified and rebuilt to provide self-propulsion and a fully automatic control system. A series of tests were run on the model to measure hydrodynamic loads produced by the B/F tank during maneuvers in waves. The six-component balance provided information for evaluating the structural integrity of the attachment through which hydrodynamic loads would be transmitted on a full-scale EPH ship. A secondary objective of these experiments was to obtain motions of the model and the magnitude of control requirements improved on the foil and rudder systems during extreme maneuvers in waves. The EPH model was run successfully in hullborne. semihullborne and foilborne modes in essentially all wave conditions up to simulated sea state 6.

The research and development hydrofoil *High Point* was selected as the vehicle for full-scale demonstration of the EPH concept. A series of feasibility designs and analyses of critical areas was performed. based on model tests and computer sitnulations, to minimize uncertainties, reduce the technical risk and provide high confidence in success of the demonstration vehicle.

The R&D hydrofoil has a full-load displacement of about 130 L. tons. With the addition of about a 70-ton displacement tank, the craft would have a full-load displacement of about 200 L. tons and would carry about 60 tons of fuel. Propulsion is provided by two existing Proteus PT1273 gas turbine engines driving four (4) five-bladed, subcavitating, fixed-pitch propellers through bevel gears and strut shafting. The tank is attached to the underside of the hull by a large strut as shown in Figure 54. Attachments are designed so that loads in all axes are resisted at the midship strut, the aft foil connection being capable of taking side and vertical up-loads only. To enhance the tank stability and craft steering, an additional rudder is added at the tank centerline aft. Fuel and ballast are contained within the same tank compartments, separated by horizontal flexible diaphragms. Displacement of either fuel or ballast is accomplished by pressurizing the opposite side of the diaphragm, utilizing ram pressure on the ballast side foilborne, static pressure hullborne, and an existing fuel pump or pressure fueling on the fuel side.

Data from such a demonstrator could be compared to structural loads from model tests and computer simulations of motions and maneuvering described above. This data base would be useful for future EPH or similar hybrid ship designs.

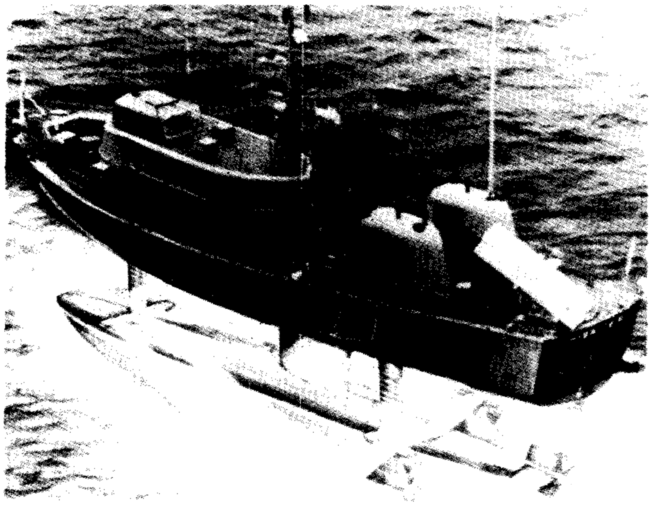


Figure 54. A 70-ton displacement tank is attached to the underside of the hull by a large strut.

Militarized Jetfoil

The Jetfoil model 929-120 family, Figure 55, was derived by Boeing from the successful commercial ship to provide an economical approach to satisfying the varying customer requirements of many countries for military and paramilitary missions. This basic Jetfoil variant is configured to accept a variety of military payloads, such as foredeck gun mounts from 20mm to 76mm. Antiship missile systems from Penguin to Exocet can be mounted on the aft upper deck. A 20 to 30mm CIWS gun or Stringer missile mounts can be located midships on the upper deck for self-protection against aircraft and missile attacks. Boarding boats, rescue gear. external fire fighting equipment and oil spill containment equipments may be carried for paramilitary missions. Navigation, communications, fire control and ESM systems can be installed to meet mission requirements. Accommodations are provided for a crew of up to fifteen. Depending on the mission equipment selected, the model 929-120 Jetfoil military variant will have a foilborne range of 400 to 700 nautical miles at 40 knots. It should therefore be a viable candidate for most 200 nautical mile coastal zone military and paramilitary missions.

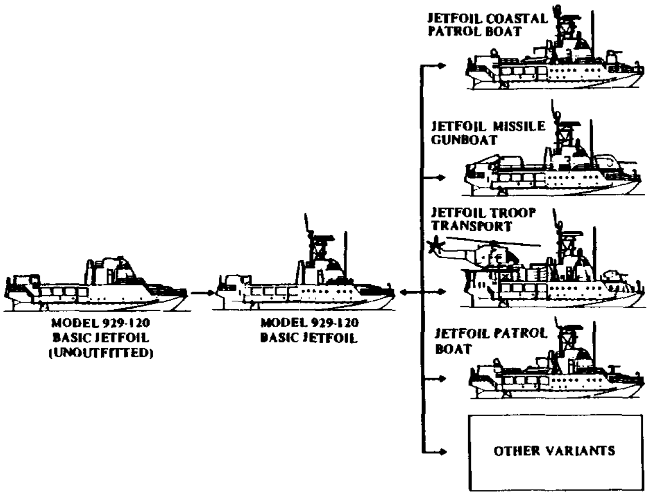


Figure 55. The Jetfoil model 929-120.

Commercial Hydrofoil Ships

The use of hydrofoils in regular commercial service dates from the mid-1950s. Over 200 are now operating in the free world and at least that many more in Soviet dominated areas. Commercial hydrofoils are under construction or have been built in at least fifteen different countries. They vary in displacement from 14 tons to 175 tons and in passenger capacity from 40 to over 300. They have been used to carry high priority freight as well as passengers and as offshore crew and work boats. Jane's *1982 Surface Skimmers* lists 56 companies operating hydrofoils in passenger service. While this is not a large enterprise compared with operators of large conventional ferries, it does represent a significant worldwide industry. This section will define by country some of the principal commercial hydrofoils in operation today.

United States

The only commercial hydrofoil built in the United States is the Boeing model 929 Jetfoil, Figure 56. The Jetfoil is an advanced design, 45-knot, 117-ton hydrofoil that was developed to provide competitive commercial marine transportation over limited open-ocean routes. The start of Jetfoil production in late 1972 followed approximately twelve years of technological and market research. The prime design consideration was to provide a craft with maximum passenger comfort at relatively high speed in seas up through state 4. The design evolved from previous Boeing experience with the hydrofoils *High Point* (PGH-I), *Tucumcari* (PGH-2), and the Boeing research craft, *Little Squirt.*

The hull is all-welded 5456 aluminum with fifteen watertight compartments which provide two-compartment

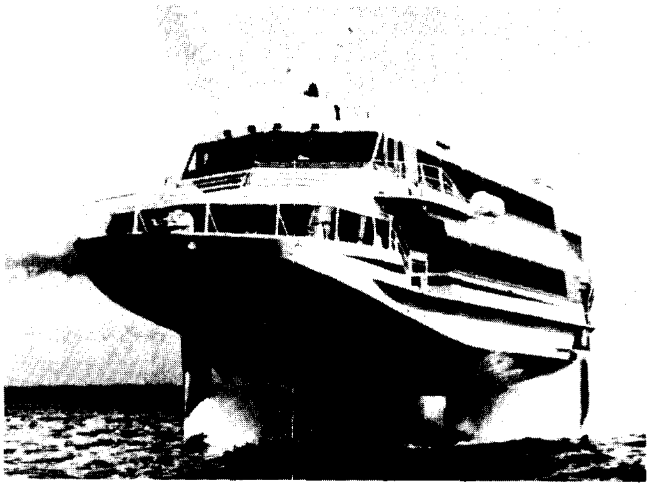


Figure 56. The only commercial hydrofoil built in the U.S. is the Boeing model 929 Jetfoil.

subdivision. Fuel is carried in one 4,200 gallon integral tank.

The retractable foil system is a fully-submerged, canard arrangement with flap control of roll, pitch and height. The forward strut is steered for yaw and directional control. Foils and struts are hollow built-up weldments of 15-5PH corrosion resistant steel.

Control is provided by a solid-state electronic automatic control system. Inputs from gyros. accelerometers and dual sonic height sensors are processed by the ACS computer to develop control commands to hydraulic actuators for the foil flaps and forward strut positions.

A 3,000 psi aircraft-type hydraulic system is used. Redundancy is employed to provide a completely fail-safe design through single level electronic, mechanical or structural failures.

Propulsion is provided by two identical gas turbine driven waterjet pump systems. Detroit Diesel Allison Model 501-KF gas turbines, rated at 3,780 continuous horsepower, drive Rockwell Rocketdyne Powerjet 20 22,300 gpm, mixed-axial-flow waterjet pumps through Cincinnati Gear reduction boxes. With the foil system extended. propulsion water is taken in at the aft centerline strut-foil pod. When the foil system is retracted, the water inlet duct is separated, providing a water inlet at the hull keel line. The propulsion water is ejected through nozzles under the hull. Reversing buckets and vectoring deflectors are provided for hullborne maneuvering and control.

Passenger accommodations are provided for 250 to 320 passengers on two decks with aircraft-type seating, galleys. toilets and baggage stowage. Air conditioning and sound insulation make the Jetfoil passenger spaces comparable to modern aircraft.

Design, materials, construction, fire protection and life saving meet or exceed the requirements of the American Bureau of Shipping (ABS), USCG, foreign coast guards and IMO. Normal operation requires a two-man crew in the wheelhouse plus passenger attendants.

Twenty-three Jetfoils have been built. Eighteen of these are in daily commercial service. Twelve of them operate on the 36 nautical mile route between Hong Kong and Port Macau; two on the 34 nautical mile route between Niigata and Sado Island, Japan; two in cross-channel service between Dover, England and Ostende, Belgium; and two in the Canary Islands. These commercial hydrofoils are averaging 98.7 percent departure mechanical reliability, 65 percent passenger load factor and have accumulated over 220,000 hours underway.

There are several additional commercial applications of Jetfoil currently under consideration, namely: an Alaska State Ferry System service for the small communities in the southeastern section of the state; a Seattle, Washington-Victoria, B.C.-Vancouver, B.C. ferry service in conjunction with 1986 World Exposition in Vancouver; New York to Atlantic City passenger service to support the various casinos; and a crew transportation system for offshore oil platforms in the Norwegian North Sea area.

Switzerland

Supramar is a company organized in Switzerland in 1952. The founder was Baron von Schertel who was an early pioneer in the development of hydrofoils in Germany. During World War II, von Schertel teamed with the Sachsenberg Shipyard to build military hydrofoils for the German war effort. After the war several of the engineers who worked on the military hydrofoils joined Baron von Schertel, who had formed a new company, Supramar, in Switzerland. This group began the development of a commercial hydrofoil. Their first successful passenger vehicle was designated PT-10, a seven-ton craft, seating 32 persons, and initial operations were on Lake Maggiore between Switzerland and Italy in 1952. In 1954 Rodriquez Cantiere Navale became Supramar's first licensee. Today Supramar continues to design and develop new hydrofoil concepts which are produced under license in different countries. All of their craft have used surface-piercing foil systems.

Italy

The producer of the largest number of commercial hydrofoils in the free world is Rodriquez Cantiere Navale, S.p.A. (Rodriquez) of Messina, Italy. They have built approximately 150 hydrofoils which have operated throughout the world. Their first hydrofoil was delivered in 1956 for operation across the Straits of Messina from Messina to Reggio di Calabria. The PT-20, built under a Supramar license, is still operational today.

Rodriquez continued to build hydrofoils under the Supramar license until 1970. By that time they had perfected their own hydrofoil designs. Since 1970 they have developed, designed, and produced their own hydrofoils which are designated by the initials RHS. Rodriquez currently produces the following hydrofoils, all of which use the surface-piercing system:

	RHS-70	RHS-I50	RHS-160	RHS-200
LOA	72 ft 2 in	94 ft 2 in	101 ft 6 in	117 ft 6 in
Beam	25 ft 9 in	19 ft 2 in	20 ft 4 in	23 ft
Displacement, tons	31.5	65.6	85	120
Passengers	69	180	205	300
Cruise speed, knots	32.4	32.5	38	35

The RHS-160 is shown on Figure 1 and the RHS-200 on Figure 57.

The RHS series hydrofoils have riveted aluminum hulls and welded steel foils. The foil systems are basically surface piercing with controlled flaps incorporated into the foil system. On all but the RHS-70, these flaps can be actuated by an optionally provided, seakeeping augmentation system (SAS). This system has been developed and built by Rodriquez Cantiere Navale and the Hamilton Standard Division of United Aircraft.

The SAS consists of an analog computer, gyro, and accelerometer interconnected with position transducers. Impulses are sent to flap-control, servovalves which are electro/hydraulically operated. Under heavy sea conditions, the SAS reduces rolling and pitching, providing a more comfortable ride.

The propulsion system uses MTU diesel engines. Conventional propellers are driven through inclined shafts. The basic design is simple and rugged following conventional marine practices. The Rodriquez hydrofoils have been proven to be most reliable and are noted for their low maintenance costs.

Japan

A current producer under a Supramar license is Hitachi Zosen Corporation of Japan. This firm has been building ships since 1882. It has been privately funded and controlled since its inception and has never required direct government investment. The company is characterized by a greater spirit of freedom and enterprise than most other heavy industry companies in Japan. This corporate personality undoubtedly had something to do with Hitachi's decision to enter the hydrofoil business. Hydrofoil construction is carried out at the company's Kanagawa works in Tokyo Bay. This is just one of their six shipbuilding yards. They have delivered over 40 hydrofoils since they acquired the Supramar license in 1962. They are currently producing the following hydrofoils.

	PT-20 MK II	PT-50 MK II
LOA	68 ft 1 in	91 ft
Beam	14 ft 4 in	17 ft 10 in
Displacement, tons	32.5	63.3
Cruise speed, knots	32	32
Passengers	62	130

A Hitachi Zosen built PT-50 MK II is shown in Figure 58.

Figure 58. Hitachi PT-50 MKII

It should be noted that the surface-piercing hydrofoils, built by Hitachi can be equipped with a seakeeping augmentation system. This electronic/hydraulic control system actuates flaps on the main lifting surface which provides a more comfortable ride in heavy seas.

Russia

In Gorki, USSR, a variety of passenger hydrofoils are constructed in an old, established shipyard which also builds conventional ships. Their early hydrofoils were produced for operation in shallow rivers and canals. They developed a foil system that utilized a combination of surface effect and the Gruenberg system. Surface effect is the loss of lift as the foil approaches the water surface. The Gruenberg system, named after the inventor, comprises a dynamic lifting system forward, such as skis or foils, which control the angle of attack of an after foil through the pitching motion of the craft as it operates in waves. The Russian system comprises two main foils, one forward and one aft, each carrying nearly half the weight. The forward foil, which is surface piercing, controls the pitch of the boat and the angle of attack of the aft foil which is mostly a submerged foil. A submerged mid-

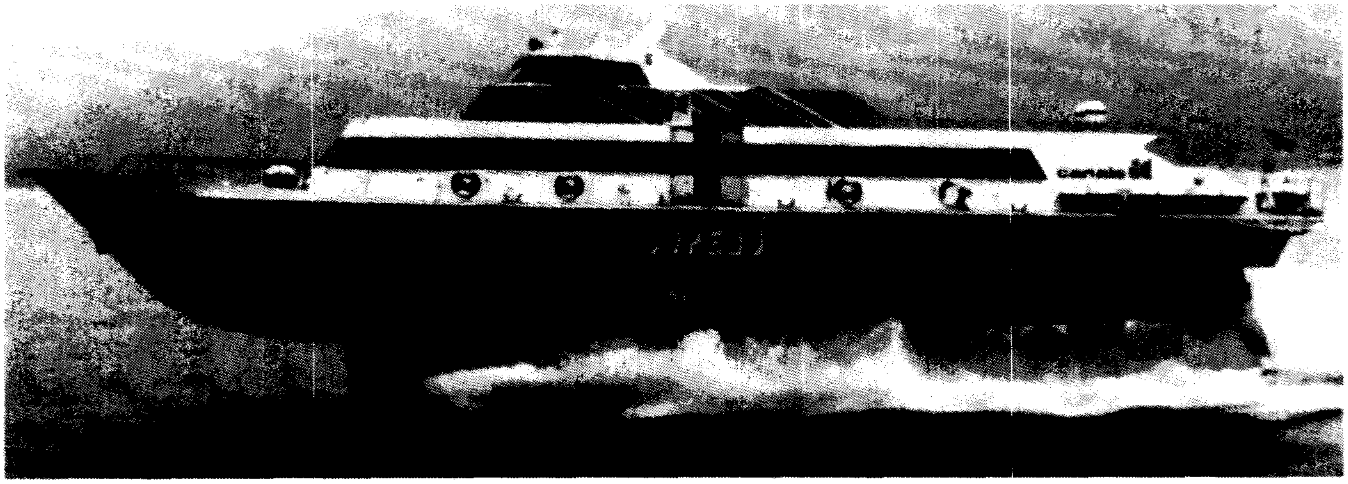


Figure 57. Rodriguez Cantiere Navale RHS-200

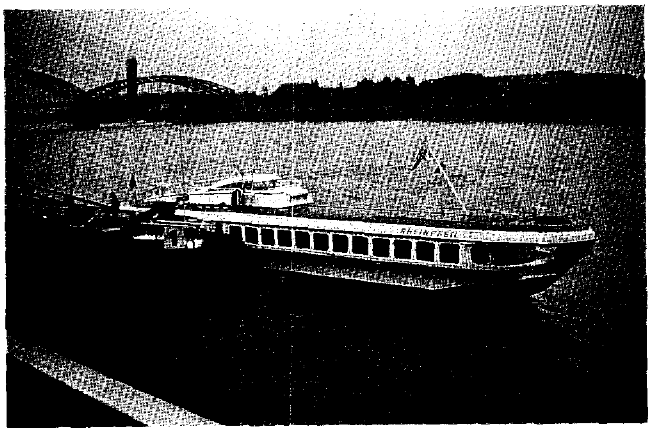


Figure 59. *Raketa* on the Rhine River, Germany

ship foil provides the balance of the lift. This concept results in a shallow draft hydrofoil ship.

The first hydrofoil of this type which has been exported is the ***Raketa,*** Figure 59. This is primarily intended for relatively sheltered water operations. The principal characteristics of this hydrofoil are as follows:

	Raketa
LOA	88 ft 5 in
Beam	16 ft 5 in
Draft	5 ft 11 in
Displacement	27 tons
Passengers	58
Cruise Speed	32 knots

One of USSR's first seagoing commercial hydrofoils was *Kometa*, Figure 60. It was first introduced in 1961 in Russia and is now exported widely. ***Kometas*** are in service in more than ten countries. The foil system uses a deeper surface-piercing forward foil than ***Raketa.*** The system comprises a bow foil, aft foil and two auxiliary foils. One of the auxiliary foils is located above the bow foil and the other near the center of gravity to assist takeoff. The interior is comfortably furnished with air conditioning as an option. The ride is quite comfortable in 1.5 meter waves. The principal characteristics of the export ***Kometa*** are as follows:

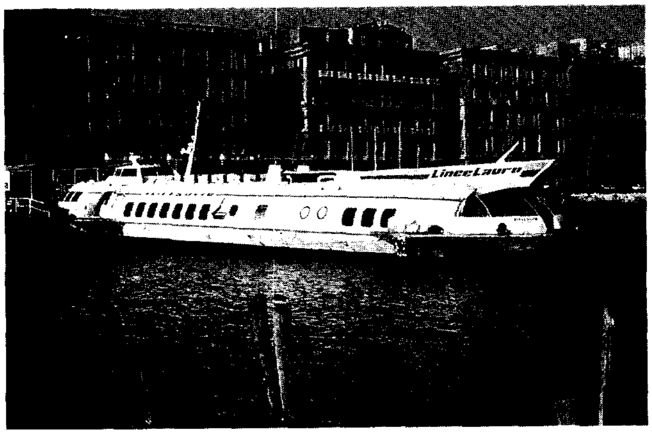


Figure *60. Kometa* Dockside, Naples, Italy

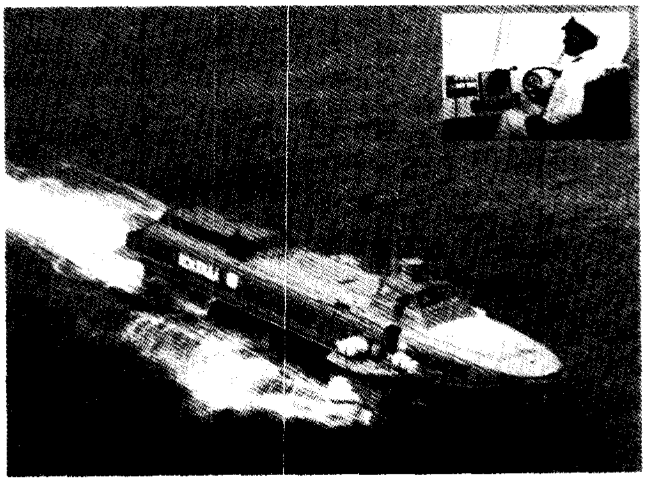


Figure *61. Kolkhida*

	Kometa-MEA
LOA	115 ft 2 in
Beam	16 ft 1 in
Draft	11 ft 11 in
Displacement	60 tons
Passengers	116-120
Cruise Speed	32 knots

The latest hydrofoil offered for export by USSR is ***Kolkhida,*** Figure 61. It is designed as a replacement for ***Kometa.*** The foil system is similar to ***Kometa*** but incorporates an automatic control system actuating flaps on the foils. As a result, improved seakeeping is provided. It is reported to have a comfortable ride in waves 2 meters high. As with ***Raketa*** and ***Kometa, Kolkhida*** is powered by marine diesels driving fixed-pitch propellers. ***Raketa*** and ***Kometa*** use diesels built in Russia. ***Kolkhida*** employs two. 12-cylinder German built. MTU diesels for propulsion. The principal characteristics of ***Kolkhida*** are as follows:

	Kolkhida
LOA	113 ft 3 in
Beam	33 ft 10 in
Draft	11 ft 6 in
Displacement	68 tons
Passengers	140
Cruise Speed	35 knots

STATE OF TECHNOLOGY

Having reviewed the current and future applications for hydrofoil ship, it is interesting to review the status of the development of hydrofoil technology. Considerable effort has gone into establishing the basic theory for hydrofoil systems operating in a seaway. Many comparisons have been made of aerodynamics with hydrodynamics. Hydrofoil cavitation is analogous to approaching the speed of sound. Mach 1, for wing design. Flutter and divergence are of concern to both airfoils and hydrofoils. Modern aircraft and hydrofoils require automatic stabilization systems. Besides learning to understand these phenomena, metallurgical solutions have been derived

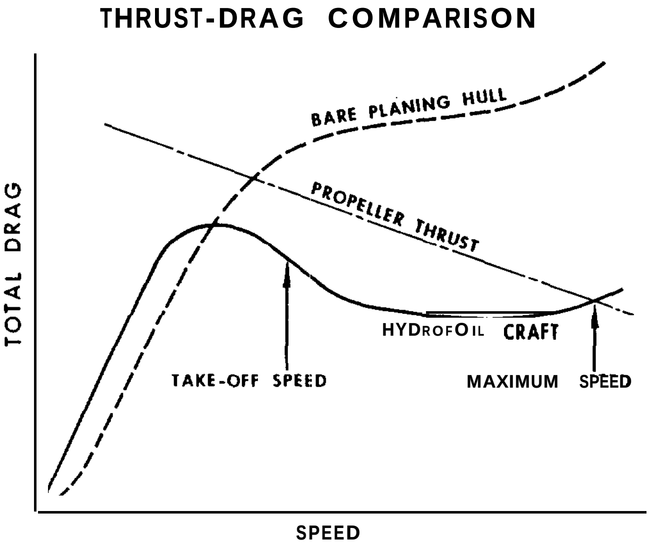


Figure 62. Typical Calm-Water Thrust-Drag Curves

HULL GEOMETRIC PARAMETER	HULL ENVELOPE			FOIL SYSTEM		ERFORM			EAWORTHINES		
	COMBAT, WEAPONS SPACES	WORKING, LIVING SPACES	FUEL, MACHINERY SPACES	FWD	AFT	H/B DRAG	TAKEOF DRAG	EIGHT	STABILITY AND FLOODING	H/B SEAKEEPING	F/B IMPACT
LBP	●	●	●	△	△	●	●	●	△	●	
BEAM	△	●	●		●	△	△	•	●	●	△
MIDSHIP DEADRISE			△			△	△	●	●	△	●
CHINE		△	△		●	△	●	A	●	△	●
LCB			△	●	●	●	●			△	●
PRISMATIC COEFFICIENT			△			●	●		△		△
BOW *DEADRISE*				●		△	△		△	●	●
BOW FLARE	●	△		●					●	●	△
KNUCKLE	△	△		△				A	△	●	△
BOW FREEBOARD		△		△				A	●	●	△
AFT FREEBOARD		△	●		△			A	●	●	
AFT BUTTOCK LINE SHAPE			△		△	△	●				

● MAJOR INTERACTION
△ MINOR INTERACTION

Figure 63. Hydrofoil Mission/Hull Form Interactions

for foil and hull materials. The following section discusses the status of these and other technologies and points the way to future progress in the field of hydrofoil development.

HYDROFOIL HULLS

The major reason for the employment of hydrofoils is to lift the hull out of the water to reduce the effect of waves and to reduce the drag at high speed. However, a naval hydrofoil ship spends a considerable portion of its life hullborne and must have an efficient hull form to keep the drag low at low speed and through takeoff. Total drag just prior to takeoff is a significant factor in establishing the power requirement. Careful attention must be paid to the hull design to minimize this effect. Figure 62 shows a generalized smooth water drag curve for a hydrofoil craft with its significant "hump" prior to takeoff. Comparison is also made with a typical planing craft to illustrate the high-speed advantage of the hydrofoil even in smooth water. In order to overcome additional takeoff drag which results from rough water, a power margin over the smooth-water takeoff drag requirements is required. Since the magnitude of this margin is a prime factor in the sizing of the propulsion system, it is essential that it not be arbitrarily overspecified. Tests in design sea states on well-instrumented U.S. Navy hydrofoils show that 20 to 25 percent margin is ample to permit takeoff in rough water in any direction.

An efficient hull form for a lower speed operation requires a narrow beam. However, a righting moment large enough to satisfy the stability criteria of reference [28] with the foils retracted generally dictates a wide beam. Cresting the tops of waves while foilborne points toward the use of a deep vee forward and high deadrise.

Another major consideration in hydrofoil hull design is the requirement for good seakeeping characteristics in a heavy sea. If hydrofoil craft are to operate unrestricted in open ocean, they must be capable of surviving storm seas in the hullborne condition. Furthermore, in certain missions, it may be expected that the hydrofoil ship will spend the greater portion of its operating lifetime in the hullborne mode. Thus, it is essential that close attention be given to the hull seakeeping characteristics. With the foils extended during hullborne operation, which is normal operation at sea, there is a significant reduction of craft motion, in both the roll and pitch modes which is normally not heavily damped as is shown in Figure 21. Thus the strut/foil system gives hydrofoil craft hullborne motion characteristics of ships having much larger displacement.

The complex interaction of hull design parameters on elements of ship performance and seaworthiness is indicated by Figure 63, [29].

Structurally, the hull must have the strength to resist wave impact and emergency landing in high seas at foilborne speeds, as well as the concentrated loads at the strut attachment points. Weight considerations dictate lightweight materials. Cost, producibility (weldability), repairability, and resistance to sea water corrosion are significant factors in the selection of lightweight hull materials. At present, only the 5000 series aluminum alloys appear to satisfy these criteria. Of these, 5456 Al has been used almost exclusively in U.S. Navy hydrofoil hulls. H-321 and H-311, (the types of 5456 Al used), has been shown to exfoliate (or delaminate) and 5456-H116 or 5456-H117 is now recommended for hydrofoil hulls. In utilizing aluminum alloys for hull material, provisions must be made for some form of cathodic protection. A sprayed zinc coating on the aluminum hulls of the U.S. Maritime Administration hydrofoil *Denison* and the PGH-1 has proven to be an excellent form of protection. Passive sacrificial zinc anodes strapped to the hull have proven adequate on other hydrofoils. Impressed current systems have also been used effectively.

Regarding the weight criticality of the hull, one must ask what is a reasonable weight for a hydrofoil hull. Overall hull weight fraction is a poor measure of structural efficiency as it depends on how densely equipment is packaged in the hull. An ore carrier, for instance, will

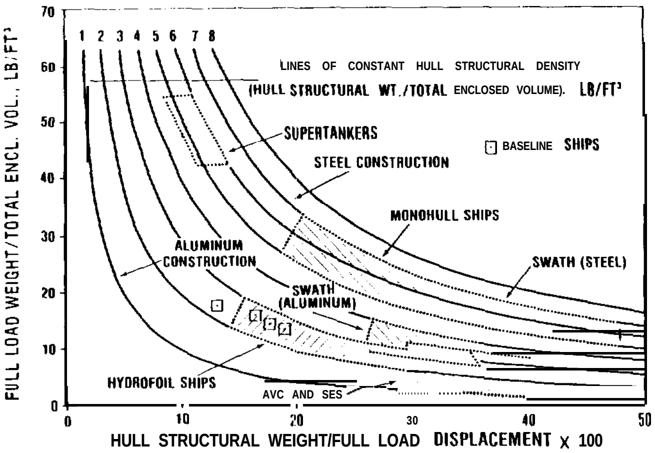


Figure 64. Relationship of Vehicle Density and Hull Structural Weight Fraction

have a far lower hull weight fraction than, say, a passenger steamer. Hull weight per unit of enclosed volume is a far better measure of structural efficiency. Hydrofoil hull weights, as shown in Figure 64, presently run between two and three pounds per cubic foot of enclosed volume.

When all the factors mentioned above are considered in trade-off studies, the design of a typical hydrofoil hull at the present time might include a length to beam ratio of 4:1; a sharp V forward; 20" dead rise aft; hard chine planing surface hull shape; be constructed of 5456 H116 aluminum with all-welded frames and stringers using extruded skin panels with integral stiffeners construction; and a weight per cubic foot of enclosed volume of 2.5 lb.

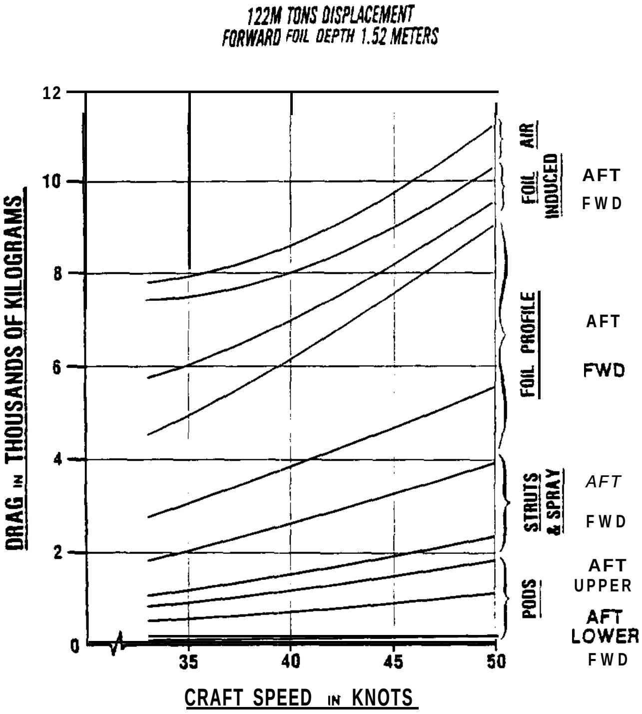


Figure 65. PCH-1 Mod 1 Foilborne Drag Build-Up

FOILS AND STRUTS

The hydrofoil lift system design process is typically one of iteration among performance requirements-hydrodynamics, structures, propulsion, hull configuration, weight, etc. It involves many iterations among the requirements of these disciplines before arriving at the final balanced design.

There are two general approaches to the design of a hydrofoil ship and its lift system. The first is the case in which the payload, range and speed are specified, and the design process results in a minimum size ship to meet the requirement. The second is where the power plant is dictated, in which case the design process results in a ship with a possible maximum payload and range with the specified power plant, consistent with a specified design speed and other requirements. Since mature power plants are generally only available in discrete sizes, the latter case is the more common practice. After the foilborne propulsion plant is selected, it becomes a key restraint. The first case is normally useful for parametric analysis or early iterations.

However, the NATO PHM project office dictated the first approach for the NATO PHM which resulted in use of the LM2500 engine operating well below its normal rating in that ship.

Selections of the strut/foil configuration and load distribution are so interrelated that they are usually approached concurrently. A hydrofoil ship is classified as having a canard. tandem, or airplane configuration depending on relative distribution of load between the forward and after lifting surfaces. A canard configuration is defined as one in which less than *35%* of the weight is carried on the forward foil, an airplane configuration as one in which less than 35% of the weight is carried on the after foil. and tandem as a distribution between these limits. Selection of the lift system configuration is influenced not only by hydrodynamic criteria, but also by external clearances and performance at off-design conditions. These constraints include: foil span, navigational draft hullborne with foils down, structural considerations, center of gravity shift, and arrangement of weapons suite and machinery.

Since the hydrofoil ship must operate in the hullborne mode as a displacement or semiplaning vehicle as well as in the foilborne mode and must accomplish the transition from hullborne to foilborne (and vice versa), it is necessary to consider both the drag of the hull over a range of speed and loadings and the drag of the lift system over a range of lift and speed. The buildup of foilborne drag for *Highpoint* is shown on Figure 65.

The lift system drag includes that drag associated with the lifting surfaces (foils) and the drag of the associated appendages (struts, pods, and fairings) required to connect the lifting surface to the hull.

The drag of the lift system can be divided into two principal components:

a) Zero lift drag, or parasite drag, including the section profile drag, the effects of fluid friction and flow separation associated with the development of the boundary layer. the spray drag, and air drag on the hull.

b) Drag due to lift which includes the induced drag, which is associated with the energy of the downwash in the wake of a lifting surface, and the wave drag, which is associated with the energy in the wave produced on the free surface.

The zero lift drag varies with V^2, making this the predominant drag at high speed. The drag due to lift, on the other hand, varies as $1/V^2$, making it predominant at low speeds. In fact, when combined, there is a speed at which the drag is a minimum which, for most hydrofoils, occurs from 5 to 10 knots above takeoff speed, as shown in Figure 66 for a typical lift system designed to carry 1,000 tons on two equal foils at a maximum speed of 50 knots. The drag due to lift is also inversely proportional to the foil aspect ratio, defined as the foil span divided by its chord. Therefore, from a hydrodynamic efficiency viewpoint, the span of a hydrofoil should be as great as practical. As seen from the foregoing, this is particularly applicable for drag reduction at takeoff and lower flying speeds. Structural and other considerations, however, limit the practical span of the foils. For example, foil span in some studies of very large hydrofoils has been limited to 100-104 ft. to allow the ships to pass through the Panama Canal. Also, it is recognized that a substantial foil overhang on either inverted "T" (single strut) or inverted "TT" (two struts) foils could interfere with dockside cranes, buildings, vehicles, etc. These practical factors force the designer toward a tandem configuration on larger hydrofoils and to maintain span and overhang to acceptable values. The major consideration which limits the degree to which one can employ a tandem configuration is the hull shape and weight distribution due to the arrangement of machinery and weapon systems and the requirement for retraction.

Hydrofoil ships with their foils down have a greater draft relative to conventional hulls of the same displacement. For a 1,000-ton hydrofoil ship, this draft will be approximately 35 feet, about 2/3 of which is the amount the foil-strut system projects below the keel. If it is required that this draft be reduced and the lift system and propulsion gearboxes be accessible for maintenance without drydocking, it is necessary to retract the foils out of the water. For larger hydrofoil ships, this is most easily done by rotating the foils up behind the transom and up over the bow. Design studies for very large hydrofoil ships indicate the weight penalty for dry retraction can be as much as 10 to 20% of the full-load weight of the ship.

A foil design is very similar to a wing design except the hydrodynamicist has to cope with cavitation, whereas the aerodynamicist has to cope with compressibility. Although both are physically unrelated, the restrictions imposed upon foil design by cavitation are analogous to those imposed by Mach-number effects on wing design. Thus, a cavitation bucket looks very similar to a Mach force-divergence bucket. Cavitation occurs when the local static pressure drops below vapor pressure, and vapor cavities are formed. These cavities increase drag and may collapse on the surface of the foil resulting in severe erosion taking place. The prediction of hydrodynamic forces and moments are now normally obtained from computer programs which generate the pressure distribution on the foil based on lifting-surface theory to assist in optimizing design performance.

Foil loading (dynamic lift divided by foil planform area) is first established at takeoff speed and/or minimum specified flying speed. 'The maximum lift coefficient which can be achieved by a foil is generally around 1.0. About 20% to 30% of this is reserved for control forces needed at takeoff, to counter the seaway, maneuvering and takeoff trim requirements.

Figure 67 shows the relationship of foil loading to takeoff speed. The limits are based on lift coefficients of 0.7 and 0.8. The minimum stable flying speed shown in Figure 67 generally corresponds to a speed a few knots below the speed of minimum drag. This corresponds to a lift coefficient between 0 5 and 0.6, which provides sufficient lift margin needed to assure necessary control forces to trim the ship, alleviate seaway disturbances and provide maneuvering transient forces and moments.

A particular foil section is selected so as to give a relatively flat pressure-distribution curve across the foil chord. This avoids a local pressure peak with resultant cavitation. Although both the NACA 16 series and 64 series have this characteristic, the 16 series has been used for Navy hydrofoils primarily because of the extent of data available. Further, it is relatively thicker where the

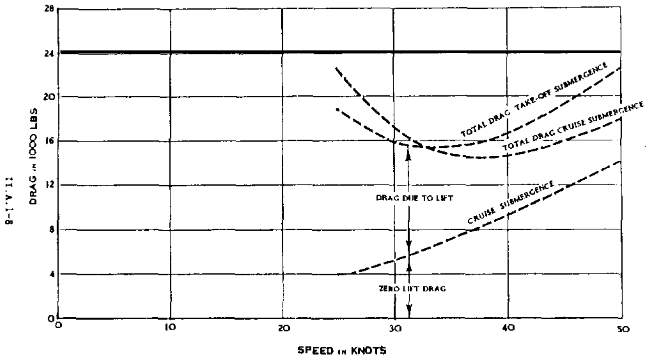


Figure 66. 1,000-Ton Hydrofoil Total Drag, Drag Due to Lift, Zero Lift Drag vs Speed, Smooth Sea Water

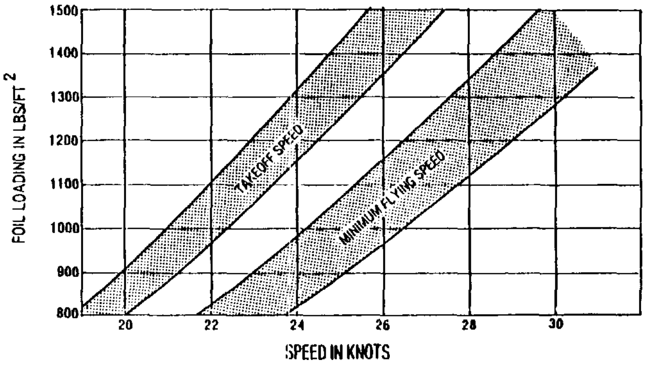


Figure 67. Foil Loading--Takeoff and Minimum Flying Speed Relationship

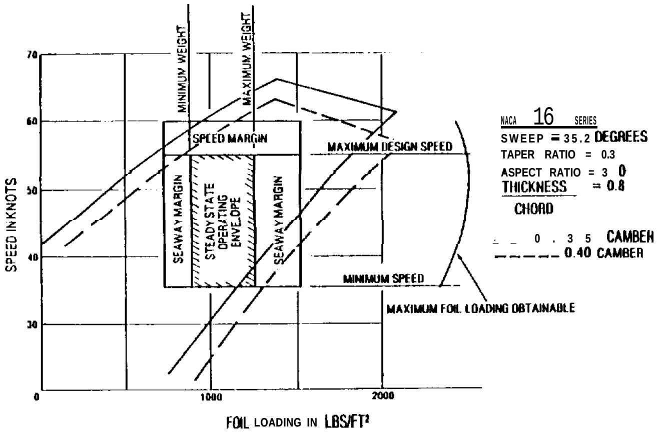


Figure 68. Foil Loading-Speed Envelope with Cavitation Boundaries of Two Different Foils Superimposed

hinge line for the trailing-edge flap is located. Figure 68 is a plot of an operating foilborne loading speed envelope with a cavitation boundary plot of a selected foil section superimposed.

Figure 68 shows that for a 0.35 camber, the foil will cavitate slightly at minimum speed and maximum weight, particularly in a seaway. If the camber is increased to 0.40, however, the entire steady-state envelope will fall within the cavitation-free area, and only slight intermittent cavitation will occur in a seaway. The same result could have been achieved by lowering the foil loading slightly. Decreasing the foil loading, however, increases foil size and weight. In selecting a foil section, the designer can opt for either speed margin or weight margin to allow for a possible future increase in ship weight (increased foil loading). Since most ships tend to grow in weight with time, the latter is the preferred option.

Strut length selection is based on the foreseen statistical wave height in the proposed worst area of operation anticipated for the ship. The length chosen should avoid broach up to and including the design sea state to retain the desired ride quality. Usually it is desired that the foils operate with a mean foil depth of at least one foil chord submergence. The length of the strut between the hinge point (if retractable) or hull hard point (if fixed) and the keel line is a function of the hull geometry. A strut length between the keel and the foil equal to the design significant wave height has been shown to be satisfactory on existing ships. However, the strut length can be adjusted to be assure a given ride quality. Although simple equations can show trends, dynamic simulations are used to determine the strut length more accurately. Variables which determine strut length include foil-lift curve slope, flap effectiveness, design sea state, foil loading, foilborne speed and specified broach frequency.

Total lift system weights for various operating ships and design studies have been included in Figure 69. The trend is toward a slightly increasing foil system weight fraction with increasing ship size. This trend is far less than originally predicted in the 1960s because the length of the struts (which make up the major portion of the weight) does not increase directly with ship size. Note that this increased weight is partially offset by increased buoyancy as the foil system volume increases with size.

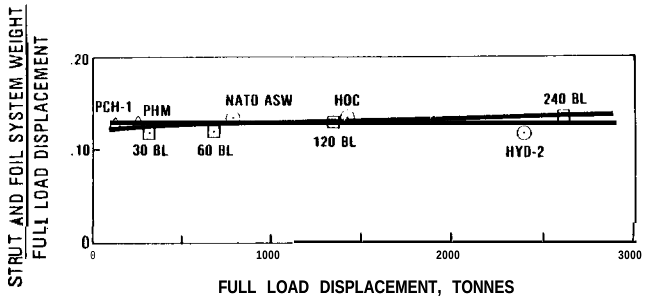


Figure 69. Strut and Foil System Weight Trend

CONTROL SYSTEMS

A hydrofoil control system comprises those components necessary to control the ship's speed, attitude, direction and to supply, if necessary, dynamic stabilization. As with any dynamic lift vehicle, the control system of a hydrofoil can be divided into five functional areas: sensors, computer, actuator, force producer and the vehicle itself. The vehicles and control system react to two inputs: the command and external disturbances (i.e., the seaway). These are shown in a typical block diagram in Figure 70.

Hydrofoil ships with surface-piercing foils, in general, do not employ an autopilot system since the foils themselves act both as sensors and control devices. This is due to the change in forces and moments with depth of foil, submergence. This provides the advantage of simplicity and high reliability but it severly limits rough water capability. In some cases, simple control augmentation may be added to surface-piercing systems to counter special stability problems that may occur due to particular mission requirements. This was the case in the design of the Canadian HMCS *Bras d'Or* (FHE 400), (Figure 20), where controllable anhedral foil tips were employed to give added stability in the takeoff and low foilborne speed range. The FHE-400 was designed for a wide foilborne speed range (3 to 1). This is considerably greater than the usual design practice where the takeoff speed is about one-half the design flying speed. This posed a special problem which required augmenting the stability at lower foilborne speeds.

Other ships have used a surface-piercing main foil and a smaller fully-submerged control foil in an attempt to

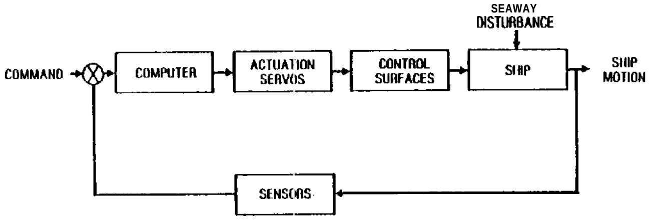


Figure 70. Hydrofoil Control System Block Diagram

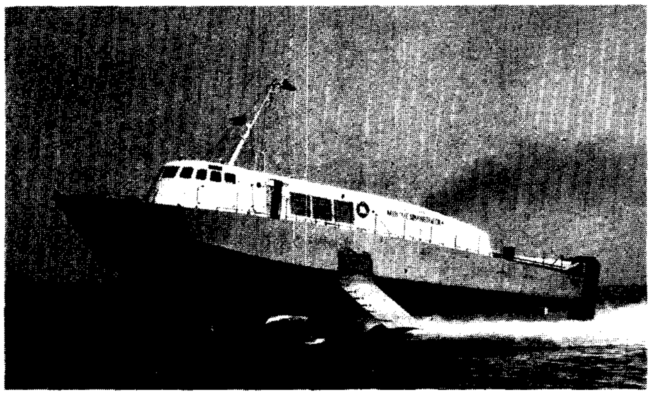


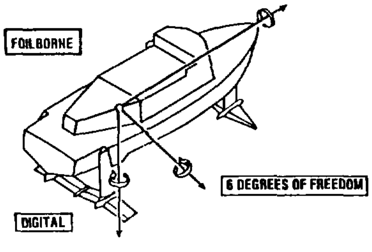
Figure 71. MARAD's *Denison*

gain the advantages of both configurations. *Denison*, Figure 71, an early experimental commercial hydrofoil built for the maritime administration, and the RHS 200, Figure 57, are examples. These also include autopilots to supply stability augmentation.

In general. it has been the conviction in the U.S. Navy that oceangoing. military hydrofoils require fully-automatic control of submerged foils to provide acceptable motions. This design philosophy has been verified through the exceptionally good rough-water performance of the U.S. designed hydrofoils. The following discussion, therefore, will be limited to the technical aspects of submerged-foil ships having some form of automatic control.

Perhaps the most significant engineering achievement produced by the Navy advanced hydrofoil systems program has been the analytic and predictive technology developed for dynamic control of a hydrofoil platform with submerged-foil systems. Sophisticated simulations have been developed which accurately model ship behavior in the total environment and over the complete foilborne operating envelope, [30] and [31].

From such simulations, foil system configuration, automatic control system functional configuration, and related subsystem design and performance requirements can be developed. Figure 72 is an overview of the PHM motion simulation.



INPUT	CONTENT	OUTPUT
• SPEED • FOIL DEPTH • HELM COMMAND • HEADING • SEA CONDITION . WAVE HEIGHT . WAVE PERIOD • WIND VELOCITY AND DIRECTION	. EQUATIONS OF MOTION • HYDRODYNAMIC DATA . MASS AND INERTIA DATA . SHIP DIMENSIONS . AUTOMATIC CONTROL SYSTEM CHARACTERISTICS . SEA DESCRIPTION	• MANEUVERABILITY • RIDE QUALITY • FAILURE RESPONSE • CONTROL SYSTEM DESIGN EVALUATION . STABILITY CHARACTERISTICS

Figure 72. PHM Motion Simulation

Predictions from analytical tools are only as good as the tools themselves. Therefore, an important link in the state of the art in hydrofoil control and stability is the state of the art of the basic analytical tools. The iterative process of developing a simulation, predicting ship behavior, measuring actual ship behavior and upgrading the simulation has been conducted on all hydrofoil ships in the U.S. Navy program and U.S. commercial programs as well.

Correlation data have indicated the accuracies of the present simulations to be very good, and, in fact, the differences between craft measurements and predictions approach the accuracy of the shipboard measurement systems. An example for PCH Mod 0 is shown in Figure 73.

There are two foilborne models in which the ship can operate in rough water as shown in Figure 74. If the hydrofoil is relatively large compared with the waves and its flying height is sufficient to permit the hull to travel in straight and level flight clear of the waves, the craft is said to "platform." In the other extreme, if the hydrofoil is small compared to the waves, it is constrained to follow the surface. This is known as "contouring" and, ideally. a 100 percent response of the control system is required. Hydrofoils with an autopilot, to give them the ability to control lift, have the option to select reasonable compromises between these two extremes and seek to provide minimum foil broach and maximum hull clearance without exceeding specified limits of craft motion and accelerations. The autopilots of the U.S. designed hydrofoils have frequency-sensitive filters which make them tend to contour waves with a low frequency of encounter (large amplitude, long period) and platform thru those with a high frequency of encounter (short period, small amplitude).

For maneuvering a hydrofoil there are fundamentally two modes; flat turns as shown in Figure 75 and coordinated or banked turns as shown in Figure 75A. For a flat turn all of the side force required to overcome the centrifugal force must be generated by the struts. For a fully-coordinated turn, all of the side force is generated by a component of the lift vector of the foils. The fully-coordinated turn is favored over flat turns for most hydrofoils because: (1) the struts experience almost no angle of attack which minimizes strut bending loads and the chance of strut ventilation, (2) it is more comfortable for personnel, and (3) approximately twice the turn rate can be achieved.

The simplest form of automatic control systems combine mechanical sensors and actuators directly linked to lift control devices. These include forward probes with skids that plane on the free surface and spring flaps attached to the struts at the air-water interface. Both types of mechanical "sensors" control trailing-edge flaps on the submerged foils in proportion to the flying height. These devices essentially make a fully-submerged foil act as though it were a surface-piercing foil. Their application

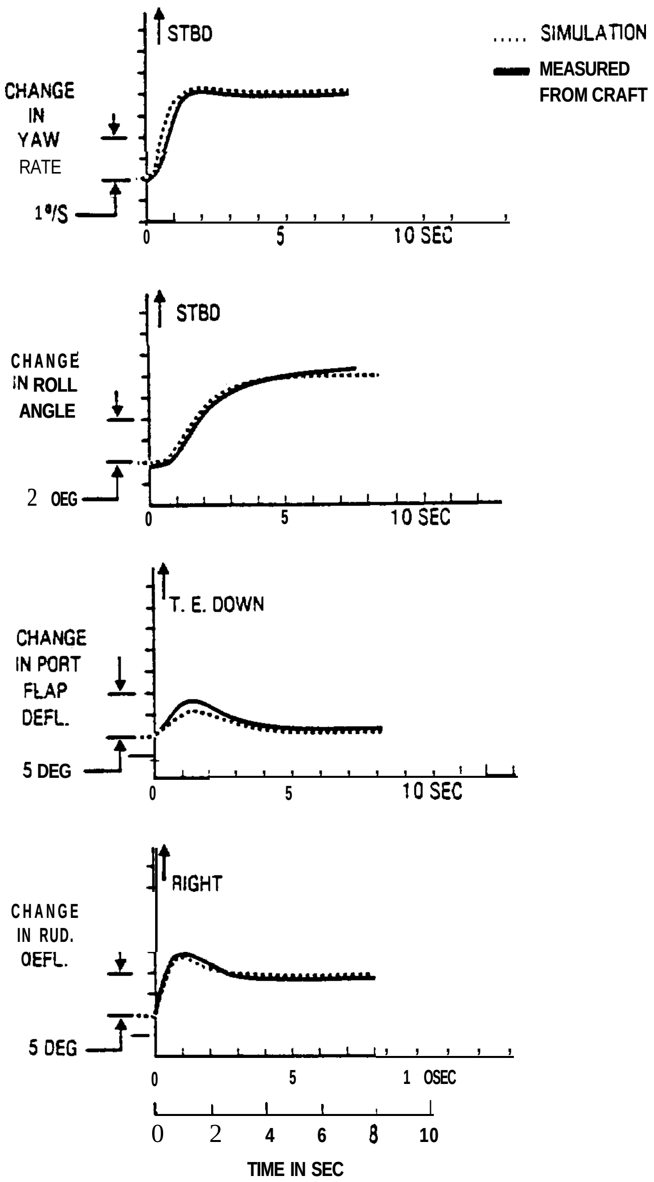


Figure 73. Turning Responses to Step Helm Command—High *Point* Mod 0

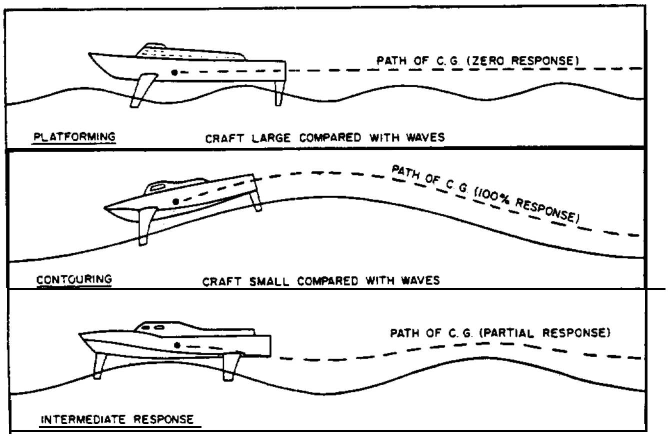


Figure 74. Comparison of Platforming and Contouring Modes

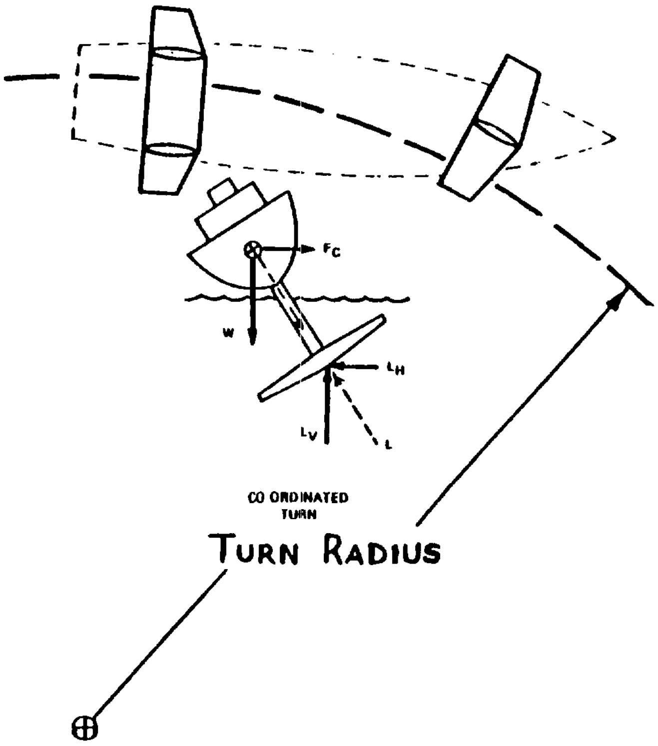


Figure 75. Hydrofoil Flat Turn

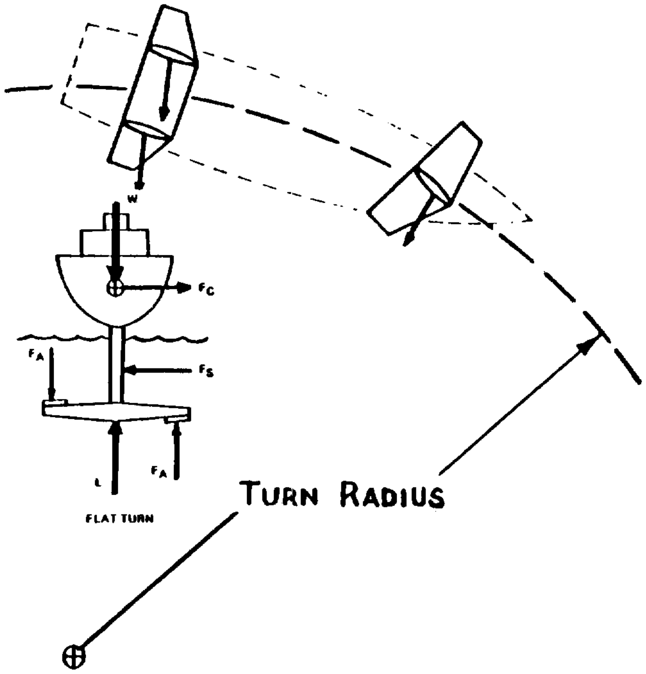


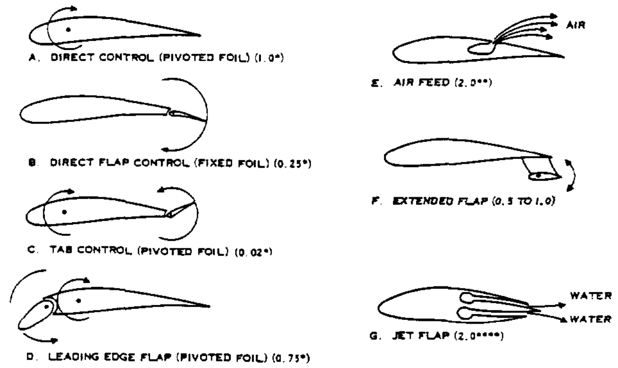
Figure 75A. Hydrofoil Coordinated Turn

is felt to be limited to small craft (under 40 tons) operating in relatively smooth water where the cost of an autopilot cannot be justified.

In the more sophisticated electronic control system, described by Johnston and O'Neill, Reference [8], inputs to the autopilot are provided by electronic height sensors, accelerometers, position, and rate gyros. Electronic sensing of local height of a hydrofoil above the water was originally done by ultrasonic devices mounted on the bow. Drop outs were frequent so that two independent sensors were used. Special gating had to be incorporated to avoid interference from background noise such as gun firing, missile firing or low-flying aircraft. Effective radar altimeters have been developed recently for sea-skimming missiles and other applications. Their use on hydrofoil ships has proven so successful that they are now the preferred height sensor.

The efficiency of energy transfer, the low compressibility of the power transfer medium and the high power-to-weight ratio of hydraulic actuation devices make a hydraulic system generally more attractive than pneumatic or electric actuation systems. Using aircraft-type components and design philosophy, 3,000 psi hydraulic systems up to 2,000 horsepower have been built and used successfully on hydrofoil ships.

Lift control can be achieved in many ways; seven of these are shown in Figure 76. The power required to actuate each. relative to full incidence control, is listed in the figure. The type of lift control device selected for a hydrofoil depends on many factors including mechanical simplicity, reliability, actuation power, range of lift control. field experience, and cost. Incidence and flap control have been well documented and have proven acceptable on existing hydrofoils. Other lift systems which show the greatest promise. particularly for large (1,000-ton) hydrofoil ships. are: (a) the trailing-edge tabs in which the actuation forces required to pivot the complete foil are supplied by the hydrodynamic forces on a small trailing-edge flap: (b) the extended flap in which a balanced flap is placed below the foil to put the flap in a high pressure region to avoid hinge-line cavitation.



NUMBERS IN PARENTHESIS ARE RELATIVE CONTROL POWER REQUIRED INCLUDING STEADY STATE DRAG PENALTY.

*Based on Bolt, Beranek, and Newman report 2511, "Hydrofoil Design for Minimum Power."
**Based on 1965 NSRDC-SUPRAMAR Tank Tests.
***Based on The Boeing Co. estimates.
****Based on Oceanics, Inc. Report 6413, "Use of Jet Flapped Hydrofoils as Ships Antipitching Fins."

Figure 76. Types of Lift Control

Electronic control systems, until the 1980s have all been of the analog type wherein craft-motion sensor outputs are processed by the control computer and continuous proportional commands are sent to the control surface actuators. Figure 77 shows the functional block diagram of a typical hydrofoil control system of this type. Operating experience to date has shown that this type of control system is adequate for subcavitating hydrofoils.

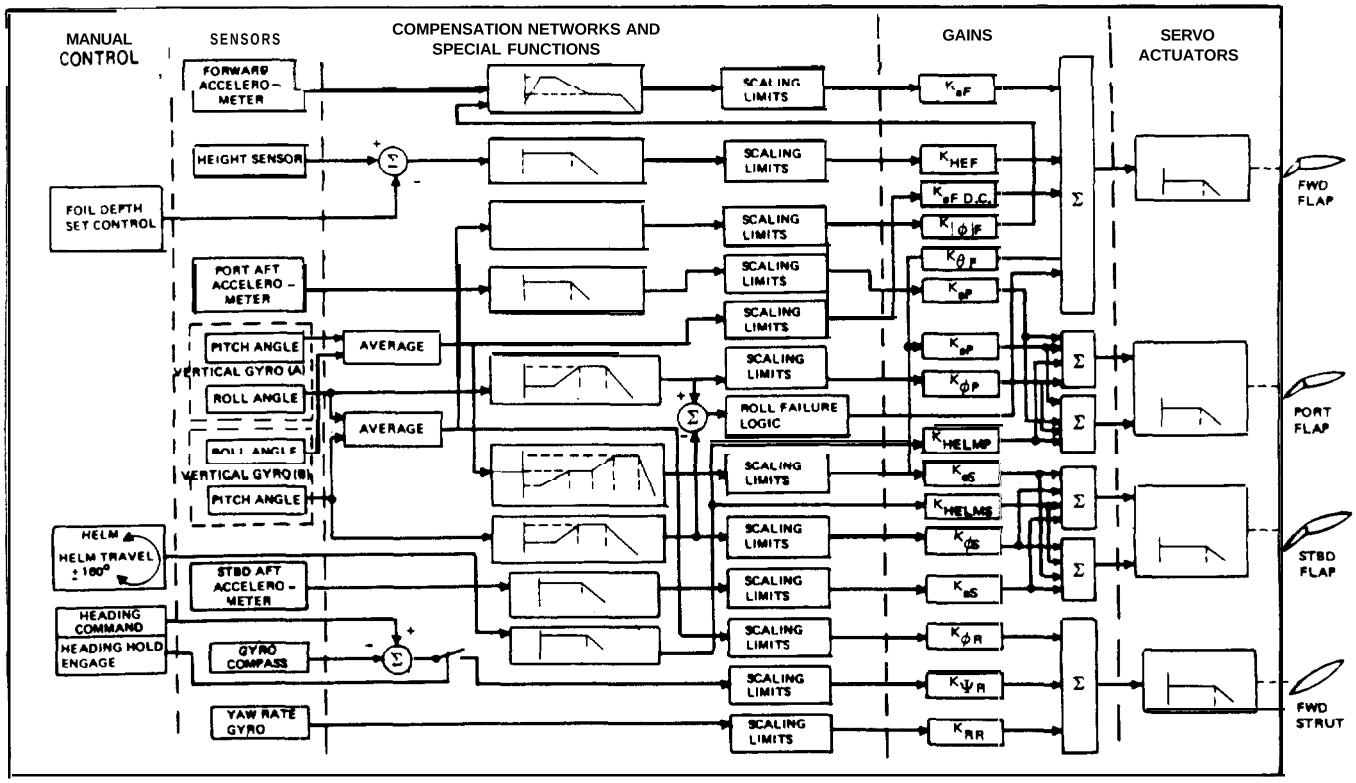


Figure 77. PHM ACS Functional Block Diagram

A more advanced control system which has the potential to further improve the performance of hydrofoils is the digital type. Digital autopilots have successfully flown the PCH, the AGEH, the Jetfoil and *Shimrit*. With a digital computer forming the core of the autopilot, it is possible to go to self-adapting control techniques and automatic self-monitoring. Further, built-in diagnostic programs to assist in maintenance and repair can be used with relative ease with a digital computer.

AUXILIARY SYSTEMS

The category of systems generally referred to as auxiliary systems includes such as electrical generators, pumps, air conditioning, etc. Although there do not presently appear to be any major technical problems, these systems do contribute a substantial portion of the total ship weight. As a result, there is strong reason to devote continued attention to reducing the weight of auxiliary system components. There are many possibilities for adapting modified aircraft practice in the design and specification.

PROPULSION SYSTEM

The three major components of the propulsion systems are the prime mover, transmission, and thrust producer. For small craft, a single system may be adequate. The large variation in power requirements for hullborne and foilborne operation of Navy hydrofoils generally dictates a separate system for each mode.

Foilborne propulsion of large, high-speed hydrofoil craft has been made possible by the development of marinized gas turbine engines. Existing aircraft jet engines have been slightly modified for operation in the marine environment and have been coupled with newly-designed free-power turbines. These are available in sizes ranging up to 40,000 hp with specific weights of around 0.5 pounds per horsepower. Blade cooling techniques have made possible the use of high turbine inlet temperatures which have brought specific fuel consumption of gas turbines down to 0.4 pounds per horsepower at rated power output, close to that of diesel engines.

Lightweight diesel engines with specific weights of 6 to 8 pounds per horsepower, because of their low cost, ease of maintenance, and reasonable mean time between overhauls, are used for foilborne power on most commercial surface-piercing hydrofoils which operate at or below 35 to 40 knots. At higher speeds (to say 50 knots) the power requirements increase 2 to 3 fold. Use of diesel engines at these power levels would be inefficient for most applications because of the large proportion of the ship weight required for the power plant.

Because of their lower first cost, higher efficiency, and flexibility of operation, diesel engines are generally employed for hullborne propulsion. However, with the improvement in fuel consumption small gas turbines are now becoming strong competitors.

The selection of a thrust producer for hydrofoil ships is complicated by a number of unique design factors. Requirements for high power at low speed associated with the takeoff condition conflict with requirements for high power at high speed during foilborne operation as seen in Figure 62. Furthermore, while maximum speed is high by comparison to displacement ships, it is not high enough to justify gas jets or air propellers due to their low efficiency. The high-speed test craft Fresh-l employed a turbofan engine for propulsion, but this selection was made to avoid interference with test foil systems. As for the air propeller, the large diameters required for efficient operation at subcavitating hydrofoil speeds preclude their use. This leaves water propellers and waterjets as the two principal candidates for hydrofoil propulsion.

For speeds up to about 40 knots, the subcavitating water propeller is, by far, the most efficient device for producing thrust. Propulsive efficiencies as high as 0.8 are attainable. At speeds, much above 45 or 50 knots, however, it is virtually impossible to avoid the inception of cavitation with attendant loss in efficiency, blade erosion, and high radiated noise. A nominal increase in cavitation inception speed can be achieved by very careful design using thin blade sections of high-strength material. The problems of design are made more difficult by the adverse effects of strut/foil/pod interaction and the orbital wave velocities near the free surface. This has led to the development of transcavitating, supercavitating and superventilated blade sections. Several families of these propellers have been developed and some designs have been applied. A 3-bladed supercavitating propeller of titanium on *Denison* and 4-bladed supercavitating propellers of titanium on the AGEH-1 have proven successful. Transcavitating propellers have proven successful on *Flagstaff*, and *Shim-it*.

Problems encountered with the gear transmission systems in early hydrofoils led to the interest in and the development of waterjet propulsion systems. Such systems, typically consist of an inlet water duct, a pump, and above-surface waterjet exhaust nozzles. Heavily-loaded gears and long transmission shafts are thus eliminated, and the number of moving parts may be substantially reduced. This simplicity, however, comes at considerable increase in required power, about 20% higher at 50 knots to about 100% higher at takeoff speed. This is demonstrated graphically in Figure 78.

Considering the weight of water within the system, a waterjet system is usually heavier than a comparable gear-driven propeller system. The PGH-1 demonstrated that the simplicity of a waterjet makes for a trouble-free and reliable propulsion system. Waterjet propulsion also results in a significant reduction in radiated noise compared to conventional transcavitating or supercavitating propeller systems. But compared to a well designed subcavitating or superventilated propeller system, it is doubtful that waterjet propulsion would offer any significant reduction in radiated noise.

In order to use the water propeller as a foilborne thrust device, it has been necessary for the gear and hydrofoil designers to develop transmission systems capable of spanning the distance between the prime mover and the propeller. The problem is formidable in that it involves

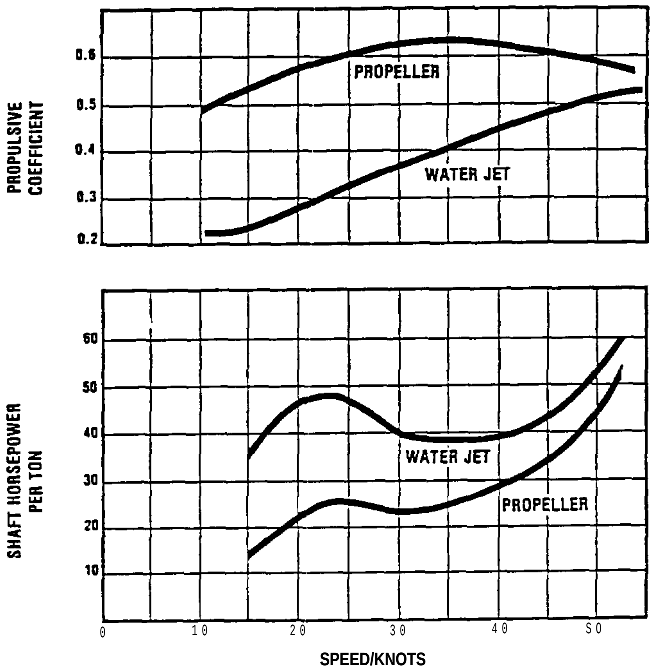


Figure 78. Typical Hydrofoil Performance

transmitting large horsepowers with a six to one reduction of rotational speed from the gas turbine to the propeller, and provision for complete watertight integrity throughout the submerged portion of the system. The problem is further complicated by the desire to provide the capability for retracting the foil system.

Commercial surface-piercing hydrofoils have used angle shaft drives to transmit the power from the prime mover to the propeller. Since their power and rotational speed reduction are relatively low and their foil systems do not retract, the angle shaft is an ideal choice for simplicity and reliability. For high power requirements and retractable systems, the right-angle bevel gear drive represents the best choice at the current stage of development. This type of "zee" drive was employed in the MARAD hydrofoil craft *Denison* and successfully demonstrated the capability of handling 13,000 hp through a single shaft and single-mesh bevel gear. A similar system is employed in High *Point* (PCH), where 3,000 hp is transmitted through a single shaft and a split bevel arrangement in the pods to distribute power to the fore and aft propellers. The AGEH was the highest power application of the zee-drive transmission with more than 15,000 hp being transmitted through two drive shafts down each main strut to single propellers on the aft end of each pod. Right angle bevel gear boxes can be designed to transmit up to 50,000 horsepower, but the size of the gear required for a conservative design is beyond the capability of existing gear cutting machines. With the present gear cutting machines, for conservatively loaded gears, right angle bevel gear boxes capable of transmitting 25,000 to 35.000 horsepower can be considered state of the art. Planetary gear boxes capable of transmitting 50.000 horsepower with an output speed of 1,000 rpm have been land-base tested. At propeller speeds of 500 to 600 rpm which are desired for large hydrofoils, these planetary boxes can transmit 25.000 to 30,000 horsepower.

PRODUCIBILITY AND SUPPORTABILITY

When discussing the limitations of hydrofoils, the issue of cost was raised. The major methods to keep the cost of hydrofoil ships competitive are to (1) apply them for military missions or commercial routes which capitalize on their unique capabilities, (2) assure that specifications properly reflect the requirements for the planned use, and (3) establish well thought out designs in which the need for simplicity, reliability, and minimized production costs is recognized and given appropriate priority throughout the design process. Incorporating the fabrication methods into carefully scheduled and monitored work tasks provides the means to control construction and assembly time and costs. Such an effort was undertaken for the patrol hydrofoil PHM program previously discussed. The following section discusses the results of the studies and actions taken to reduce and control production costs for this program and production techniques employed by Rodriquez in constructing surface-piercing commercial hydrofoil ships.

PHM PRODUCIBILITY AND PRODUCTION

After completing construction of the PHM lead ship. detail planning for the follow-on production program was undertaken. At that time firm planning was for fifteen ships, five for the U.S. Navy and ten for Germany, with a reasonable expectation that additional ships would be procured. The lead ship was constructed using a minimum of tooling, and construction costs had been higher than expected due. at least in part, to welding and distortion problems in manufacturing the hull and foil system.

A producibility study was initiated with the goal to establish an efficient production and management plan and to identify design changes which would facilitate construction and reduce costs.

The production plan resulting from this study involved modular construction of the hull and foil systems utilizing production tooling for assembly of the modules. The modular assembly schedule is depicted in Figures 79 and 80. This approach allows efficient assignment of the work force and improved production learning compared to other construction methods. A revised work breakdown structure was established to collect costs for elements of the assembly sequence rather than ship functional elements in order to enable management to maintain high visibility of cost as the work progressed in each station. The plan also incorporated industrial engineering and manufacturing planning techniques normally applied in the airplane production programs permitting efficient utilization of manufacturing personnel from other programs as the work force expanded. The actual PHM production facility is shown in Figure 81.

Significant redesign was necessary to accommodate the revised production assembly plan as well as to reduce work content in manufacture. In many cases these objec-

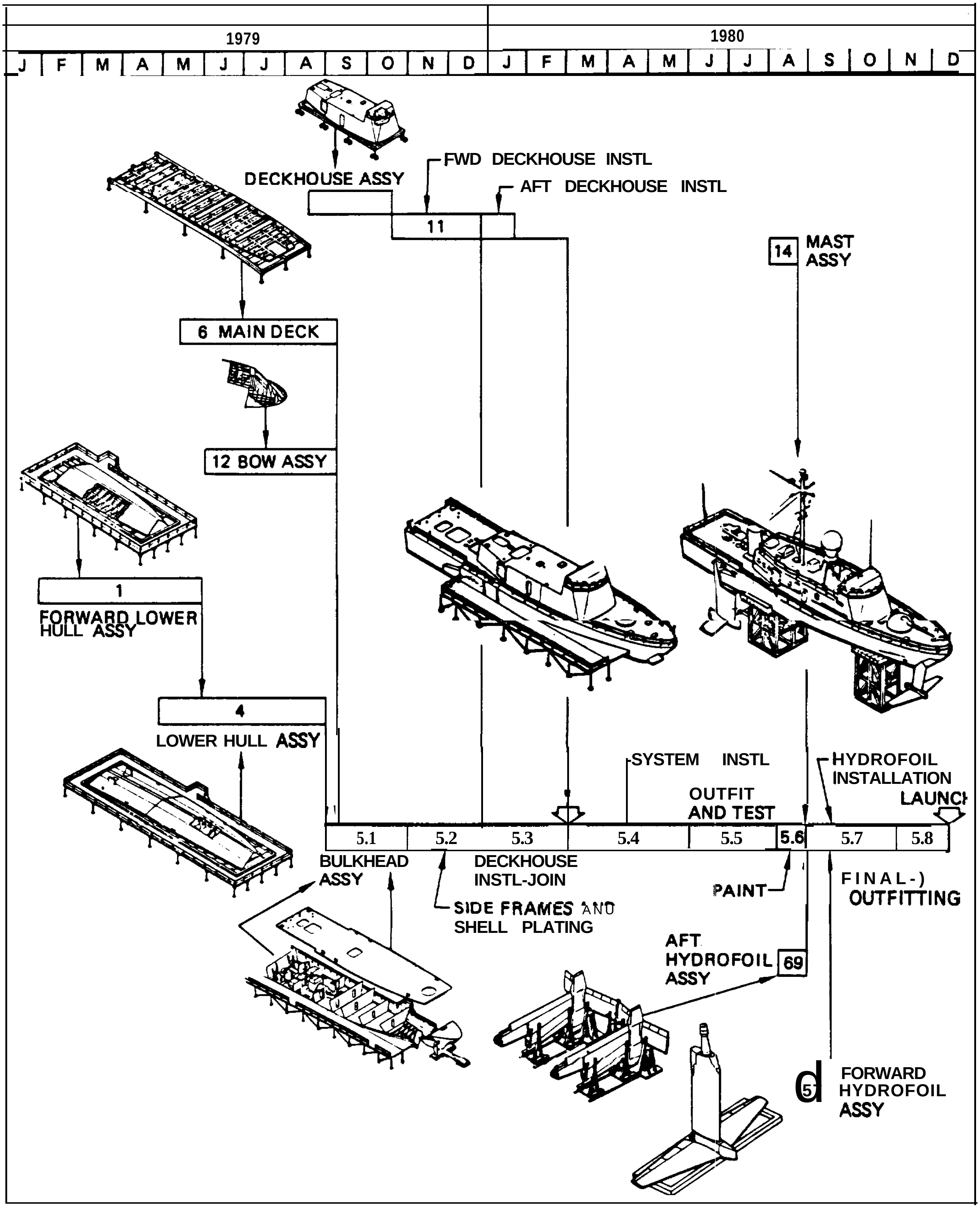


Figure 79. PHM Production Assembly Schedule

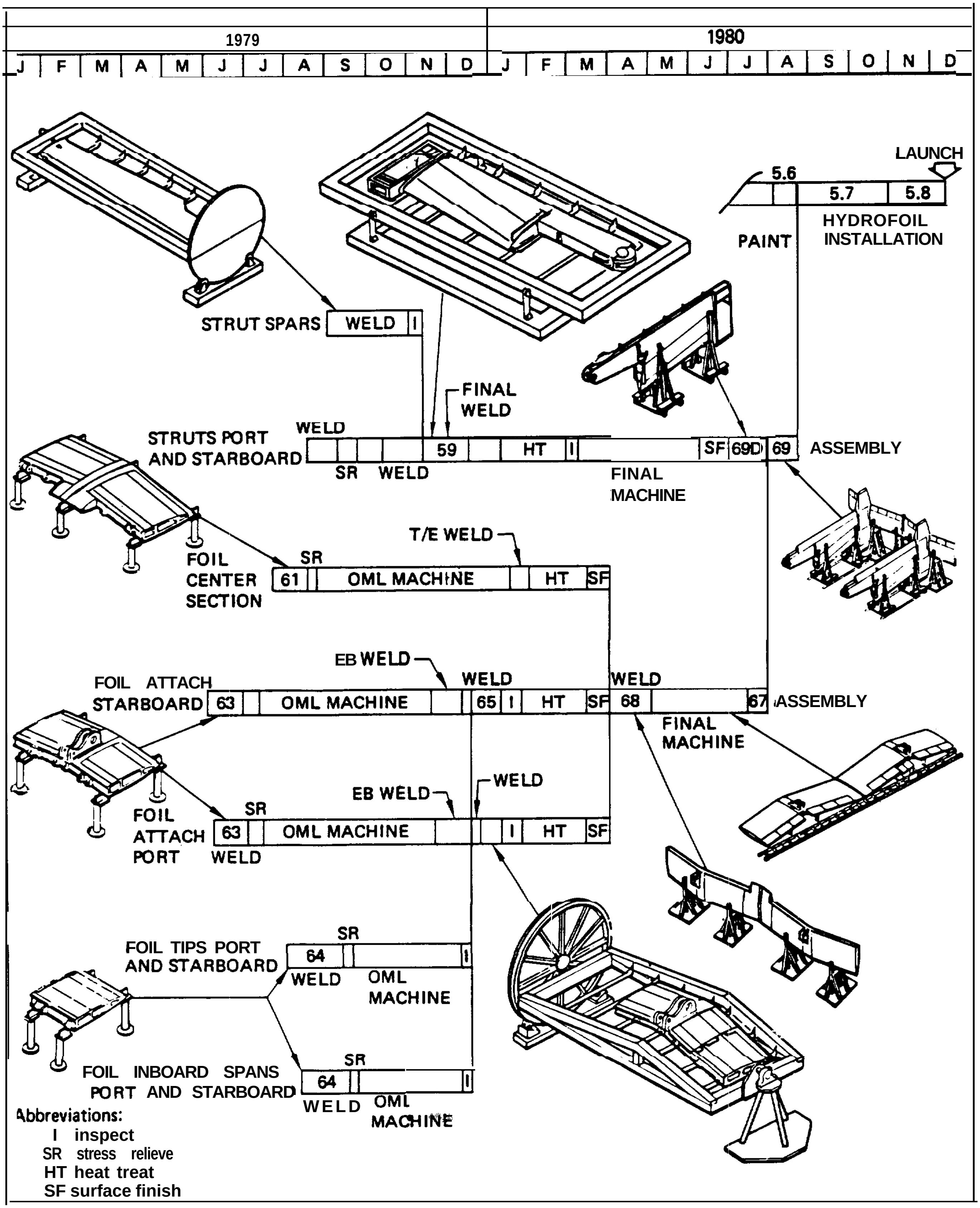


Figure 80. PHM-3 Aft Strut and Foil Production Assembly Schedule

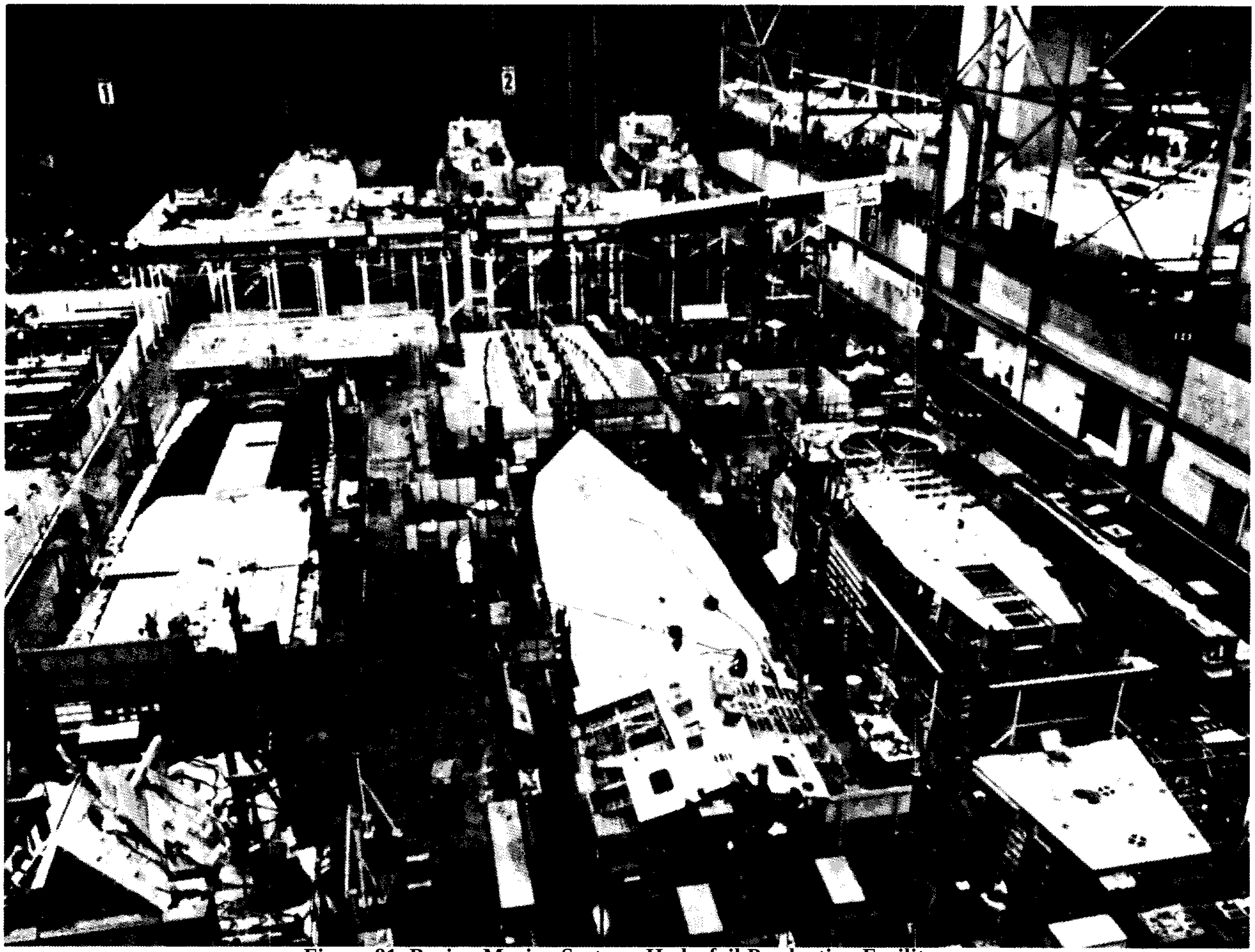


Figure 81. Boeing Marine Systems Hydrofoil Production Facility

tives are complementary. For example, to fabricate the entire main deck as one assembly, a deep-flanged beam was incorporated in the deck assembly at each bulkhead location for the production break. On later assembly, terminating the bulkhead stiffeners on the beam flange eliminated any need for their exact alignment with deck stringers. A brief discussion of other representative design changes to reduce work content and costs is presented in the following paragraphs.

Lead Ship Hull Design

To reduce the amount of welding and the resulting weld distortions, a decision was made at the outset of lead ship design to use wide-ribbed extruded panels wherever practical considerations of fabrication and material usage would permit. These panels were used extensively for decks and side shell and were initially expected to be

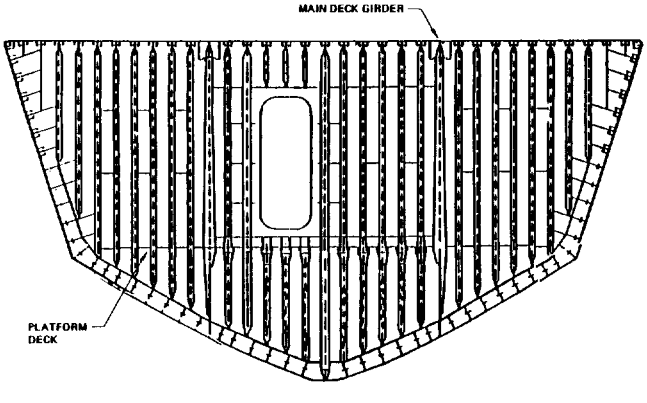


Figure 82. Lead Ship Bulkhead

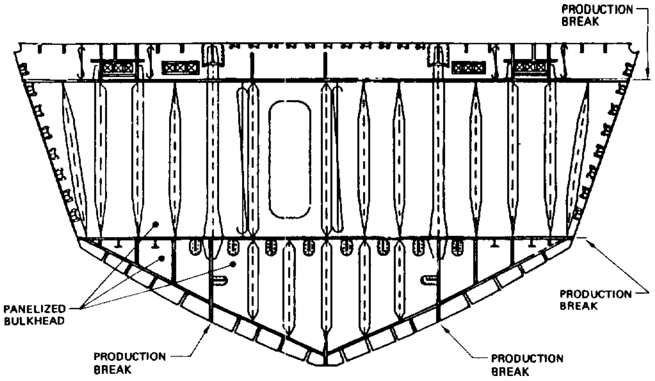


Figure 83. Follow-on Production Series Bulkhead

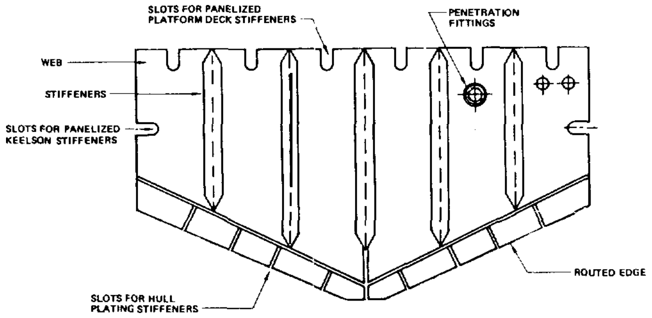


Figure 84. Panelized Bulkhead Segment

used on bulkheads. However, the introduction of large local loads in the bulkheads caused by foilborne wave impacts on the hull bottom made the use of such panels impractical for the bulkheads.

Accordingly, typical bulkhead construction consisted of "tee" extruded stiffeners welded to plate webs. A typical lead ship transverse watertight midships bulkhead. chosen as a representative example of a hull structural element which was later redesigned, is shown in Figure 82.

Local reinforcement of bulkhead webs was provided by insert plates butt welded in the plane of the web. Residual stresses caused by welding resulted in excessive distortions at the corners of these: insert plates.

For structural continuity through the platform deck area, bulkhead and deck stiffeners were intentionally aligned on the lead ship and watertight collars were provided at the intersection of longitudinal deck and side shell stiffeners and at the bulkhead web.

Brackets and chocks, added to achieve stiffener continuity, were difficult and costly to install because of poor weld-accessibility caused by low profile and close stiffener spacing.

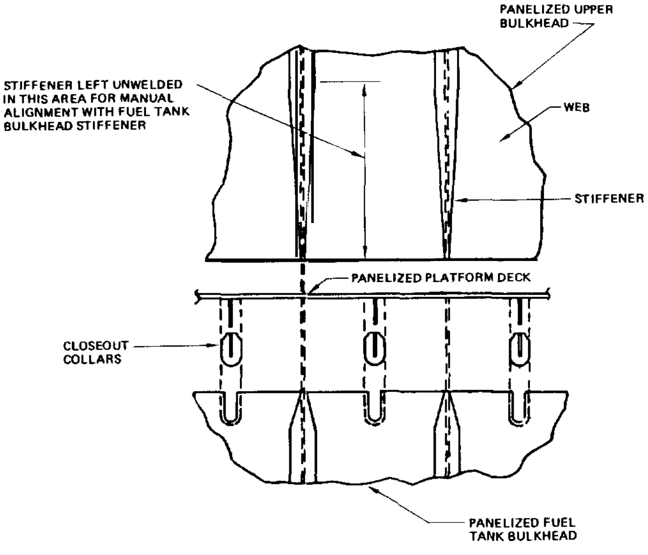


Figure 85. Typical Bulkhead Design Detail

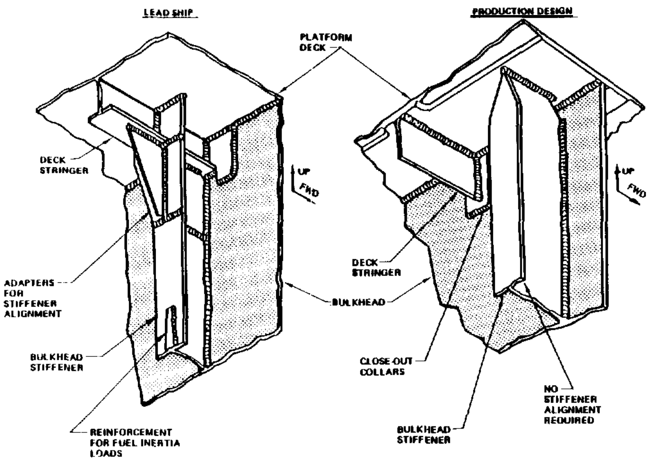


Figure 86. Comparison of Bulkhead Stringer Configuration

Production Hull Design

In the lead ship design, too many parts were used, access to welds was difficult and subsequent fit-up was time-consuming due to weld distortion. The production design resulted from extensive study of lead ship design and construction problems.

Key features of the revised bulkhead design include offset stiffeners, snipped stiffeners, thicker skin gage, panelized bulkhead segments, provisions for penetrations and a design integrated with the manufacturing plan. The resulting follow-on production series bulkhead design is shown in Figure 83.

The termination of bulkhead stiffeners on a beam header at a production break below the main deck simplifies installation and fit-up of the deck module. It also provides for an area in which an orderly arrangement of electrical, hydraulic and piping runs can be made. Production design bulkhead penetrations necessary to accommodate these systems are unencumbered by the presence of bulkhead stiffeners, a more efficient arrangement than on the lead ship. The design provides for a maximum of panelized welding (mechanized welding of stiffeners to the web) of bulkhead segments. One such bulkhead segment is shown in Figure 84.

To ensure good fit-up and minimize the need for trimming on installation, panel segments are trimmed to net size by routing after all welding is complete. An increase in the basic bulkhead web gage permits a reduction in the number of bulkhead stiffeners and thus the amount of welding compared with the lead ship.

Figure 85 is typical of design detail developed to provide simple assembly/subassembly fit-up with a small number of loose parts and maximum access for the welder. Note that the manual alignment of stiffeners above the platform deck is the only fit-up on assembly required with this design. The panelized fuel tank bulkhead segment, which is machine profile routed after subassembly welding. is a part of the welded lower hull module.

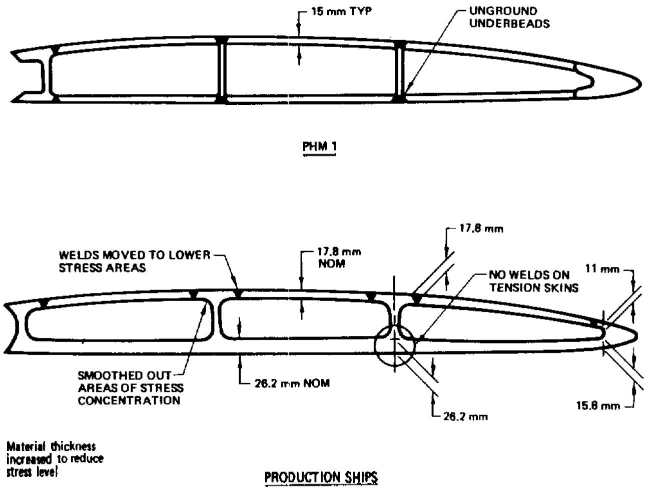


Figure 87. Comparisons in Aft Foil Configuration

Slots are precut in the bulkhead with sufficient clearance to permit easy installation of the platform deck onto the lower hull module. The flat bar longitudinal stiffeners on the platform deck provide for a simple one-piece collar closeout with good welding access. The vertical bulkhead stiffeners are intentionally offset from the platform deck stiffeners in order to accommodate the fit-up detail shown. The bulkhead stiffeners above the platform deck are left unwelded for a short distance on the panelized bulkhead segment to permit manual alignment with stiffeners below the deck prior to final weld closeout. This is in contrast to the fit-on-assembly approach and difficult weld-behind-flanges configuration used on the lead ship. Figure 86 should be examined in order to allow better visualization of the differences in the two bulkhead configurations. The contrast is even more evident when numerical comparisons are made. For this specific example. the bulkhead shown in Figure 83, there are 75 percent fewer individual parts, a reduction of 58 percent of the length of welds, an estimated 71 percent fewer fabrication man-hours and an estimated 68 percent reduction in total cost. All these reductions were gained with a less than five percent increase in weight. Further details of factors involved in the production hull design are contained in Reference [32].

Examining the results of the study for the entire hull shows a 49 percent reduction of individual parts, a 59 percent decrease in total weld length and a 720 percent increase in the use of mechanized welding. The estimated hull weight reduction was about nine percent. Therefore, the additional engineering effort did accomplish its objectives: a simplification in design, a reduction in production cost, and an improved end-product.

Strut and Foil Design

The foils and struts of the PHM for the lead ship were constructed in a fairly conventional manner with machined leading and trailing-edge sections and skin and spans connected by tee welds as shown in the upper part of Figure 87. Difficulty was encountered in maintaining contours and the underbeads of many of the complex tee welds were not accessible for inspection or grinding.

Early in the operational life of the lead ship, cracks appeared in the skins of the foils. Investigation indicated that material fatigue was the primary cause of failure. The lead ship foils and struts had been designed to a strength criteria using available loads data from earlier test programs. A detailed review of previous load data and data from rough-water testing done after the lead ship had been designed was undertaken. This study confirmed that the levels of loads used in the design were generally correct, but the frequency of high loads was much higher than previously anticipated. Therefore, the foils and struts for the production ships were redesigned using fatigue criteria, analytical techniques and design approaches developed for airplane design. The production foil cross-section shown in Figure 87 illustrates the major differences in the resulting design. One may note the leading and trailing edge, tension surface and spars are machined from a solid billet. Stress level is lowered by thicker skin. Radiuses are ample. Upper-surface skins are butt welded in areas of lower stress, and the assembly approach permitted both side inspection and back grinding of almost all welds. The ability to maintain foil and strut contour was much improved. In the redesign, the foil section was also changed from NACA 16-206.5 to NACA 16-306.5, an increase in camber indicated as desirable by operational test data from the lead ship.

In addition to satisfying the requirement for fatigue resistance, the foil and strut redesign incorporated desired producibility improvements such as fewer individual parts, less weld length and increased mechanized welding. The use of electron beam (EB) welding for heavy gage steel structure (foil billets), and plasma arc welding for high rate straight line weld in medium gage structure simplified construction. The result was a less complex but heavier foil system. Most of the weight change can be attributed to the upgrading in the system's fatigue capability.

Taking advantage of the lessons learned from the lead ship construction and operational experience resulted in a considerably more producible and effective ship as confirmed by the operational performance of the PHM squadron.

RODRIQUEZ CANTIERE NAVALE **HULL CONSTRUCTION**

The techniques employed by the Rodriquez Shipyard in Messina, Italy. in the production of their RHS series hydrofoils hulls are outlined in this section. The Rodriquez fabrication method is representative of those utilized by shipyards with production rates of 5 to IO boats per year. Their method is to minimize tooling requirements, except for the interfaces of the foil system, and to maximize the use of templates and station measurements for the assemblies. Prefabrication of major assemblies such as deckhouse and pilothouse are accomplished with the completed elements brought to the erection site for final assembly.

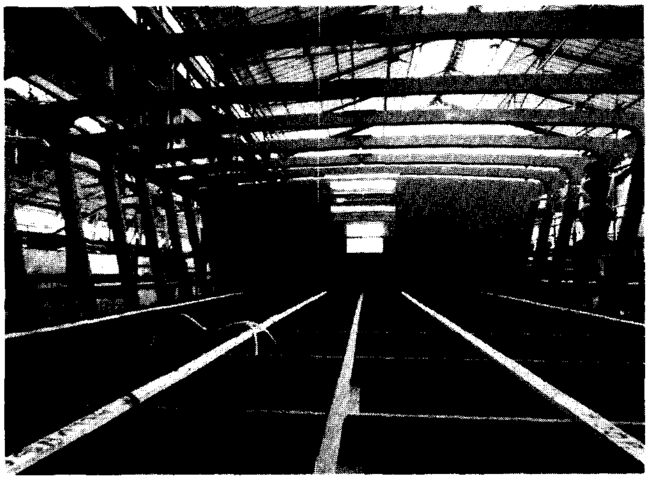


Figure 88. RHS Hydrofoil Hull Framing

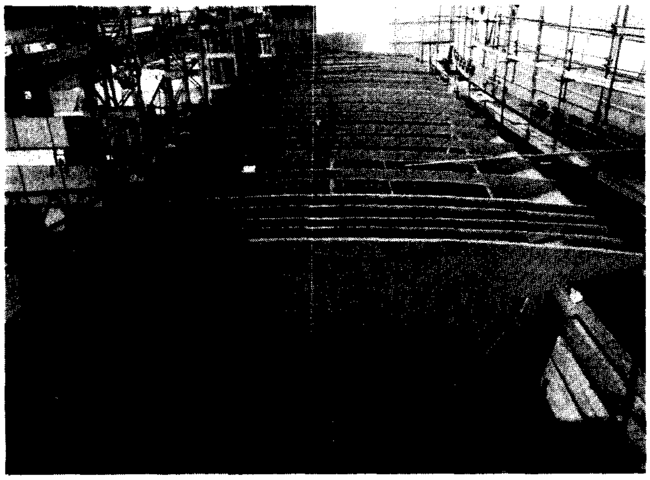


Figure 89. RHS Hull with Completed Framing and Bulkheading

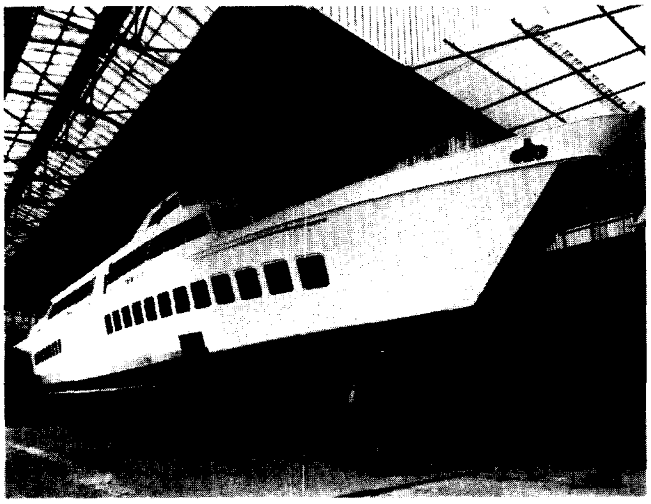


Figure 90. Completed RHS 200 Hull

The hulls are fabricated from aluminum plates with the Italian trade name of Peraluman which has a 4.4% magnesium content. The yield strength is about 25 kg/mm^2. The bars and shapes used in the construction are of an aluminum alloy with the trade name Anticorooal. This alloy has a content of 1% silicon, 0.6% magnesium, and 0.3% manganese. The yield strength is about 30 kg/mm*.

The hulls are longitudinally framed with prefabricated transverse web frames as can be seen in Figure 88. The web frames, keelsons. stringers and special beams are all welded assemblies. These and the watertight bulkheads are set up on station, and the skins and decks are riveted to them. The watertight bulkheads are also riveted structures. They rivet the hull and bulkheads because they know how to do it with good quality, known strength and lack of distortion. A riveted bulkhead can be seen in Figure 89.

The RHS hulls are subdivided into watertight compartments, the number depending upon the size of the hydrofoil. For example, the RHS 160 has five main watertight compartments. The compartments under the stem and stern platform are further subdivided by watertight floors with a double bottom in these areas. The fuel tanks are integral with the hull in double bottom areas.

On the larger designs, the upper deck is continuous from stem to stern while the platform deck is interrupted by the engine room. These decks are also riveted.

Welded steel assemblies are used for the stern, port and aft foil attachments, and the propeller struts. These elements are prefabricated and brought to the final assembly site.

The hull is essentially erected, bottom, side, and deck plated and completely assembled at a single position in the building shed. This can be seen in Figure 90 where the hull on the erection site has been assembled and painted. A considerable portion of the auxiliary systems is installed while the hull is in the building shed. The hull is then moved to a marine railway where the foils. struts and propulsion plant are installed. Final outfitting takes place alongside the pier.

The foils, struts and rudders are constructed from ASERA/52 and type 1 Nicvage steel having a yield stress of 60 kg/mm'. These assemblies are all welded using spars and ribs with a plate skin. The assemblies are stress relieved in their shops before final finishing. The connections of the struts and rudders with the foils are done with flanges and hinges. It is possible to easily dismantle and separate the foils in several pieces.

The Rodriquez Cantiere Navale Shipbuilding techniques have been developed over a period of 30 years of building commercial hydrofoils. More than 12.5 hydrofoils are currently in regular service on routes in 23 countries. Their production methods take into account the experience gained from the operations of their craft under very differing conditions,. These conditions have varied from the cold regions and rough seas of Norway, Sweden, and the English Channel to the hot and humid climates of Hong Kong, Rio de Janeiro and Egypt. Some of these hydrofoils have been in service for nearly 30 years.

SUPPORTABILITY

Hydrofoils are high-performance ships which operate in a different regime than displacement hull vessels. Vessel weight and consequently space are limited to that which can be lifted from the surface of the water and sustained foilborne for any given foil and power plant configuration. Since the payload is relatively limited, planning for underway repairs requiring spare parts and support equipment must be judiciously examined to ensure that optimal use is made of the payload available for these items. The onboard systems design provides essential redundancy so that normally the mission or trip can be successfully completed even though certain equipment failures may have occurred. Repair or replacement of failed equipments is normally planned to be accomplished during inport periods.

Manning is also limited on a hydrofoil, primariiy because of weight, space and mission endurance considerations. Each military crew member must also be supported with food, water, berthing and habitability items. These space and weight requirements then impact the payload available for mission equipment and fuel. Therefore manning is primarily geared to essential operational personnel again tending to drive maintenance toward being accomplished in port. On a commercial vessel each additional crew member detracts from the profitability.

A hydrofoil is more maneuverable and faster than any displacement hull vessel, and its mission response time should also be faster in order to capitalize on these characteristics. A commercial hydrofoil must likewise be responsive to on-time trip departure to maintain its over-the-water speed advantage compared to the displacement hull vessel or other competitive services. Mission/trip completion reliability must also be high for these same reasons. Therefore, in order to optimize availability, maintenance and other support functions are planned to minimize the time down for these essential items. This goal is realized by such design characteristics as built-in test capability, corrective maintenance by module or equipment replacement, quick-disconnect fittings on service connections, system/equipment redundancy and preventive maintenance requirements and cycles geared to being accomplished during short inport periods.

Reliability/Maintainability Program

In order to realize a consistent support concept for all ships systems and equipments for the PHM and Jetfoil programs, Boeing Marine Systems (BMS) established and used a reliability/maintainability program during the ship design phase. Requirements and goals were established for reliability and maintainability (R&M) factors at the ship level, system level, and subsystem/equipment level. As the ship's design progressed, critical systems were analyzed to predict conformance with the allocated reliability and maintainability factors. Reviews were held at key points in the design so that discrepancies between R&M requirements or goals and analyzed predictions could be identified and resolved. During the ship's test phase and during customer operation of the vessel, equipment or system failures and maintenance data were continuously monitored and related to the vessel or system operating hours in order to determine the actual reliability and maintainability factors achieved. In cases of severe discrepancy between predicted and actual R&M factors, appropriate design change actions were initiated. Customer experience data has been retained and used to influence the design of new or variant vessels, [33].

Commitment to a similar reliability and maintainability program has been required of suppliers of installed equipment. Engineering coordination has been conducted between BMS and the equipment suppliers to

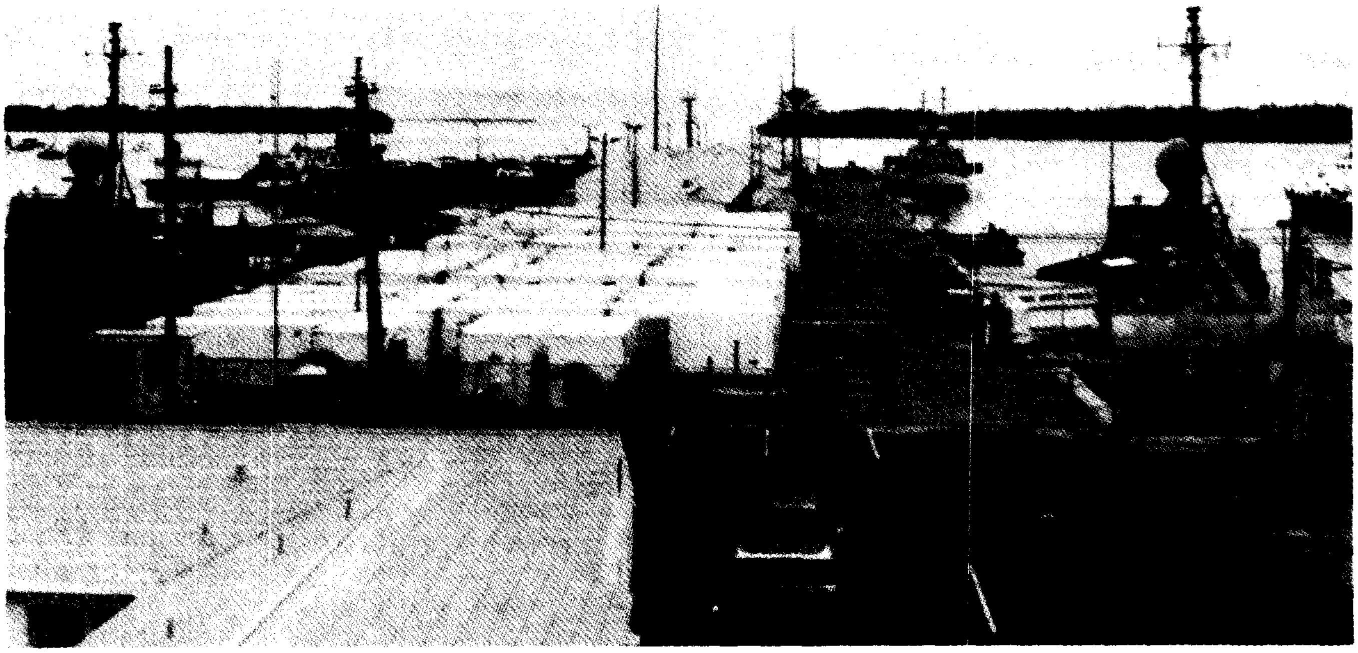
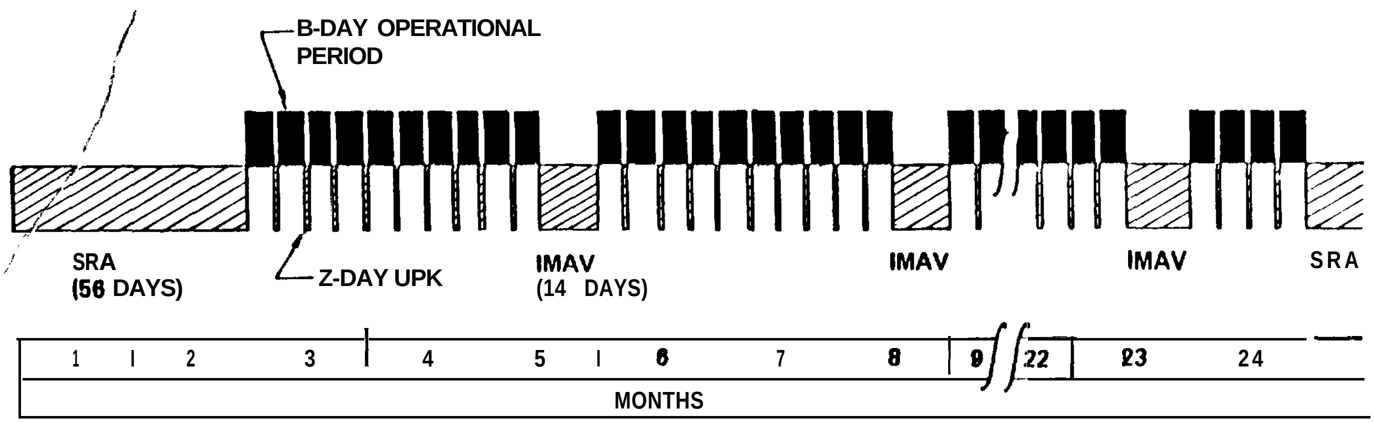


Figure 91. PHM Squadron Two at Key West, Florida



Abbreviations:
SRA selected restricted availability
IMAV intermediate maintenance availability
UPK upkeep period

Figure 92. Planned Biennial Utilization Cycle

optimize preventive maintenance cycles with the planned operational profile. to obtain product support data. and to improve the equipment as required to satisfy R&M requirements.

PHM Support Program

The patrol hydrofoil (PHM) was designed to operate for five days (extendable to seven days in a tactical emergency) without requiring care or preventive maintenance. This was achieved through use of high-reliability components and/or built-in redundancy for certain critical systems/equipment. The ships now routinely operate on longer missions of up to 14 days. There are very few corrective maintenance actions expected or planned to be accomplished while underway. Maintainability has been optimized for these few tasks, so that only built-in test equipment, simple portable test equipment and standard hand tools are required to effect repair. Each PHM is manned by nineteen enlisted men and five officers. The PHMs are based as a squadron at a main base with an intermediate maintenance activity (IMA) at the main base, Figure 91. Up to four PHMs can operate for thirty-day periods from a forward base supported by a mobile detachment of technicians and equipment from the main base.

The patrol hydrofoil maintenance support concept is based on three levels of maintenance: (1) organizational, performed onboard by the ships crew; (2) intermediate, performed onboard the patrol hydrofoil, or a tender, or at a shore station by the IMA; and (3) depot, performed at a shipyard, overhaul depot, or at a contractor's plant. The planned maintenance and repair cycles, Figure 92, are: (1) "Post Operational Inspection and Maintenance Period," an eight hour period after each sortie during which preventive maintenance and minor corrective maintenance is conducted, and "Upkeep Period," a two-day period scheduled fourteen times a year after equivalent operating periods during which preventive maintenance and minor deferred maintenance is accomplished; (2) "Intermediate Maintenance Availability (IMAV)." an upkeep period of approximately two weeks every three months between SRAs (selected restricted availabilities) scheduled at an IMA during which major preventive maintenance, deferred maintenance and certain progressive-overhaul work items are accomplished; (3) "Selected Restricted Availability (SRA)," an eight-week period every two years scheduled at a shipyard, during which preplanned progressive-overhaul work packages are accomplished. The maintenance and repair philosophy includes a class maintenance plan (CMP) to replace and refurbish selected equipments on a periodic basis. Preventive maintenance is incorporated into the maintenance and material managemenl system (3M) and consists of the maintenance planning and procedural instructions of the planned maintenance subsystem (PMS).

PERIOD		VOYAGES SCHEDULED	VOYAGES COMPLETED	PERCENT COMPLETED
JUNE 1982 THRU 06/30/83		309	298	96.4%
07/01/83 THRU 12/31/83		325	325	100.0%
01/01/84 THRU 09/30/84		602	601	99.8%
	TOTAL	1236	1224	99.0%

VOYAGE CANCELLATIONS

SHIP	CANCELLATIONS
PHM-I	7
PHM-2 - -6	5

Figure 93. PHM Squadron Voyage Completion Record

The IMA is housed in 8' x 8' x 20' vans built to ISO standards containing maintenance shops, support equipment, administration, spare parts, food preparation and service, and other necessary services. These ISO vans are configured for rapid mobilization. Four vans (two units containing spare parts and one each mechanical maintenance and electrical/electronic maintenance) are intended to support up to four patrol hydrofoils for up to thirty days as a forward based detachment. When required, a berthing and a sanitation van can also be placed at the forward base.

Concurrent with the PHM program, the Navy implemented the advanced ships information system-technical (ASSIST). This system was developed by Boeing under contract for the U. S Navy hydrofoil advanced development program. The ASSIST program documents operations and maintenance experience to quickly identify problems which require follow-on evaluation or corrective action and to provide experience data useful for guidance on future programs. It was used during the PHM-1 test and evaluation period and has been continued with the follow-on production ships.

Information is collected in three general categories, voyage assessments, failure and maintenance events, and technical problems. Voyage assessment data includes departure and arrival information, underway time by ship modes and sea states, operating times on selected equipments, performance assessments of ship systems' operations, and descriptions of unusual events. Failure and maintenance data includes identification of failed equipment. description of failure and repair action, manhours expended, equipment downtime, and adequacy of support. Problems concerning ship hardware, support equipment, manuals, and operating procedures are documented on a problem report for follow-on investigation, action, or monitoring by the ship's force and/or the involved technical communities.

With the resulting high visibility of problem areas and prompt corrective action, the PHM fleet is rapidly maturing to a reliable fleet asset as shown in Figure 93.

Jetfoil Support *Program*

The Jetfoil was designed to operate in passenger-carrying revenue service with a two-man operating crew plus cabin attendants. The vessel employs redundancy on critical systems to ensure successful, on-time trip completion without requiring underway maintenance. The basic Jetfoil maintenance concept is "on-condition" and is defined as replacement or repair of vessel equipment when

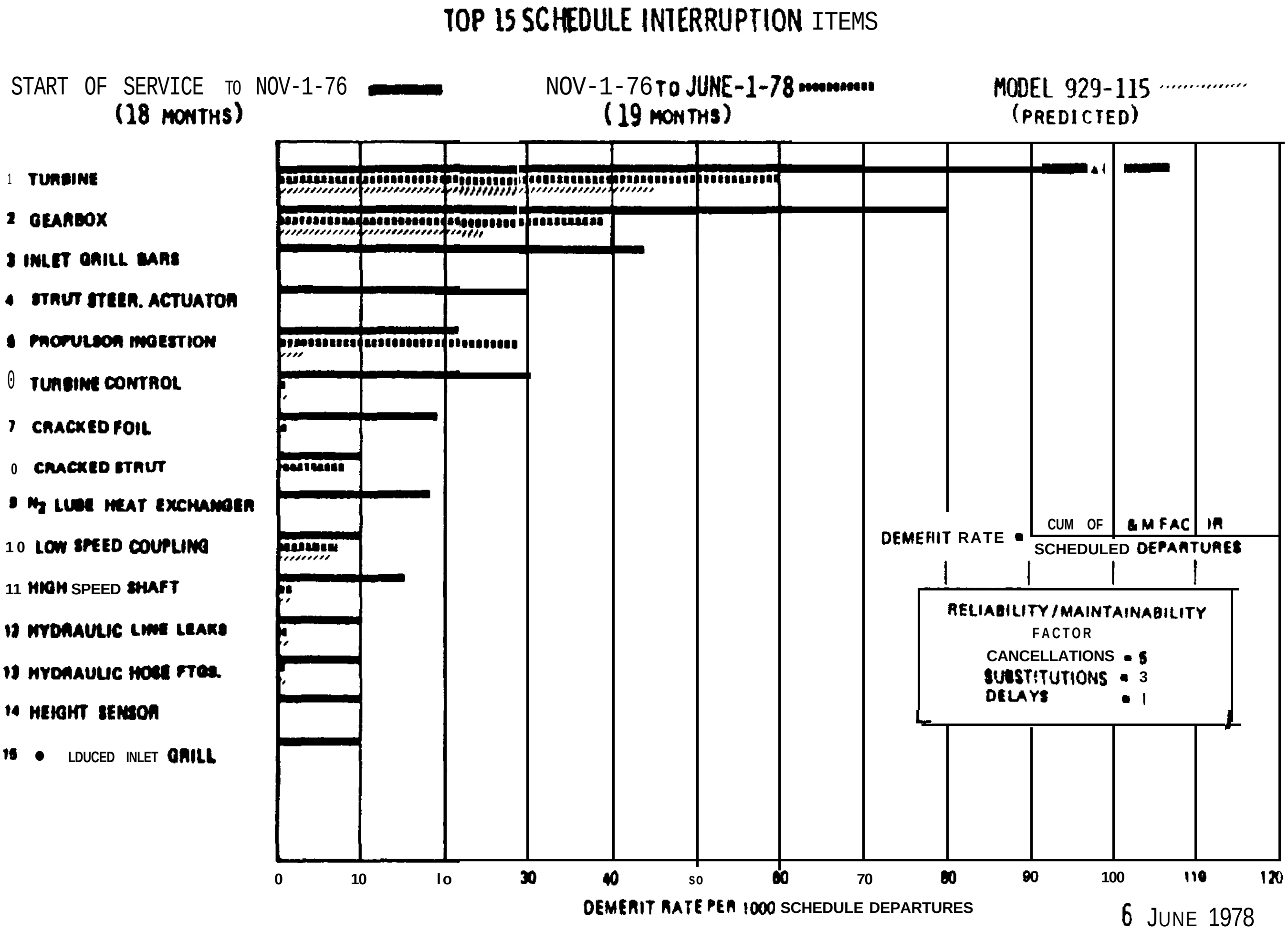


Figure 94. Equipment Reliability/Maintainability-Jetfoil Fleet

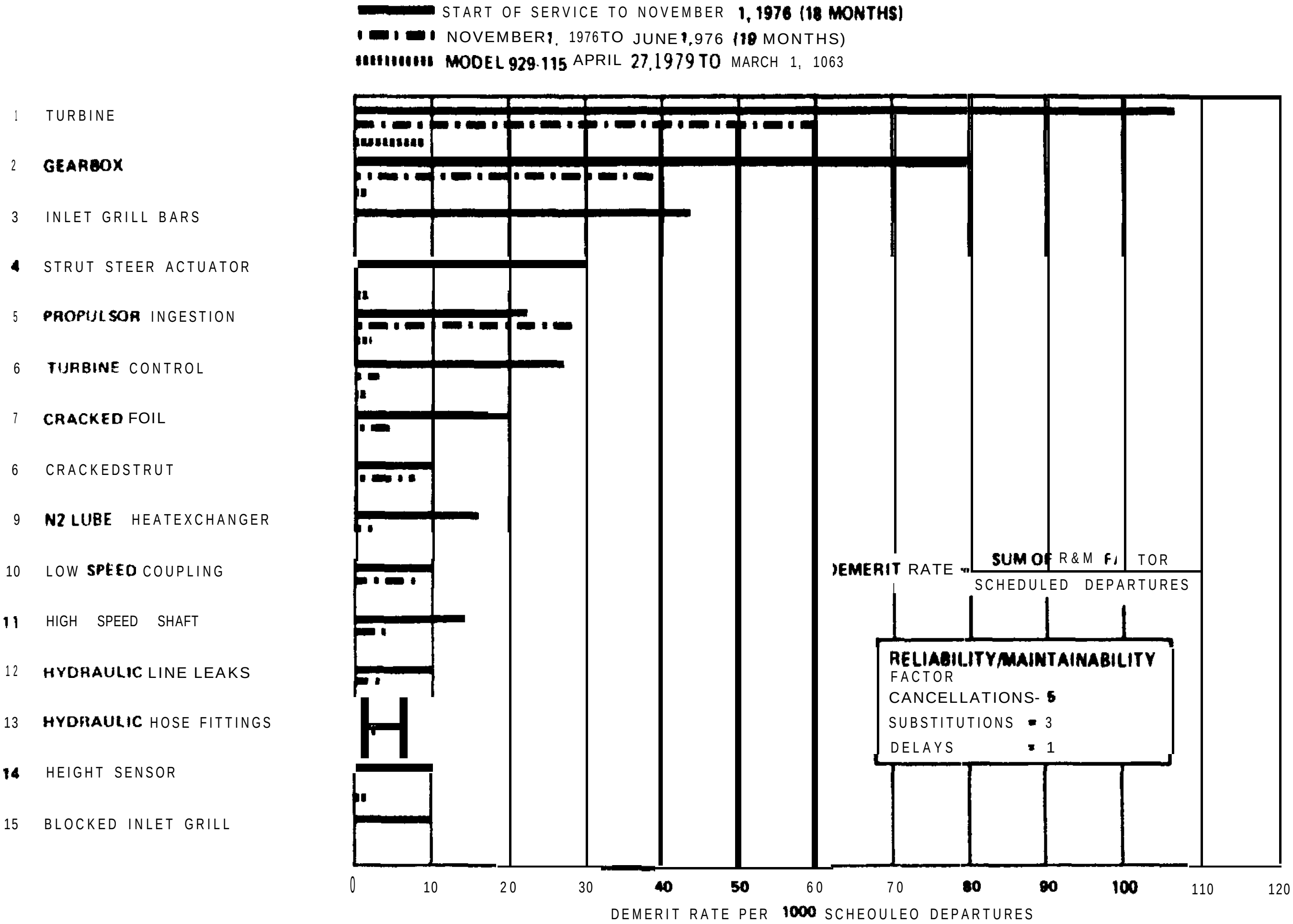


Figure 95. Equipment Reliability/Maintainability-Jetfoil Fleet

failure occurs or when the equipment is worn, operates out of tolerance or shows signs of incipient failure. Only a few items such as automatic control system gyros, fire protection squibs, primary hydraulic pumps, and emergency flares are "time limited" and replaced at scheduled intervals. The vessel is normally operated on a daily schedule with each overnight period available for maintenance, cleaning, and servicing. The only other scheduled downtime is for an annual inspection and haulout which requires approximately two weeks. The Jetfoil operators maintenance team consists of three basic skill levels. These are the skilled mechanics and technicians required for troubleshooting and replacement or repair of engines, hydraulic systems, and electrical/electronic equipment; the semi-skilled personnel for servicing, painting, and maintenance helpers; and the unskilled personnel for general cleanup and janitorial tasks. Corrective maintenance is generally removal and replacement of complete modules which then are either discarded or returned to the vendor for refurbishment. This minimizes the downtime as well as skills and support equipment requirements at the commercial operator's facility. A comprehensive system of maintenance planning and preventive maintenance provides a high degree of in-service reliability and availability. The maintenance task cards (MTCs) cover the daily, weekly, monthly, quarterly, semiannual, annual, and special preventive maintenance tasks. The MTCs are oriented by work area and provide maintenance instructions, list of material, special tools, and test equipment to accomplish each task.

From the beginning of revenue service in 1975, an aggressive product improvement effort has achieved a rapid and consistent reliability growth. Figure 94 shows the top fifteen reliability/maintainability (RIM) problem areas during the first eighteen months of operation, the effect of early improvements and the predicted values for an improved model. The model 929-115 which incorporated performance improvements as well as problem corrections into hull number 11 and on, entered revenue service in 1979. Figure 95 adds the actual 929-115 R/M data in place of the predicted data. Note that the turbine engine, which is still the number one problem, is an order of magnitude smaller, and most of the original fifteen have disappeared.

Figure 96 summarizes the Jetfoil fleet experience to date. The ships operate on a daily basis as intended and provide a dependable high-quality passenger transportation vehicle.

	NUMBER OF BOATS	FLEET DEPARTURE RELIABILITY %	LOAD FACTOR	CUM PASSENGERS	CUM HOURS (UNDERWAY)	CUM PASSENGER MILES
1975	5	81.7	55.4	323,525	1,999	11,646,900
1976	6	88.9	60.6	832,655	14,448	58,839,313
1977	8	92.8	62.8	1,680,524	32,815	129,689,557
1978	10	96.9	66.2	4,469,674	46,230	200,776,111
1979	10	96.7	69.3	7,052,341	62.895	299, 435.447
1980	14	96.6	67.4	10. 232. 228	88,395	436.950.611
1981	17	97.8	66.7	14.083.335	114.272	592.485.189
1982	18	97.9	63.7	20.012.248	153,016	817,631,584
1983	19	98.8	65.0	25,508,315	186,624	1,029,395,407
1984 (ThruOct I	19	99.2	64.5	30,883,318	220.532	1,435,831,380

Figure 96. Jetfoil Fleet Experience

Support Experience

BMS hydrofoil support experience has been accumulated since the design and construction of *High Point* in 1962 to date and has Included customer support for *Tucumcari*, six patrol hydrofoils, twenty-one Jetfoils, and one military variant Jetfoil.

As of the end of August 1984. the PHM fleet had operated about 22,900 underway hours of which 5.000 hours were foilborne. They have operated off the west coast of the United States, through the Panama Canal and in the eastern Pacific to and in the vicinity of the Hawaiian Islands. They are currently operating in the Caribbean and have recently operated for as long as twenty-one days at sea with only fourteen hours in port.

The Jetfoil fleet has accumulated 220,532 underway hours and carried over 30 million passengers while achieving a fleet departure reliability of 99.2%. The High *Time* Jetfoil has accumulated more than 18,000 underway hours, about 85 percent being foilborne. Jetfoils are in revenue service across the English Channel, in the Canary Islands. in Japan. and in Hong Kong. The *Bima Sumadera* I (Jetfoil 0022), while operating in Indonesian waters from 3 November 1982 to 30 December 1982, traveled approximately 10,000 miles and logged 245 hours underway of which 223 hours were foilborne. During this period it set the record for Jetfoil continuous foilborne operations of 11.1 hours at an average speed of 43 knots over a 479 nautical mile course.

During all of this accumulated service experience, Boeing Marine Systems has provided initial on-site support for each vessel and continuing support off-site.

SUMMARY

This chapter includes information demonstrating the maturity of the hydrofoil whether its intended mission is military or commercial. Proven ships are on the market to satisfy a wide range of requirements. The capability to design a new ship to meet new or varied requirements based on proven technology has been discussed. Most importantly, the techniques have been established to produce hydrofoils efficiently and at lower cost. Furthermore, the reliability of hydrofoils has been demonstrated along with the determination of support systems to insure low-cost maintainability

As to the future of hydrofoil development, the basic technology is in hand to produce larger and even more capable vehicles. Promising designs have been carried to the model phase and are awaiting the mission requirements to justify proceeding to fruition. Hydrofoils do and will continue to provide effective transportation and to operate effectively in military missions. The future is now dependent upon the imagination of the planners. The technology is available to meet their visions.

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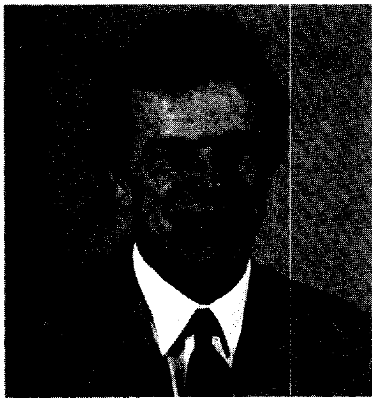
CHAPTER VI

THE SURFACE EFFECT SHIP



THE EDITOR

Edward A. Butler *is a recognized leader in the design and engineering of advanced ship systems. In the past he has applied his marine engineering background to such projects as the Navy's SKMR-I, PCH-I, SES-IOOA and IOOB, and Maritime Administration's* Columbia and Denison. *Most recently he was director of design and systems engineering, and acting project manager for the Navy's 3K SES acquisition program. Mr. Butler is currently the SES program manager in the Ship Design and Engineering Directorate of the Naval Sea Systems Command.*

INTRODUCTION

It has been 25 years since the invention of the surface effect ship (SES) concept and over 5 years since the last comprehensive review of its potential capabilities [1]. To date. over 460 SESs have been developed and are operational throughout the world. The U.S. Navy's interest has been focused upon the technology required to optimize these ships and demonstrating this technology by the development of many testcraft prior to their introduction as mature mission systems in the fleet.

Although the top speed of most operational SESs is below 40 knots, the historical thrust was to develop a 80-100 knot capability. This was initiated in 1969 with the award of construction contracts to Aerojet General for the SES-IOOA and to Bell Aerospace for the SES-100B testcraft. Both of these 100-ton testcraft were extensively operated to successfully validate the architectural and engineering technologies developed in parallel with their design and subsequent modifications. Most noteworthy in performance. the SES-100B established a sustained speed record of 91.9 knots in a slight chop and operated at 35 knots in 6-8 feet waves. The SES-100A was modified in 1978 to become a %-scale version of the then ongoing U.S. Navy 3000-ton, SO-knot prototype (called the 3K SES) contract design and construction program. Unfortunately for the advancement of modern ships, the 3K SES program was terminated on 7 December 1979, just three weeks prior to the initiation of hull construction. This singular termination based mainly on the lack of a military mission for this large prototype caused the total frustration of Admiral Elmo Zumwalt's thrust, as Chief of Naval Operations (1970-1974), for a "100-knot Navy." However, a political decision cannot alter physical laws, and an extensive high performance and SES data base has been developed and continues to be expanded and applied towards more modern surface ships.

Mr. Allen Ford invented the SES, then called a captured air bubble (CAB), in 1960. as a solution to the problem of excessive lift power required to maintain the air gap of a ground effect machine (GEM) when traveling over water. This invention has since been developed to obtain a more efficient open-ocean ship. As compared to an air cushion vehicle (ACV), the SES hull, which pierces the water surface (hence. nonamphibious), has less air leakage, better longitudinal stability, and an acceptable form for utilizing water propulsion systems, which, at speeds to about 120 knots, are more efficient than air propulsion. The shape of the hull with its hydrodynamic stability surfaces can be significantly varied in planform to meet all design requirements, from small, calm-water "air-lubricated" barges to large ocean-capable ships. The practical design speed regime of such ships varies from 15 to + 70 knots.

These, and many other attributes and developments of the SES. are discussed in this chapter by an experienced group of pragmatic individuals who have been collectively committed to this field for over 200 man-years.

First the SES and its nomenclature are described by Mr. Robert Cramb of RMI, Inc., a long-time technologist in the field of SES, ACV and SWATH. This simplistic approach to acquaint you with SESs and their unique physics is referred to throughout this chapter.

The *Special Attributes and Limitations* were contributed by Mr. William White, of the Naval Sea Systems Command, who has been dedicated to this field as designer and manager since 1971. Admiral F.H. (Mike) Michaelis, USN (Ret) wlhose active duty included squadron, wing, and carrier battle group command. Commander Naval Airforce, US Atlantic Fleet and finally, Chief of Naval Material provides the insight and background commensurate with fleet requirements and projected needs in his contribution to the section on *Current and Potential Applications*.

The *State of Technology* is introduced by Dr. Harvey R. Chaplin, the Aviation and Surface Effects Department head at the David Taylor Naval Ship Research and Development Center (DTNSRDC). He has been actively involved in modern ship (GEM, ACV, SES. PARLAC, WIG) R&D since 1957. It was he who brought Mr. Allen Ford to DTNSRDC in 196.5. and it is Mr. Ford who contributed the section on *Resistance and Hull Form.* Other

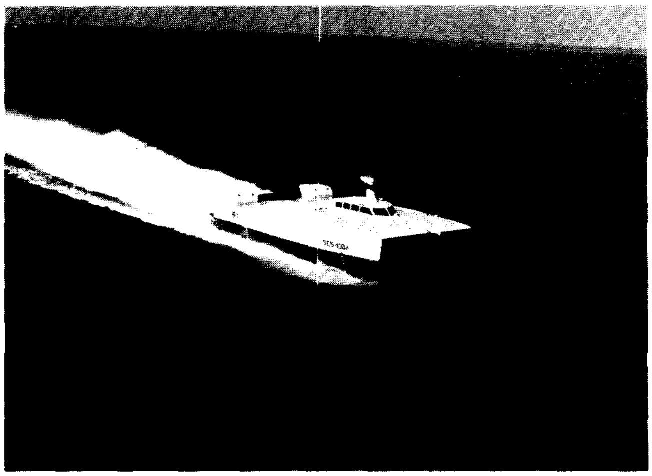
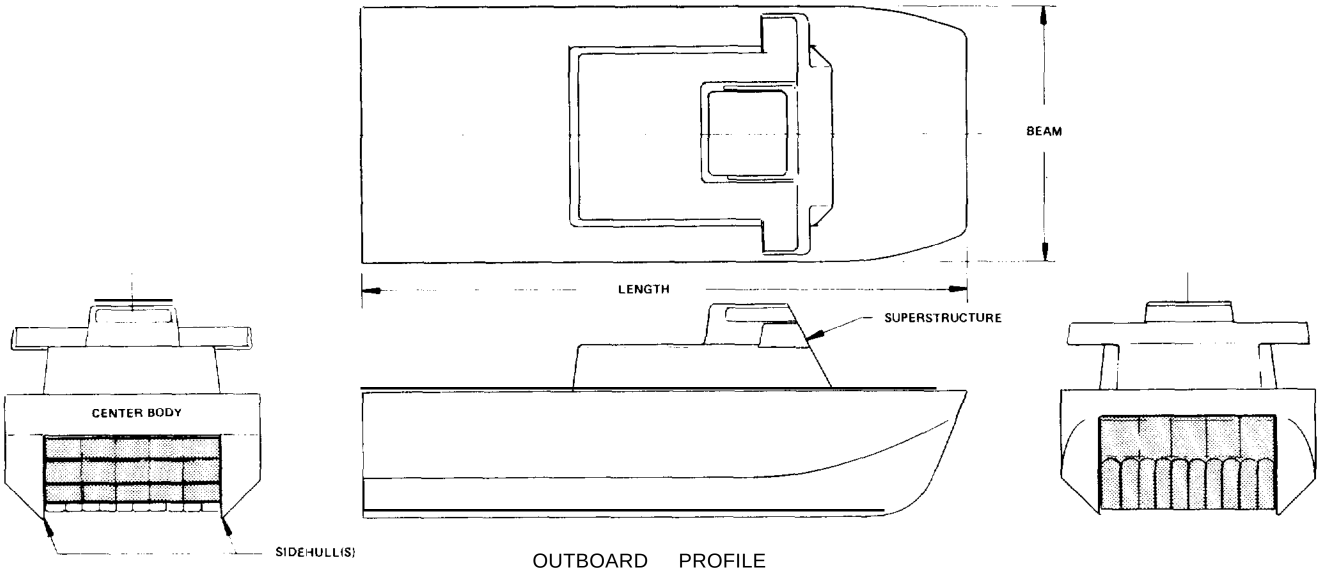


Figure 1. SES-100A

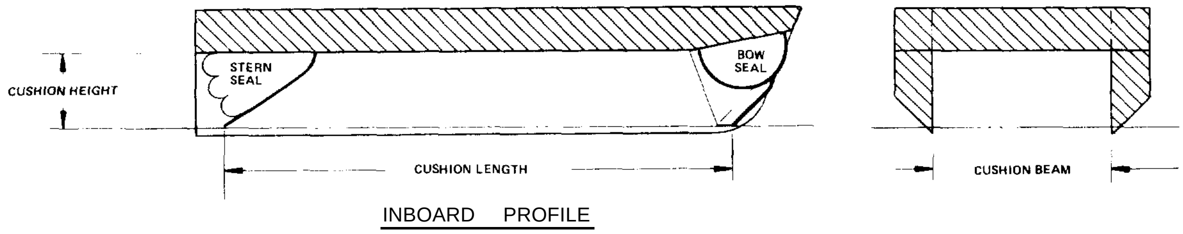
contributors within Mr. Ford's SES Division are Mr. Stephen Chorney on *Stability and Maneuverability* and Mr. William Richardson on *Structures and Materials*. The discussion on *Seakeeping* was prepared by Mr. John Adams of Maritime Dynamics, Inc. who developed the functional and operational ride control system installed on contemporary SESs. Propulsion is covered by Mr. Robert Etter of DTNSRDC, formerly from Hydronautics, Inc., as the hands-on designer and manager of Navy research and development for waterjet inlets, and supercavitating propellers. Dr. Gabriel Boehler, professor of mechanical engineering at the Catholic University of America has also been particularly involved in ACV and SES lift air systems since 1956 and has contributed the discussion of *Lift Systems*. The art of *Seal* technology is ably covered by Mr. Benton H. Schaub, Jr. of DTNSRDC whose recent work includes the design, test, fabrication and installation of several developmental seal systems.

The section on *Producibility* is introduced by Mr. John J. Kelly, president of Bell Aerospace Textron, whose company has manufactured the majority of U.S. SESs and ACVs. This leads into an enlightening discussion on the *Production Aspects of SES* by E. (Ted) G. Tattersall. BSC, DLC (Hons), CEng, FRINA and technical director of Vosper Hovermarine Limited who developed the first British SES.

The Appendix, entitled *Wing-In-Ground-Effect Vehicles* was contributed by Capt. James W. Kehoe, U.S.N. (Ret.) and Kenneth S. Brower who are partners in Spectrum Associates, Incorporated of Arlington, Virginia. They were assisted by Robert A. Wilson and Harry A. Berman of DTNSRDC. Both Capt. Kehoe and Mr.



OUTBOARD PROFILE



INBOARD PROFILE

Figure 2. A Generic Surface Effect Ship (SES)

Brower are well known for their work on foreign warship design practices. The Appendix briefly describes the configuration of the vehicle, the basic technology involved, its attributes and limitations, its performance characteristics, and its potential military applications.

DESCRIPTION OF CONCEPT

SESs share many of the same components and nomenclature with monohulls, but, because they are physically different, there are new shapes and terms to become familiar with in order to describe, design and operate these ships. Most obvious is the external shape. As illustrated by the 100-ton, 70-knot. SES-100A testcraft (Figure 1) an SES does not have a sharply pointed slender bow and a deep draft commensurate with its size. Instead, it is supported on an air cushion which reduces draft, lowers overall resistance and ship motions, and increases performance. It has a catamaran-type hull form which contains the air cushion with flexible structures called seals at the forward and aft ends. A pressurized air supply is provided to the cushion by a lift system.

A generic SES is illustrated in Figure 2. The major distinct features include the air cushion, sidehulls, bow and stern seals, centerbody, superstructure, propulsion system, and lift system.

AIR CUSHION

The air cushion is the major influence on the size and proportions of an SES. The cushion area depends on the weight to be supported and the nominal design pressure of the lift system. As will be explained, the proportion of the cushion length-to-beam (l/b) ratio depends upon the required speed and performance characteristics. The beam may also be constrained by operational factors such as the width of the Panama Canal or the size of a host ship's well deck.

The cushion height is established by a trade-off between the desire to have it exceed the majority of waves encountered in the proposed operating environment and transverse stability considerations.

SIDEHULLS

Figure 3 gives a fisheye view of the sidehull and seal elements for our generic SES. The sidehulls extend the full length of the craft, and the seals are straight-across, "two-dimensional" closures at each end of the cushion cavity. Partial-length (e.g., ⅔-¾ length) sidehulls with a "wrap-around" bow seal have also been successfully employed on the SES-100B (Figure 4). The sidehull configuration is developed to provide the particular on- and off-cushion characteristics desired. The lower portion of the hull has a fine cross-section to minimize drag when on cushion. The upper portion of the hull is as wide as practicable to facilitate installation of machinery and to provide sufficient buoyancy in the off-cushion mode of operation to maintain the wet deck at the desired height above the water. Stout bow stems and sidehull keels are generally provided to assist in beaching and docking. The lower hull deadrise angles, on the order of 30 to 45 degrees, have been found generally to minimize drag while providing required roll and yaw stability. Hulls are shaped for minimum aero-hydrodynamic drag and producibility. Hard chines and spray rails are included in most designs to minimize wave and spray sheet wetting. Rub rails are often incorporated at the outer hull chines to minimize hull damage.

The configuration of the after sidehull depends upon the type of propulsor installed (i.e., water propellers or waterjet pumps) and top speed requirements. Figure 3 shows typical waterjet and water propeller installations. For the waterjet pump, an inlet is provided at the base of the hull. The inlets are carefully shaped to minimize cavitation and loss of energy. Pump nozzles are installed in the transom. For high-speed applications, hull cutouts may be included aft of the waterjet inlet to reduce hull wetted area. For a propeller installation, the hull is shaped to optimize flow into the propeller. The propellers are installed as low and as far aft as possible to maximize

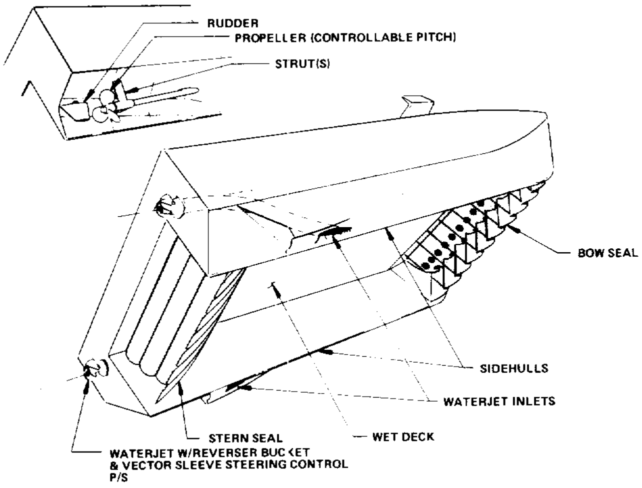


Figure 3. Sidehull and Seal Elements

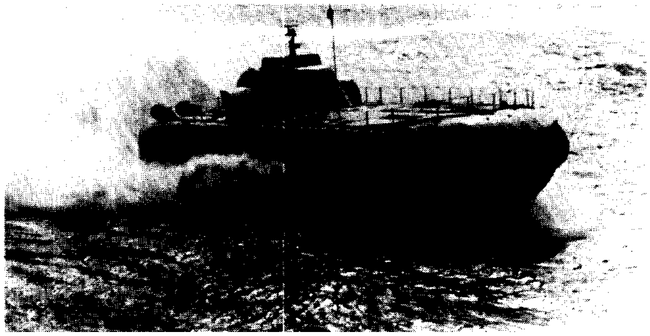


Figure 4. SES-100B

immersion. High speed SESs often have transom sterns while low speed SESs have tapered or rounded sterns to eliminate flow separation and reduce drag.

SEALS

The purpose of the bow and stern seals is to contain the cushion between the sidehulls while providing low drag and positive contributions to craft stability. Seals are generally flexible. inflated structures made of elastomeric-coated fabric. For high speed operation, other material such as wood, fiberglass and metal have been used at the water interface. To improve operational flexibility, seals may be provided with retraction mechanisms.

CENTERBODY

The principal structural element spanning the sidehulls and including the ship's wet deck and weather deck(s) is the centerbody. In designing a centerbody, attention is given to sizing for transverse structural loads and bow slamming loads, as well as overall longitudinal bending loads. Because of its rectangular planform, the centerbody is configured as an efficient box structure of longitudinal and transverse bulkheads. The subdivision of these bulkheads depends upon weight, producibility, damage control, and equipment installation considerations.

SUPERSTRUCTURE

Superstructures are generally configured with some consideration for minimizing aerodynamic drag and protection of the crew during high speed operations without undue construction cost penalties. Otherwise, established naval architectural practice is utilized to configure operating bridges and other topside arrangements.

PROPULSION SYSTEM

Both water propeller and waterjet pump propulsion systems have been used successfully. Prime movers have included gas turbines for very high power requirements at light weight. Diesels have also been used for more modest power and speed requirements. Gas turbine engines require sophisticated reduction gearboxes whereas diesel engines have used simpler gearboxes.

The current trend is to install a propulsion system in each sidehull for simplicity while providing excellent handling and maneuvering characteristics. Waterjet propulsion systems may use sleeves to vector the waterjet, reverser buckets to change the direction of the flow of the jet, and/or thrust modulation for maneuver control. Propeller-driven ships may employ rudders and either controllable-pitch propellers or reversing gearboxes for their maneuverability.

LIFT SYSTEM

The lift system consists of a prime mover, fans, air distribution ducts, and a ride control unit. The prime movers may be gas turbines for very-high-power, lightweight installations, or more generally, diesel engines for fuel efficiency. Again, reduction gearboxes are required with gas turbines; for diesel engines direct drive is often possible depending upon the particular engine selection.

The lift system can be characterized as a low-pressure, high-flow system with the air entering the cushion from the fans and exiting from the cushion through the nominal flow gap under the stern seal and through leakage around the bow seal and sidehulls. Centrifugal, axial, and mixed flow fans have been used in various installations. Generally, the air flow is distributed to the bow and stern seals and the cushion. This has been accomplished by dispersal of the fans and prime movers and/or by the use of distribution ducts within the craft.

Subsequent sections within the discussion on the *State of Technology* cover, in more depth, the unique aspects of the design and hardware that have been developed and are available for SES and other modern ship designs.

ATTRIBUTES AND LIMITATIONS

ATTRIBUTES

Design Flexibility

It is the breadth of the SES design spectrum that is the major attribute of these ships. For example, they can be designed to operate at any speed up to about 100 kts. Their geometry can be tailored as a function of mission requirements from low l/b ratios of about 2 up to high l/b ratios of about 10. Potentially they can be built to any size, as the design problems tend to get easier as the ships get larger. The current design approach towards full displacement sidehulls (more than 100% of the hullborne buoyancy is supported by the sidehulls) yields many benefits with almost imperceptible on-cushion performance penalties. These benefits are discussed in some detail since they have dramatically broadened the overall utility and efficiency of SES and made the concept attractive for almost all naval surface combatants and many commercial applications.

First, the full displacement sidehulls allow SES to operate efficiently as a catamaran at low speeds when off cushion. This dual mode. hullborne at low speeds and cushionborne at low and high speeds, allows efficient operation when loitering in congested areas where precise low speed maneuvering or patrolling is required. It must be emphasized that full hullborne and full cushionborne operation represent 'only the extremes of operation. Typically, the amount of lift is varied incrementally as desired from 0 to 100% to optimize the performance for each unique operating condition. These intermediate lift settings are known as "partial cushion" operations. It usually only takes a few seconds to shift from hullborne to cushionborne operation simply by increasing the lift air supply rate.

Secondly, when the bow and stern seals are deployed in the hullborne or partial cushion mode, the plenum under the hull serves as a passive motion-damping accumulator that significantly reduces motions in large seas. This effect is so dramatic that the USCG uses this drifting technique to maintain patrol station for extended periods [2].

As a third benefit, SES structural loads are a strong function of centerbody-to-water clearance. When on cushion, the wetdeck is sufficiently high to greatly reduce the structural bending moments and permit high-speed operations in high seas without slamming. The thin sidehull SESs have zero wetdeck clearance in the hullborne mode which results in large structural loads at any significant speed in high seas. Adopting the full displacement sidehulls increases the centerbody clearance in the hullborne mode and reduces the structural loads by as much as a factor of 3. This allows a reduction in the weight of the hull structure which results in a more efficient ship.

Fourth, since the full displacement sidehulls only need to be optimized for low-speed hullborne resistance, they can be more efficient than most traditional monohulls whose shape must be compromised to be effective at both low and moderate speeds. This usually means that the SES hulls can have fine sterns without transoms which are reminiscent of early steamships at the turn of the century. This low-speed hull shape may fully compensate for the added wetted surface and hull interference effects of the catamaran form.

Finally, the full displacement sidehulls have enough internal volume and deck area to become a useful part of the ship. Typically. the lowest part of the sidehull is reserved for tankage. The rest of the sidehulls are used for machinery, auxiliary systems, and storerooms. Installing the main propulsion engines in the sidehulls has allowed recent SESs to utilize conventional monohull propulsion systems instead of expensive customized systems often found in earlier designs.

Volume Efficiency

Most designs generally have higher volumetric efficiencies than monohulls or other advanced ships. This is due to the rectangular shape of the centerbody which has a block coefficient approaching 1 compared to 0.7 for a monohull combatant. As a result for a given payload, the SES will require typically 5 to 10-percent less enclosed volume to carry that payload. For a wide range of payloads above 500 lt the SES has about a 30-percent higher volumetric efficiency. Thus, with equal performance (speed and range), full load displacement is about 70% of a destroyer-size monohull. The magnitude of this advantage can change as a function of other requirements such as speed, range, seakeeping and design standards. Deck areas also follow the same trends as illustrated for volumes. In addition, SESs, with their relatively wide overall beam which is carried the full length of the ship, are highly suited to the arrangement of military payloads and sensors. This is especially true for the handling and deploying of aircraft and modular weapons.

Draft

SESs have shallow draft when they are operating on cushion due to the large low pressure cushion area. Appendages such as rudders may increase the navigational draft. Typically the forward draft is shallow enough to allow beaching, and this inherent capability has been demonstrated and is an ‘operational option. Further, the low draft allows SESs to enter harbors and dock at piers too shallow for monohulls with the same payload. The shallow on-cushion draft is also typically less than the running depth of torpedoes making these ships virtually immune to contact torpedo explosions. The small percentage of the hull in the water significantly reduces the effects of an underwater explosion as recently demonstrated by a series of full-scale underwater shock tests conducted by Bell Aerospace-Textron on one of their commercial 110-ft SESs. The results of those tests are illustrated in Figures 5 and 6, courtesy of Bell. The hull experienced 60 to 80% less shock than a monohull. This great shock attenuation, due to the small amount of the

Figure 5. BH-110 Underwater Shock Test.

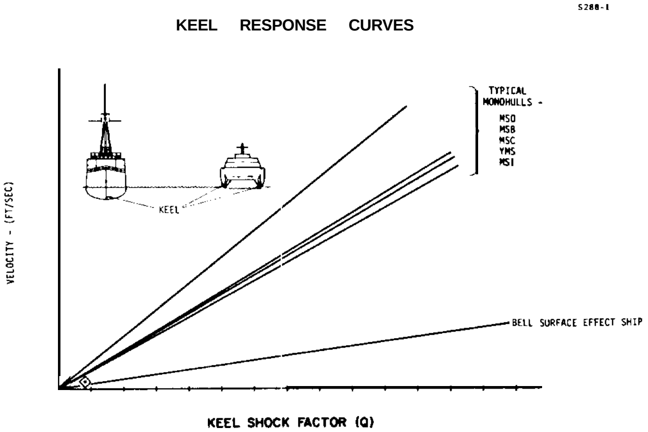


Figure 6. BH-110 Keel Shock Response.

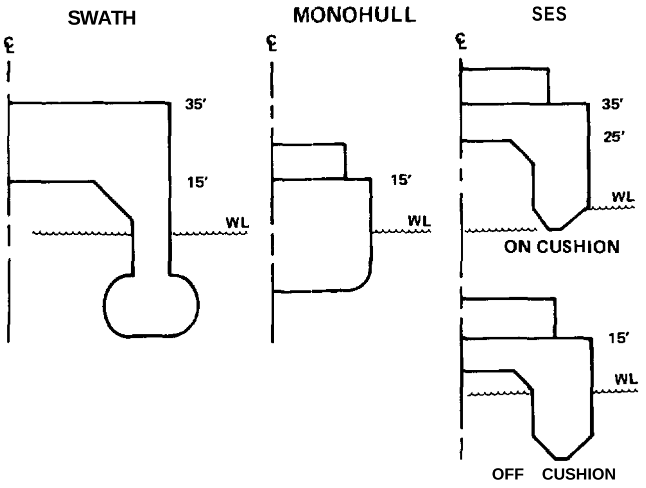


Figure 7. Large Escort-Freeboard and Cross Structure Clearance.

ship in contact with the water and its shallow draft, means that the design strength built into an SES for traditional seakeeping loads is more than adequate to handle these shock loads. Thus an SES minesweeper might have only half the structural weight of a conventional monohull with identical sweep capabilities.

Maneuverability

The widely spaced sidehulls which normally contain both the propellers and rudders provide the potential of very good maneuverability at all speeds. Low-speed maneuverability is so good that SESs can turn in their own length and seldom require bow thrusters, or outside assistance in docking.

Freeboard

SESs, when operating in the hullborne mode, tend to have approximately the same freeboard as similar sized monohulls as illustrated in Figure 7. However, when the SES pops on cushion, its freeboard increases dramatically-in many cases by a factor of 2. This high-on-cushion freeboard provides safe dry decks in high sea states. As an example, an SES frigate typically would have an on-cushion freeboard of 35 feet compared to about 15 feet for the equivalent monohull. This freeboard is continuously adjustable anywhere between on and off cushion heights through control of the lift system. The USCG has found this capability to control freeboard extremely beneficial in the boarding of other ships and craft. It is also handy at dockside when loading and unloading during different stages of the tide.

Intact and Damaged Stability

As discussed in a later section, on-cushion stability is the most critical stability parameter for SESs, and much research and development has gone into establishing procedures to ensure that adequate reserve on-cushion dynamic stability is maintained at all times.

Regardless of configuration, when hullborne, SESs have the same high initial stability associated with catamarans. They also possess high tons-per-inch immersion and moment-to-trim characteristics similar to monohulls. As a result, SESs are very stable ships that do not require fuel compensating systems or dead weight ballast. These intact stability characteristics carry over into the damaged condition as well. Typically SESs do not have to counterflood to maintain acceptable trim and roll angles after damage as would be the case for an equivalent monohull. Most SESs are constructed with double bottoms or tank tops to prevent vertical propagation of flooding from grounding or underwater sidehull damage. The longitudinal and transverse compartmentation required for structural efficiency usually allows them to sustain damage in excess of monohulls and remain operational if key subsystems are operable. This is often the case since most systems are duplicated in each port and starboard sidehull. The probability of damaging both simultaneously is small due: to the wide beam separation between the hulls.

In this same sense, most SESs have sufficient lift system capacity to remain on cushion after substantial damage to seals or sidehulls. The BH -110 has operated at 20 knots after sustaining damage to almost its entire stern seal, and, in another incident, after losing about 20% of its bow seal.

Speed Powering

In the hullborne mode, SESs have larger wetted surface than monohulls of equal displacement. However, since SESs have less displacement than equivalent payload-carrying monohulls, this reduces the wetted surface sufficiently so that even in the hullborne mode they have about the same resistance. When on cushion the wetted surface of an SES is drastically reduced which permits high speed operations with reasonable power. The crossover speed point between rnonohulls and SESs in terms of which has the lowest total powering requirements, is a function of ship size.

Typically, a destroyer with a 1000-ton payload and a 6000-mile range would require 1600 tons of fuel as a monohull and 1150 tons when configured as an SES. This represents a 40-percent savings in fuel when operating at today's peacetime monohull fleet speeds. The fuel savings become even more dramatic as speed increases.

Seakeeping

When operating on cushion, the lift system with active ride control provides a very good ride when compared to a monohull of equivalent size. Typically, as verified by model test and full scale trials, SESs do not experience hull slamming until the significant wave height exceeds the wetdeck height. As a result, a frigate-size SES with a 25-foot wetdeck height could operate at full power without slamming in sea state 6. The only speed reduction would be that due to the wind and waves, and, when at the lower speeds more typical of monohulls, an SES can operate in sea states up to about twice the height of the cushion which in this example would be full sea state 7. The physical reason for this capability is that, unlike a monohull, SWATH or hydrofoil which rides about a mean draft at about the middle depth of the hull, strut, or foils, an SES operates with the mean waterline close to the keel. This provides significantly more freeboard and clearance than an equivalent-size monohull displacement-ship. In addition, the SES pneumatic ride control system operates effectively at all speeds and headings in either a platforming or contouring mode. This is especially important for slow-speed operations where synchronous motions can cause discomfort in other types of ships that rely on fin stabilizers which are less effective at low speeds.

This seakeeping, when combined with the low pitch, roll, and heave motions of an SES (which are typically 2 to 3 times less than an equivalent monohull), make SESs attractive candidates for missions that require operation in areas where sea states 5 and 6 occur a significant percentage of the time.

Radar Cross Section

The rectangular shape and lack of compound curves makes SESs especially suitable for reducing the overall radar cross section. Illustrative of this is the SES-200 which is practically slab-sided. Figure 8 illustrates the reduction in radar cross section at off angles. This represents a truly dramatic reduction of about 98% over 85% of the azimuths.

Synergism

This term summarizes quite accurately what makes an SES so attractive. Most of the key attributes complement each other. For example, the highly efficient box-shaped centerbody permits smaller enclosed volumes with significant reduction in radar cross section for equal payloads. High wetdeck height reduces structural loads which permits lighter structure for equal reliability. Less structure and more efficient volume require less supportive distribution systems and lower installed power for a given speed and payload. Less power means less fuel which also means less ship to carry it.

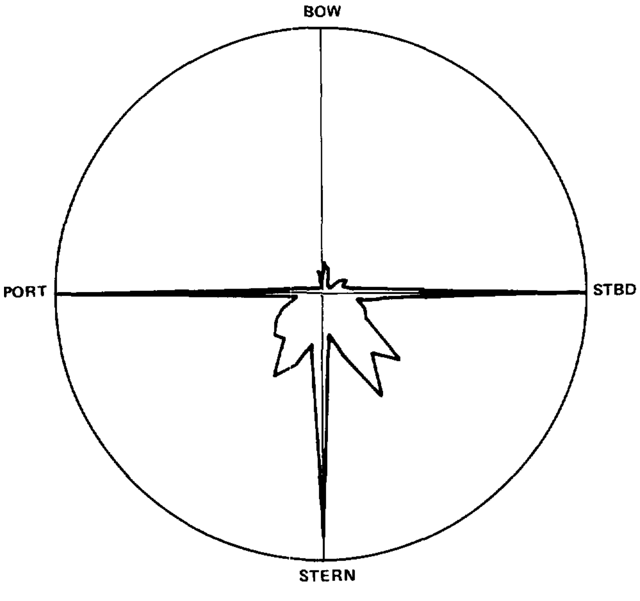


Figure 8. SES-200 Radar Cross Section.

The regulated air cushion height also permits high speed operation in high sea states without requiring increases in ship size just for seakeeping. In addition, the air cushion dramatically reduces the high speed resistance due to wetted surface and wavemaking, further minimizing total power requirements.

The cushion beam complements the ships survivability, arrangability, and stability. The resulting shallow draft reduces the effects of underwater explosions which further reduces the structural weight and overall ship size. The widely separated sidehulls and propulsors provide excellent high and low speed maneuverability with smaller rudders. The cumulative synergistic attribute is that for most military payloads and missions SESs are from 30 to 100 percent smaller and more efficient than alternative equivalent payload carrying hull forms. This, based upon experience to date, translates directly into lower acquisition and life cycle costs for many applications.

LIMITATIONS

Weight

When on cushion, these ships are sensitive to weight in two ways. First. weight growth reduces the top speed. The resulting speed loss with weight growth is similar to monohulls for high l/b SES that operate at below hump speeds. The impact of weight growth on low l/b SESs is more critical due to the presence of a hump in the drag curve as explained more fully in the section on *Resistance and Hullform.* A power margin must be included in the design to accommodate any increase in hump drag due to weight growth. Typically 20-30% powering margins are included in low l/b configurations to guarantee the ability to transit the primary drag hump into the high-speed regime.

The low l/b SES requirement for high thrust at low hump speed as well as at top speed complicates the design of the propulsion system. A partial solution to this low l/b hump drag weight growth sensitivity has been the development of full displacement sidehulls. This permits the SES to bypass the hump by operating in the hullborne or partial-cushion mode until hump speed is exceeded.

A second aspect of weight sensitivity is associated with top speed requirements. Low-and moderate-speed SESs (less than 40 kts) have almost the same response to weight growth as monohulls. In this speed regime, which includes the majority of commercial SESs, they can be built almost entirely of standard marine subsystems and still carry sizable payloads.

High-speed SESs (40-60 kts) are more sensitive to weight. However, they respond favorably to weight reduction efforts in their design and construction and can use standard marine subsystems if care is taken in their selection and application.

Very-high-speed SESs (60-80 kts), in order to maintain acceptable power levels and payloads, require strict attention to weight conscious design and control. Many standard marine systems are too heavy to permit reasonable payload-weight fractions. As a result, aerospace and other lightweight subsystems must be adapted. This adds significantly to the cost for engineering, acquisition, and operations (maintenance and repair). Thus, very-high-speed SESs must offer significant increases in performance to justify their expense.

In parallel with weight is sensitivity to longitudinal center of gravity (LCG) shift. While hullborne, SESs respond to LCG movement similar to monohulls. When cushionborne however, trim strongly affects the drag and horsepower requirements. LCG shifts of greater than 10% of a ship's length can adversely affect cushionborne performance if not monitored and maintained through trim control.

Vertical Accelerations

SESs can operate safely at higher speeds in higher sea states then equivalent length monohulls. However, the vertical accelerations in the higher frequency range caused by this higher speed can be irritating if not adequately regulated. Typically, displacement ships do not operate at high enough speeds to excite these frequencies whereas SESs do. The current-generation control systems attempt to maintain constant cushion pressure and are very successful at it. However, other contributions to accelerations such as hydrodynamic sidehull and seal forces together with the impact of very long ocean swells are not currently controlled. The next generation of controllers will directly regulate the accelerations caused by these secondary sources. In summary, SESs currently have significantly lower accelerations than monohulls of equivalent payload and speed, but they still have room for improvement with the inclusion of improved control systems.

Seals

Bow and stern seal designs and materials appear adequate for SESs of up to about 20,000 tons and cushion pressures approaching 1000 psf. Current large size seal experience is much more limited, so there is the potential of running into unforseen problems as seals for 4000-ton and larger SESs are required. Seals require maintenance and periodic replacement. and this added cost must be recognized in the design process. These acquisition and maintenance requirements significantly increase for very-high-speed SESs.

CURRENT AND POTENTIAL APPLICATIONS

Discussion of applications necessarily takes one from the exciting R&D world of technology and validation, as presented in a later section, into the pragmatic and demanding world of operations, the world in which hull forms become platforms and cease to be an entity unto themselves. If accepted, the platform becomes part of a system. To accept a new platform, it must make a contribution to the system. That contribution could be unique and so badly needed that it pays its own freight. The amphibious capability of the ACV, for example, became a central feature in support of the ship-to-shore movement of men and material. If an advanced hull form does not make a unique contribution, it must at least contribute to the productivity of the mission-or, productivity in the sense of doing more with less, doing the job more efficiently, or both. For example, better seakeeping permits mission accomplishment in a smaller ship for less investment and operating cost. Higher speed could open the door to a new application or improve productivity of an existing one. The blending of hull form and mission equipment is a system effort. Technical requirements, weapons, sensors, and the platform all need to work supportively.

A few years ago, SESs were thought of mainly in terms of speed. While speed is a highly desirable attribute in many missions, preoccupation with speed should not be at the expense of other operational characteristics critical to the team operation of fleet and task forces. A goal of a higher speed than offered by today's monohull carries with it the requirement to steam efficiently across the full range of fleet speeds.

The historical evolution of the SES can best be marked by three distinct periods over the past twenty years, [3]. The first phase represented by the XR-1, XR-2, XR-3, 100A and 100B, [4] culminated in the Navy's 3K SES program. These SESs were characterized by low l/b ratios and thin sidehulls. They were designed to operate almost exclusively on cushion at high-post-primary hump drag speeds. This configuration has proven to be efficient for missions such as passenger ferries where continuous high-speed operation is desirable. Over one hundred of this type are in operation in the free world [5]. The Russians have in excess of 350 SESs in use as river ferries. Most of these have been very successful and have, over the last decade, proven to be a very cost-effective form of moderate speed marine transportation [6].

The second generation of SESs were of high l/b ratio with thin sidehulls such as the USN XR-5 and certain Russian designs. For operations that do not require speeds in excess of 50 to 60 kts for 100- to 1000-ton SESs respectively, this planforrn is very desirable. Due to their low-speed drag characteristics, the Russians have found these high l/b SESs to be very efficient (25 plus knots) river transport "buses" that can stop to take on or discharge passengers anywhere along the route simply by nudging the bow into the river bank with their shallow on-cushion draft. The thin sidehulls do not provide much buoyancy. When operating hullborne, the centerbody provides most of the buoyancy.

The third generation of' SESs, commencing with the XR-5A and BH-110, modified the shape of the catamaran sidehulls to provide extra buoyancy. These sidehulls provide in excess of 100 percent of the hullborne buoyancy and permit the SES to float like a true catamaran in the hullborne mode. This characteristic is now included in the majority of new U.S. Navy SES designs, for with full-displacement sidehulls, these ships can now operate efficiently at very low speeds with traditional SES seakeeping characteristics.

As was discussed previously, the emerging list of SES attributes stemming from experience with the ships and craft available today has much to offer the Navy of tomorrow. But platform changes do not occur in a casual manner. As noted in the beginning of this section, the SES platform must make a strong contribution to the mission through enhancement of the weapon system. For the U.S. Coast Guard WSES, the speed, habitability/seakeeping, and endurance represented a significant upgrading compared with available patrol boats for combating the drug trade in the Caribbean, and this need for upgrading was urgent.

So mission enhancement is the major driver in selecting an SES as a new hull form, and if it is to be a bluewater ship that will operate with the fleet, it must not be a logistic burden to the fleet commander and, in all cases, it must be affordable.

Where are we in the U.S. relative to the SES? Figure 9 shows most existing SESs and Figure 10 shows the SESs built in the past 10 years that the Navy and Coast Guard have operated successfully. All three were derivatives of the BH-110. The original BH-110 was first a work boat in the Gulf of Mexico, then a Navy/Coast Guard test vehicle, and, after modification by the Navy from 110 ft. to 160 ft. length, a test ship for proving (late '83) the efficiency of higher length-to-beam ratios.

Where we are going in the near term is also shown in Figure 10. The "prospective" grouping shows the PBM and the MSH. An RMI Inc. SES design (Figure 11) has been selected (July 1984) by the Navy for the PBM. The PBM is a 110-ton ship-transportable patrol boat to be manned and operated by Naval Reserve personnel. It promises extensive flexibility in meeting in-shore patrol and special operations anywhere in the world.

The MSH is an in-shore mine hunter/minesweeper. The Navy awarded a contract for the lead MSH in November 1984 to Bell Aerospace. For the MSH mission, an SES hull form (Figure 12) offers several unique attributes listed earlier: a full load displacement about one-half of an equivalent monohull due to the attenuation of underwater shock transmitted to the hull because of the decoupling effect of the air cushion, resulting in increased safety to personnel and equipment as well as reduced construction costs that would otherwise be expended to protect hull mounted equipment; a large uncluttered deck area; a low acoustic signature; and the potential for high-speed, going from one mine clearing job to the next. This latter factor represents a substantial dollar saving when considering force levels needed to serve a large number of widely separated ports along a single stretch of coastline.

The next grouping in Figure 10 is "near term potential." It is depicted as a single block of varying-mission ships up to displacements of 1000 tons. That block subdivides into individual potential requirements of varying size from about 200 tons up to 1000 tons. These potential requirements include a Coast Guard cutter, larger than the WSES, offering extended endurance and a platform of ample size for support of staging and servicing (but not hangaring) a helo. With helo eyes, SES speed and seakeeping, this ship could operate independently and efficiently against the illicit drug trade in the Caribbean, along the East Coast and other sea approaches to the U.S.

For the ship-to-shore movement, speed continues to be

SHIP	NO.	BUILT	WT.	SPEED	MISSION
HM-218 (England)	93	196X-84	-30	35	Ferry/Crewboat
Rudolf (USA Corp of Eng)	I	79	24	37	Survey
Bell/Halter 110 & MKII	2	1980-81	121	33	Demonstration Crewboat
Molenes (French)	I	81	5.5	20+	Experimental
HM-221 (England)	3	X2	35	31	Fireboats
WSES (USCG)	3	82	140	30	Patrol Boat
SES 200 (USN)	1	82	200	30	Demonstration
Aronow	1	83	15	60	Prototype
Halter	1	83	-20	40+	Fishing
Air Ride Express	I	83	47	30	Crewboat
HM-527 (England)	5	83	105	36	Ferry

Figure 9. Existing SES

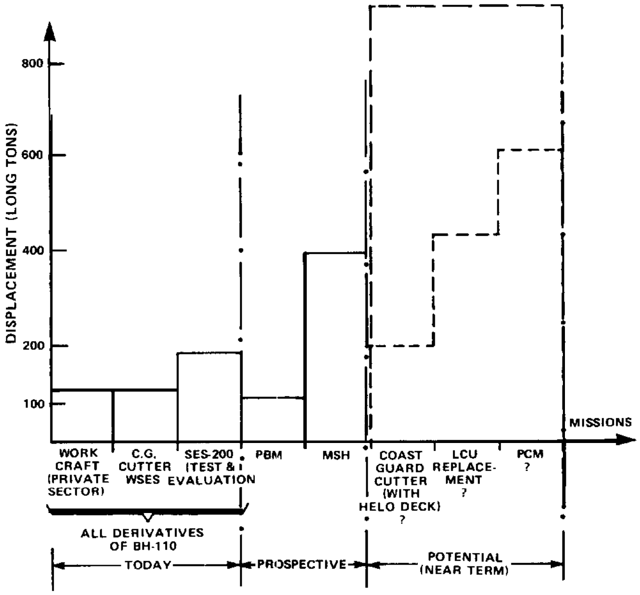


Figure 10. SES Status

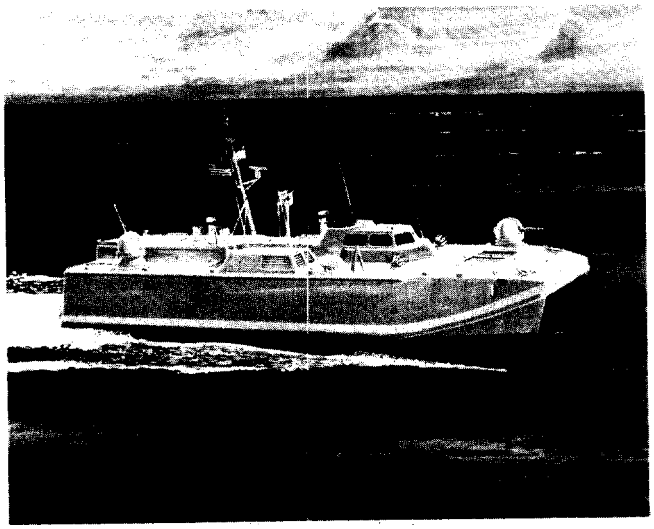


Figure 11. U.S. Navy PBM

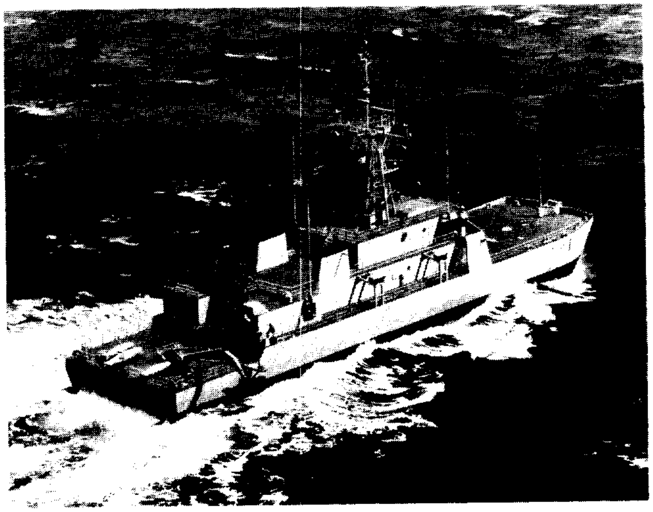


Figure 12. U.S. Navy MSH

a significant factor. SESs are being developed for delivery of vehicles that either can swim the last few hundred yards or need to be delivered no further than the beach.

There are also several applications of ships to patrol out to the edge of the continential shelf involving ASW, surveillance, etc., that are associated with increased national interest and activity in hemispheric security.

Taken totally, Figure IO is a general depiction of growth in the family of in-shore missions that have been selected and some potential candidates for future selection of the SES hull form. It indicates gradual growth in ship size as more missions are added.

Continuing growth in ship size opens the door for open-ocean application. Unlike most in-shore missions that may be characterized as "independent," blue-water missions, for the most part, must conform to fleet rules of operation. As previously noted, such ships must operate efficiently at all fleet speeds and not create a logistic burden for the fleet commander. At the same time, growth from in-shore to fleet assignments must be accomplished in prudent steps in order to assure low risk and affordable (competitive) cost. The first ship for blue-water application, therefore, is constrained in size by risk considerations on one hand, but on the other hand must be large enough to do a blue-water job without constraining the task force it serves. In summary, there must be a good operational reason for taking the venturesome step to blue water. That first step has been pegged generally at 1500-2000 tons by the development community. It is a good size from a risk-suppression viewpoint. The materials, the power plants. structural technique, and the other technical issues are considered to be well in hand. The question remains then, is it big enough to pass the litmus test of mission requirements, blue-water sustainability, and seakeepingihabitability?

If one looks at today's warship size, the immediate reaction is that 1500-2000 tons will not fill the requirement. Figure 13 shows full-load displacement for U.S. warships. Generally speaking there are **no** combatants that travel with U.S. task forces that displace less than **3500** tons.

However, displacement of warships expected to cruise worldwide is mainly dependent on two requirements:

(I) Mission payload which is distributed among requirements for weapon suite (including on-board sustainment), range, speed, and personnel complement; and

(2) Seakeeping/habitability

It is the excellent seakeepingihabitability of SESs smaller than 3500 tons that should open the door for early use in fleet service.

An SES at 1500-2000 tons can be expected to have seakeeping capabilities equal to some of the larger monohulls now steaming with task forces and to provide much higher speeds when called upon to do so. Extrapolation

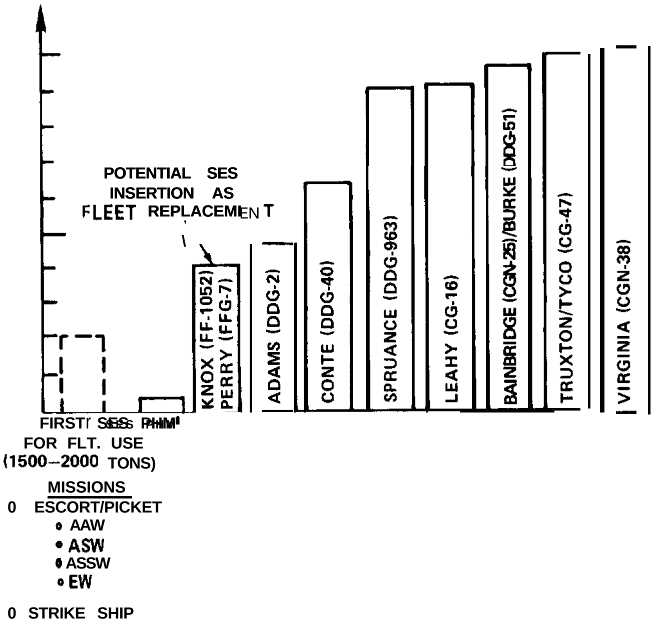


Figure 13. Navy Surface Ship Family (up to 10,000 tons).

POTENTIAL MISSION APPLICATIONISES CHARACTERISTIC MATRIX	SPEED	SEAKEEPING/ CAPABILITY	NEAR-MISS SURVIVABILITY	TORPEDO ATTACK IMMUNITY	EXPANSIVE DECK AREA AND INTERNAL VOLUME	TOPSIDE AND ANTENNA WT. MARGINS	AIR ENHANCEMENT
INSHORE							
PATROL	P	P	P	S	P	P	P
MINE HUNTER/SWEEPER	P	P	P	S	P	S	–
SPECIAL MISSION	P	P	S	S	P	S	–
SHIP-TO-SHORE							
VEHICLE TRANSPORT	P	P	P	S	P	S	–
ROCKET FIRE SUPPORT	P	P	P	S	P	S	–
INTRA-THEATER							
REPOSITIONING OF HIGH PRIORITY CARGO FROM MAJOR OFF LOAD PORTS TO PORTS CLOSE TO BATTLE AREA	P	P	P	S	P	P	–
FLEET/OPEN OCEAN PICKET/ESCORT							
ANTI-AIR WARFARE (AAW)	P	P	P	P	P	P	P
ANTI-SUBMARINE WARFARE (ASW)	P	P	P	P	P	P	P
ANTI-SURFACE SHIP WARFARE (ASSW)	P	P	P	P	P	P	P
ELECTRONIC WARFARE (EW)	P	P	P	P	P	P	P
SPECIAL MISSION (OPEN OCEAN)							
MISSILE ATTACK SHIP	P	P	P	P	S	P	S
AIR SUPPORT SHIP	S	P	P	P	P	P	P

KEY: P PRIMARY S SECONDARY – NOT APPLICABLE

Figure 14. Potential Mission Application/SES Characteristic Matrix.

of the SES-200 and the Coast Guard WSES experience in rough seas, backed up by considerable analysis and testing, supports open ocean operation for the 1500-2000 ton displacement class.

The SES hull form, therefore, would seem to offer an opportunity to revisit the lower displacements of the WWII period in search of good payload/seakeeping balance in lower-cost ships.

Accepting the proposition that a 1500-2000 ton SES can handle blue-water fleet operations, the remaining question, in focusing on this size as a blue-water entry point, is whether such ships can pay their way missionwise.

Figure 14 lists missions and unique characteristics of SESs. It shows that the missions of picket/escort ships with designated tasks of AAW, ASW, ASUW, or some combination of these tasks, brings some very desirable characteristics to the mission. While there are currently no established requirements for picket ships, the Navy has in fact used picket/escorts in some form in every war or conflict from WWII onward. The outer air battle requirement developing today, and its need for widely spread formations, make the picket/escort concept increasingly important.

Unlike the earlier "all-out-speed-boat" approach, today's SES is generally efficient at all fleet speeds. It is most efficient, however, at speeds higher than fleet speeds. It therefore should be an ideal hull form for any fleet function that requires speeds well in excess of fleet speeds during a significant portion of time while operating with the fleet. Fleet outer perimeter defense functions in widely spaced fleet formations, whether ASW, AAW, ASUW, or surveillance, need SES characteristics. These missions require additional speed for repositioning, bogey investigations, refueling, etc., as shown in Figure 1.5 [7]. To the degree that repositioning can be achieved rapidly, the number of ships and men required to perform tasks in spread formations. can be reduced without jeopardizing integrity of fleet defense.

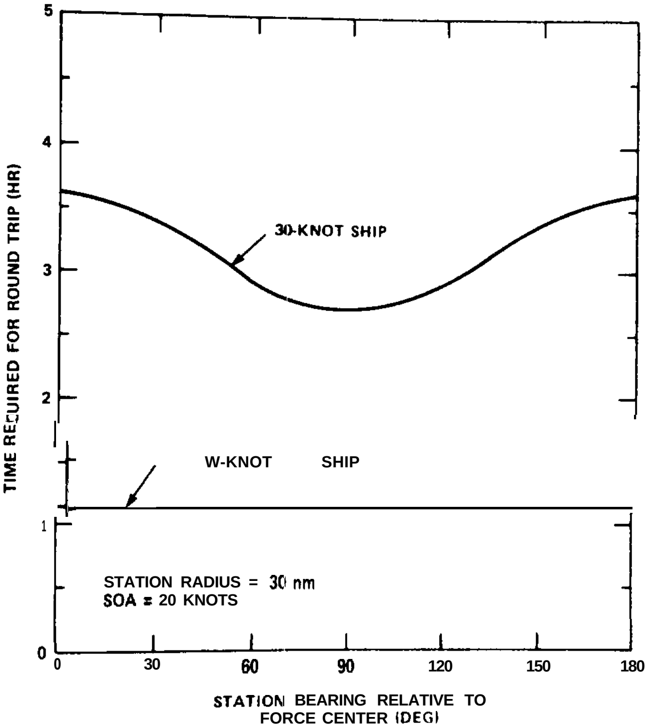


Figure 1.5. Influence of Ship's Speed on the Time Required for a Round Trip To/From a Perimeter Station From/To Formation Center.

A valuable member of the escort/picket family would be an AAW ship carrying a capable antiair suite such as Aegis, or a derivative, and 50 to 80 missiles in vertical launch tubes-lighter weight tubes that exhaust to the cushion or overboard. With the missile range made available in the Standard Missile 2 Block II, and the ability of the ship to reposition rapidly along the defense periphery as the threat develops, this ship can be a valuable contributor to the fleet defense network. It would meet the displacement limit by not loading it down with high density hardware such as major caliber guns and their high-density ammunition. Instead. missiles for self-defense would be provided along with a close-in weapons system (CIWS). It would also be an ideal electronic warfare (EW) listening and reporting post as a second mission. These are clearly missions that would be welcomed in wartime as part of any fleet formation including amphibious, underway replenishment, and high-value convoy task groups.

In the ASW task, this picket/escort could work ahead, or out on the flanks of the formation in quiet waters using a passive linear array sonar. It could listen at fleet speeds and reposition at twice fleet speed without fully retracting the array.

In both configurations, the 1500-2000 ton SES provides an air platform for VTOL operations. Finally in either AAW or ASW configuration, the ship steams in

Table 1. U.S. Navy SES Manned Testcraft.

ITEM	*XR-ID*	*XR-3*	*XR-5*	*SES- 100A*	*SES-IOOB*
Overall Length, ft.	49.9	24	46'9" (excl OB)	79'8"	78
Maximum Beam, ft.	19	12	8'5"	41'10½"35	
Displacement, lb.	50,000	5,685	9.000	289,650	206,000
Maximum Speed, Kt.	40	25	25	80 (approx)	90+
Propulsion Engines	2 T-53-L7 Lycoming GT	2-40hp 0. B	2-130 h.p. O.B.	4-TF 35 GT (propul + lift) 15,000-Total	3-P&W FT12A-6 Marine G.T.
Total H.P.	1300	80	260	12.000	13,500
Propulsors	2-Waterjets with flush, variable inlets	2-Conventional O.B. sub-cav props	2-Conventional O.B. sub-cav props	2-Waterjets with flush inlets	2-Semi-sub Super-cav Var-pitch props
Lift engines	502-1OMA Boeing GT	5-3hp Briggs & Stratton	Onan Alternat.	(See propulsion engines)	3-UACL ST6J Marine G.T.
Total H.P. Fans	300 3-centrifugal	15 3-axial 1' dia x 15"	25 6-axial 6.74" dia x 6.25" (electric)	3,000 3-axial	1.860 7-3.7 centrif + 1-4.15 centrif
Cushion Area, Sq. ft.	588	258	262.2	1.998	1,907
Cushion Pres, Lb/Sq. ft.	65	22	34.3	93	108
Flow, Cu. ft./sec	670 normal 1,140 max	183	145	9,000	5,280
Seals					
Bow	bag & planer	2-dim Stay-stiffen planing	3 bag type	bag & planer	bag & finger
Stem	2 panel hinged				
Material	Fabric-reinforced rubber Fiberglass/epoxy planer	Rubber-coated fabric	Neoprene	Fiberglass, Aluminum, Rubberized fabric	Rubberized fabric
Steering	Waterjets	Steerable 0. B.	Steerable O.B.	Extensible Skegs. Steerable Water-jets	Twin Super-cav. Rudders

near sanctuary so far as torpedo attack is concerned, and will have the capability to outrun all known submarines.

Listed in Figure 14 as having special mission potential is a missile attack ship. Also of the 1500-2000 ton class, this ship would carry a large number of cruise missiles, would detach from the fleet, dash at twice fleet flank speed in silence for 1000 miles, launch and return to the fleet or to a replenishment site. This ship would be designed as a low observable from overhead. It probably would be the least expensive missile attack mode that could be put together should this mission be needed. Its survivability should be high.

The potential SES special mission, air support ship recognizes the increase in the fleet's aircraft population that will come with Tiltrotor and other VSTOL aircraft under current active development. In 1983 the Navy identified 13 potential uses for JVX (Tiltrotor) derivatives in addition to 3 currently planned missions. The SES hull form is an excellent selection for this mission; it provides more flight deck area per displacement ton than any other. Considerable flight and hangar deck space will be needed in the next decade to bed down aircraft that a large part of the time will stage to other platforms within the fleet formation to do their job.

Before closing the section on blue-water SES applications, the rapidly producible frigate for wartime is worthy of note. It might very well be that a 1500-2000 ton SES designed modularly to simplify variable equipping for any of several missions, and minimally manned, is the answer to this important asset yet to be defined.

The foregoing samples of Navy/Coast Guard applications for SES predicts growth of mission numbers and ship size. The high potential for SES in future applications requires a steady program of ship construction backed up by R&D to support a system approach.

STATE OF TECHNOLOGY

Surface effect ship technology has evolved in a way which makes it dangerous to generalize about its current state. Following the invention of the SES and fruitful early explorations of its fundamental properties in the 60s, the ensuing decade produced a tremendous focused effort by the U.S. Navy to mature, validate and apply the technology. No other modern ship technology development, except for the Polaris submarine, has ever been so intensively pursued or systematically planned and executed. In technical terms it was a highly successful effort, producing a priceless reservoir of high-quality, well-documented technical information. Five, U.S. Navy, progressively-developed manned testcraft, as summarized in Table 1, were applied towards the solution and

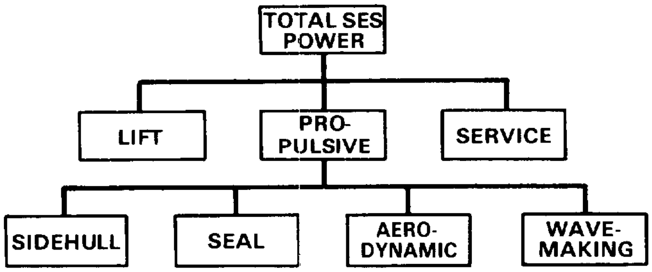


Figure 16. Surface Effect Ship Powering and Drag Components.

demonstrations of the maturity of the SES science. The XR-I, SES-100A and 100B contributed significantly towards the systematic focus for an 80-knot surface combatant. This ultraspeed performance came with the application of aerospace technology to control the inherent weight sensitivities of these smaller testcraft.

The 80s opened with successful commercial SES developments which, though drawing heavily on the ultraspeed performance technology base, involved new innovations such as higher length-to-beam ratios, high-buoyancy sidehulls and dramatic departures from earlier design philosophy with more modest performance goals and more conservative marine design approaches to the structures and machinery afforded by these less weight-sensitive craft. Current indications are that renewed SES developments will follow a course of more modest performance goals and technology sophistication, with the adoption of other length/beam ratio hullforms. This course holds the promise of much greater military capability than the commercial development trend, but much greater economy and affordability than the trend towards ultraspeed. What follows is a statement of the technological base and the systematic relationships that have been developed of the various design descriptions that are available to bring SES designs to fruition.

RESISTANCE AND HULLFORM

The total powering components are shown schematically in Figure 16, with the largest being propulsive power. Through its propulsive system, thrust is produced which accelerates the SES up to a speed at which the thrust balances the resistance or drag. The propulsive power (P,) required to maintain that steady velocity (V), is a function of total drag (D_T) and propulsive coefficient (PC) (or efficiency) as follows (in consistent units):

$$P_p = \frac{D_T V}{(PC)} \tag{1}$$

The total drag (D_T), as suggested in Figure 16, is made up of sidehull drag, fore and aft seal drag, aerodynamic drag, and wavemaking drag (which will be discussed in more detail shortly). There are two ways of predicting the SES drag. One is to predict, on a theoretical basis, the drag components. This has the advantage of generality, and the drag of many designs can be predicted and compared [8-11]. The second means is to build a geometrically scaled model and perform drag measurements in a towing tank in calm water as well as wave conditions, and then Froude scale the results to full scale [12]. This model scaling method has the advantage of greater accuracy in predicting full-scale drag and power. Both methods are used and both depend upon and are improved by the other.

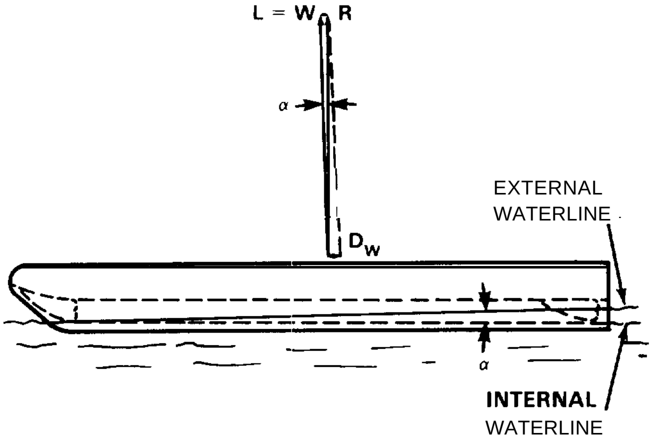


Figure 17. Vector Representation of Wavemaking Drag.

The second largest power requirement is for the lift fan. Cushion pressure supports most of the weight on a frictionless planing surface of air (at high speed). Without cushion airflow, the propulsion plant would require additional power far in excess of the fan power required to maintain the same maximum speed. When there is enough lift air to maintain full cushion pressure, additional lift air will still lower drag, at first significantly and then more gradually. The optimum cushion air flow is defined as that at which the power required to increase flow is greater than the reduction in propulsion power needed to maintain a constant speed. In general, the optimum flow increases modestly with speed and sea state.

To complete the powering picture of Figure 16, service power is required for ship machinery, crew and mission support.

Wavemaking and Other Drag Components

Wavemaking is perhaps the least obvious of the drag components, but understanding it is important to an appreciation of design tradeoffs that need to be made [13]. First, to remove any misunderstanding, it has nothing to do with encountering existing waves in a body of water. Rather it relates to an interaction between the cushion and the calm water surface over which it is traveling. The appropriate hydrodynamic situation is illustrated in Figure 17. When an SES is at high speed in calm water, the inside water line tilts down by some angle α as a reaction to the cushion pressure. A long wave is then generated aft; hence the name "wavemaking drag" or "wave drag." Thus the resultant force (R) that the cushion exerts (generally upward) tilts aft of vertical by the angle α. R can be broken into a vertical or lift component (L) (equal to craft

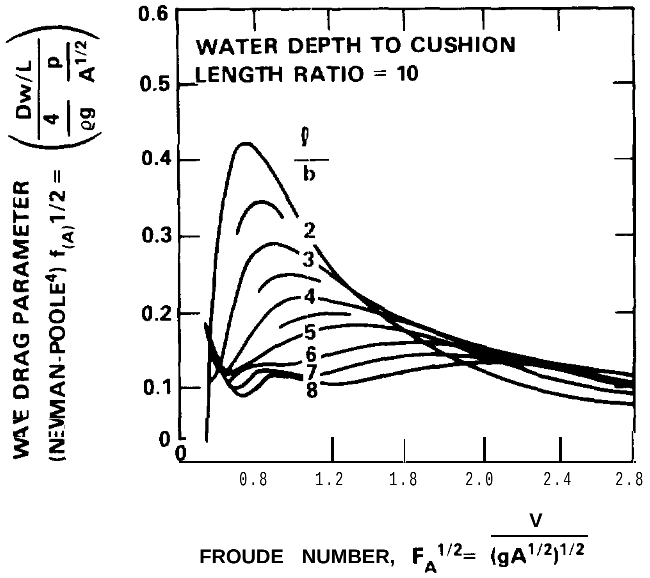


Figure 18. Wave Drag Parameter Based on $A^{1/2}$ Versus Froude Number Based on $A^{1/2}$.

weight, W), and a horizontally directed wavemaking-drag component (D,.).

Figure 18 illustrates one useful method of presenting wavemaking drag [14,15]. The wavemaking drag-to-lift ratio (D_w/L) on the ordinate is normalized by $p/A^{1/2}$ where p is the cushion pressure and A is the cushion area. The abscissa is the Froude number based on the square root of the cushion area ($F_A{}^{1/2}$). Figure 18 is useful in illustrating a wavemaking drag for different length-to-beam ratios. For example, in comparing the wavemaking drag of two SESs with different l/b, but the same speed (and each having the same displacement, and the same cushion area and pressure), the wave drag coefficients can be read at one value of Froude number.

The conclusions that can be drawn from Figure 18 are that, for SESs of higher l/b, (but the same displacement, cushion area, and cushion pressure), the wavemaking drag is generally substantially lower than that for a lower l/b, except at very high velocities (or Froude numbers), where the higher l/b, SES wavemaking drag is slightly greater.

The physical significance of the primary (highest speed) wavemaking drag "hump" in each of the drag curves is that at hump the trough of the generated wave positions itself below the stern seal and maximizes the angle α and the wavemaking drag (D_w). Figure 17, as drawn, shows a speed condition much higher than "hump" speed with the wave trough far aft of the stern. At speeds below the "primary hump" speed, the first trough of the wave moves forward of the stern seal. The stern seal then rests on a wave peak, thus minimizing α and D_w. At still lower speeds a second wave trough moves below the rear seal to again maximize the angle α, and the wavemaking drag (D,) at the secondary "hump" (not shown in Figure 18). Tertiary and higher order "humps" tend not to exist due to their high wave slope even though they are predicted in some theories [14,15].

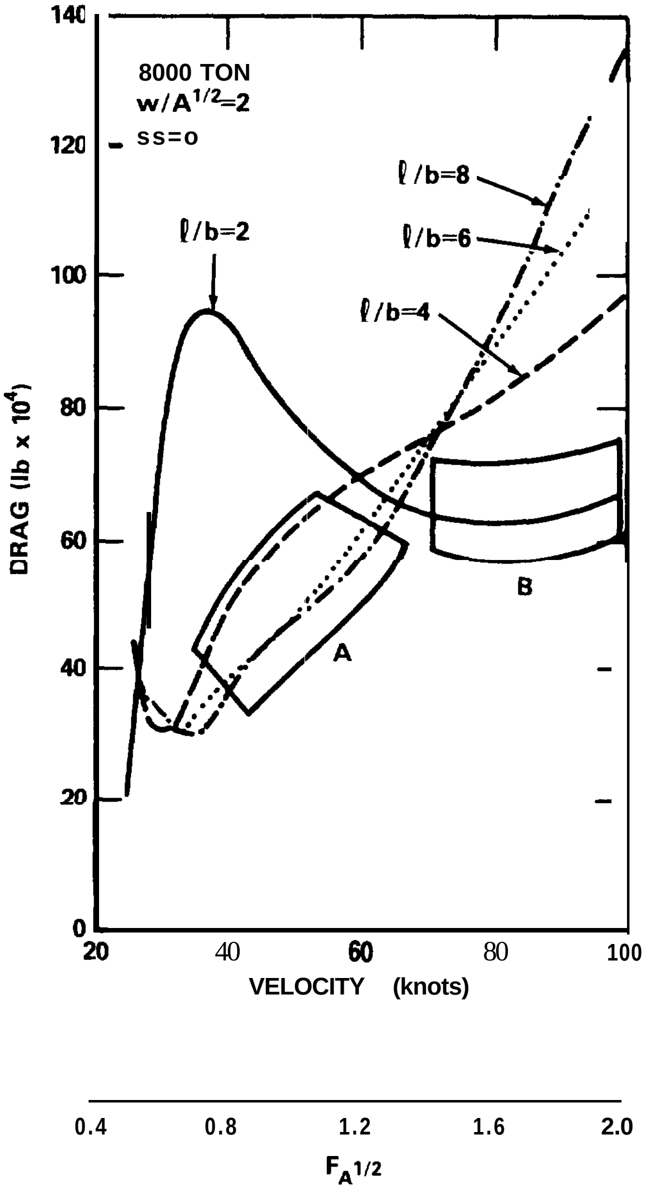


Figure 19. Total Drag of an 8,000-Ton SES as a Function of Velocity and Length-to-Beam Ratio.

Figure 19 shows a plot of total drag as a function of velocity for several ships of different l/b with the same displacement or weight (W) and cushion area (A). In this example, the displacement is 8,000 long tons, about that of a DD-963 class destroyer. The ratio W/A (or w) is normally approximately equal to cushion pressure (p) particularly at high speeds, because of the small lift contribution of the sidehulls and seals. The general shapes of the curves of Figure 19 are as expected, having seen Figure 18. At speeds to about 40 to 50 knots, the wavemaking drag (D,) predominates, particularly for an l/b of 2. At higher speeds, however, the sidehull and seal skin friction drags become important. For higher values of l/b, the sidehulls are longer; hence, the drag rises more steeply with speed.

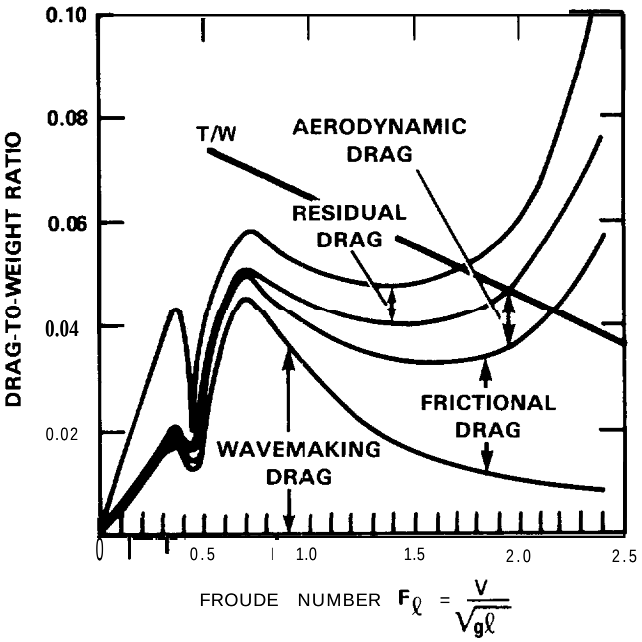


Figure 20. Drag Components of an SES of Length-to-Beam (l/h) = 2.0

The following conclusions can be drawn from Figure 19:

1) Region A is the natural design speed regime of higher l/b SES.

2) Region B is the natural design speed regime for lower l/b SES.

This is based on the fact that, in each region, the SES with that l/b has the lower total drag. Design region B has the advantage of higher speed, but there is a pronounced primary drag hump (at a speed between 30 to 40 knots for the 8,000-ton SES). Region A offers lower but still appreciable speed, a lower drag and power and a less pronounced hump drag (in the 30 to 50-knot speed regime for the 8000-ton SES).

Figure 20 shows typical drag components for an SES with a l/b of 2. Figure 21 shows the same drag components for an SES with a l/b of 6 [17]. These two sets of drag components are significantly different. In the l/b of 2 case (Figure 20). there is a pronounced drag hump at a Froude number of about 0.7, which is primarily due to wavemaking. Wavemaking drag rises with the square of vehicle weight. Therefore unplanned weight growth can prevent the ship from transiting through hump speed, by causing the drag to exceed the thrust available. In the l/b = 6 case (Figure 21), frictional hydrodynamic drag (of the sidehulls primarily) plays a more dominant role than cushion wavemaking drag. In this case, weight overload will only result in a small speed loss because increasing the wavemaking drag (e.g. in the Froude number range from F, of 0.7 to 1.0) results in only a modest total drag increase.

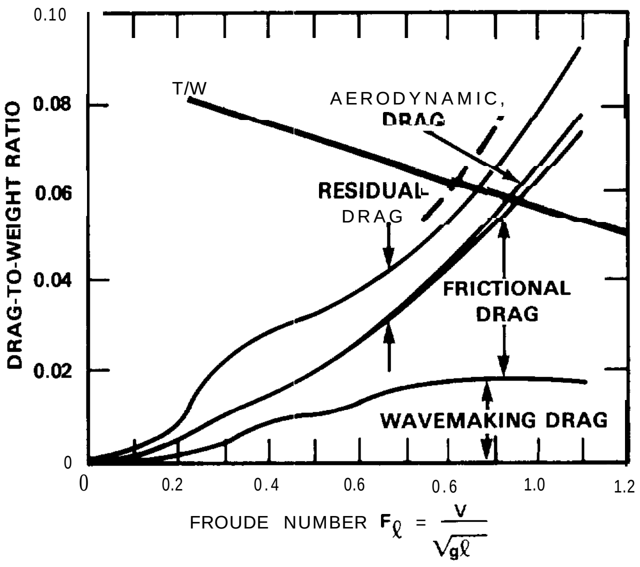


Figure 21. Drag Components of an SES of Length-to-Beam (l/h) = 6.0.

To quantify this point, typical thrust-available-to-weight lines as a function of Froude number are drawn on Figures 20 and 21 and are labeled (T/W). In Figure 20, the thrust-to-weight margin ($T/W-D_T/W$) at the primary-hump speed (F, = 0.7) is about 26% of the wavemaking drag (Dw) at that speed; therefore a 13% weight increase will prevent achievement of hump speed. This is because wavemaking drag increases are proportional to the square of weight; other drag increases are relatively negligible. In this case the velocity decrease will be 66% (from F, = 1.75 to 0.6), a very large degradation in performance.

In Figure 21, the results of a 13% increase in SES weight are also examined. The resultant 26% increase in wavemaking drag results in less than a 5% decrease in velocity (F, from .87 to .83), a very reasonable degradation when compared to the first case.

Figure 22 shows an early SES testcraft (the XR-3 with l/b of 2) in operation [18]. It's in a high-speed (post-hump

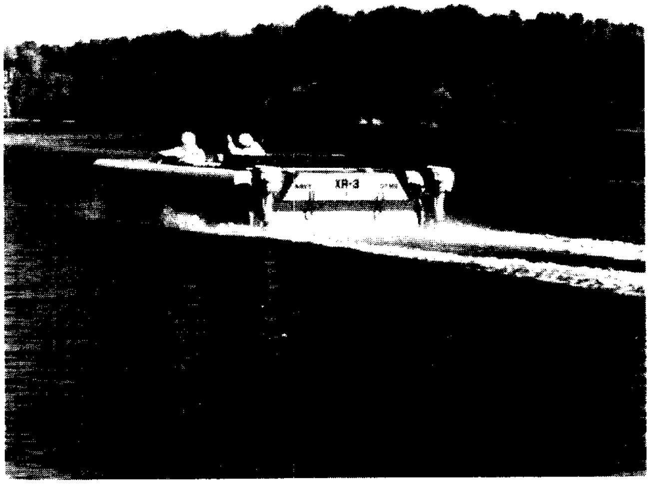


Figure 22. Stern View of the XR-3 Testcraft in High Speed Operation.

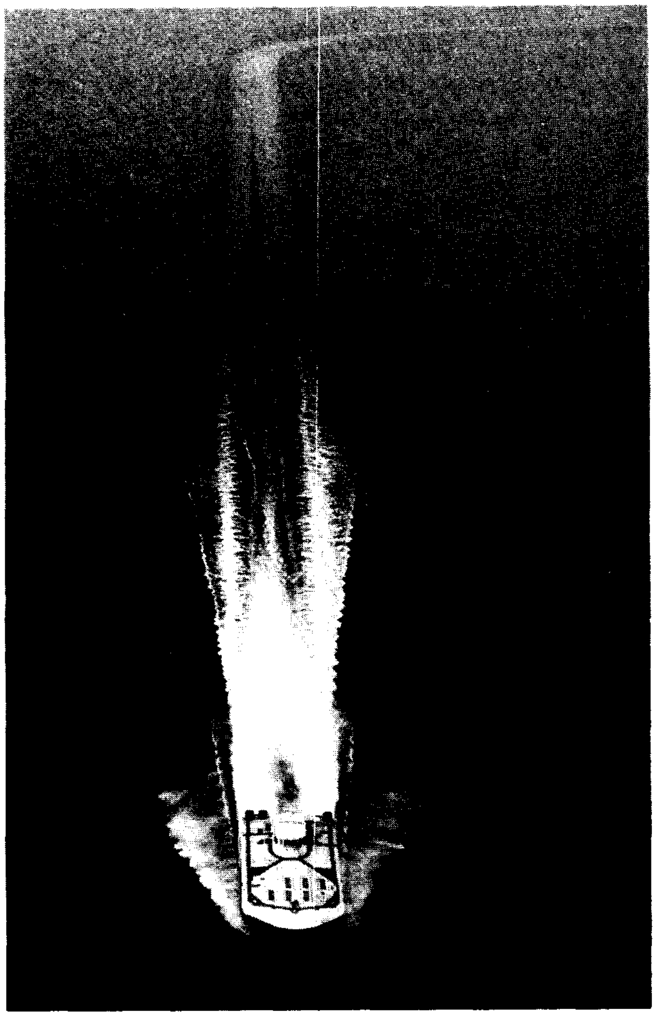


Figure 23. A Broad View of the Wake of the SES-100B at High Speed.

speed) condition, with its small stern wake visible. The water aft of the XR-3 that has passed under the cushion (inboard of the propulsion units) can be seen to be slightly lower than the other relatively undisturbed water. This picture is in essential agreement with the schematic sketch of Figure 17.

A broader view of a wake generated by an SES is shown in Figure 23. This SES testcraft is the SES-100B proceeding at a speed in excess of 50 knots. The SES-100B has an l/b slightly above 2. As can be seen, its high-speed wake is very small for a 105-ton craft.

Figure 24 is a picture of the XR-5, an l/b = 6.5 testcraft, undergoing tests at a speed of about 25 knots (F, = 1.2). In addition to showing a close-up view of the XR-5, it also shows the wake of the XR-5 and that of a small chase boat. It is interesting to compare the wake patterns of these two craft as a demonstration of wavemaking drag. Even though the planing chase boat weighs about two thirds as much as the XR-5, it is utilizing considerably more power at the same speed. This power and weight comparison is consistent with the fact that the lighter chase boat has a larger wave pattern, even though the speeds are the same. The smaller wake pattern of the XR-5 testcraft is indicative of the SES's lower wavemaking drag [13].

Figure 24. The XR-5 SES Testcraft (Length-to-Beam Ratio 6.5) at a Speed of About 25 Knots (F_l = 1.2).

SES-200 and BH-110 Powering and Speed

With this background in the subject of SES resistance and powering it is instructive to look at the power-versus-speed relation of the SES-200 (Figure 25) and the BH-110. The SES-200 was obtained from the BH-110 by adding a 50-ft midship structural plug. This increased the l/b from 2.65 (BH-110) to 4.25 (SES-200). The same powerplants, propellers, fans, and all other systems were retained [20]. The physical characteristics of the original and stretched SES are given in Table 2.

Table 2. Characteristics of BH-110 and SES-200

Parameter	BH-110	SES-200	Relating Factor
Displacement (Weight) (W) LTon	140	200	1.43
Length Overall. ft.	110	160	1.45
Beam Overall. ft.	39	39	1.0
Cushion Length, ft.	83	133.3	1.60
Cushion Beam. ft.	31.6	31.6	1.0
Cushion Area (A). ft^2	2598	4163	1.60
l/b	2.65	4.25	1.60
W/A = w, lbs/ft^2	121	108	0.89
$w/A^{1/2}$. lbs/ft^3	2.31	1.61	0.70

The parameter ($w/A^{1/2}$) in Table 2 is essentially the same as the cushion loading parameter ($p/A^{1/2}$) contained in the ordinate of Figure 18, except that $w/A^{1/2}$ does not account for the sidehull and seal lift contributions. The wavemaking drag-to-lift ratio for the SES-200 will be lower at almost all speeds by virtue of the higher l/b. It

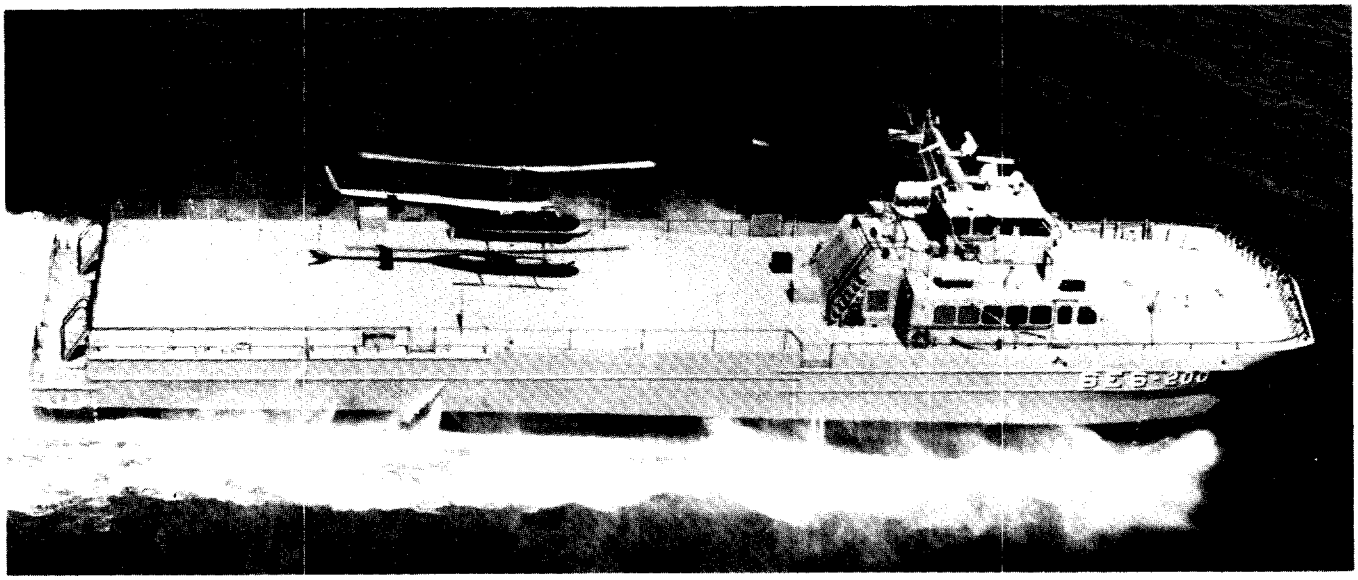


Figure 25. SES-200 Navy Testcraft (Nominal Displacement 200 Long Tons), with Helicopter Hovering Over the Aft Deck.

will also be lower by virtue of the lower cushion loading (1.67 for SES-200 versus 2.37 for BH-110).

Figure 26 compares the calm water speed power requirements for the 140-ton BH-110 with the 200-ton SES-200. As shown, the BH-110 has a 2-3 knot higher speed; however, between 10 and 27 knots the SES-200 required substantially less power. In this speed range, the reduction in wavemaking drag achieved by increasing the length-to-beam ratio and reducing the cushion loading was greater than the increase in hull drag from the 50-foot extension and increase in weight.

The outstanding performance of the SES-200, shown in Figure 26, is also demonstrated by its range and payload. After it left the Elell-Halter construction yard in New Orleans, it made a 1500 mile nonstop unrefueled transit around the Florida Keys to the SES Test Facility at Patuxent River, Maryland, at an average speed of 23.4 knots arriving with approximately 34% of its fuel remaining [20,21]. In the modification from the BH-110 to the SES-200, the lightship weight was increased by 28% (from 100 to 128 long tons); while the useful load was increased by 100% (35 to 70 long tons). The SES-200 is designed to have a range of 3000 miles at speeds between 25 and 30 knots without refueling [22,23]. Range is normally calculated for an SES using the Breguet range equation [18] which is a formulation that takes account of the fact that SES drag and fuel burn rate (at a constant velocity) vary with ship weight as fuel is burned off [24].

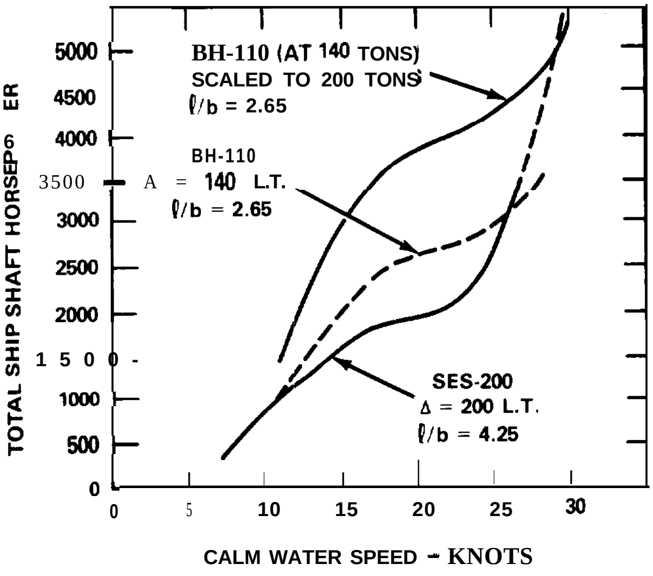


Figure 26. Comparison of BH-110 and SES-200 Performance.

If the BH-110 were scaled up by geometric and Froude scaling to be a 200-ton SES (by increasing the length, beam and cushion pressure proportionately), then it could also be compared to the SES-200. This has been done in Figure 26 (the highest of the three curves). In this case, 2,500 shp would only result in a velocity of about 13 to 14 knots as compared to 24 knots for the existing ship.

Between 25 and 30 knots, however, the SES-200 power can be seen to rise sharply (the dashed section is an extrapolation of existing data). For sustained operating speeds in excess of 29 knots, the l/b = 2.65 design may, indeed, be preferable; however, installed power for such an SES design would have to be substantially larger than that on the SES-200 at present.

SES-200 Scaled to Larger Displacements

Figure 27 shows the results of geometric and Froude scaling of the SES-200 to larger displacements (2,000. 4,000 and 8,000 tons) [19]. The 28-knot calm water top speed of the SES-200 Froude scales to the top speeds shown for the larger SESs; these are 41 knots for 2,000-tons, 46 knots for 4,000-tons, and 52 knots for the 8,000-tons. Table 3 provides the principal characteristics of the SES-200 and these larger SESs scaled-up versions.

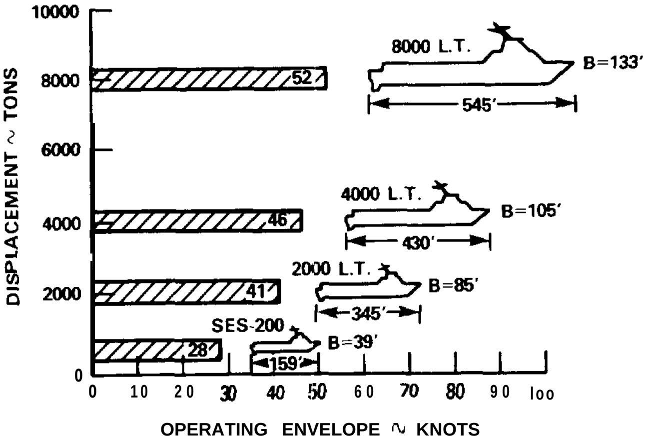


Figure 27. Operating Envelopes for 4.25 Length-to-Beam SES

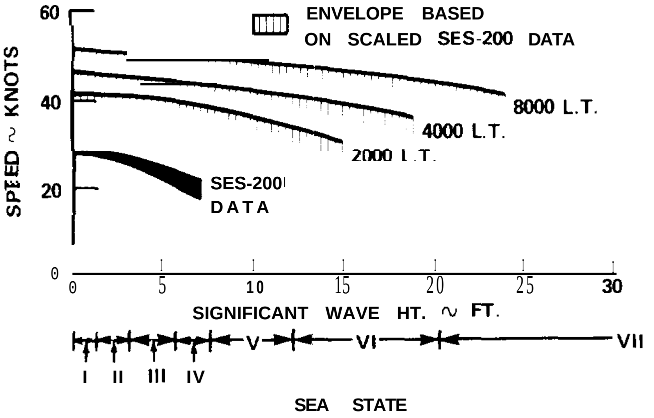


Figure 28. Speed vs. Sea State for 4.25 Length-to-Beam SES

The results of Figure 2’7 relate to calm water conditions. Naturally, in higher seas, the maximum speed of the SES-200 drops off. This is shown in Figure 28 by a small dark band of velocities for each sea state. The width of the band represents the fact that head. bow, beam, quartering and following seas all degrade speed, but somewhat differently: all degradations, however, fall within the dark band. Figure 28 also contains speed degradation for the larger scaled versions.

The SES-200 has operated at full power in sea states I, 2, 3 and 4 without excessive motion, slamming or deck wetness [19]. By Froude scaling these results also apply to the larger SESs and the proportionately higher seas shown in Figure 28.

It should not be inferred. by the SES-200 extrapolations to larger displacement SESs that these would necessarily be the recommended or optimum designs in each case.

Other SES Design Trends

Several major design trends are shown in Figure 29. On the right, the midship section of the SES-IOOB is pictured; these are relatively thin sidehulls. For several reasons. more buoyant sidewalls, such as those pictured on the left of Figure 29, have been considered and used for subsequent designs [25]. One reason is that propulsion engines fit down into such a sidehull more readily, with a reasonable amount of room for maintenance. Another reason is that the more buoyant sidehulls float the SES higher out of the water in the off-cushion (or catamaran) low-speed mode. The result is to raise the wetdeck and provide better low-speed (off-cushion) performance from both a powering and structural (wet-deck slamming) point of view. They also provide increased roll stability and improved partial cushion operations. Full displacement sidehulls were incorporated in the SES-200.

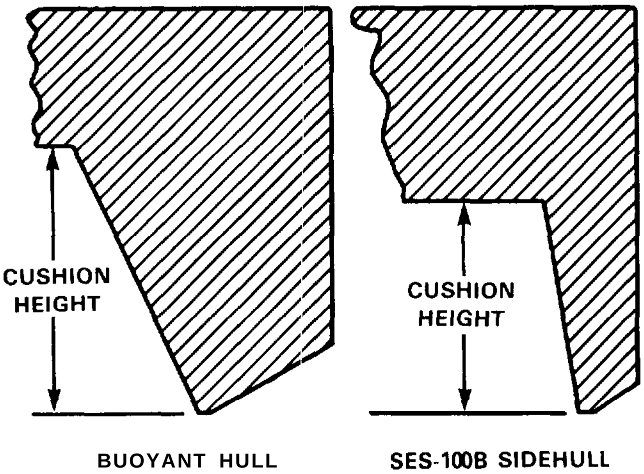


Figure 29. SES Sidehull Designs

A second design trend incorporated in the SES-200 was to make the wet deck at the bow higher (relative to the bottom of the sidehulls) than at the stern [25]. This has two effects, one is to augment the buoyancy at the bow (with depth) where the sidehulls are very thin. This allows a more bow-up trim (or at least a level trim) of the wet deck in the off-cushion (catamaran) low-speed mode. The second effect is to raise the bow more during high-speed (on-cushion) operation.

A third design trend, also illustrated in Figure 29, is that of increasing the cushion height along the entire length, which is independent of sidehull shape.

In spite of the advantages enumerated for more buoyant sidehulls. there are circumstances where thin sidehulls can be advantageous. Such a case is a ship which spends a lot of operating time at the high end of the off-cushion (catamaran) speed regime, where thinner sidehulls would have a lower drag and power requirement [26].

The surface effect catamaran shown in Figure 30 is an SES with two cushions in tandem and four relatively thin sidehulls. The cushion height in such designs is normally very high. Its characteristics are discussed in Reference [27].

All of the foregoing design trends tend to raise the wet deck higher out of the water. This results in improved off-cushion (low-speed) performance, as well as improved on-cushion (high-speed) performance, from both a powering and wet-deck slamming point of view.

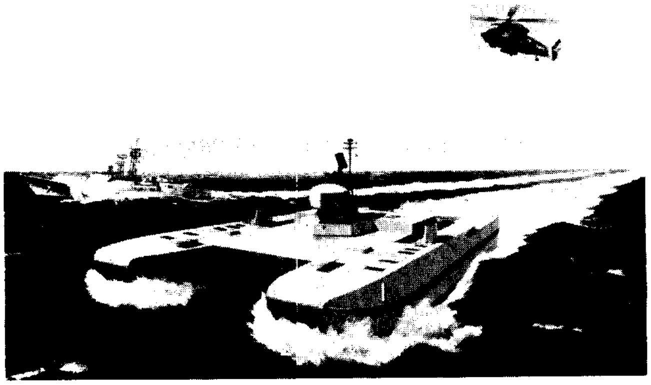


Figure 30. Surface Effect Catamaran—SECAT

STABILITY AND MANEUVERABILITY

The predominant features affecting stability include: location of the center of gravity (both longitudinal and vertical from the keel); sidehull length and deadrise; the type of bow and stern seals; the size and location of skegs, fences, and rudders; the type of propulsion system; and the type of maneuvering system. This large number of possible variations illustrate how many components contribute to the stability characteristics. Since the early SES design investigations in the 1960s, the nonlinearities in forces and moments which result from extreme conditions have been assessed principally from the results of static and dynamic stability model tests. Although a great deal of such test experience has been accumulated, these tests have mostly been limited to the characterization of specific designs with little attempt or opportunity to systematically explore any wide variation in hull form or basic stability parameters. Even model testing which followed the only known capsize of an SES (the XR-1 manned testcraft, on the Delaware River in December of 1964) was limited to the exploration of craft beam and sidehull deadrise [28, 29]. As a result of the model tests. the beam of the XR-1 was increased to improve roll stability. This accident and the model test that followed highlighted the significance of dynamic forces on the stability of SESs at speeds and the high degree of roll/pitch/yaw coupling that exists.

Intact static stability, although not completely representative of the stability characteristics of SESs at speed, provides a starting point in understanding the behavior of these craft.

Displacement ships achieve roll stiffness through lateral separation of centers of gravity and buoyancy, while the SES experiences forces due to both sidehull buoyancy and cushion pressure. At zero velocity, the buoyancy provides the restoring force, while cushion pressure acts in a capsizing sense. due to the vertical separation of the centers of gravity and pressure. To further complicate this issue, as the SES heels, the cushion pressure is progressively lost and the proportion of weight supported by buoyancy increases until at some point buoyancy takes over completely. At low Froude numbers ($F_n < 0.5$) this intact roll stability characteristic is quite common since the dynamic terms from forward speeds are not yet large enough to have a significant effect on the roll response.

At $F_n > 0.5$, forces developed on the planing surface of the sidehulls, on rudders and appendages, and from propellers acting in inclined flow are all very important in determining the stability behavior. In broad terms, roll stability reduces with increasing ship speed. This decreased roll stability, which is also common in a high-speed conventional ship, can be very critical during high-speed maneuvers, especially at $F_n > 0.8$. During high-speed maneuvers the primary capsizing moment is the centrifugal force of the ship. Because of the dominant effect of centrifugal force, directional stability also plays an important part. As modest changes in trim can produce marked changes in roll, any alternation to pitch or yaw stability will be reflected in the roll stability. Thus, factors such as seal design, inclined propeller force, rudders, appendages, etc., all play a significant role in designing a stable SES. Rudder sizing must be carefully assessed in order to produce a favorable inward banking moment to be balanced against the increased rate of turn and the effect of emergency rudder reversal for collision avoidance.

Added to more fundamental variables such as length-to-beam, sidehull shape and lift power, it will be appreciated that this adds up to a complex analytical problem to accurately predict a stable SES design.

The substantial database from model tests, in a nondimensional form, for various configurations has allowed the development of various maneuvering simulation programs to assist the designer in establishing stability criteria. These maneuvering simulation programs were developed:

1) To solve stability problems with a mathematical representation of dynamic response to a realistic disturbance.
2) To develop a realistic database of static and dynamic stability characteristics derived from testing various length-to-beam models that represent the linear and nonlinear behavior of forces and moments and coupled forces and moments as a function of forward speed, angular attitude, and rate of angular displacement.
3) To explore and analyze the effect of craft dynamic behavior of various dominant parameters such as vertical center-of-gravity (VCG) location, rudder size, propeller size and inclination, etc., for normal and emergency maneuvering operations.
4) To identify stability limits of given configurations during unusual system failure (propulsion or maneuvering) in a turning maneuver and produce means of controlling these instabilities.

Maneuver simulation programs basically take the equations of motion of the vehicle and solve for a given situation. By using known hydrodynamic parameters established either from model and full-scale tests or theory, a relatively realistic representation of the ship motion characteristics can be simulated [30,31]. For example, location of vertical center-of-gravity limits for high-speed

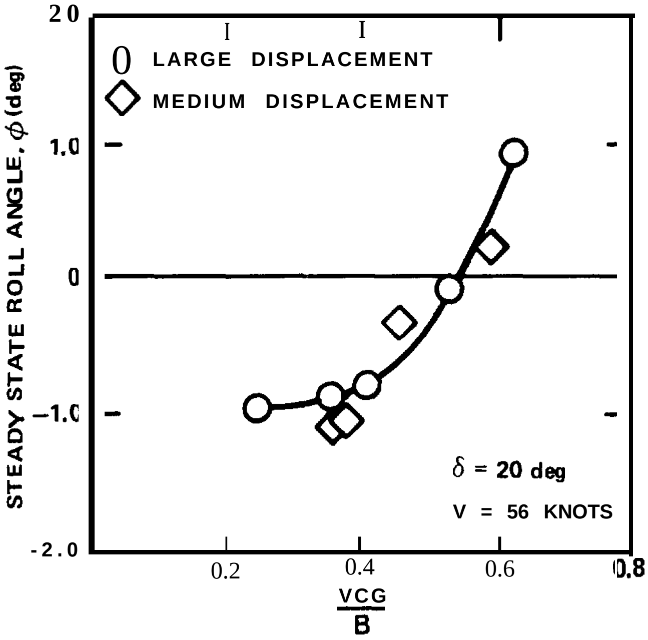


Figure 31. Roll Response of' l/b 5.0 Medium (1500 LT) and Large (10,000 LT) Displacement SES

turn maneuvers can be determined. Figure 31 shows results for normal high-speed maneuvers and illustrates that a definite VCG limit must be established in an SES design in order to provide a roll stable ship. These limits can also be checked for the case of high-speed propulsion or rudder failures. Having the worst-case results simulated, the designer can then produce a design that can respond safely to these situations.

The U.S. Navy and the U.S. Coast Guard have in recent years developed simulation routines that use model data or testcraft data to establish stability standards for safe operation of SESs at various ship speeds. These programs are used as tools in determining and establishing the stable limits of a craft for which there is established model data. The Coast Guard has taken some steps in establishing stability standards by using their SES maneuvering simulations. This program has provided guidance to the designer to establish "safe" stability limits while not invoking rigid standards that would hamper the development of state-of-the-art designs. The Navy. although it has not published a standard stability criterion, has been using maneuvering simulations which have a very sizable database to establish safety limits for various length-to-beam ratios and to provide information on controllability in the event of a propulsive failure when in a high-speed turn.

Results from simulation programs have shown that wide spacing of propulsor and rudder permits use of differential thrust for improved maneuvering. The program also showed that inclined rudders provide a way of improving roll stability for various ship maneuvers. Inclined rudders have been applied successfully to the HM2 and HM5 series of SES built by Vosper Hovermarine in England.

Research is continuing to refine simulation programs to increase confidence-levels in the prediction of stability and maneuvering characteristics. Purely theoretical approaches are useful for early stage sensitivity studies [30]. Use of the methods of numerical hydrodynamics should improve existing approaches for examining three-dimensional flow around sidehulls at the free surface and will undoubtedly provide an even more solid analytic base for future designs [33].

SEAKEEPING

Waves induce motion by affecting the air cushion that supports the SES and by creating hydrodynamic and hydrostatic forces which act on the catamaran hulls.

Pumping is the term used to describe the passage of waves through the air cushion. In this compressible process, the rate of change of cushion volume is converted to a rate of change of cushion pressure in accordance with the gas laws. In moderate seas these pressure changes do not exhibit significant variation along the length of the cushion, and therefore they only produce heave (vertical) motion. In large waves the pressures exhibit some spatial variation due to partitioning of the cushion, and the resulting pressure gradients contribute to pitch (angular) motion.

The wave train that passes through the air cushion undergoes an unsteady deformation because the water surface deforms under the action of cushion pressure. That is, the free surface does not behave like a rigid boundary but instead participates in determining the net change in cushion pressure.

The bow and stern seals are flexible structures which ideally should track the rough water surface to maintain a uniform rate of air leakage. In practice, the seals may be deformed by the waves or they may be unable to compensate for relative motion between the craft and the water surface as they are restrained from dropping below the sidehull keel line. For these reasons, the cushion leakage is not always uniform and the wave induced variation in leakage can cause additional heave motion.

Hydrostatic and hydrodynamic forces are primarily responsible for pitch and roll motion. Hydrodynamic pressures acting on the sidehulls produce added mass and damping effects. Additionally, impact pressures may act on the wet deck during slamming in large waves. Hydrostatic pitch and roll restoring forces for hullborne and cushionborne operation are produced by sidehull buoyancy.

Motions

SES motions largely depend upon the degree of synchronism or tuning between the wave encounter periods and the ship's natural heave, pitch and roll periods as well as the damping in each of these modes. For cushionborne operation, examples will be presented to demonstrate that SES heave and roll periods are so short that tuning with large amplitude waves in high sea states does not occur. Tuning with the pitch period can be minimized if the SES

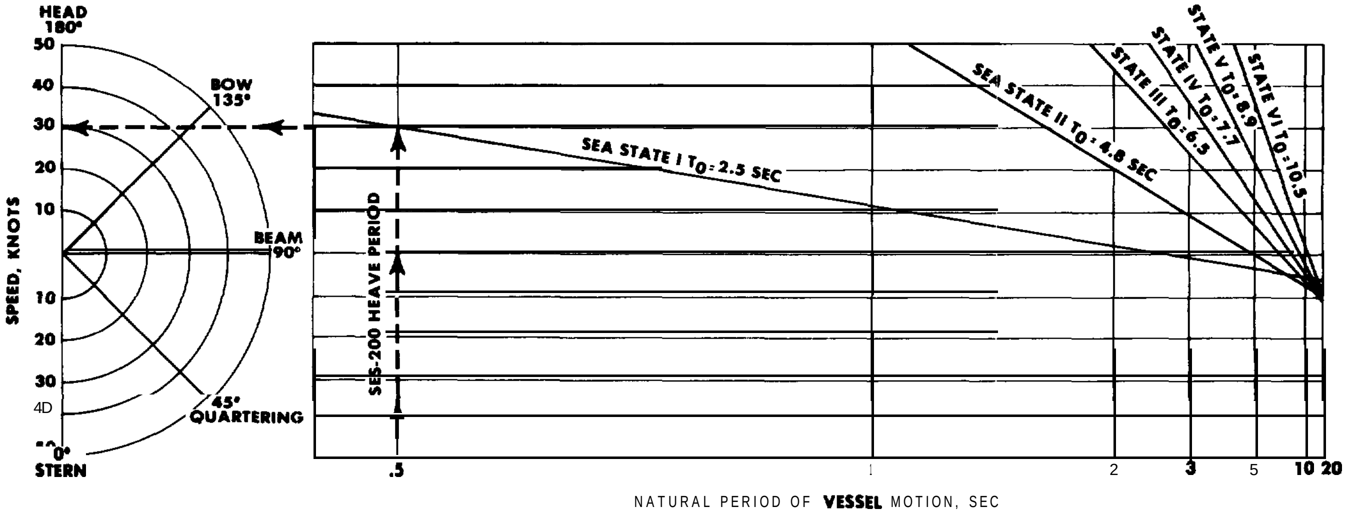


Figure 32. SES-200 Heave Period.

operates at high enough speed to avoid synchronism with the longest waves in prevailing storms. As this is not always practical, the SES must have sufficient pitch damping to operate when resonant conditions occur.

Figure 32 is a nomograph that identifies combinations of sea state, ship speed, and wave direction where the wave period of maximum energy matches the natural period of ship motion [34]. This nomograph was constructed by making the following simplifying assumptions

1) Seas are long crested.
2) Wave periods of maximum energy for a given sea state are based on the Neumann wind/wave relationship [35].
3) Natural periods of ship motion do not change with speed.

During cushionborne operation, air pressure supports most of the weight, and the natural heave period of this pneumatic suspension system is so short that tuning with large amplitude waves does not occur. As an example, Figure 32 shows that the SES-200 which has a 0.5 sec heave period experiences tuning during head sea operation at a speed of approximately 30 knots in sea state 1. As the heave damping is fairly low, this results in a relatively bouncy ride which has been referred to as the "heave bounce" or "cobblestone effect."

In other conditions such as larger waves, reduced speed or off head seaway directions, Figure 32 shows that the encounter periods are much longer than the heave period and tuning cannot occur. There will be some response at the heave resonance. However, most of the wave energy and resulting heave response is concentrated at lower frequencies where only those wave components which cause large changes in the cushion volume produce significant response. The cushion pumping minima, i.e., the frequencies where an integral number of wave lengths just fit into the cushion and hence produce no forced response, can be observed in test data.

Heave damping decreases with increases in the slope of the lift fan curve at the nominal operating point (Figure 33). Flatter fan curves increase the damping and steeper curves reduce damping,

Ride Control

A ride control system (RCS) provides a means of increasing the heave damping which in turn reduces the wave-induced pressure changes in the air cushion.

These systems have been successfully demonstrated on small and large Navy testcraft, and the RCS is now recognized as an integral part of the SES system. It is used full time during cushionborne operation as it substantially improves the ride at moderate-to-high speed and is particularly effective at smoothing out heave motion in the vicinity of the resonant frequency, as shown in Figure 34.

In this figure, the SES-200 heave acceleration is plotted in ⅓rd octave band format for RCS-Off and RCS-On operation at full power in low sea state 2/high sea state 1 conditions. Also plotted are the ⅓rd octave band acceleration limits given in 130-2631, "Guide for the Evaluation

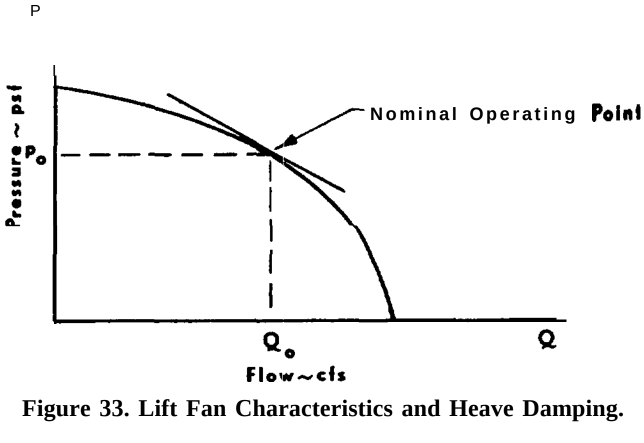


Figure 33. Lift Fan Characteristics and Heave Damping.

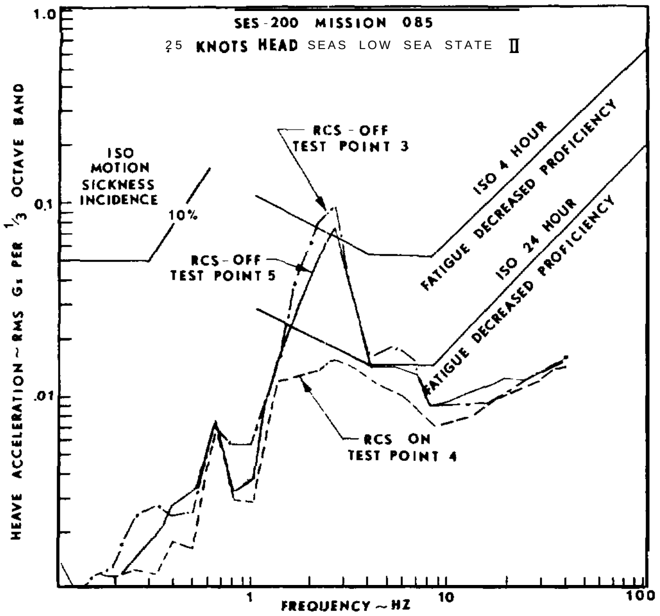


Figure 34. SES-200 Heave Acceleration per ⅓ Octave Band Low Sea State II.

of Human Exposure to Whole Body Vibration." As shown with the RCS-Off, the accelerations at the 2 Hz heave frequency exceed the 4-hour criteria. With the RCS-On, the accelerations are below the 24-hour criteria at all frequencies.

A ride control system (Figure 35) regulates the cushion pressure by using cushion vent valves (VVs) and/or fan inlet guide vanes (IGVs) to modulate the mass of air in the cushion. IGVs modulate the cushion in-flow which increases the damping by flattening the slope of the lift fan curve. Vent valves produce the same effect as IGVs by modulating the cushion outflow instead of the in-flow. A number of these devices have been laboratory tested and verified on such testcraft as XR1-D, SES-100A and SES-200.

As indicated in Figure 35, it is desirable to use an integrated system employing both fan and vent valve flow control. The IGVs are used in the lower sea states to throttle the fan inlet flow. This is more efficient than dumping pressurized air overboard through vent valves. However, during large pressure excursions in high seas, the vent valves are used in conjunction with the IGVs to increase the total flow modulation capability.

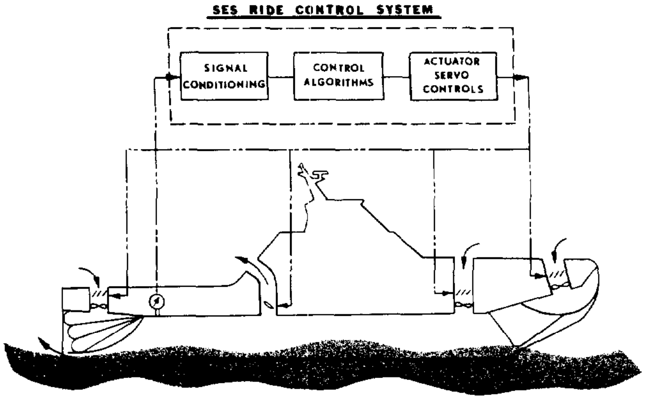


Figure 35. SES Ride Control System.

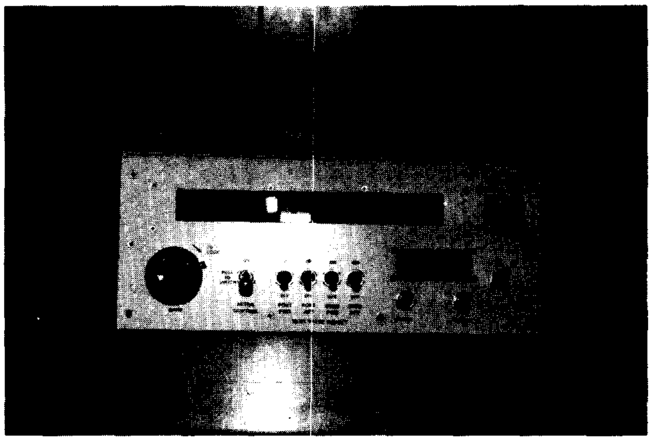


Figure 36. RCS Control Unit.

As a result of Navy development work, the control unit and the vent valve hardware have reached the prototype stage and have been subjected to rigorous shipboard testing on the SES-200. These components, which are illustrated in Figures 36 and 37, were designed and fabricated by Maritime Dynamics, Inc.

The control unit is a dedicated microprocessor-based system that can be used on different size vessels simply by changing control law coefficients stored in software. The vent valves consist of a set of louver vanes that are mounted in a modular frame. Each module contains a hydraulic actuator to drive the vanes, a servovalve to direct flow to the actuator. and an actuator position feedback transducer.

Control algorithm design has proceeded along both classical cut-and-try approaches as well as by the state variable methods of modern control theory. There are numerous lightly-damped modes in the pneumatic suspension system of an SES which enter in the control system's bandwidth and extend it to quite high frequencies. For this reason, it has been found that the linear quadratic Gaussian method of modern control theory of-

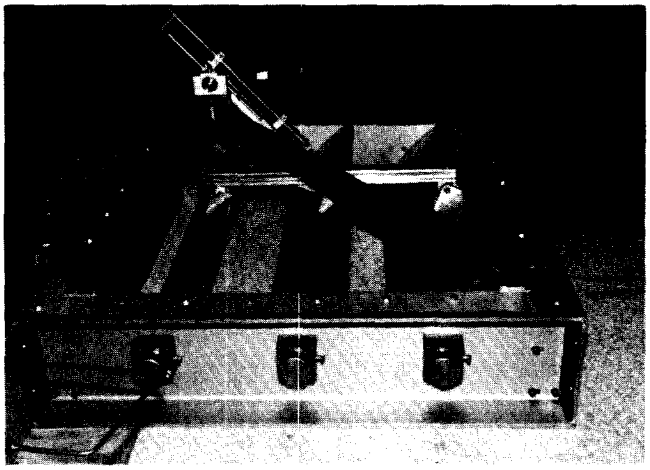


Figure 37. Vent Valve Assembly.

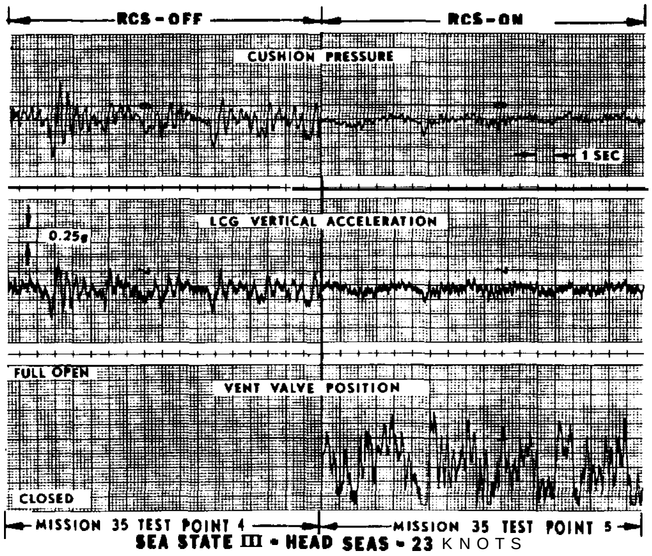


Figure 38. RCS Performance on SES-200.

fers the most systematic approach for arriving at a regulator that offers a good compromise between performance and stability while maintaining realistic constraints on control power and actuator motions.

Vent valves expend lift power by dumping pressurized air overboard while devices which throttle the fan inlet flow absorb power by decreasing the overall lift fan efficiency. If additional lift power is not installed to compensate for these effects, a small speed loss may have to be accepted during RCS operation. Also, a small amount of hydraulic power is required to move the fan and vent valve control surfaces.

The system on the SES-200 was tested without providing any additional lift power for ride control. Even though this caused the system's effectiveness to diminish with increases in sea state, the system was capable of reducing the RMS heave accelerations by 50% in sea states 1 and 2. 30% in sea state 3 and 25% in sea state 4 [19]. These reductions were obtained by limiting the vent valve motions such that the speed losses were restricted to less than 1 knot. Strip charts illustrating the system's effectiveness in sea state 3 are shown in Figure 38.

Pitch

SES pitch motion is typically favorable to high speeds in heavy weather due to the platform's low displacement-length ratio and fine sidehull lines. Pitch damping derives primarily from sidehull inviscid and viscous damping. Several planing seal concepts have been tested which provide additional pitch damping.

Typical trends exhibited are that only wave components longer than the sidehull length cause appreciable motion, and the largest responses occur when the encounter period in large head seas tunes with the natural pitch period. As synchronous pitching can give rise to slamming, it exerts the largest single influence on reducing SES speed in heavy weather.

Since the SES primarily offers a speed advantage, it is desirable to avoid synchronous pitching by achieving supercritical operation. This is accomplished by adjusting the hull form and weight distribution to obtain as long a pitch period as possible and then operating the ship at a sufficient speed to avotd synchronism with the large waves in the prevailing storms.

The SES-200's 3-second pitch period is plotted on the nomograph in Figure 39. In this example, the ship does not achieve supercritical operation. Therefore, the pitch period tunes with the waves in sea state 3 for head sea operation in the 20-25 knot range. However, the SES-200 has sufficient pitch damping that the motions measured under these conditions did not exceed the 3-degree single amplitude limit that is typically used to assess a surface ship's potential for helicopter operation [19, 36].

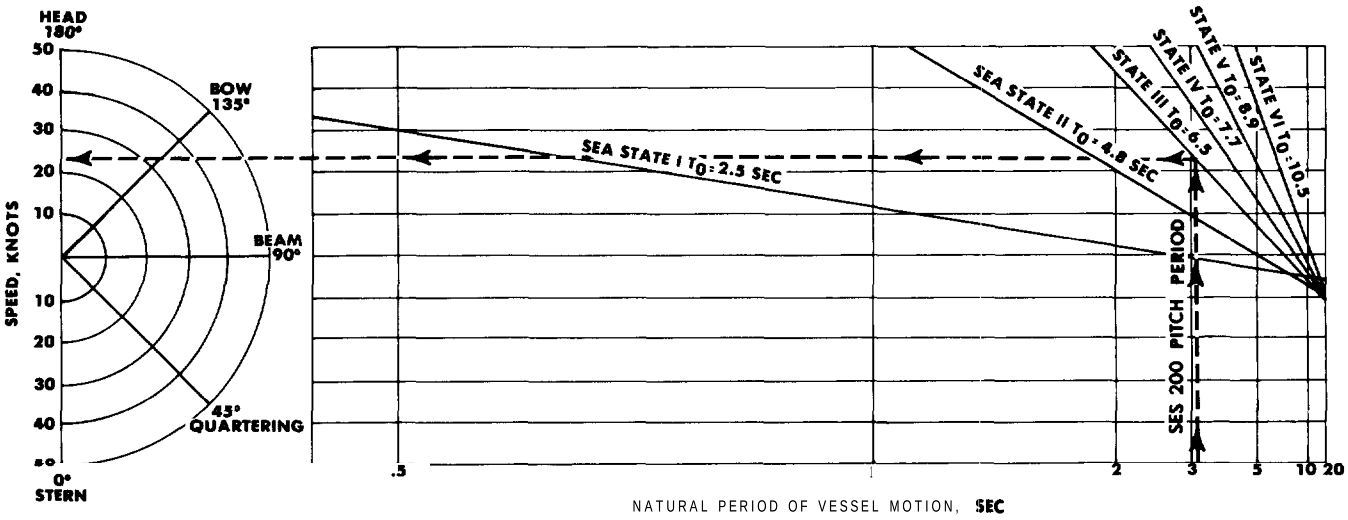


Figure 39. SES-200 Pitch Period.

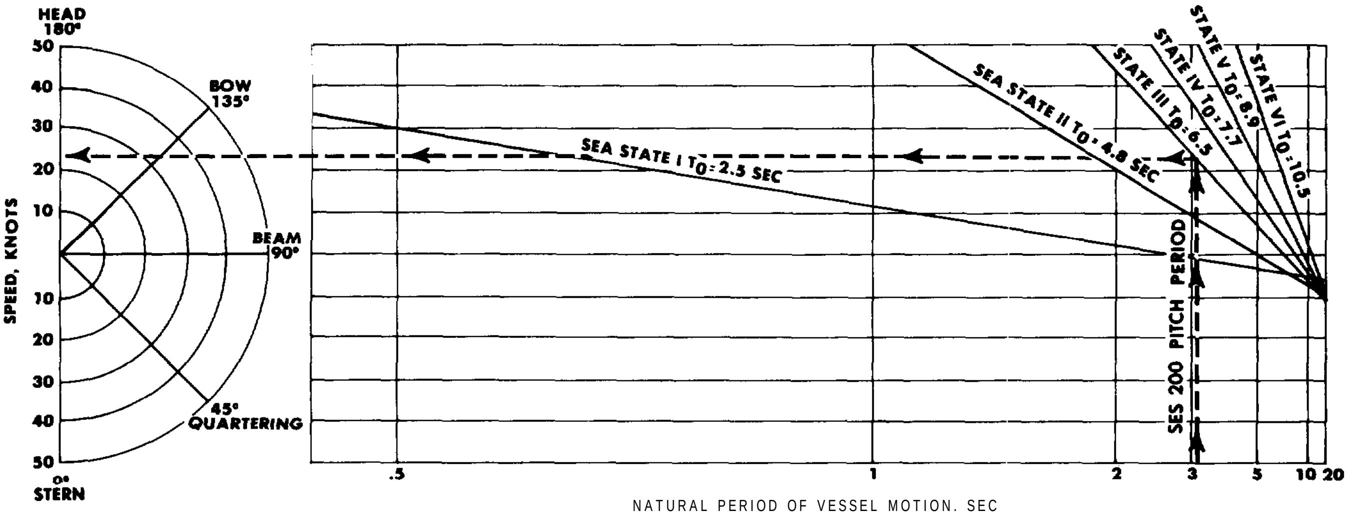


Figure 40. SES-200 Roll Period.

Roll

The SES's catamaran hull provides a short natural roll period and large roll restoring moments for both hullborne and cushionborne operation. The SES-200's roll period is plotted on the nomograph in Figure 40. Synchronous bow, beam and quartering sea conditions occur in low sea states. However, the wave forces are not large enough to cause excessive motion under these conditions [19]. During forced rolling in larger waves, the SES-200 tends to roll with its deck edge parallel to the water and therefore does not experience large roll amplitudes.

One adjustment which SES operators learn is that the heave and roll periods are much shorter than those found on monohulls of comparable length, hence the vertical and lateral accelerations occur at higher frequencies. In general, this has not caused any habitability problems. Additionally, both Navy and Coast Guard operators have commented very favorably on the SES's lateral stability in a seaway.

*Slamming and Shipping **of** Green Water*

SES slamming is confined primarily to head and bow sea conditions when the significant wave heights greatly exceed the wet deck height. Full-scale hullborne and cushionborne slam data were acquired using the XRl-D and XR-5 testcraft. Critical areas identified for design purposes are the bow ramp and the wet deck at the stern. When speed is reduced to minimize or eliminate slamming, cushionborne operation provides the best ride.

SES decks are often damp from spray entrained in air escaping from the cushion. However, the ample freeboard afforded by cushionborne operation keeps the deck free of green water. High freeboard also keeps the bow and deck edge from plunging into waves during extreme motions.

Motion Prediction

Model Tests. Tow channel model tests are often performed to evaluate the motions of a candidate SES design. If the atmospheric pressure is not Froude scaled, model tests do not completely scale the SES heave resonance, therefore care must be used when predicting motions near the heave resonance points.

However, even without atmospheric pressure scaling, the pitch motions and the low-frequency heave motions are properly scaled. Since these low-frequency responses are important to seakeeping, motion sickness indices, and ship operations, such as helicopter launch and recovery, the model test is a very useful design tool.

Simulation. Both linearized frequency domain and nonlinear time domain motion simulations have been used to evaluate SES motions. In past applications, program predictions have been successfully correlated with measured experimental values and full-scale results.

The linearized treatment of an SES differs from the case of the monohull in that the linearization takes place about the mean values in the wave environment of interest rather than calm water conditions. This effectively accounts for the change in mean heave and pitch position that occurs during operation in different sea states.

The advantage of a linear program is that statistical results are obtained using standard power spectral techniques. This exact treatment of statistics is, of course, obtained at the expense of approximations of the physical model of the craft. In the 'case of an SES, the most severe nonlinear element is the cushion leakage in large waves. When an accurate representation of the cushion pressure variation with time is needed, a nonlinear time domain simulation is usually utilized.

Future Developments in Motion Control

Twin Cushion. The surface effect ship catamaran (SECAT) is a twin cushion SES that offers both increased stiffness and damping in roll because the heave stiffness and damping of each cushion act on the cushion separation arm. This concept, which has been investigated at model scale [27], provides sufficient static roll stability to permit the use of a considerably higher center of gravity location than a single cushion SES of the same planform area. In turn, this may permit the use of higher wet deck heights which facilitates operation in higher seas.

This concept also provides a means for an air cushion regulated RCS to operate effectively on roll (as well as regulating heave acceleration as in a single cushion SES). This would be accomplished by regulating the pressure in each cushion independently.

The use of a single horizontal foil to damp pitch motion was also investigated during the SECAT model test program. This foil was very successful on SECAT as it has been on other catamaran ships [37], and early single cushion SESs such as the SES-100A, which used multiple foils for additional pitch damping.

Rudder Roll Stabilization. Much success has been achieved in damping displacement ship roll motions by using the rudder as a stabilization device [38]. These principles also have been successfully applied to the HM2 and HM5 series of SESs built by Vosper Hovermarine in England.

Future: New ride control strategies using inertial reference systems and bow height sensors to anticipate the wave action are being investigated and future tests on the SES-200 may be forthcoming.

STRUCTURES

The box like shape of the SES greatly simplifies the design and fabrication of the hull. Typically the structural weight fraction (structural weight/total ship weight) runs between 28 to 35%. This section presents the structural design method which was. developed for SES and which is also compatible with all surface ships. It addresses the reliability method for load determination and prediction of structural weight, as well as design criteria and materials.

Using the reliability approach to design various ship types which are seen as candidates for performing a given mission yields an important benefit. It is a method for making direct comparisons which are independent of the dominant physics (most important physical effect) for a particular type of ship. This comparison is made by specifying that the reliability of the ship or of a particular subsystem, such as the structure, be the same for all the candidate ship types or variants proposed for a given mission. The effect of specified changes in reliability upon total ship size and weight may be evaluated by using nonlinear optimization programs such as SHIPDOC [39], which. since it uses the ship description as data to the optimization, may be used to evaluate any ship type.

Using overall or global structural loads as an example, it is found from experiments that the cause of the greatest load acting on the structure is different for different ship types. For a monohull, t'he longitudinal bending moment arising from the differences between weight and buoyancy loads (W-B loads) is dominant; for a SWATH, the transverse bending moment due to forces acting on the sidehulls is largest or dominant; while for SESs the off-cushion longitudinal load due to head sea slamming in survival sea states is dominant.

This difference in the dominant load for the SES compared to a monohull, coupled with the difference in how the SES is supported (by air cushion), leads to increased flexibility for the designer with regard to shape and proportions. The wetdeck height may be adjusted to provide the optimum balance between structural loads (and therefore structural weight), motions, stability, and resistance.

While cushionborne, the wetdeck rides high enough above the calm water surface so that for multithousand ton SESs it is above the significant wave height for sea states 5 and 6. When operating hullborne, current design practice results in the wetdeck being clear of the calm water surface by an amount corresponding to between 1-3% of the cushion length. This occurs in part because many mission requirements result in (a) higher l/b ratios ranging from 4-8, (b) increased thickness of the sidehulls, and (c) a relatively higher wetdeck than for lower l/b designs. The SES is thus a ship in which the principal payload section is hydrodynamically separate from the portion of the hull affected by the passage of water.

This significant uncoupling of the shape from hydrodynamic constraints has several important consequences. First, from the designer's point of view, there is increased flexibility in the choice of the SES's shape and therefore general arrangements. Secondly, the shape can be more easily tailored to provide simplicity (and therefore lower cost) of fabrication. Thirdly, and not so obvious, there is a relative change in the magnitude of the various physical forces which influence the required structural strength. The most important physical forces for the overall structural design are experimentally determined to be those due to slamming on the forward part of the wetdeck while in a hullborne operating mode in a head sea survival sea state. This experimental finding is quite different than that for a monohull for which the weight minus bouyancy force distribution load is dominant. An extremely important consequence is that much monohull experience is not directly applicable to SES overall load estimation since dominant loads are physically different. Further, current monohull design practice is to use a nominal load determined by the static balance of the ship on a wave of arbitrary shape and proportion, in conjunction with material allowables. for a given overall loading condition. Thus the design method for overall strength used for monohulls is not applicable for SES.

The method which has evolved over a period of years is to use what are called first principle, rational, or engineering science methods. These methods experimentally and analytically estimate the forces and the variability of the forces which act simultaneously on the ship. This approach also examines the properties and the variability of proposed materials. Finally, because both forces and materials are experimentally found to have variability in their magnitudes and properties, a reliability is chosen which is commensurate with the mission at an acceptable risk. This selected reliability determines the value for forces and material property values to be used for design.

For other than local and point loads, there are two types which the entire structure must withstand. One is the largest single event load over the ship's lifetime and the second is the cumulative fatigue loading. For SES the single largest lifetime load usually requires that more strength be provided in the structure than is demanded by cumulative lifetime fatigue loading.

Lifetime Load Estimation

The method used to arrive at loads uses experimental results from model and manned testcraft, extrapolates these results to the desired size, lifetime operational time, and desired reliability level. Physical scaling laws and a reliability approach are used to account for any other differences between model and full-scale operational time as well as for estimating the design load corresponding to a particular reliability level.

Load magnitudes have been measured using both towed tank models and manned testcraft ranging in length from 7 feet to 80 feet. Many of the towed tank models are also constructed to Froude-scale the structural stiffness so as to be able to model the dynamic response due to wave impacts on the seals and hard structures. These models contain known load paths so that the response distribution may be measured using only a few load sensors. It is more difficult to estimate the total load acting on manned testcraft because, as predominately performance models, they contain multiple and redundant structural paths which complicate load measurements.

Current structural load models have sensors which simultaneously measure the longitudinal distribution of bending moment, transverse bending moment, local pressures, accelerations, and model motions. The model is tested in a random sea environment corresponding to a particular sea state for a sufficient length of time to accumulate a statistically significant number (approximately 400) of events or encounters. For structural load tests the models and manned testcraft are predominantly tested in head sea conditions since both previous experimental work and numerical simulations indicate that head sea conditions result in the most severe loads.

There are three steps in making use of experimental or numerical results obtained in random seaways: 1) find the statistical distribution which best fits the experimental data, 2) find the most probable maximum lifetime load, and 3) find the factor which multiplies the most probable lifetime load to result in a load which has the specified reliability (specified risk of exceedance).

The results from the experiment are analyzed to see how well they fit a particular statistical distribution. The distribution most usually found to represent the results is the Weibull distribution.

$$P = 1 \quad e^{-(x^{c})}$$

where P is the probability that the load is x or less in magnitude, x is the load of interest and c is the slope of the distribution. The slope c = 2.0 corresponds to pure wave motion related responses, while slope c = 1.0 corresponds to pure slam related responses. Both of these special cases previously have been found to represent theoretical responses of ships in a random seaway.

Having found a statistical distribution which represents the experimental results for a particular sea state, speed, heading, and loading condition, the next step is to estimate the most probable lifetime load by finding a load value (X_{mp}) corresponding to the number of lifetime encounters. This is estimated from the operational profile which shows the distribution of lifetime hours in a particular sea state, speed, loading condition, and operating mode. The most probable load is the largest, or extreme load most often measured when a large number of ships are sent into the same operating conditions, or conversely, the largest or extreme load most often measured if a given ship were exposed to the same operating conditions for a large number of times.

The final step in design load specification is to find the factor which covers a specified probability of occurence of the most probable loads. This factor which would cause the largest load to be exceeded only in 1% (1 in a 100, or 0.99 reliability) or 0.01% (1 in 10000, or 0.9999 reliability) may be computed, and, when multiplied by X_{mp} gives the desired once-in-a-lifetime design load with a specified reliability for the particular operating conditions.

Cumulative Fatigue Loading

The cumulative fatigue loading may be estimated by application of a cumulative damage rule such as Miner's rule.

$$\sum_{i} \frac{n_i}{N_i} = K$$

where

n_i = actual number of cycles at level i
N_i = number of cycles at level i to cause failure (usually obtained from S-N curves for the material)
K = constant of summation, approximately ⅓ to ¼ for 3 to 4 ship fatigue lifetimes

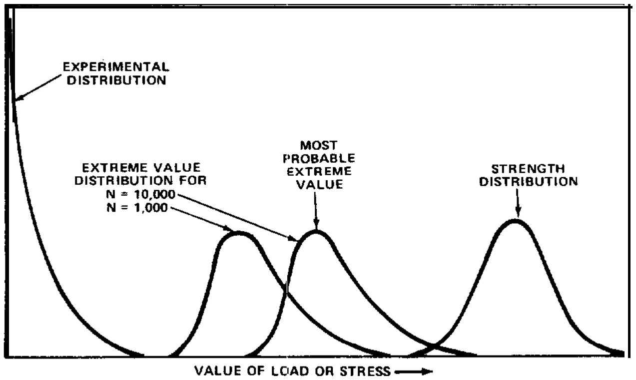


Figure 41. Probability Density Distributions.

In order to apply Miner's rule we need to know the number of loading cycles for each loading intensity. This information is known since we have the experimentally estimated probability density loading curves which were earlier used to estimate the extreme values. The stress which is used for computation is the nominal stress multiplied by the stress concentration factor applicable at a particular location. If the fatigue stress found for the lifetime number of loading cycles is greater than the cumulative damage stress, then the fatigue strength of the ship is adequate. Due to uncertainties in the order of applied loads, the ship is usually required to show a fatigue life which is 3 to 4 times greater than the estimated lifetime of the ship.

Figure 41 presents a typical result from a reliability analysis of both primary loads and required strengths.

Four probability density distribution curves are shown. The leftmost shows the experimental data distribution. The two middle curves show the distribution of the largest, or extreme values, for repeated trials when the test sample size consists of 1000 events and of 10000 events. The shape of these distributions depends upon the sample size and distribution of the experimental data. The rightmost curve shows an estimate of the distribution of the strength of the ship.

If we build a large number of "supposedly identical" ships and then incrementally load them to failure, there will be a range of failure loads since there are strength differences, due to differences in the metallurgical strength of the plates and shapes, shape thicknesses, straightness of plates and shapes, weld strength, quality of fit up (alignment), principal dimensions and location of decks and stiffeners on decks, residual stresses, and amount of stress relieving. If we count the number of failures due to each incremental load and divide by the total number of failures, the resulting plot will approximate the shape of the strength probability density curve.

The most likely load corresponds to the peak of the probability density curves. The magnitude of the load corresponding to the peak of the strength curve is called the most probable strength.

The shape and magnitude of the load curve can be found by applying extreme value theory [40] to the results of experimental tests. The exact shape and magnitude of the structural strength curve is not completely known, however ongoing work is providing better definition to this area [41]. In the meantime, two assumptions are made: first, that the shape of the curve is Gaussian, and second, that the overall strength of the ship is taken to be that corresponding to the yield strength of the material in tension (not the ultimate strength), or the buckling strength of local structure where the yield or buckling strength is taken to be that corresponding to using the as-welded minimum mechanical properties. There are three elements of conservatism in using this approach: (1) 99 percent of the welded joints are stronger than minimum mechanical properties, (2) the difference in strength between yield and ultimate strength is ignored, and (3) the post buckling strength of the structure, which may range from 1.3 to 2.0 times the yield buckling strength, is ignored.

Structural Criteria

The structural criteria specifies the load magnitudes and their combinations, the factors of safety, and sometimes the material allowables and analysis methods or guides to be used.

Combined load sets are the sets of loads which occur simultaneously on a structural element. Each set specifies the overall or global loads, such as bending, and ship motion loads such as acceleration, and local area loads such as fluid or point loads. Material properties, rather than material allowables, are specified which is consistent with using lifetime loads estimated from actual data.

Materials

Materials used to date for hulls are high-strength marine service aluminum alloys of the 5000 series and glass reinforced plastic (GRP). The SES-100A and SES-200 are predominantly 5086, the SES-100B is 5456 and all of Vospers HM-2 and HM-5 series craft are GRP. As SES sizes grow larger, the use of high strength steels becomes attractive, especially those having yield strengths of 80 ksi and above such as HSLA, HY80, and HY100. The choice of which material to use from a weight viewpoint is determined by comparing the weight of an aluminum structure plus fire insulation sheathing requirements against the weight of a steel structure.

Structural Design

Once the structural criteria specifying the combined loads and factors of safety are available, the remainder of the design can be carried out by current design techniques including the use of structural optimization programs such as described by Hughes [42].

The resulting structure is usually a longitudinally-framed plate and grillage. Closely-spaced longitudinal stiffeners, which may consist of tees and/or flatbars, usually result in a minimum weight design. Additionally, large amounts of permanent set are often tolerated in the wet deck area since the deck is usually close to the neutral axis and so contributes little to longitudinal strength.

PROPULSION

The rigid sidehulls of the SES in contact with the water provide the means for marine propulsion systems which use water rather than air as the medium of thrust production. This allows the SES to avoid the inefficient, large and noisy air propulsors required by the amphibious ACV.

The types of propulsors which are suited to the SES include conventional fully-wetted or transcavitating propellers, fully cavitating or supercavitating propellers either surface-piercing or fully submerged, fixed or con-

Table 3. Principal Characteristics, 4.25 Length to Beam SES

	SES-200	2000 *L.T.*	*4000 L.T.*	8000 *L. T.*
Length Overall (ft)	159.1	345	430	545
Beam Overall (ft)	39.0	85	105	133
Depth Molded (ft)	15.2	33	41	52
Wet Deck Height (ft):				
Bow	7.5	16.2	20.4	25.6
Stern	5.0	10.8	13.6	17.1
Cushion Length (ft)	133.3	287	362	456
Cushion Beam (ft)	31.6	68	86	108
Primary Hump Speed (kn)	33	48	54	61
Froude Scale Ratio (X)	1	2.2	2.7	3.4

trollable pitch propellers, and waterjet propulsors with fixed or variable area inlets of either the flush/semiflush or strut-pod type. Air propulsors of the open propeller or jet type will not be discussed as they are not appropriate competitors to the "water-medium" propulsors for SES application in the speed ranges of interest.

The propulsor selection is a part of an overall design process in which numerous practical trade-offs must be made. Critical factors affecting the selection of the propulsion system include top and cruise speeds, ship length-to-beam ratio (l/b). ship size, range and endurance, sidehull geometry, engine matching, draft, vulnerability, and maneuverability.

Speed

When deciding on a propulsor type, the first consideration is the maximum and cruise speeds desired. One subdivision of speed categories which has been used is as follows:

0 to 20 kts	Low Speed
20 to 40 knots	Moderate Speed
40 to 60 kts	High Speed
60 to 80 kts	Very High Speed
Above 80 kts	Ultra Speed

Five to fifteen years ago there was a great deal of interest in SES capable of ultra speeds. The U.S. Navy at one time envisioned a "100-knot" fleet as a desirable goal. As the SES program evolved through the 1960s and 70s, the speed goals were reduced to the very high speed category and finally to the high speed category. Although the technical problems associated with the higher speeds were by no means trivial, the reasons for this speed reduction had more to do with mission, cost, and fuel economy than with the technological difficulty of achieving the speed goals.

The principal physical consideration in achieving high speed is cavitation. The vaporization and subsequent collapse of vapor bubbles in the water can introduce problems of noise, unsteady force, material damage and reduced efficiency. The avoidance or management of cavitation at the propulsor is the single factor which most affects the type best suited to a particular speed range. While speed and cavitation are major factors in selection, they are certainly not the only factors. At any speed several candidate propulsors may be considered optimum depending on the goals of the design and other physical factors.

Figure 42 shows the approximate installed propulsive efficiency range for propellers and waterjets. Based on this plot and in the absence of other criteria, one would be inclined to choose conventional propellers in the low and moderate speed ranges, conventional or fully cavitating propellers in the high-speed range and surface-piercing or partially-submerged propellers in the very-high and ultra-speed ranges.

Length-to-Beam-Ratio

The selection of l/b largely determines the shape of the resistance curve of the ship over its speed range. Since the propulsor is required to provide adequate thrust and thrust margin, for acceleration over all portions of this speed range, the l/b ratio directly affects the selection of the propulsor. As discussed earlier, low l/b designs result in higher drags at the so called "hump" condition (peak wave drag) but provide a low relative drag at high speeds. High l/b designs have reduced hump drag, sometimes to the point of insignificance, but they have increased high speed drag. The requirement that high thrust levels be provided at both high-speed and low-speed conditions may require the use of controllable pitch propellers or, for

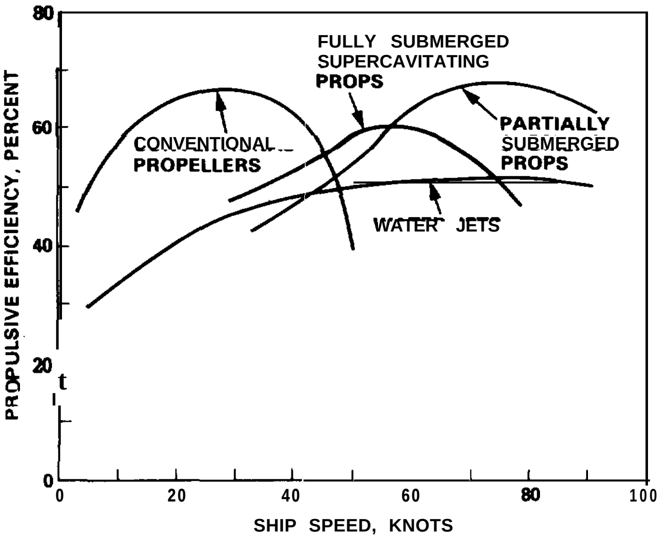


Figure 42. Approximate Installed Efficiencies for Various Propulsors

a surface-piercing propeller, control of the amount of submerged disk area. For waterjet propulsors, high hump resistance may dictate the use of variable-area inlets or sophisticated pump designs.

Size

In accordance with Froude scaling where the wave resistance of a hull is characterized by the Froude number (F,) based on length, the hump speed increases with size even if the l/b is unchanged. Thus, reasonably large l/b ships are capable of cruising at relatively high speeds while remaining in the sub-hump speed range. This greatly simplifies the propulsion problem and produces a resistance curve more like that of a displacement ship. Another influence of ship size on propulsor choice is the high horsepower level required by a large, high-speed SES and the difficulty in combining and transmitting such power to a limited number of propulsors. This tends to make the waterjet propulsor more attractive relative to the propeller due to its modularity. It is easier to divide the total propulsive power of an SES, with limited structural stern width, among several waterjets than among several propellers. Overlapping tandem and contrarotating propeller designs, as well as locations at other than the stern, have all been investigated to alleviate this problem.

Range or Endurance

A long range (nautical miles) or endurance (hours) requirement will tend to favor the more efficient propulsor. As shown in Figure 42, the propulsor type which has the advantage will depend on the speed of the ship, but the waterjet is usually at a disadvantage relative to a propeller. Since the range or endurance requirement will be specified at cruise speed rather than top speed, the impact of size and l/b on lower-speed resistance is especially important.

Sidehull Geometry

Since the sidehulls provide the only rigid structural contact with the water, propulsors and propulsion machinery will normally be located within or near the sidehulls. Sidehull geometry is influenced by the design philosophy of the overall ship. Relatively narrow sidehulls (in the limit a virtual knife-edge at the waterline) provide lower drag but minimal contribution to stability. Such sidehulls will require local “fairings” near the stern to provide adequate width for propulsor installation. Wider sidehulls which are designed to provide larger restoring moments automatically afford a more suitable machinery and propulsor mounting area. Even these, however, may require local modification near the stern to provide an adequate surface for installation of a flush waterjet inlet or an active or passive system to change the effective propeller disk area as a function of ship speed. Corner radii or fairings may also be required to assure acceptable performance in the cross flow induced by ship maneuvers and the presence of the air cushion. Proper selection of these features will reduce the probability of air ingestion or broaching of the propulsor which would produce large variations in shaft loading. In extreme cases these events have caused overspeed shutdowns of gas turbine powered ships. Sophisticated engine control systems have been incorporated to virtually eliminate this occurrence even if broaching occurs.

Engine Matching

Propulsion engines are manufactured in finite sizes and ratings and, even at the stage of parametric or speculative studies, designing the propulsor to a “rubber” engine without regard to available candidates is not advisable. Engine power-torque-rprn limits are developed by the manufacturers and, with the selection of a candidate gear ratio, the propulsor requirements can be related to these engine characteristics. At low ship speeds, torque limits are more likely to govern, while at high speeds rpm is frequently limiting. Controllable-pitch propellers offer the most flexibility in matching propulsor and engine requirements. In practice, propulsor operating bounds such as thrust breakdown or cavitation inception may be more restrictive than engine limitations. The requirement for high thrust at the hump speed, for example, may result in the selection of nonoptimum cruise or top speed matching, especially for a fixed-pitch propeller.

A further complication to the matching of propulsor and engine occurs when the SES is designed with an “integrated” lift and propulsion system. In this type of system the propulsors and lift fans are both driven by the same power system. This offers an advantage in terms of emergency conditions if more than one engine is connected to a common power train. Another positive aspect of the integrated system is that by increasing the inertia of the system, engine overspeed control to handle the effects of propulsor broaching or air ingestion is simplified. While the integrated approach has been successfully used, the inherent mechanical and design complications make its selection generally unattractive.

Draft, Vulnerability, Maneuverability

For applications where shallow draft and protection against damage due to impact with debris or docking facilities is a consideration, the waterjet propulsor maintains an advantage relative to the propeller. This is commonly important for ferry service in crowded harbors. The vulnerability advantage of a waterjet is not so great when compared to a fully-submerged propeller and the draft advantage is not so great when compared to the partially-submerged propeller. The low speed maneuverability of a waterjet-propelled SES is excellent due to the steerable jet which needs no forward speed to function as a stern side-thruster. Docking and low speed maneuvering are normally off-cushion operations during which the exiting waterjet will probably be below the waterline. In cases where it is not, care to evaluate the possible effects of jet impingement must be taken.

Propulsor Design

Conventional Propellers. A "conventional" propeller refers to the subcavitating marine propeller having a fully-wetted blade profile (typically NACA or ogival) on which the local static pressure at any point remains well above vapor pressure for most operating conditions and to the transcavitating propeller which operates with substantial partial cavitation. The profiles of the transcavitating propeller are selected to tolerate conditions where cavity lengths are generally less than one chord length and where only a portion of the root-to-tip span is cavitating. In practice, even the subcavitating propeller occasionally experiences some cavitation. Cyclic variations in angle of attack due to shaft inclination or variations in the wake may result in cavitating conditions over at least a portion of the disk area. In fact, designing to eliminate totally the risk of occasional cavitation may result in lower efficiency for the propeller and not represent the optimum overall solution. It is certainly necessary to design to ensure freedom from excessive caviation damage or vibration. If a minor amount of cavitation is to be tolerated, then it is essential that the propeller be made of a cavitation damage resistant material.

Ships which operate in the previously defined low-speed range (O-20kts) normally present a relatively good regime for the design and operation of subcavitating marine propellers. This is true especially for an SES operating with a modest amount of shaft inclination. The relatively slight immersion of the hull results in a wake at the propeller disk which is not nearly so severe as for a displacement ship of similar size. If both of these sources of periodic angle-of-attack variation are minimized, the propeller will be operating in an environment approaching the uniform inflow case.

In addition to the problem of circumferential variation in blade incidence angle, avoidance of unacceptable cavitation must be achieved over the entire range of thrust and speed required by the particular ship design. Several factors cause a propeller to operate at "off-design" advance coefficients (J),

$$J = \frac{V}{nD}$$

where V = the speed of the ship
n = the rotative speed of the propeller
D = the diameter of the propeller

Among these are the extent to which the nominal resistance of the hull deviates from being proportional to the square of the ship speed and the extent to which sea state, ship payload or nonstandard operating conditions cause the nominal resistance curve to assume a new shape. The first factor is best illustrated by the previously mentioned SES hump resistance (see Figure 43). As sea state increases, a family of higher resistance curves results, increased payload or non-standard operations (such as reduced cushion pressure or engine out conditions) produce a similar effect. The propeller designer must account for these conditions and try to keep the operating envelope of the propeller within the "cavitation bucket" for the blade sections chosen. Variable-pitch propellers, in effect, produce a series of geometries each with a different bucket and optimum J. In the moderate speed range (20-40kts), minimizing cavitation is more difficult but still achievable. At the high end of the moderate speed range it may be necessary to use transcavitating propellers capable of operating with significant amounts of cavitation.

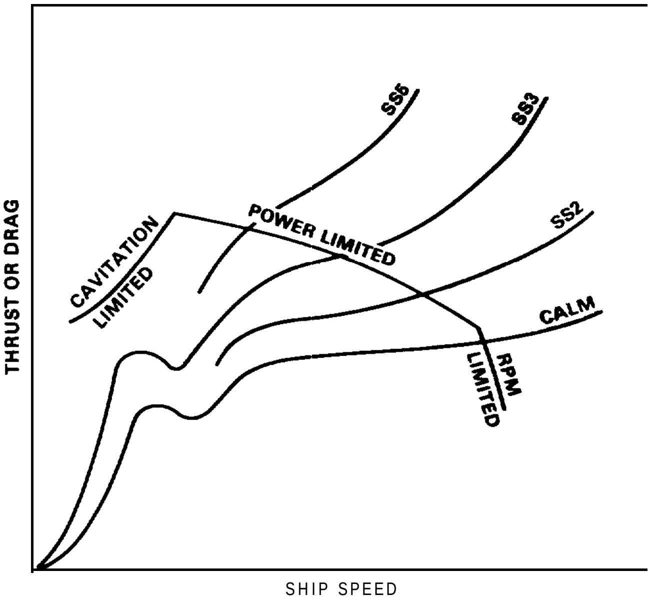


Figure 43. Typical Impact of Sea State and Propulsion System Bounds on SES Performance

The most straightforward SES propeller design approach is familiar to designers of conventional ships. This is to select a suitable candidate using the design charts developed for standard series marine propellers such as Taylor, Troost, Wageningen, etc. [43]. In the high end of the speed range Gawn-Burrill or Newton-Rader series data are of interest [44]. Moderate-sized propellers meeting the requirements of series selected geometry may be procured as more or less off the shelf items from numerous manufacturers. Unfortunately, this approach will not always result in a satisfactory solution. The series propeller is constrained to a particular geometry which may be an unsatisfactory match to the requirements of the ship resistance curve, wake or other factors.

An alternative to the series data selection method is the use of analytical methods The most common of these is the lifting line approach in which each blade of the propeller is represented by a vortex filament [45]. To apply this approximation to wide-bladed marine propellers, velocity corrections or "induction factors" must be employed. A more complete theoretical approach to propeller design employs lifting-surface theory in which bound vortex circulation is varied not only by radius but also along the chord of the blades [46]. Lifting-surface theory is exercised for (detailed propeller design and when employed is preceded by parametric optimization using lifting-line theory. Various formulations are available in the form of computer programs. The lifting-surface versions are complex and require specialized experience to interpret the results. These methods allow the designer the freedom to deviate from series geometries and loadings to achieve the required propeller performance.

Figure 44 shows the installation of a conventional propeller on the BH-110 SES. This may be considered typical of such an installation with a moderate shaft angle, one prop and one downstream rudder per sidehull, and designed for a top speed of 35-40 kts. The BH-110 has independent lift and propulsion systems driven by diesel engines. The propeller wa.s selected using the Gawn-Burrill data and is 3.5 ft. in diameter. Based on the thrust loading and local blade cavitation number, the propeller was predicted to have a slight and acceptable (2½ percent of blade area) amount of back cavitation [47].

In an application such as the one discussed, the design for a conventional propeller for an SES is, in principle, no more difficult than a propeller design for a conventional ship of the same speed. The wake from the strut and shafting system is similar but the hull wake is actually less severe. Depending on ship life-cycle cost, stringency of technical specification and number of ships of the class, it may be advisable to conduct propeller model tests to verify or fine-tune the propeller performance and propeller-hull interaction. This is in accordance with standard design practice for any type of ship. The state of the art of conventional propeller design is mature, and good results may be obtained when those skilled in the art apply existing design tools. Most of the advanced or developmental work being clone on conventional propellers deals with unsteady pressure forces, propeller-hull interaction, highly skewed blades and other problem areas which are actually somewhat less severe for SES than more common hull forms. An unusual application which could prove advantageous for SES arrangement constraints is the operation of fully-wetted propellers at partial submergence [48]. Little work has been done in this area to date and a great deal more would have to be understood to recommend this approach, especially when off-design performance is. critical.

Supercavitating Propellers. In general, when an SES reaches the high-speed range (40kts +) it becomes difficult or impossible to achieve acceptable performance with a conventional propeller. Supercavitating or superventilated propellers are designed to operate acceptably in this high-speed range by operating with a fully developed blade cavity which springs from the leading edge of the blade and completely envelopes the back of the blade collapsing well downstream of the blade trailing edge. Transcavitating propellers occupy the middle ground and operate with cavity lengths less than the full chord length. The difference between supercavitating and superventilated propellers is primarily the nature of the gas-filled cavity. Supercavitating propellers have cavities filled primarily with water vapor. Superventilated propeller cavities are filled primarily with air. Usually the distinction between these two types is not made and supercavitating is used to refer to both. The most common type of supercavitating propeller for SES application is the partially-submerged supercavitating propeller (PSSCP), as installed on the SES-100B, which actually operates superventilated with a natural air supply entrained from the surface.

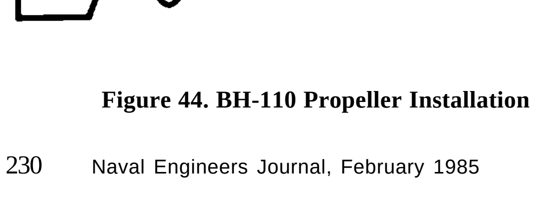


Figure 44. BH-110 Propeller Installation

As in the case of the subcavitating propeller, the design and off-design operating points required of the supercavitating propeller determine its characteristics and achievable efficiency. The resistance of the ship at hump speed and the variation of resistance due to the environment and loading conditions may require a variation in operating advance coefficient which dictates the use of a controllable-pitch propeller. This is entirely analagous to the conventional propeller. Rather than keeping the supercavitating propeller sections within the “cavitation bucket” as required for subcavitating propellers, the designer is faced with the requirement to provide reasonable high-speed or cruise efficiency while avoiding low speed thrust deterioration caused by low advance coefficient operation. For fixed-pitch supercavitating sections, the increased angle of attack at low J can generate huge blade cavities which greatly compound cascade and cavity interference problems. The use of controllable pitch will result in some sacrifice in design point efficiency and, thus, craft maximum speed, but greatly improve the low advance coefficient performance.

While subcavitating propeller designers have a broad range of series data and well founded design techniques to choose from, the supercavitating propeller designer is faced with a much more limited choice. The phenomenon of supercavitation at high ship speeds was first observed near the turn of the century and empirical design of such propellers for racing boats and hydroplanes began shortly thereafter. However, little theoretical understanding of the problem was developed until the 1950s [49]. In addition, racing propellers were not faced with the requirement for long life and, as discussed later, the structural design of supercavitating propellers interacts strongly with their hydrodynamic performance. Since that time progress in the theory and design of such propellers has been achieved chiefly under U.S. Navy sponsorship.

In terms of series selection, very little systematic data have been collected. There are several designs, however, which have been extensively documented. Selection of one of these would require matching of the propeller characteristics to the particular ship and engine requirements. The probability of an optimum match for an

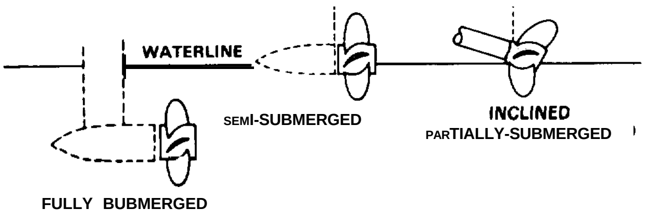


Figure 45. Typical Propeller Installation Schemes

arbitrarily chosen ship is limited. A much higher probability of optimization would result from a design of a new propeller using one of the available design approaches.

Having stated this, however, we must face the fact that the design process for supercavitating propellers is long, complicated and far less documented than for conventional propellers. No complete direct analytical method exists for these props (say analagous to fully-wetted lifting-line theory) and the interaction between blade structural strength and hydrodynamics is more severe due to the necessity for sharp leading edges and containment of the blade section within the generated cavity. A method used by DTNSRDC [49] uses fully-wetted lifting-line and lifting-surface theory with interference effects between cavities and blades accounted for in the lifting-surface calculations. Reference [50] uses a momentum theory approach which takes into account cascade and cavitation effects on the velocity field. In this process, linearized two-dimensional section characteristics with empirical factors are used. Unlike the DTNSRDC method, off-design performance is also predicted. As previously mentioned, the structural design of supercavitating propellers plays a more interactive role with propeller hydrodynamics than it does for subcavitating designs. When a supercavitating propeller is operated partially submerged, additional highly unsteady blade loading is introduced due to the periodic impact, entrance and exiting of the blade sections at the water surface.

Supercavitating propellers may be operated either fully or partially submerged (see Figure 45). If fully submerged they may be mounted using a strut-pod arrangement or on an inclined shaft supported by struts. The strut-pod introduces higher appendage drag and a larger wake into the propeller disk. Tractor propellers, where the propeller is mounted on the forward end of the pod, have been investigated. The inflow to the propeller is thus improved, but the mounting system suffers damage due to the cavity flows from the propeller. If fully-submerged propellers are to be operated superventilated, large quantities of air must be supplied by external means. The partially-submerged mounting may use either an inclined shaft or horizontal shaft arrangement. It offers the advantages of reduced appendage drag, even to the possible elimination of hub drag, and the ability to naturally ventilate the propeller blades. The inclined shaft arrangement has much to recommend it from a machinery arrangement standpoint [51]. Furthermore, experiments have indicated that the inclined shaft arrangement with blades raked at an angle equal to the shaft angle may develop significantly higher propulsive efficiencies than those of other arrangments [52].

An example of the application of partially-submerged supercavitating propellers to a surface effect ship is the SES-100B. One 6-bladed, 42-inch-diameter propeller on each sidehull was designed to operate with variable partial submergence. The blades were controllable pitch with supercavitating sections of forged titanium. These propellers drove the 105-Iton gas-turbine-powered testcraft to speeds in excess of 90 knots. Controllable ramps were provided to increase the submerged disk area for takeoff through the hump resistance peak. Experience with this propeller indicated that submerged area control could be achieved by the natural behavior of a ventilated cavity triggered by a small hydrodynamic wedge on the sidehull.

Several areas of supercavitating propeller performance require further development. In particular, a supercavitating lifting-line/lifting-surface theory; a better method of predicting off design performance and performance at partial submergence; nonlinear section data; better understanding of the effect of shaft inclination; and methods to design tandem, contrarotating, overlapping, ducted and other “nonconventional” arrangements need to be addressed. In the case of the supercavitating propeller, it is even more imperative that model tests of the propulsor be conducted to verify design and off-design performance than for conventional propellers.

Waterjets. Waterjet propulsion actually predates the open screw as a marine propulsor by many years. Widespread application of this form of propulsion has, however, been limited by the lower propulsive efficiency of waterjets for most applications [53]. As indicated in Figure 42, it becomes more competitive with other propulsors as ship speed increases. The waterjet propulsor is more complex than the open propeller due to the greater number of components involved. These include the propulsion pump, thrust nozzle, thrust vectoring and reversing mechanisms, ducting, debris grill, inlet and appendages or fairings for the mounting of the inlet (See Figure 46). The technology for design and performance prediction of each of these components is at differing levels of development. The pump, nozzle and thrust vectoring or steering and reversing bucket hardware are usu-

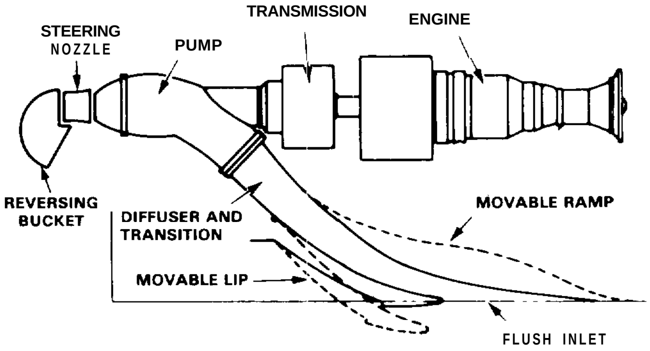


Figure 46. Typical Waterjet System Showing Alternate Variable-Area Flush Inlet Schemes.

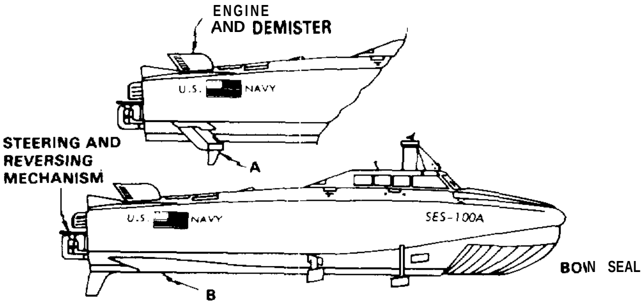


Figure 47. SES-100A Configured for Pod-Strut Inlets (A) and Flush Inlets (B)

ally procured as a unit from a limited number of designs available from several manufacturers. The ducting, grill, inlet and appendages or fairings are frequently designed and built as a part of the ship structure following the pump supplier's guidelines. At high power levels, the pumps become custom designed items. Many utilize high blade-area-ratio impellers or inducers designed to tolerate partial cavitation at low inlet pressure. The design techniques for the most advanced axial or mixed flow designs are proprietary to the manufacturers and utilize technology originally developed for pumping low pressure cryogenic rocket fuel in the U.S. space program. On the other hand, relatively conventional centrifugal pumps have been successfully used as propulsion pumps even at high power levels. The waterjet inlet and associated appendages, at least for high-speed applications, are as critical as the pump to the success or failure of the system. Inlets used may be of the pod-strut or the flush/semiflush type. (See Figure 47.) These may have fixed or variable inlet area. Variable area may be achieved by the use of auxiliary inlets or primary inlets whose geometry is changed as a function of operating conditions.

The need for variable area is primarily associated with the avoidance of cavitation and establishment of acceptable inflow angles into the inlet opening. This is analagous to variable pitch for marine propellers. The propeller advance coefficient characterizes overall blade angle of attack. With a waterjet. the inlet velocity ratio.

$$IVR = \frac{Q/Ai}{V}$$

where: Q = the mass flow r-ate of the waterjet system
Ai = the area of the inlet opening
V = ship speed

characterizes the inflow angle or angle of attack of the inlet leading edge.

Relatively small SES with high top speeds and low lib will be the most likely candidates for variable area inlets (or variable-pitch propellers). For these ships, the resistance curve dictates nearly equal thrust at low speed and high speed and results in large variations in inflow angle. By providing a larger area at low speed and a smaller area at high speed, this inflow angle variation can be minimized.

The strut-pod or "ram" inlet provides more uniform inflow, higher energy recovery, and some directional stability, while the flush or semiflush inlet provides less drag and better resistance to debris impact. At low design speeds either type of inlet may be of the type where the inlet structure "closes" downstream of the inlet. At high speeds this may be impractical and the inlet may operate base-vented. throwing a long ventilated cavity downstream. The ventilated inlet is in some ways analagous to the supercavitating propeller. The reduced wetted area possible under ventilated operating conditions may provide a frictional drag reduction to partially offset the cavity drag. Published design methods for waterjet inlets are quite limited [53]. It is recommended that inlet designs, especially those intended for high speed operation, be model tested.

Ducting design is strongly influenced by inlet and pump imposed geometry. Conveyance and diffusion of the ingested water from the inlet to the pump with minimal losses is critical. Extensive separation or highly nonuniform flow can cause severe cavitation and vibration problems at the impeller. Flush inlets are most severely affected by this problem. Some recent designs have devised means of bypassing the hull boundary layer so that it is not ingested by the flush inlet. This slightly reduces propulsive momentum efficiency. A waterjet momentum analysis technique may be used as an iterative tool in evaluating the impact of pump characteristic curves, internal losses and inlet drag on system performance [53]. Idealized momentum analysis for a waterjet, as for a propeller, leads to the conclusion that lower slip stream velocity (larger propeller or jet diameter) yields higher efficiencies. When real effects such as fluid friction, system size and weight, transmission considerations, etc. are considered, an optimum efficiency at a reasonable finite size results.

An example of waterjet propulsion is the SES-100A. The 70kt + craft was originally configured with dual variable-area strut-pod waterjet inlets feeding water to two gas-turbine-driven two-stage, two-speed waterjet pumps. It was later converted to flush variable area waterjet inlets having movable ramps and fixed lips. (See Figure 46.) Note the addition of a stern stability fin with the flush inlet to compensate for the pod-strut contribution to the directional stability. Both waterjet inlet systems performed adequately and demonstrated the feasibility of either. A fixed area inlet was later installed with a fluidic valve successfully replacing the variable area mechanism and represents the most advanced inlet control concept development to date.

Unlike propellers, virtually no series data appear for waterjet systems to allow candidate selection. This is not surprising since the waterjet system is more strongly integrated into the overall hull design than the propeller. "Open water" waterjet performance is almost a contradiction in terms. Manufacturers' requirements in terms of pump NPSH (net positive suction head), flow rate, or inflow uniformity define what is required of the inflow to the pump. Short of experience and experimental verification, little assurance can be provided the designer that the particular inlet-ducting system he has selected, if untested, will actually meet stringent requirements. Less demanding design requirements may be more easily achieved with careful selection by an experienced designer, reliance on previous smaller designs, or by using tested designs provided by the pump manufacturer. Diffusing and turning flow ingested at the inlet as the fluid is conveyed to the pump impeller plane, particularly a hull boundary layer ingested by a flush inlet, is not an easy hydrodynamic task. But if the inflow requirements of a particular pump are met, then the performance can be obtained from published characteristics. The method of presentation however, is not standardized and comparisons among competing systems may be difficult. Further analytical and experimental investigations into methodical waterjet series would certainly improve the probability of success for the designer of waterjet propulsion systems.

Propulsion Summary

To put the relative use of each type of propulsor into perspective, Reference [6] was reviewed to determine the frequency of various propulsion systems in SES currently operational or at least in late stages of design. The countries for which SES were documented included the USA, UK. USSR, France, China, Japan, Republic of Korea and the Netherlands.

The USA has about 25 existing models, variants, and designs with sizes from 24 to 1,800 tons and speeds from 30 to 80 knots. Most designs under 40 knots have fixed-pitch subcavitating or transcavitating propellers. At 40 to 50 knots variable-pitch propellers are indicated. A number of ships in the 43-75 knot range have waterjet propulsion. Above 80 knots variable pitch PSSCPs are used. The ship services indicated are ferries, crewboats, patrol craft and a hydrographic vessel. Listed in earlier editions of Reference [6] was the U.S. Navy 3K SES design at 3,000 tons with a design top speed of 80 knots. The 3K SES was to be propelled by four waterjet propulsors each driven by a marine gas turbine.

In the UK, from a single dominant source, nine designs are listed with propellers indicated for all. Top speeds vary from 30 to 35 knots for fixed-pitch props while a single design at 40 knots uses a variable-pitch propeller. In all cases, fully-submerged configurations are used with moderate shaft inclination. Major uses include ferries, crewboats, patrol/strike craft, a firefighter, hydrographic vessel and multirole harbor craft. All of these are in the size range of 40 to 90 tons. Japan's major supplier of SESs is connected with the UK company and probably offers similar designs.

The USSR lists nine designs most of which are for ferry service. Other uses include a naval vessel and fire tender. Top speeds vary from 19 to 36 knots and sizes vary from 15 to 53 tons. In spite of some relatively low-speed craft all but one are indicated as being waterjet propelled. Limited-draft ferry service is a major reason for this choice. The naval vessel is propelled by twin propellers.

In France, a 5-ton model of a planned larger vessel has been built which uses waterjet propulsion. Larger vessels in the 200 to 4,000-ton range are planned with top speeds of 40 to 65 knots, all propelled by waterjets. China lists 4 designs used for ferry service and in the 30-ton size range. Two of these are waterjet-propelled while the other two use propellers. The speed range is 22 to 31 knots. The choice of waterjets was probably dictated by shallow river service. The Republic of Korea lists five SES designs, all using propellers. One of these designs, at 12 tons and 25 knots, uses stern drives rather than an inclined shaft. Other ships indicate top speeds from 30 to 50 knots with power options available in each size range. Sizes vary from an 8-meter craft at 4 tons to a 23-meter craft whose displacement is not listed. The Netherlands lists three designs from 62 to 185 tons each with a top speed of 40 knots and with two fixed-pitch propellers. None of these designs have actually been constructed.

Reference [54] provides a comprehensive outline of the trade-offs involved in the selection of propulsion systems for advanced marine vehicles, including SES, for the higher speed ranges. This and References [43], [47], [49], and [53] provide extensive bibliographies for further reading on the subject. Unfortunately, much of the work conducted in the field of high speed propulsion systems does not appear in the open literature.

LIFT FANS

The technology of lift fans has matured, benefitting from an increased awareness of available industrial fan know-how and from U.S. Navy R & D efforts such as development of the DTNSRDC lift fan evaluation rig, testing of the XR-ID, and the SES-200 research craft, together with extensive design studies of military SESs between 100 and 20,000 tons [55-85].

There has been, ever since the inception of the SES concept, a feeling that the cushion under the ship's bottom should be used to improve seakeeping, as a "buffer" between the rough ocean surface and the ship. However, it was soon realized that the existence of a passive cushion, regardless of size, was not always sufficient to guarantee good ride qualities since the cushion is essentially a dynamic reservoir which could just as easily amplify as reduce sea motions. Hence, there arises the need for a dynamic control of the ship cushion system. There are many ways, passive and active, to accomplish this, and, in most of these schemes, the lift fan plays an essential role. Research has shown that variable geometry (VG) fans are an economical way to provide ride control. This was demonstrated through model tests: at DTNSRDC from 1974 to 1980 [58-62], at Aerophysics Company from 1980 to 1983 [63-65], in ship operations with the XR-ID craft [66], and will be further assessed in tests with the SES-200.

The concept that any fan, including the SES lift fan, can operate as a dynamic, rather than a static control system offers a new dimension in fan operation. Traditionally, fans have been steady-state systems. Their regulation in industrial processes through many devices, including inlet guide vanes (IGV), has been available for a long time, but it is essentially a quasisteady process, with frequencies of 0.1 Hz or less. A ship may be required to react to wave pumping responses of the order of 5 Hz. This means that cushion pressure has to be sensed continuously and fed through the proper signal processor to the IGVs, the position of which must be changed up to 5 times per second in such a way as to maintain a constant ship attitude and thus minimize vertical accelerations of the ship. In this concept, the dynamic (instantaneous) slope of the pressure-flow curve can be made to assume any desired value, including the zero slope desirable for decoupling vertical accelerations from sea motions.

Function

The lift fan provides a cushion of pressurized air beneath the ship that helps support it at a pressure sufficient to keep the sidehulls submerged at a favorable depth to minimize drag as well as airflow leakages along the hulls and to elevate the centerbody of the ship above the water. The cushion pressure must be variable to adjust for changes in the weight of the ship resulting from fuel expenditures. This means that there must be a "slow" way economically to change the characteristics of the lift fan system, for example, through changes in the engines' power setting and rpm, or through changes in IGV settings. It produces an airflow rate adequate to provide an acceptable ride over the ocean surface which for a ship, is an inverse function of speed and sea state. Research in the past ten years has shown that "dynamic" modulation of the lift system, e.g., a "fast" way to change its performance characteristics. is effective in controlling motions of SESs. "Fast changes" in this context means 5 to 10 Hz; "slow" means .05 to .1 Hz.

Requirements

SES fan requirements originate with the ship designer in the form of a required total airflow and pressure rise for a given ship. Fan type, fan rpm and number of fans are determined through dialogue between the ship and fan designers.

For preliminary design purposes, the total airflow required by an SES to attain optimum performance can be determined, semiempirically, from model towing tank tests [57]. The airflow has been found to be primarily a function of the cushion beam, as the majority of airflow escapes the cushion past the fore and aft flexible seals. The number of fans used is a design variable. The minimum should be two for reliability reasons (experience has shown that an SES can operate on its cushion with half the airflow). The maximum number of fans is usually dictated by the results of a trade-off of total ship system weight, volume, arrangements and complexity and normally is expected to be 4 or 6. A fan can be SWSI (single width-single inlet) or DWDI (double width-double inlet); for the same diameter, the DWDI configuration provides twice the airflow of the SWSI.

When the SES detailed design stage is reached, it is desirable to obtain precise airflow requirements from actual towing tank tests. This airflow is a direct function of the speed required in a given sea state as dictated by the mission requirements, and that condition can be simulated accurately in a towing tank.

The fan pressure is directly related to the cushion pressure and can be shown as static or total pressure rise. SES designers normally express fan pressures as total pressures (with the corresponding total efficiency).

The cushion pressure follows scaling laws, increasing with the total displacement of the SES less any sidehull buoyancy. During early stage design, it can be assumed that the losses due to dynamic head and duct friction can amount to up to 20 percent of the total fan pressure.

Fan Types

There are four principal types of fan wheels [68–75]. An easy way to distinguish fans is by representing, as on Figure 48, a cross-section of the wheel and its housing and the relative direction of the inlet and of the exhaust flow with respect to one another and the axis of rotation. The shaded areas indicate the blades, which are responsible for maintaining the flow through the fan and creating the pressure rise.

An axial fan has inlet and exhaust airflow parallel to one another and to the axis of rotation, hence its name. The pressure rise is created because of the lift generated by the motion of the air around the airfoil-shaped blades, in a manner similar to the creation of lift on an airplane wing.

The centrifugal (radial) fan has the inlet flow parallel to the axis of rotation and turned ninety degrees by the wheel so as to exhaust in a radial direction. Most of the blade is in the radial direction, and therefore the airflow is subjected to a strong centrifugal acceleration, which is responsible for the creation of the majority of the pressure rise, hence the name: "centrifugal."

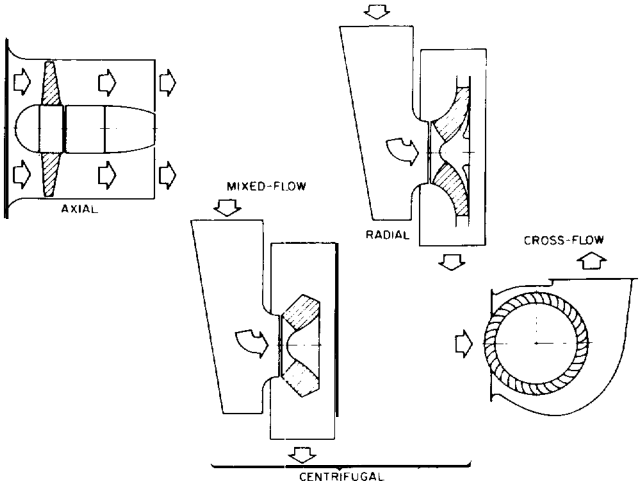


Figure 48. The Four Major Fan Wheel Types in Typical Configurations.

The mixed-flow fan has blades which are somewhat axial at the inlet and somewhat radial at the discharge and is therefore partially axial and partially centrifugal. In most of its aspects, the mixed-flow fan is more centrifugal than axial.

In general, the axial fan performs best when handling large airflows (or "capacities") at relatively low pressures; centrifugal fans can handle relatively large pressures and smaller airflows. The mixed-flow fan handles intermediate flows and pressures. The pressure rise capability of any one fan can be increased by "staging," i.e., running the fan airflows "in series." As to the airflow, it can be increased by running "in parallel."

To understand the cross-flow fan, one must visualize the fact that the axis of rotation is perpendicular to, rather than in the plane of the paper. Blades are disposed, as shown, inside an annulus and their span is parallel to the axis of rotation, i.e., perpendicular to the paper. Airflow moves from left to top, penetrates to blade annulus over a typical sector, as shown, crosses the axis of rotation, and emerges on the other side of the wheel with streamlines still parallel to the plane of the paper. The cross-flow fan has been known for one hundred years, but has had very few applications compared to the other types. It has long term potential for SES applications because the elongated shape of the exhaust lends itself to an even air distribution into the seals.

The typical shapes of the pressure-flow curves that correspond to a particular type of fan can be found in Reference [24].

Fan Selection

The convention of selecting a fan for a particular application on the basis of similarity parameters, such as specific speed, was adopted because of its overwhelming success for water pumps, where it was introduced at the beginning of the twentieth century. The fan laws are the mathematical expressions of the fact that when two fans are both members of a homologous series their performance curves are homologous. At the same "point rating," i.e., at similar points of operation, efficiencies are equal. The ratios of all other variables (size, rotative speed, gas density, capacity, pressure, horsepower, sound pressure level and efficiency) are interrelated.

There are ten fan laws that can be used to predict the performance of any fan when test data for a fan of the same series are available. They are most readily found in Table *58* of the *Buffalo Forge Handbook* [71].

The dimensional performance of a fan is usually expressed as a plot of pressure rise between fan inlet and exhaust against capacity, for a given rpm.

From the fan laws, the pressure rise (Ap) is proportional to the square of the rpm (N) and the capacity (Q) is proportional to (N). Therefore, one could plot the pressure rise across the fan, Ap, as $\Delta p/N^2$ against Q/N, and any plot by another name will be proportional to it.

There are four "classical" fan similarity parameters: the pressure coefficient (Ψ); the flow coefficient (Φ); the specific speed (NJ; and the specific diameter (D,). Unfortunately, there are no less than eight definitions of these coefficients, plus three more used by the French and Belgians. The data presented here for representing the dimensionless characteristics of SES lift fans are expressed in the author's preferred systems, e. g., the Csanady coefficients [73], together with the names suggested by Eck [68].

The four parameters are defined as follows:

Flow Coefficient, $\Phi = \dfrac{Q}{\omega\, d_2^3} = \dfrac{Q}{2U_2 d_2^2}$

Pressure Coefficient, $\Psi = \dfrac{gH}{\omega^2 d_2^2} = \dfrac{gH}{4U_2^2}$

Speed Coefficient, $\sigma = \dfrac{\omega\, Q^{1/2}}{(gH)^{3/4}}$

Diameter Coefficient, $\delta = \dfrac{d_2 (gh)^{1/4}}{Q^{1/2}}$

Note that the expression: $gH = p_o - p_i/\rho = \Delta p/\rho$ only applies for low-speed incompressible flow. If compressibility is significant (blade tip speeds above 400 to 500 ft/sec), the compressible expression for H is as follows:

$$H = C_p J T \left[\left(\frac{p_o}{p_i} \right)^{\frac{k-1}{k}} - 1 \right]$$

The symbols used in the above equations are defined below. Though the above coefficients are nondimensional, it is suggested that they be used only in the English system of units (minor discrepancies occur because "g" has different values in the metric and in the English system of units).

Q = airflow, cfs
ω = fan wheel angular velocity. rad/sec
d_2 = fan blade diameter, ft
U_2 = fan blade tip speed, ft/sec
g = acceleration of gravity, 32.2 ft^2/sec
H = total fan adiabatic head
p_o = absolute pressure at fan discharge, psf
p_i = absolute pressure at fan inlet, psf
p = air density, slug/ft^3
C_p = specific heat (at constant pressure) of the fluid
J = thermodynamic constant (778 ft-lb/Btu)
k = ratio of specific heats for the fluid.

It is useful to represent all existing and projected SES lift fans in a plot of diameter coefficient and maximum efficiency against speed coefficient (Figure 49). This is the same plot as Figure 176 of Reference [24], and Figure 4 of Reference [68] (except for the changes in definitions of coefficients).

A double use can be made of the results of Figure 49. First, the abscissa, the speed coefficient, σ, has been used for a long time as a way to "classify" the four types of fans discussed earlier. By its above definition σ, is a direct function of airflow, is an inverse function of pressure rise, and is proportional to rpm. Therefore. large values of σ correspond to large airflows and rpm, which, as was indicated earlier, is a characteristic of axial fans. Small values of σ correspond to large values of pressure

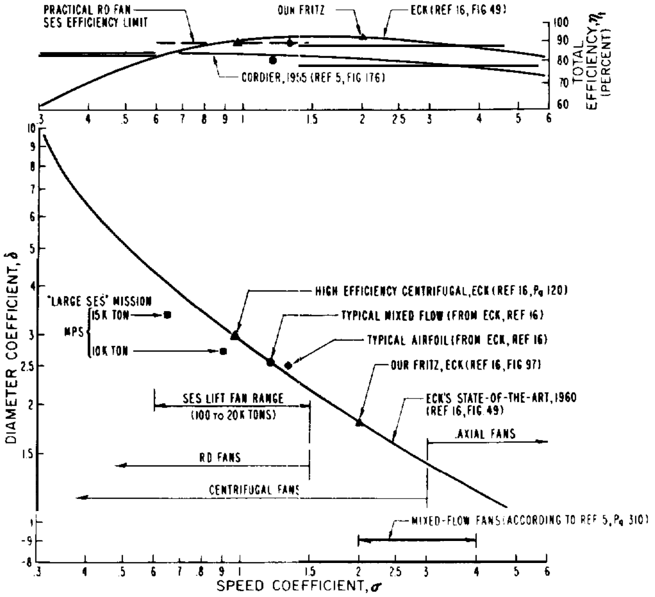


Figure 49. Generalized Fan Sizing for SES Lift Fan Applications.

rise and smaller rpm, i.e., to centrifugal fans. Specifically, axial fans correspond to values of σ larger than 3, centrifugal fans to values smaller than 3. Around 3 (say, between 2 and 4) lies the mixed-flow fan. According to Baljé a typical cross-flow fan also lies between 2 and 4 [75].

Second. using σ as the abscissa, two quantities can be plotted against the ordinate: the diameter coefficient δ and the maximum efficiency, η. Both are plotted here in a log-log grid. Therefore, since to each fan requirement there corresponds a given airflow, a given pressure rise and a given rpm, any fan can be represented as a point on the δ-σ and the η-σ diagrams, respectively. In addition, based on test data available in a given time frame, one can draw an "optimum" relationship between δ and σ, and between η and σ. The curves shown in Figure 49 show the state of the art, as perceived in 1960 [68]. Because it shows different trends, the Cordier 1955 curve for efficiency is also shown.

In conclusion, use of Figure 49 allows an assessment of any proposed fan. First, does it fall within the proper fan type? Second, does it meet the state-of-the-art efficiency potential?

For clarity, all existing and proposed lift fans are not shown on Figure 49; only "typical" cases. The two most interesting examples are described by Eck [68]. They are a 1955 centrifugal type, for $\sigma = .96$, which has efficiencies near 90 percent, and "our Fritz," for $\sigma = 2$, with an efficiency of 91 percent. These two examples allow Eck to raise the Cordier 1955 efficiency curve by 10 percent, and to claim that, from now on, the centrifugal fan is more efficient than the axial fan. The typical airfoil fan is shown around $\sigma = 1.3$ and meets its efficiency potential. However, it cannot meet the duty for large SESs (a = .65). The typical mixed-flow fan, according to Eck, is to the left compared to the "classical" range (σ between 2 and 4), but its demonstrated efficiency of 0.80 is much below Eck's envelope of 0.90. The mixed flow fan shows promise but is not currently fully developed.

Finally, rotating diffuser (RD) fans are found to fall in the range of σ below 1.5 and to match the u-range needed for large SESs (0.6 to 1.5). Also, through that range, the RD fan has demonstrated efficiencies between 85 and 90 percent.

Diameter coefficients for cross-flow fans fall much below the Eck curve. This would automatically disqualify them from further consideration, but because of their unique operating characteristics, they should not be ruled out for future SES development.

RD Lift Fan

The rotating diffuser (RD) centrifugal lift fan is currently installed in the U.S. Navy's SES 200 as the rear fan system and is to be installed in the U.S. Navy's PBM (patrol boat, multimission), scheduled to become operational in 1986. The RD fan has demonstrated good aerodynamic efficiency (85% to 90% total efficiency at the design point), good stability characteristics, and full compatibility with a variable geometry (VG) ride control system. It is therefore presented here as an example of an off-the-shelf commercial system that meets existing and proposed SES mission requirements.

The RD fan was first developed for industrial applications in 1953 by Etablissements NEU, of Lille, France. Original wheels had 4-foot diameters. Since 1965, wheels up to 12-foot overall diameter, with installed power of up to 12,500 HP, have been put into operation.

The RD fan was first proposed in the competition for the hydro-skimmer. (SKMR-1) testcraft in June 1961. Studies and full scale experiments on this design were supported by the U.S. Army and the U.S. Navy in the 1960s [77-80].

An RD fan was designed in 1970 for the SES-IOOB lift fan system. A 20-inch SWSI (single width-single inlet) fan test wheel was built by Aerophysics Company in 1974 and tested in 1979, statically and dynamically [64]. An improved 20-inch diameter DWDI RD wheel was tested also between 1980 and 1983 [63-65].

A technical assessment of the applicability of RD fans for current and future SES applications is presented in References [82] and [83] and a typical RD fan is shown in Figure 50. It looks like a mixed-flow fan because it has a fully-bladed axial inlet, as well as a centrifugal (radial) discharge. However, in accordance with the presentation of Figure 49, the RD fan aerodynamically belongs to the centrifugal, rather than to the mixed-flow family.

The RD wheel has a shroud over the full length of the blades extending beyond. the blades to form a rotating diffuser, as shown on Figure 50. The characteristics of fans used for 30 years for industrial stationary applications and marine forced-draft blowers are as follows:

- a high pressure rise in standard configurations. A pressure rise in excess of 1000 pounds per square foot is easily obtained with a single stage.

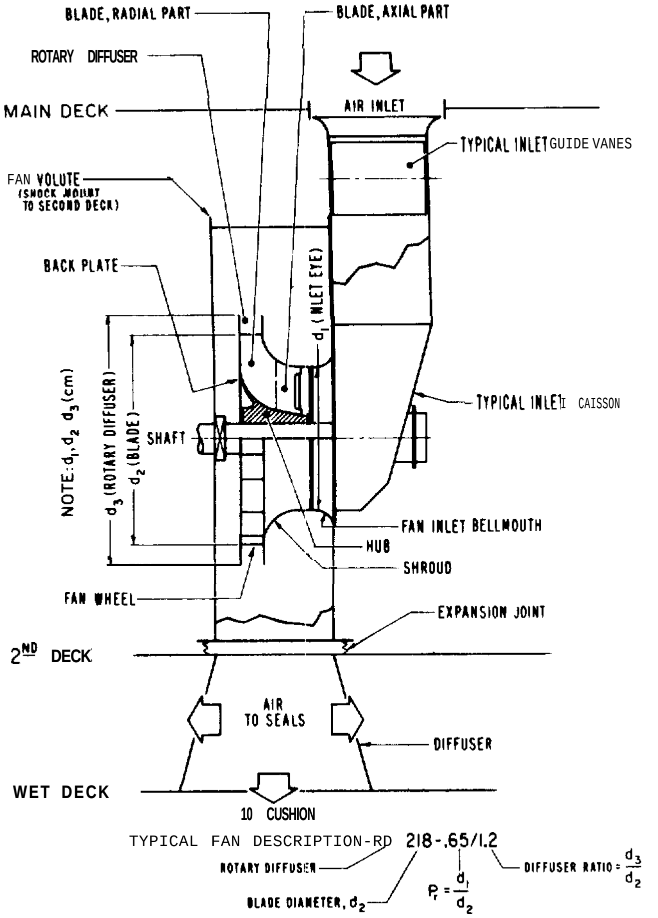


Figure 50. Schematic of Components for SES Lift Fan System & Nomenclature for Rotary Diffuser (RD), Centrifugal Fan Wheel.

- a high efficiency over a wide range of duties. Efficiencies over 85 percent are achieved with an extremely flat efficiency curve.
- inherent resistance to surge. A negative pressure flow curve down to zero flow can be obtained as required.
- inlet vanes can be used to control the capacity from full to near zero flow without surging, with little loss of efficiency.
- a rugged. reliable unit. A very sturdy fabrication because of the continuous attachment of the blades to the hub and shroud. Because of its design, stresses are low compared to other wheel types for the same duty.

Additional requirements for SES lift fan application over requirements for industrial applications are met as follows:

- Lightweight fabrication was demonstrated in earlier programs, [78, 81].
- Model tests during the past five years have demonstrated excellent performance and ability of a variety of inlet guide vane configurations to provide ride control (by modulating the IGVs at 2 hertz or better) [63-65].
- Preliminary design and tests of lightweight full-scale RD fans have shown ability to meet fatigue life requirements accounting for dynamics of ship motion [81].

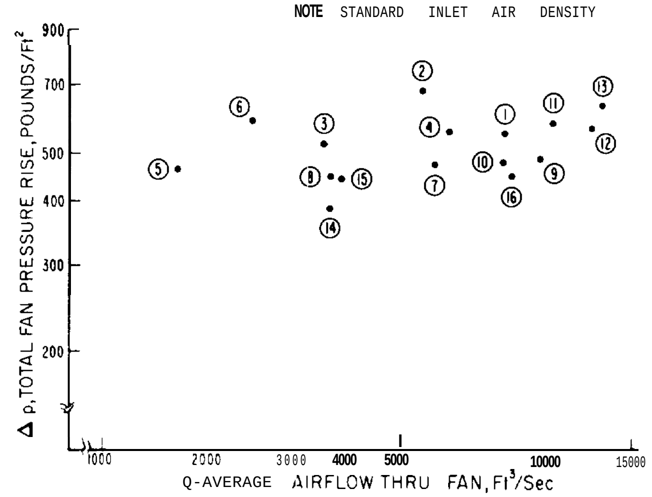


Figure 51. Pressure-Flow Duty Points of Typical Operational Large NEU Fans Installed in the Past 15 Years.

The question is often asked about the state-of-the-art availability of large centrifugal fans in the pressure and flow range needed for large SESs. Through the courtesy of Ets. NEU, of Lille, France, Table 4 was prepared which shows a list of industrial fans delivered by NEU in the last fifteen years, in a range of sizes, pressures and airflows similar to the highest anticipated SES lift fan requirements [83]. Design point performance is plotted on Figure 51. It is estimated that the fans listed have a total operating time in excess of 3 million hours. A typical large RD wheel is shown in Figure 52.

Nonrotating Components

Nonrotating components of the fan system are shown schematically on Figure 50. They are the inlet duct (or plenum, or caisson), the inlet guide vanes (IGVs), the inlet bellmouth, the fan housing (or volute), the diffuser, and the discharge ducting.

There are two major possible configurations for the inlet: the inlet box or caisson, as shown on Figure 50,

Figure 52. Photograph of Two RD Fan Wheels, Model 307-.55-1.3, Original on the Right (1970), and Improved Version on the Left (1972).

Table 4.

FAN IDENTIFICATION (FIG. 51)	FAN TYPE	NUMBERS OF WHEELS DELIVERED	DATE OF INITIAL FABRICATION	RPM	BLADE TIP SPEED, m/sec	Ap psf	Q ave., cfs
1	RD 218-.65-1.2	18	1976	1500	561	546.	8,150
2	RD 200-.55-1.3	10	1977	1500	610	660.	5,520
3	RD 185-.5-1.3	6	1976	1500	541	520.	3,470
4	RD 220-.55-1.09	2	1979	1500	558	551.	6,220
5	RD 185-.38-1.2	3	1977	1500	505	458.	1,720
6	RD 220-.38-1.2	2	1962	1500	571	582.	2,450
7	RD 200-.6-1.2	10	1962	1500	525	484.	5,850
8	RD 200-.65-1.3	8	1969	1500	509	447.	3,570
9	RD 260-.6- 1.3	2	1976	1200	525	484.	9,570
10	RD 240-.6-1.3	4	1976	1200	522	478.	8,080
11	RD 307-.5-1.3	4	1977	1000	568	572.	10,170
12	RD 307-.55-1.3	8	1973	1000	561	556.	12,120
13	RD 307-.55-1.3	8	1973	1000	594	624.	12,830
14	RD 185-.55-1.2	4	1973	1450	466	385.	3,350
15	RD 280-5.1-1.3(s)	6	1965	1000	499	442.	3,750
16	RD 280-.53-1.2	6	1975	1000	502	447.	8,370

which is a streamlined duct designed to minimize fan inlet losses, and the plenum, which is an open chamber upstream of the fan. If space is limited, the caisson should be used because it is highly efficient, occupies a minimum volume, and its geometry is compatible with IGVs of the radial or damper type. If ample space is available, the plenum configuration is simplest as it uses the ship's existing structure and only requires a hole in the upper deck.

There are three major types of IGVs, shown schematically on Figure 53: axial, radial, and multivane damper types. The role of IGVs is not simply to throttle the flow, but to change the aerodynamic operation of the fan by means of the powerful action on the fan's inlet velocity triangle.

Extensive tests of axial, radial and multivane damper IGVs were made for a number of RD fan SES configurations [62–65]. Typical results are shown on Figure 53. This demonstrates that the airflow can be changed by a factor of two or more through a change in IGV angle, while maintaining efficiency above 80%.

The multivane damper IGVs are preferable because they have the least number of vanes, therefore the least number of moving parts.

The fan's inlet bellmouth is completely conventional. Its geometry must match the fan configuration to which it is paired.

For a centrifugal fan, the fan volute can have parallel walls on a spiral casting and a rectangular discharge duct. Higher-pressure fans may require volutes with circular cross-sections.

A diffuser downstream of the fan's volute is optional. It is useful to recover some dynamic pressure, and thus increase slightly the static pressure rise of the fan. Diffusion may be accomplished both axially and/or radially. The rotating diffuser accomplishes most of this diffusion within the fan itself.

There is little to say about discharge ducting except that its use should be minimized. When cushion lift fans are to be used for ride control, long discharge ducts reduce the dynamic effect of the fan on the cushion.

Summary

The SES lift fan is not just an air mover which provides a pressurized cushion of air below the ship. It is a system whose characteristics may have a significant impact on the overall performance, habitability and mission capability of the ship. It has different characteristics from those of the ACV lift fan: lower airflows, higher pressures, and the ability to influence the ride control of the

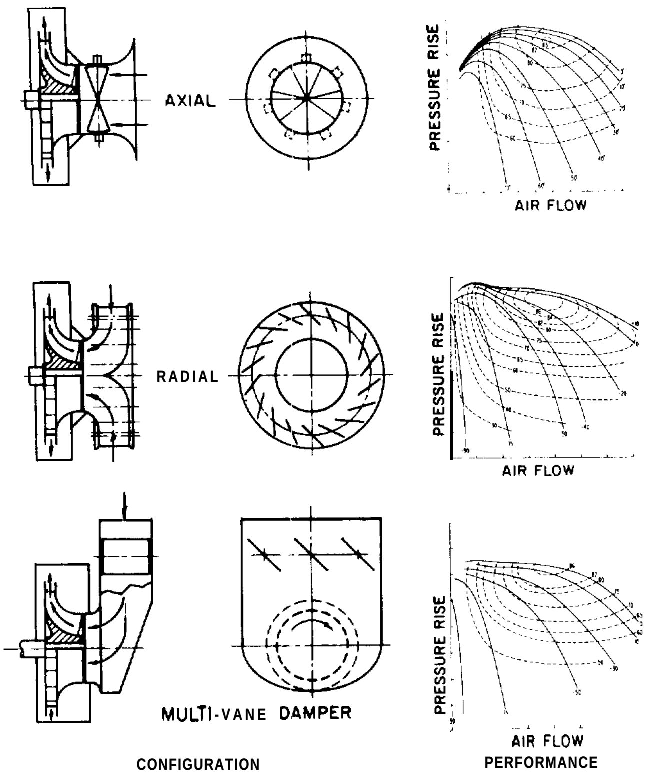


Figure 53. The Three Major Types of IGVs for Centrifugal RD Fans & Their Performance as a Function of IGV Angle.

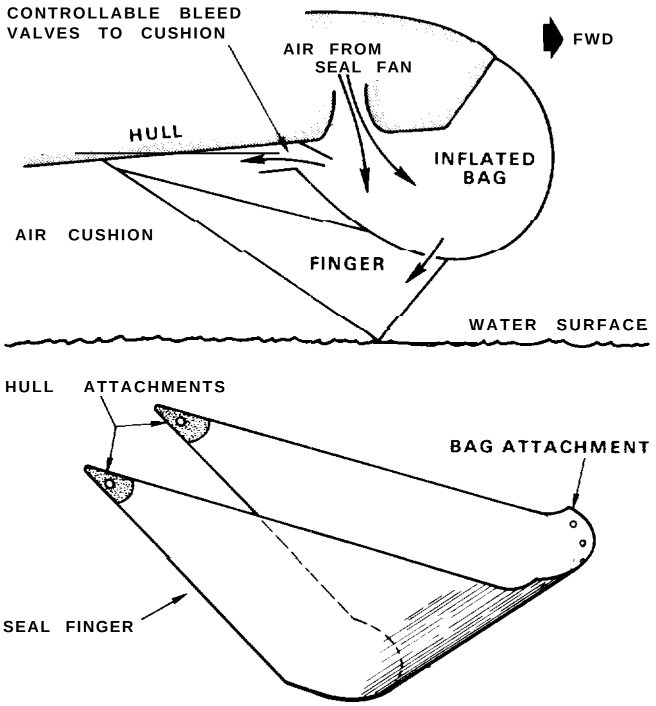


Figure 54. Bag and Finger **Bow Seal SES-100B**

ship through an active variable-geometry system. Lift fan technology is mature and available for SESs through the 20,000-ton size. The rotating diffuser (RD) fan, together with variable geometry dynamic inlet guide vanes is available off-the-shelf with a background of thirty years in steady-state operation and five years in dynamic (ride control) prototype operation. Improved lift fan systems of other types may become available, but are not currently required.

BOW AND STERN SEALS

The seals which are located at the bow and stern and extend between the sidehulls to contain the air cushion must be designed to withstand loads originating primarily from pneumatic (cushion pressure) and hydrodynamic (water contact) forces. Worst case seal loads generally occur at high speed in head seas, however, other headings, different sea states, maximum speed astern, and configuration change loads (off-cushion to on-cushion transition, seal retraction, etc.) must be considered.

Operating at high-speed in large seas normally presents the controlling design case for bow seals. Cushion pressure forces it forward while hydrodynamic loads drag it aft. This results in alternating loads of large magnitude since peak cushion pressure and maximum seal wetting rarely coincide.

Flexibility

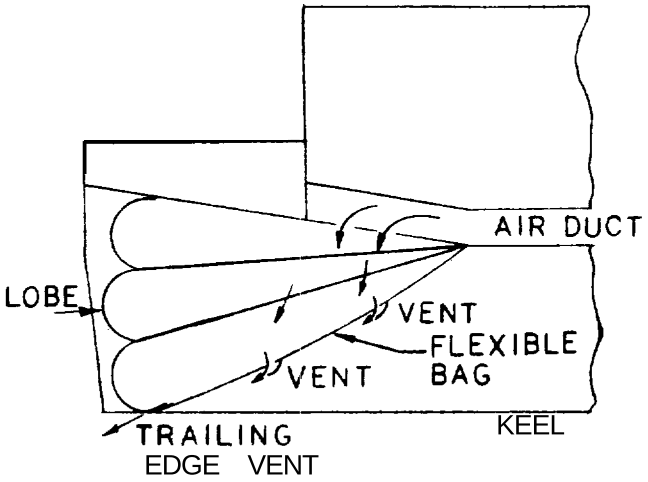


Figure 55. 3-Lobe Stern Seal SES-200

One characteristic central to all seal structures is the degree of flexibility. While it is feasible to build fully rigid seals which are integral with the hull structure, seal loads at high-speed in a seaway caused by slam and planing forces result in high seal weight and increased ship motions and hull girder bending moments. Thus seal designs tend to fall into flexible and semiflexible categories.

Flexible seals are primarily tensile structures constructed of taut loops of fabric which are either fixed to the ship's structure or restrained by cables or straps. Seal geometry is determined by the inflated shape of the fabric and varies locally due to hydrodynamic forces.

Typical bow seal designs are the bag and finger (Figure 54) and the hard mounted finger, a variation formed by mounting the finger directly to the bow structure. The bag and finger seal was adapted directly from hovercraft seals and used by both 100-ton testcraft. The hard mounted finger is a further simplification developed for the BH-110 by Bell Aerospace. ([86, and 87]).

Flexible stern seal design has been limited to the full width multilobe bag (Figure 55). This concept has been successfully developed by Bell for the SES-100B and BH-110.

Semiflexible seals incorporate rigid elements which carry bending and compressive loads in addition to tensile loads. Thus seal geometry is not strictly dependent upon inflation forces. The rigid elements are joined by hinges or flexible elements resulting in the description semiflexible.

Both the XR-1D and SES-100A stern seals are hinged, two-panel assemblies (Figure 56) which extend full width. Seal geometry is controlled by cushion pressure in a three lobe bag, a spring at the intrapanel joint, and the position of the retraction system.

Other semiflexible seals designs use flexible elements rather than hinges to control seal geometry [86]. These include the XR-1D bow seal (Figure 57), the XR-5 seals (Figure 58), the SES-100A-1 bow seal (Figure 59 and Reference [88]), and the transversely supported membrane (TSM) bow seal (Figure 60) currently under development by the Navy using the XR-1E and SES-200.

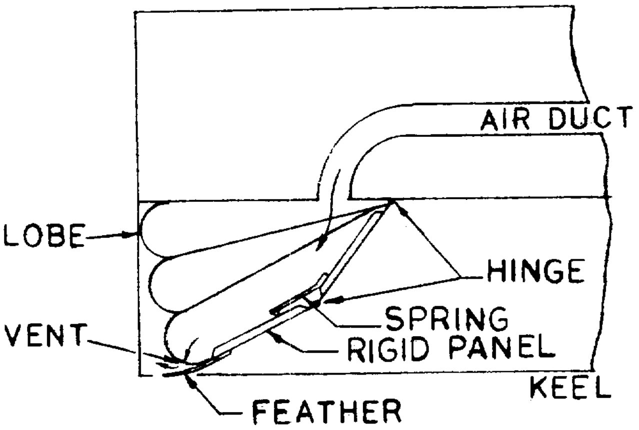


Figure 56. 2-Panel Hinged Stern Seal XR-ID **and SES 100A**

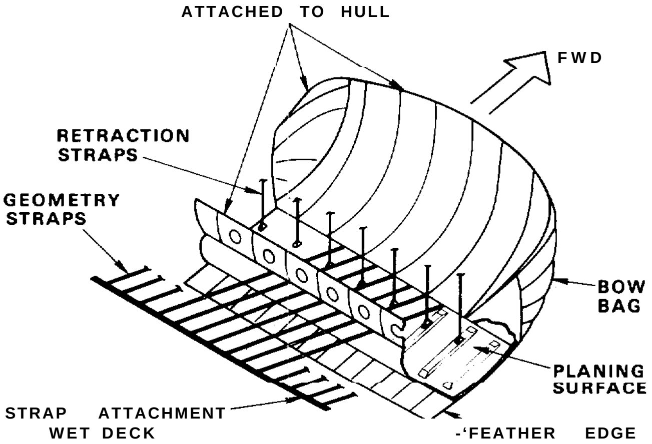


Figure 57. Single Planer Bow Seal

The XR-ID and SES-100A-1 seals incorporate single or multiple rigid planing elements (planers) which are positioned with restraint straps. Intraplaner joints constructed of multiple laminations of seal material are bolted to adjacent planer edges to unify the SES-100A-1 seals. Both designs incorporate a thin fiberglass shingle or feather to provide a flexible, lightweight planing element at the water interface.

The XR-5 seals incorporate full length steel spring stays which attach to a hinged plate at the front and are supported at two points by restraint cables. The stays **and** restraint cables support and shape a flexible fabric bag which controls cushion pressure.

The TSM bow seal consists of two functionally specific elements: a bag to provide clearance and cushioning in large seas, and a parasol to provide water contact and seal the cushion. The parasol incorporates small plates of multilayer unidirectional fiberglass bonded between layers of elastomer-coated fabric to provide bending stiffness in the span between the webs. The plates are assembled on a carrier with spacers to provide a laterally-oriented subassembly which is supported continuously along the edges by the webs and referred to as a batten. The webs are then joined at a common point to form the semicircular shape of the parasol.

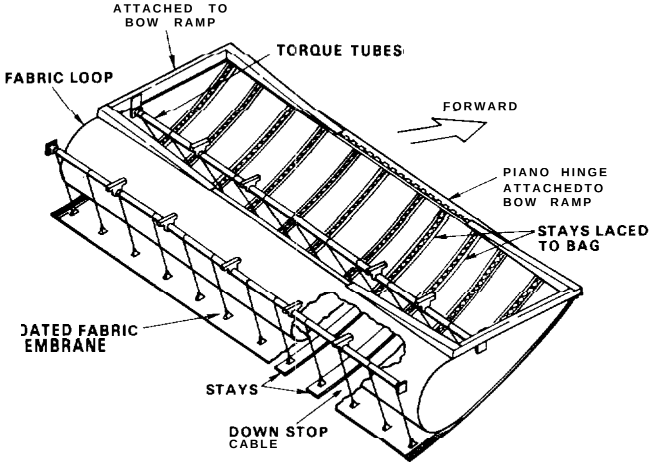


Figure 58. Stay Stiffened Fabric Membrane Seal

Lift and Drag

Ideally the seal would skim the water resulting in no air leakage, no lift, and no drag. Practically, however, all seals touch the water in a seaway and even in calm water some wetting is desirable to minimize air leakage and reduce total ship power. Seal drag arises from wetted surface (viscous) and, in planing seals, from the inclination of the total force vector. While drag is parasitic, seal lift may reduce the total cushion lift requirement and provide pitch moments, and to a lesser extent roll moments, which contribute sufficiently to ship stability to permit incorporation of finer hull lines, etc. It should be noted that flexible seals produce lift and moments indirectly through changes in wetted length and thus cushion area (Figure 61).

Seals which produce lower moments may reduce ship motions in a seaway. The parasol shape of the TSM bow seal has the characteristic of small increases in wetted length and thus cushion area for large increases in bow immersion (Figure 62). Where seal moment contributions

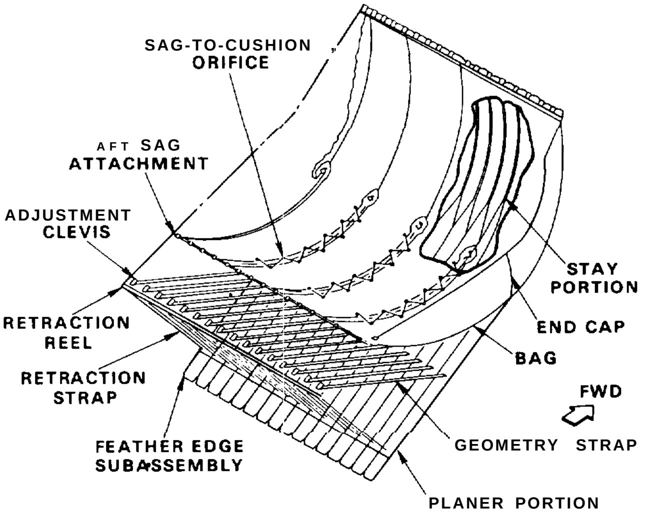


Figure 59.. Planing Bow Seal

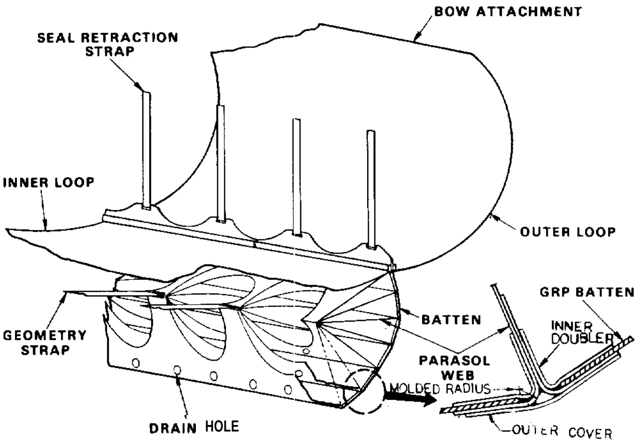


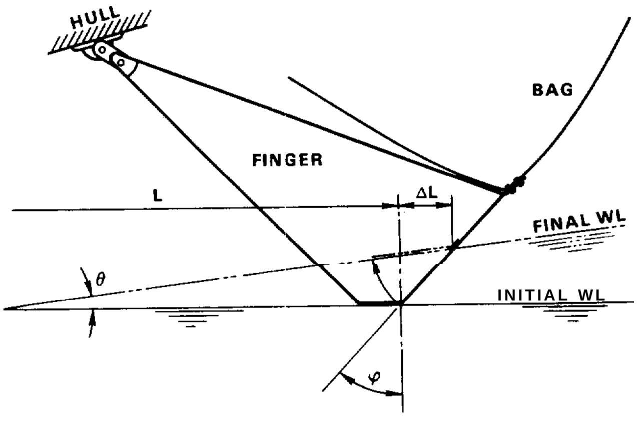
Figure 60. TSM Seal Concept

are not significant to ship stability, as in high l/b SESs, this characteristic can be of considerable benefit.

Sealing Efficiency

Between 10 and 25 percent of an SES's power requirement is attributable to air leakage from the cushion. Some of this leakage is inherent (wave pumping) and some is desirable for ride stability and control. However, sealing efficiency can be very significant to overall efficiency.

Single assembly seals. such as the multilobe bag stern seal, and all semiflexible seals, would appear to have better sealing efficiency than finger seals since the free edges where leakage occurs are limited to the perimeter. However, finger seals, because of their low mass and flexibility, follow the water surface very closely and thus may have better efficiency at high speed in moderate seas.



L: CUSHION LENGTH
AL: INCREASE IN L CAUSED BY BUCKLED FINGERS
9: RAKE ANGLE (FROM VERTICAL)
θ: DOWN TRIM ANGLE

Figure 61. Seal Fingers-Pitch Restoring Mechanism

Geometry

Seal geometry ranges from two-dimensional, as in various planing seals, the TSM seal and bag type stern seals, to three-dimensional as in the SES-100B's torodial bag and finger bow seal. Other seals are of intermediate dimensionality, such as the SES-200 bow seal which has a small rake resulting in opposite hand fingers port and starboard.

Two-dimensional seals attach to a uniform transverse bow structure and thus consist of identically repeated structural elements, such as fingers or planers. Because of their geometric simplicity and repetition they are simpler to design and construct. It should be noted that the water surface on which the seal rides is never two-dimensional due to the ship's bow wave and to sea state. This can lead to complications when attempting to predict loads in elements such as intraplaner joints which join laterally continuous assemblies.

Three-dimensional seals consist of a number of differing elements. Where the elements are fully three-dimensional of themselves, i.e., the torodial bag, curved fixtures and presses must be used to bond joints between a number of small panels which approximate the desired shape. The chief advantage claimed for these seals is the reduction of on-cushion bow slamming loads. However, depending upon the performance specification off-cushion slamming may produce the worst case loads.

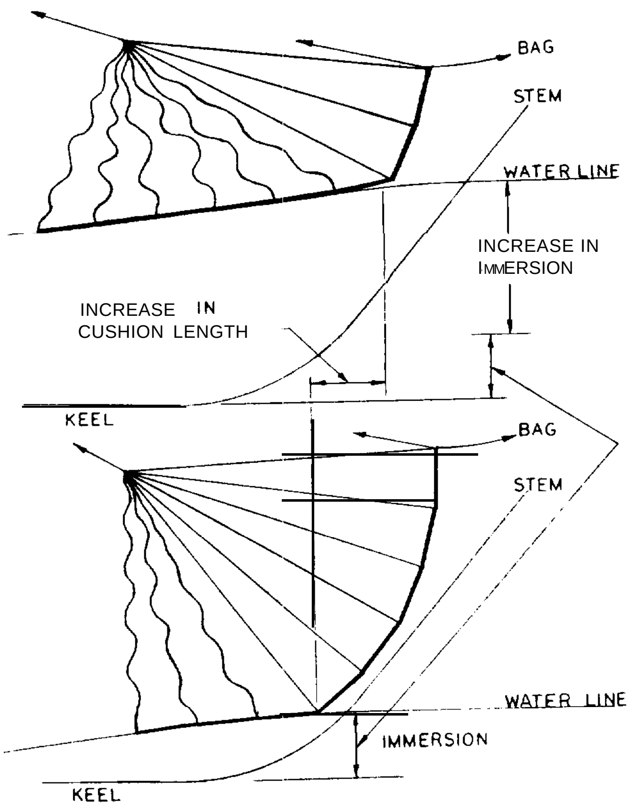


Figure 62. TSM Bow Seal Geometry

Materials and Hardware

Nearly all fabrics used to date have a basket-weave (open) flat-strand construction using nylon fibers. Some testing of Kevlar and metallic based fabrics was undertaken during the 1970s, however, incompatability of mechanical properties between the fabric and the coatings led to high wear rates and limited possible applications to relatively static structures.

The elastomer coating is required to stabilize the fabric weave, particularly at free edges. It also makes the fabric water and air tight, adds mass and damping, and provides a bonding surface which optimizes adhesion to the fabric cord. Elastomer coatings most often used are PVC-nitrile, neoprene, and various blends of natural rubber with polybutadiene and buna-N [86]. The natural rubber blends offer the best elasticity and lowest hysteresis. Hysteresis is a very important property since bending the fabric alternately stretches and compresses the coating and hysteresis results in heat buildup. PVC-nitrile coatings have the advantage of high-strength cold bonding while natural rubber blends require hot press vulcanizing for best joint strength.

All but one of the semiflexible designs described here have rigid elements of multilayer laminations of unidirectional GRP. The primary advantages of this material are wide availability (e.g., 3M Scotchply 1002 or 1003), low cost, high strength-to-weight ratio, and compatibility with the marine environment. For instance, Scotchply 1002 has a specific gravity of 1.85 (.067 lbs/cu. in), a flexural strength 167,000 psi, and a flexural modulus of 6,000,000 psi. In unidirectional applications, 1002 has a strength-to-weight ratio 3 times better than high strength alloys such as 7075-T6 aluminum.

Attachment members are used primarily in semiflexible seals and include straps, ropes and cables which restrain and in some cases retract the seal. Straps generally have been preferred because their shape simplifies clamping and rolling. A number of materials have been used, however, Dacron (polyester) has been preferred for its low elongation, creep and cost. Nylon has been proposed for applications in which increased shock absorption is desired. Other materials include stainless steel, GRP and Kevlar.

Durability

Assuming that structural strength design margins (including fatigue) are adequate, a number of wear mechanisms limit seal life: flagellation in finger seals, flutter and erosion, abrasion, foreign object damage, impact with the ship's structure and wear at load concentration points.

Flagellation is a high frequency and high "g" bending phenomenon which occurs in the water contact zone near the trailing edge of the finger. Elastomer hysteresis results in heating and subsequent fatigue and flaking of the coating. After the coating flakes off, the fabric weave unravels and forms a tangled "beard." On a new edge, formation of the beard slows the wear rate.

Flagellation is the primary wear mechanism limiting the life of finger seals. Studies of flagellation have been completed using the SES-100B and a tow tank test rig at DTNSRDC [89]. Using miniature accelerometers placed at various distances from the trailing edge, accelerations were found to be in excess of 4000 g's near the edge at frequencies approaching 200 Hz. These motions are dependent upon speed and cushion pressure (Figure 63) and have a threshold velocity (approximately 25 to 30 kts) below which motions are not highly excited. For instance, the SES-200 operates at speeds generally below 30 kts and has a finger wear rate which requires tip renewal (lower 12") at between 1500 to 3000 hours, while large hovercraft and the 100-ton testcraft, which have similar cushion pressures but generally operate at speeds of 40 to 60 knots. have wear rates which require finger tip replacement every 300 to 700 hours.

Semiflexible seals avoid flagellation by the use of stiff members at the water interface. Motions measured on the TSM bow seal produced accelerations below 2.50 g's at frequencies below 40 Hz. Providing other wear mechanisms are minimized, semiflexible seals hold the promise of greatly extended seal life and thus lower life cycle costs.

A wear mechanism somewhat analogous to flagellation affects the trailing edge feathers used on planing seals. Feathers, which are constructed of multilayer unidirectional GRP, show significant deterioration along the trailing edge, particularly at the corners, due to intralamina bond failure and erosion. Instrumented feathers used on the SES-100A-1 revealed high-g and high-frequency motions similar to flagellation. Static seal tests have demonstrated reedlike motions in bow seal feathers which would naturally occur when water contour and cushion pressure resulted in the required leakage channel.

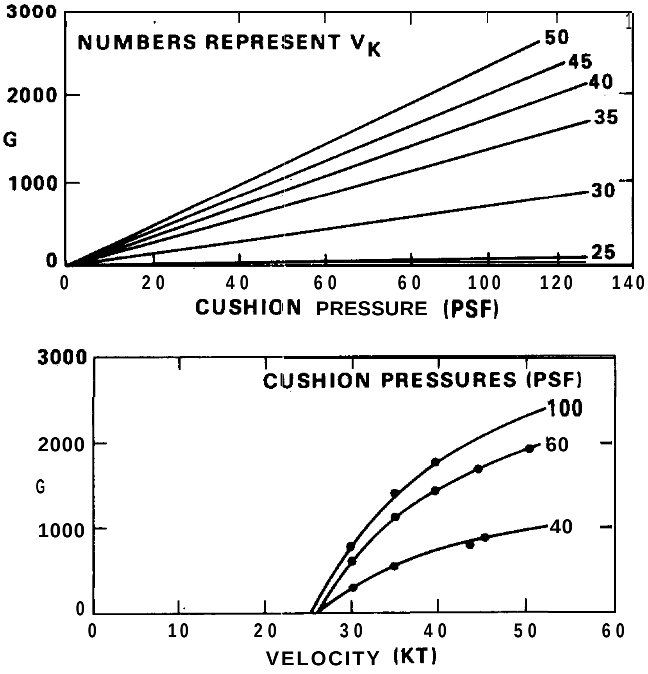


Figure 63. Finger Accelerations vs. Speed and Pressure.

Recent research indicates that feather durability can be improved by use of a woven (vice unidirectional) face laminate and by using higher resin content in the laminate. This improves both peel resistance and intralamina bond strength leading to improved durability at the expense of gross strength properties.

Fingers occasionally exhibit intermittent flutter (buzz) where sidehull or intrafinger fit is poor resulting in an air escape path. However, this is not a significant wear mechanism.

Relative motions between adjacent free components result in friction and in some cases snagging. Typically, fingers show flaking or delamination of the coatings followed by fraying of the fabric between adjacent fingers and between the outboard finger and the stem. This wear is more severe near the water surface where motions are greatest.

The primary wear mechanism limiting the life of flexible stern seals is abrasion between the end of the seal and the sidehull. End caps are fabric panels which hold the seal shape and reduce air leakage at the edge. They wear both against themselves at the lobe joints (particularly at fastener heads) and against the sidehull. Recent stern seal designs have eliminated the end caps and controlled leakage with better sidehull fit.

Semiflexible seals generally have a wear or rub strip along each edge. Even though seals are typically constructed with a small edge gap, lateral motion results in occasional sidehull contact. In addition to providing a wear surface, this strip also functions as an air seal, a shock absorber, and local reinforcement.

Eventually every seal will encounter a snag, etc., resulting in local damage. If the damage does not result in gross failure, additional damage may result from stress concentration (crack or tear propagation) or local wear acceleration.

Tensile stress in flexible structures, such as fingers and bags, is called hoop stress. It originates from cushion pressure and is directly proportional to the pressure and the radius of curvature. In two-dimensional structures, hoop stress is oriented along the circumference. Thus a tear along the axis of the cylinder results in a local stress concentration that is dependent on the length of the tear and the construction and elasticity of the material. Thus, punctures may result in no additional damage while a tear of a few inches perpendicular to the stress may continue to propagate during pressure peaks. As the tear continues to lengthen, the propagation occurs at a lower pressure.

Fingers occasionally fail prior to their normally flagellation-limited life span due to propagation of a tear up the face of the finger. Inspection of the failure shows that the tear originated at a sharp discontinuity in the lower leading edge of the finger. This may indicate that flagellation has attacked a point of local damage until the stress concentration was sufficient to continue the failure up the face of the finger.

Semiflexible seals may also incur impact damage; however, by comparison with flexible seals which have been in widespread use for nearly 20 years, very little operational data is available. The TSM bow seal's hybrid parasol structure is designed to provide improved impact and tear resistance. In 200 hours of operating experience with segmented battens, there have been no instances of parasol tears or delaminations due to foreign object damage although scratches in the parasol's outer cover indicate several encounters.

Invariably the ship will encounter a sea state or operating condition which causes the seal to be slammed against the wet deck. Flexible seals have a clear advantage in that their attachments are simpler, and the fabric conforms to and is supported by the wetdeck. However, any small protrusion, such as a rivet or other fastener, will form a snag or abrasion point which limits seal life.

Semiflexible seals incorporating rigid planers must be supplied with bumpers or other impact limiting mechanisms to prevent local damage. Retraction mechanisms and strap attachment brackets, if located in the impact area, must be recessed to prevent local damage and cutting and tangling of straps.

Wear at load concentration points, which occurs at strap clamps, pins, edge bead attachments and intraplaner joints, is more of a maintenance problem than a seal life limitation. The usual approach to correcting the problem involves installation of local wear doublers, lubrication points, and periodic replacement of the worn elements.

Modularity

In general, modularity promotes redundancy and maintainability while lowering total cost. When a number of identical or similar elements are combined, failure of one element is less likely to cause gross failure and each element may be replaced separately. Cost is usually lowered because a smaller element may be fabricated more easily and in larger quantities although several different types of elements may be required.

The SES-100A-l seals were highly modular as are the BH-110 and SES-200 bow seals. The TSM bow seal is partially modular in that it incorporates a number of identical straps and clamps.

Redundancy

This is the ability of a seal to continue to function normally even though one or more of its substructures has failed. For instance, the straps and webs which maintain the geometry of a semiflexible seal are quite redundant. Failure of a large number of scattered central (versus edge) elements results in higher loads in the remaining elements rather than gross failure.

Major elements with sealing functions (versus support) generally have no redundancy. For instance, complete failure of a planer or bag results in direct loss of sealing function. If the lift system does not have sufficient reserve flow capacity (a type of redundancy), cushion pressure will drop and ship performance will be impaired.

The most redundant seal currently available is the hard-mounted finger seal used in the BH-110 and SES-200. The entire sealing function is carried by the fingers. When a single finger fails, adjacent fingers expand by increasing their frontal radius to fill the resulting gap and nearly eliminate air leakage. However, the increased radius results in increased stress and, thus, increased susceptibility to tearing. The SES-200 has operated with only a slight increase in air leakage and no loss of performance with a single centrally located finger approximately 70% torn.

For a given finger size and strength, increasing the number of fingers reduces the radius and thus increases the redundancy and weight. If the outboard fingers are half width and all fingers are capable of a 50% increase in radius without failure, then the seal will be fully single redundant. That is, cushion pressure will continue to be maintained even though any single finger has failed. Some increase in air leakage is inevitable as the tear approaches the wetdeck since finger attachments constrain the adjacent fingers from completely filling the gap at the top.

Maintainability and Repairability

Ideally, seal life at least should equal the ship's normal drydock cycle permitting most maintenance to be conducted ashore. However, given current seal durability, provision for maintenance and repairs afloat must be considered. Use of divers should be avoided due to high cost and low productivity. Thus, seal systems incorporating easily-replaced modules are preferred.

The SES-200 bow seal fingers are designed to be replaced by a small crew in approximately 2 hours [87]. Due to the ship's high displacement sidehulls and trim system, 2 to 3 feet of wetdeck clearance can be obtained at the finger's trailing edge. This permits a crewman to go under the ship in a small skiff for installation and removal of hardware.

The interior of the SES-200 TSM bow seal is fully accessible through enlarged vent holes in the bow seal plenum. This permits instrumentation, straps, and clamps to be inspected, adjusted or replaced. With the installation of a retract system, the entire parasol may be lifted clear of the water for inspection and minor repairs. Removal of the parasol is accomplished by loosening strap clamps followed by release of the bag-to-parasol joint. A crane and a spreader bar is used to lift the assembly from the water. The entire operation can be completed in about 3 hours by 4 experienced crewmen. Installation takes longer due to the necessity to adjust each strap to the proper length using portable winches. A work platform is used to aid installation of the parasol to bag joint.

Other than replacement of modular elements, repairs take the form of mechanically-fastened or bonded patches. The marine environment with its high humidity, surface oils and uncontrolled temperatures virtually eliminates all but the most local cold bonded repairs. Thus, most waterborne repairs take the form of flexible or rigid patches held by mechanical fasteners. Because of load concentrations which occur at the fasteners, this type of repair usually has a limited life.

If the damaged element is removed and taken to a repair facility (possibly onboard), the damaged areas may be dried, cleaned and buffed prior to hot press vulcanizing or vacuum bag bonding of repair patches. Worn or torn fingers are routinely refurbished (retreaded) several times to extend their life. This process involves total replacement of the finger's lower panel.

Future Directions

The bow and stern seals of the SES-200 and BH-110 series are mature designs which are currently undergoing evolutionary product improvement at Bell Aerospace Textron. Finger life is being extended through the use of new fabrics, particularly in the lower panel. Stern seal durability has been improved with the elimination of the end caps. Material strength and flagellation resistance continue to improve partially due to research in hovercraft seal materials.

Modularity of bow seals can be improved through use of purely two-dimensional bow structures. Maintainability can be enhanced through elimination of as many bolted connections as possible. Stainless steel bolts are subject to severe corrosion when used in an aluminum structure in wet applications.

Using the SES-200, TSM bow seal development will be continued in an effort to greatly extend bow seal life. The second generation seal will incorporate improved joints and attachments to enhance durability in high sea states. Elimination of as many bolts as possible will be a major goal. After this seal has demonstrated reasonable durability, a third-generation modular parasol incorporating lighter weight materials is planned. As in the multiple planer seal, the intrasegment joint will present the most difficult design problem.

Alternate materials include carbon fiber laminates, Kevlar cloth, sandwich structures incorporating Nomex or other lightweight core, and natural rubber blend coatings.

In the longer range, extension of the TSM concept to stern seals should be investigated along with continued development of parametric design software to optimize performance and economics.

PRODUCIBILITY

Producibility of SESs compared with conventional marine equipment have greater similarities than differences. The differences arise from material design processes and skill distinctions that raise what has become almost a classical question: Are they shipbuilding or aerospace products? In fact, they are both to a certain extent, but SESs cannot be placed in a single category. The fundamental distinction obvious to traditional shipbuilders is material selection and the degree of attention to weight control.

Looking at recent experience, for SESs which have been constructed and are in operational service, producibility has been addressed by setting a goal to make maximum use of conventional marine equipment. This goal has been more successful than might have been anticipated several years ago. There is an economy of scale at work because, it is easier for the larger SESs to accommodate this heavier conventional marine equipment than has been the case for smaller craft. Therefore, as a natural evolution as we build larger SESs, producibility will continue to improve.

There are very few SES-unique components. Previously, the lift fans were components that required attention beyond that currently expected for similar equipment. However, essentially infinite fatigue life has now been achieved, and relatively simple, rugged lift fans are in service. The lift seal system has benefitted greatly from both SES and ACV operational experience, and the design has been refined so that service life now is many times greater than achieved only a few years ago. Further improvements in this area are expected.

Aside from design and manufacturing processes, other aspects of producibility a.re customer and certification agency requirements. With the current U.S. transition from exclusive U.S. Coast Guard to American Bureau of Shipping (ABS) requirements, there are some clarifications needed to determine just what the commercial builder will be expected to do. Previous experience with commercial designs, currently under exclusive Coast Guard surveillance, was quite straightforward and of no significant problem to the builder. There have not been any developments to date that would cause concern about ABS involvement. However, this has yet to be fully addressed.

Military programs are an entirely different matter. The need to produce craft and small vessels for the U.S. military, with its worldwide missions and sophisticated military logistics requirements, does translate into significant influences on producibility and supportability. The prospect of a conventional or 'commercial builder producing advanced platforms for the military would require significant adjustments in the way they normally do business.

One of the chronic problems with military products has been a lack of sufficient production quantities to facilitate capital investment and to permit selection of production methods which achieve reduced unit costs. Also, there is difficulty in projecting program or market stability to achieve routine and other improvements. Fortunately, with recent experience, there have been significant improvements in both quantity and stability; to a lesser extent, there has been success in the willingness of subcontractors and vendors to commit to approaches enabling reduced unit costs based on quantity production. Another benefit has been a movement toward standard marine components, thereby achieving producibility, not because of market success or attributes of the advanced hullform, but rather the economy of scale created by the broader marine industry.

SES Production in the UK

Some of the detailed aspects of producing surface effect ships can be understood by reviewing the experiences of a leading builder, the UK firm of Vosper Hovermarine, Ltd. Such a review is presented in the following sections.

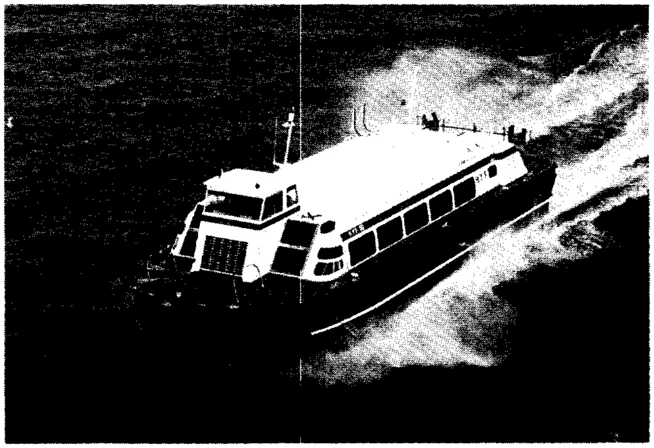


Figure 64. HM218 SES Operated by Hong Kong & Yaumati Ferry Company

Apart from a very brief three year period from 1960 to 1963 when shipbuilder, William Denny & Brothers, attempted to produce first generation craft, the sole thrust in this regard has evolved from the original Hovermarine Ltd., founded in 1965 and has continued through to the present day company, Vosper Hovermarine (VHL). In total over one hundred SES craft have been produced in the two plants at Woolston, Southampton, England, which essentially have met a market demand in the commercial section, as indicated in Figures 64 and 65. However, when most countries' defense institutions are looking to cost effective approaches to procurement it is relevant to consider commercial methods that have succeeded in a competitive market which demands high operational utilization and a quality product. References [90-95] summarize the philosophy and methodology that have gone into the production aspects of British SESs to date.

From the start, and bearing in mind the miniscule beginnings in terms of financial resources, governmental support and the few dedicated advocates, the first priority of the Hovermarine company was to determine the size, speed and cost of a craft that could penetrate the only identified market that potentially could provide at least a small batch production requirement-the commercial ferry market. The hydrodynamic, mechanical and transport efficiencies of the early conceptual designs were not

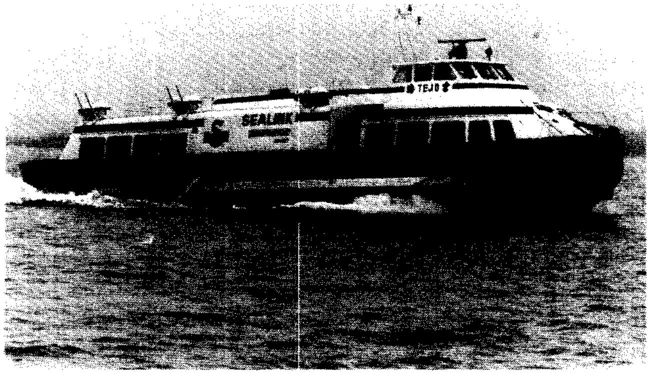


Figure 65. HM527 SES Operated by Sealink Ferry Company, Hong Kong

difficult parameters to deduce within a reasonable band of accuracy-the difficulties came when decision had to be made as to what material the hull should be made from, what kind of prime movers should be installed, what company systems had to be established and adhered to in order to maintain a quality product and what information and support systems are required for efficient production.

Although a number of the pioneers in this business were aeronautically biased because of their educational background and were more receptive to novel approaches to transport problems, the market to be faced was distinctly marine and a conscious decision was made that the product had to reflect this in all its aspects. Hence, now naval architects form the backbone of the design department, marine commanders operate the craft and marine engineers maintain them--the craft can be fundamentally integrated into any existing operating company employing displacement type ferries. The only anomaly which still remains, which is in name only, is that the Civil Aviation Authority of the United Kingdom is the agent of government to ensure safety of designs and constructions, but in implementing their responsibility marine considerations predominate and the marine division of the Department of Transportation is fully involved with any operational requirement.

In developing a high performance marine platform, weight is an important consideration and indeed is a basic control parameter. The experience with rivetted light alloy structures-an established technology-was obviously a lightweight contender but the apparent cost compared to an evolving technology in glass reinforced plastics (GRP) showed even then (1965-1970) considerable cost penalties for the ultimate weight saving. At the size of craft being considered, which started off as a 50-ft vessel, a welded light alloy structure appeared fraught with problems which could arise from distortions, corrosion and fatigue-although with some weight penalty most of these could be reduced considerably. With an abundance of woodworking and local laminating skills it was decided that the HM200 series craft would be built of GRP. The combination of highly skilled and experienced supervision with semiskilled shop floor operatives seemed to produce the right combination as far as the hull structure was concerned.

The essential prime mover throughout commercial SES development has been the marine high speed diesel with the small gas turbine only given cursory consideration being overwhelmed by the high capital, fuel and maintenance costs of the units being offered. Gasoline engines were not considered for ferry craft because of safety reasons though for small craft weight and cost appeared reasonably compatible. In aiming to reduce the overall development costs and risk, transmission systems were chosen for the early HM200 series that were comprised of off-the-shelf items some of which have been extremely reliable and some of which were highly unreliable. As far as the lift machinery was concerned, power transmission through reinforced neoprene castellated belts proved a considerable success story which at the time of choosing was novel in its application. On the other hand employing "proven" constant-velocity joints in the propulsion transmission system was disastrous—this item was substituted by a relatively unorthodox helical screw gear built not specifically for this application but adapted externally for the HM200's mounting arrangement and has proved very successful. These little examples are only quoted to relay the point that whereas it seems totally reasonable to purchase standard marinized components it should not be taken as a guarantee of high reliability in a high utilization environment in which a large proportion of the vessels are used at near full throttle for approaching 3000 hours per year or can be in a mixed role activity-slow/fast cycles, up to 5000 hours per year. In this environment the capability of the gear to withstand very frequent stops and starts, rapid reversals etc., are sometimes well in excess of what manufacturers claim as the "capacity" of their component to do the job.

As the company expanded with an increase of business, obviously the systems procedures had to grow. It is, of course, essential to have a company procedures manual which defines in a comprehensive way the logic, authority and documentation required to push things through the system and provide feedback. In practice, while all managers must understand the procedures and keep such at the back of their mind for reference, the efficient flow of work through the system depends on people reacting sensibly to small perturbations from the ideal and on some few occasions having to cut major corners to meet the demand. Providing the management team shares and implements the responsibility, no major problem should occur and a quality product should result.

A "small company" is a very relative term but, in general, it has been found that units of less than 500 people can cope in this way and that production units much larger than this, certainly in excess of 2000, have difficulty in providing the natural flow of communication that derives from physically being geographically close and having a willingness to act as one of a large "family."

The small company in many ways physically surrounds the product and this is a considerable production advantage. Remote departments and/or subcontract design would add an order of complexity and cost-occasional consultancy help can be brought into the production arena. It isn't just quaint, that, while all modern functions including network planning and, where appropriate, computer-aided design, have their place even in a small company, in the end the hardware designer has to verbally communicate with shop floor supervision and the operator. This has been the custom since the dawn of history of marine construction. In any company system that avoids this fundamental need, lack of team spirit and motivation problems can result and quality will be impaired.

A high standard of quality is required for SES, both in the design and production where weight, material selection and material conformity is critical. Strict control of all processes is therefore required from conception to completion. It is also imperative that all requirements are

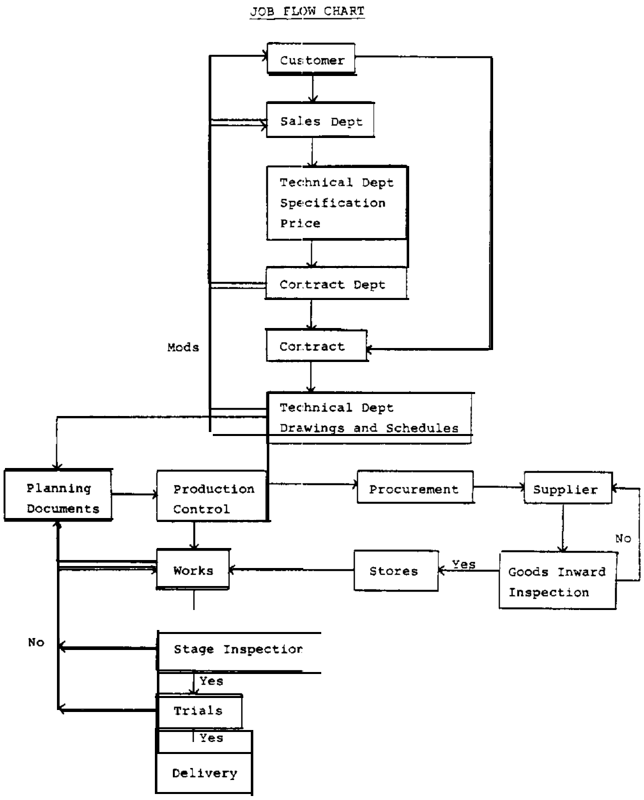


Figure 66. Job Flow Chart

defined by drawings or instructions and that changes are formally authorized, distributed and recorded.

Vosper Hovermarine is approved by the UK Civil Aviation Authority as a design and build organization. The company also meets the quality assurance requirements of the Ministry of Defence (Navy) 05-21. In order to achieve the above standards all activities are controlled by departmental procedures giving clearly defined responsibilities and processes against which departments are audited. The job flow chart is illustrated in Figure 66.

Planning, procurement and production functions are the general responsibilities of the company's general works manager. Central planning is undertaken by project foremen under the direction of the production control manager. Information is fed into this department from all sources to produce a master plan. From this network the computer produces bar charts which are activity, procurement, trade and date oriented. These become the working document for supervisors. The plan is continually reviewed and revised as necessary.

A materials manager is dedicated to the procurement of all materials. Schedules/parts lists which accompany the drawings provide fully detailed information to enable the buyers to fulfill their task. Flexibility in selection of suppliers is only given to the buyers for raw materials and for items made to company drawings. The remainder of the suppliers are defined by the technical department. Materials are delivered ahead of the date required in order that any delay can be contained within the program.

The production facility consists of two main buildings. Plant One is used for the construction of the hull and superstructure and Plant Two is used for fitting out. The former building is specially designed for the laying up of GRP structures with special heating and ventilation systems. Continuous monitoring of the environment inside this complex is carried out. See Figs. 67 and 68.

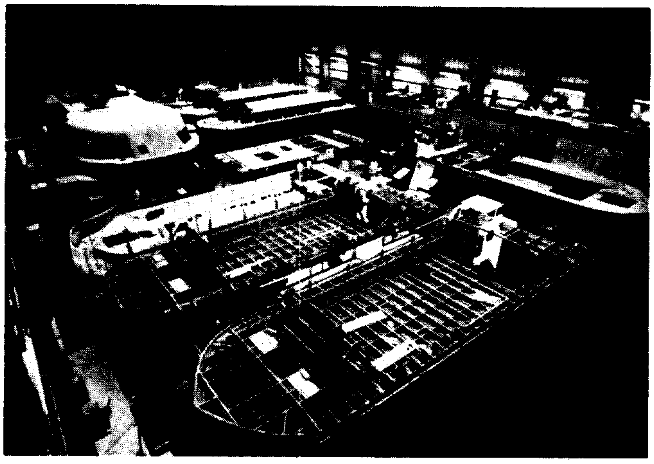


Figure 67. Internal View of Vosper Hovermarine Plant 1

Each trade, e.g., fitters, laminators, electricians, is headed by a trade foreman. Each craft build is headed by a project foreman who is responsible for liaison with the trade foreman, in order to meet the agreed program. He is responsible for calling progress meetings and reviewing planning documents.

During construction of the vessel there is direct contact between the works and the technical departments, when any difficulties or errors are resolved. Formal procedures are used when an alteration is required so that drawings are amended and the change authorized and recorded. See Fig. 69.

Quality assurance is the responsibility of the technical director which, on a day-to-day basis, is implemented by the chief quality assurance engineer. The quality assurance department is responsible for the inspection of all purchased material. Performance monitoring of suppliers is carried out on a regular basis. The QA department also produces check lists for all stages of build which are signed, dated and defects recorded. There are three levels of inspection:

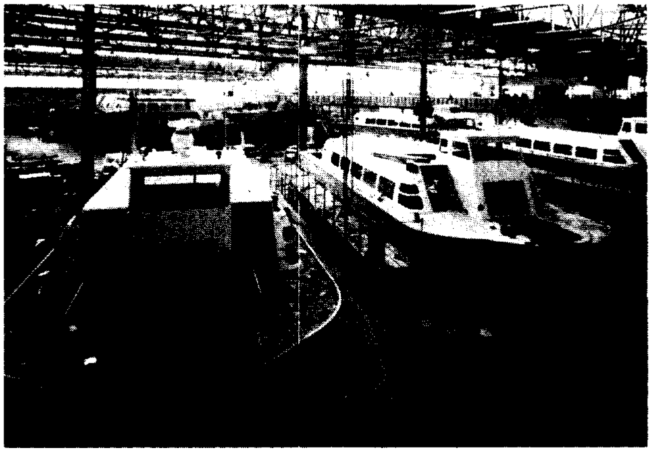
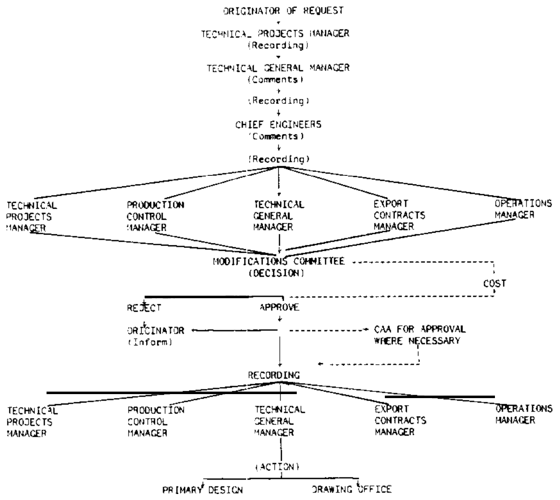


Figure 68. Internal View of Vosper Hovermarine Plant 2



INFORMATION REQUESTED BELOW TO BE COMPLETED BY THE PERSON REQUESTING THE CHANGE.

Category 'B' Items: Development Changes

(1) Classification Authority requirements.
(2) Trials feed back from Wash Up meetings.
(3) After-sales feed back of repetitive failures and general criticism of the product.
(4) Changes to reduce D.O., Material and Works costs.
(5) Improvements generally.

What craft numbers affect?			
Are Classification Authorities involved?	Yes	No	
Will weight change?	Increase	Decrease	No
Are materials affected?	Yes	No	
Will material costs change?	Increase	Decrease	No
Will Works hours change?	Increase	Decrease	No
Will Design and D.O. hours change?	Increase	Decrease	No
Will this affect publications?	Yes	No	

Figure 69. Ship Alteration Procedures

Level 1: Company QA department and approving authority.
Level 2: Company QA department
Level 3: Supervision on the work floor

Formal in-depth investigations are carried out on unusual defects that appear during build and after delivery and a report of the findings distributed. Internal QA audits are carried out to ensure that the company procedures are being adhered to.

The trials engineer is responsible for carrying out trials to meet requirements documented by the technical department. Results are passed back to the QA department, including a record of defects. Trials can absorb periods from one week for a small standard vessel to nine months for a large prototype craft.

Materials Selection and Null Configuration

The overall structure needs to be built from materials fully compatible with both the manufacturing capabilities of a good standard boat manufacturing organization and the maintenance capabilities available in the markets throughout the world-particularly less developed areas. Both glass reinforced plastic and welded aluminum alloy materials were carefully considered and GRP selected because it provided the above features, plus many other significant advantages.

- lower costs and reasonable weight
- readily repairable
- freedom from corrosion
- greater resilience-ability to absorb shock loads
- better finish and fairness to the hull
- ease with which complex double curvature shapes can be fabricated
- large one piece mouldings for water tightness
- minimum maintenance costs
- electrolytically inert

The selection of GRP for the hull material also provides design flexibility to allow changes in the length of the boat with minimum impact on manufacturing yet can give customised design for specific customer requirements.

The GRP materials generally used in Hovermarine craft are high strength woven glass rovings (WR) and unidirectional glass rovings (UR) in conjunction with a high heat distortion temperature, low water permeable, isophthalic polyester resin, the combination of which with glass rovings gives further additional features to the craft such as:

Better Insulation Against Fire. Additionally GRP structures have the significant advantage over aluminum alloys in that they have a very low thermal conductivity, enabling them to remain on scene to carry out fire fighting and/or rescue duties in areas of intense heat.

In extreme cases GRP hulled lifeboats built by Watercraft UK have survived a series of tests carried out by the Ministry of Transport, in conjunction with the Admiralty, to examine the performance of these craft in simulated 'burning oil on sea surface' conditions. The oil was ignited and burned very fiercely for five minutes with the craft totally engulfed. The results showed the structure to remain satisfactory and also because of the materials basic thermal insulation properties, the suitability for human occupation as regards temperature was deemed acceptable. VHL have produced two special purpose craft employed for fire fighting purposes. Four HM218s (See Figure 70) are in operation with the Port of Rotterdam as multipurpose patrol craft including a limited firefighting capability and two HM221s have been produced as dedicated fire fighting vessels for the city of Tacoma, Washington. (Fig. 71).

Fire Barriers. Other demanding tests carried out at Admiralty research laboratories illustrated the effectiveness of a glass-rich layer-provided by woven roving laminates on the inside of the hull-in reducing the risk of ignition. The burning was confined to the surface resin layer only, there being little penetration beyond. To further reduce the incidence of fire, areas of high risk, i.e., engine rooms etc, are coated with an intumescent polyester resin, or a rock fiber wool blanket to meet the exacting standards of Lloyds Register of Shipping and the British Civil Aviation Authority (C.A.A.). The **use** of

Figure 70. Port of Rotterdam Multipurpose Patrol Boats

Figure 71. City of Tacoma, Washington, Fire Boats

end grained balsa as sandwich panel cores combined with woven roving has shown considerable fire barrier capabilities.

Resilience and Shock Resistance. The modulus of resilience is defined by

$$\frac{f^2}{2E}$$

where f is the proof stress, and, E is the modulus of elasticity. For woven roving laminate materials the modulus of resilience is approximately twice that of aluminum alloy and six times that of mild steel. This particular property makes for a tough structure able to withstand the rough treatment metered out in the commercial boat markets.

Design Freedom. Using high quality GRP the whole hull structure design can be tailor-made to suit the stresses applied by loading conditions.

All intersections of stiffening members can be readily feathered out and reinforced to avoid load concentrations inevitable when using preformed sections of aluminum alloy. Hence the designer of a GRP hull has far greater freedom and greater flexibility to put in the correct quality and quantity of material in exactly the right place.

The assembly of machinery, engines and shafting also becomes very much more straightforward with a GRP hull. The shafting alignment is carried out by means of a wire and light source through sighting plates. The bearings can be preassembled onto a base structure, positioned “on the light source” and laminated into place. Extreme accuracy can be maintained since very little distortion occurs.

Quality Control of GRP Structures

With the evolution of the larger Hovermarine HM500 series, the GRP processes, methods and materials needed to be upgraded to maintain the structural performance required.

The first area for additional attention and improvements was within quality control and to this end some significant changes were instituted. The principal reinforcement materials are carefully selected to much closer weight tolerance than normally sold by the suppliers. These materials are then further inspected for defects “on the roll” by additional check weighing of random samples. The resin which is selected and tested for minimum water permeability. high heat distortion temperature, good weathering resistance and good laminate strength is standardized throughout all production components. The material is bulk stored in tanks and pumped into a resin mixing bay. This area is solely responsible for metering and mechanically mixing the catalyst and accelerators under stores and inspection supervision. The individual works operations are divided into job instructions, each with a standard quantity of materials. By the institution of simple process controls between storemen, works supervisors, and works inspectors a high level of weight and quality control is achieved “on the job” which in turn improves the overall laminate quality control.

All hull, deck/superstructure, and wheelhouse structures are constructed with clear unpigmented resins which ensures:

- The operator and his immediate supervisor are able to detect any faults in wet-out or layer inconsistencies. e.g.. overlap positions while the work is being carried out.
- The external surveyors and works inspectors may readily examine the laminate for conformity to required standards.
- Laminate position and quantity marking can be examined and logged by all supervisors, inspectors, design engineers and even management personnel.

Recording of all material batch numbers, used for a particular structure, plus recording environmental conditions, weighing all material used against a given job card number instituting stage inspection history cards, (witnessed by supervision, works inspection and where necessary independent surveyors) is standard practice on all GRP work and provides good control on the manufacturing processes.

Each major craft moulding is constructed such that “test” coupons are built at the same time and as an integral part of that moulding, using exactly the same materials, processes, labor and equipment.

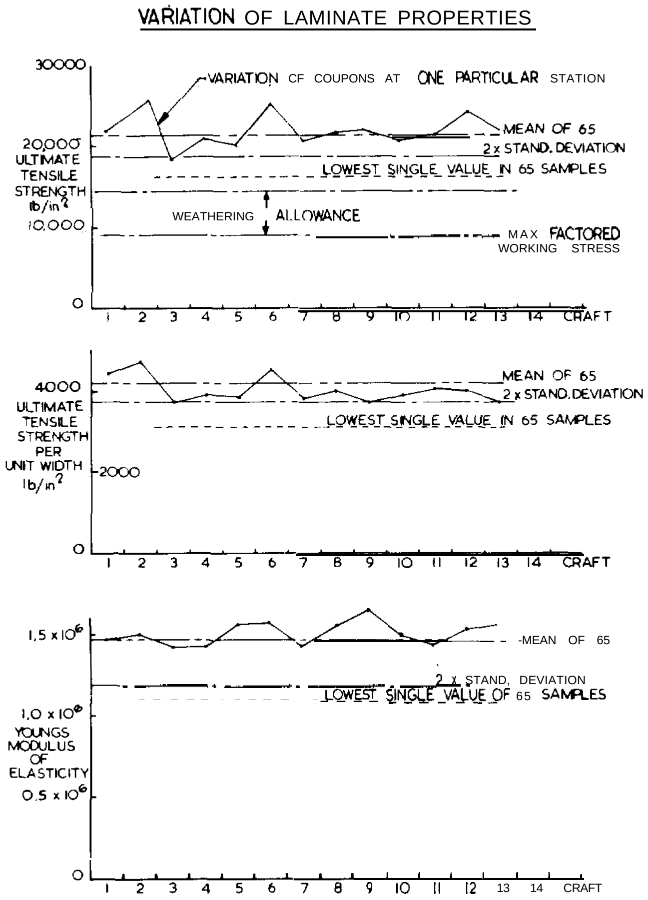


Figure 72. Variation of Laminate Properties

The actual strength of a laminate obviously varies from craft to craft and it is necessary to test these coupons to check on quality and to record whether or not the laminate properties are being held within acceptable tolerances and to highlight any trends or deviations away from those tolerances. It appears logical therefore to create a set of quality control charts based on a known population standard. Ideally the standard population data would be derived from extensive testing of laminates prior to the final design check out and the building of further production craft. Typically fifteen to twenty sample coupons are cut from each craft from four particular stations.

Figure 72 illustrates for one station an example of the variation for thirteen craft of ultimate strength as stress and strength per unit width and also Young's modulus. Also indicated is the spread of test results in terms of twice the standard deviation and the lowest single value in the batch.

In order to understand more fully the variations in laminate strength a grid comparator is constructed as Figure 73. The carpet grid relates stress, strength per unit width and the resin/glass ratio based on the theoretical relationship.

$$\sigma = \frac{P_{ult}}{t_f(1 + \frac{r\gamma_f}{\gamma m})}$$

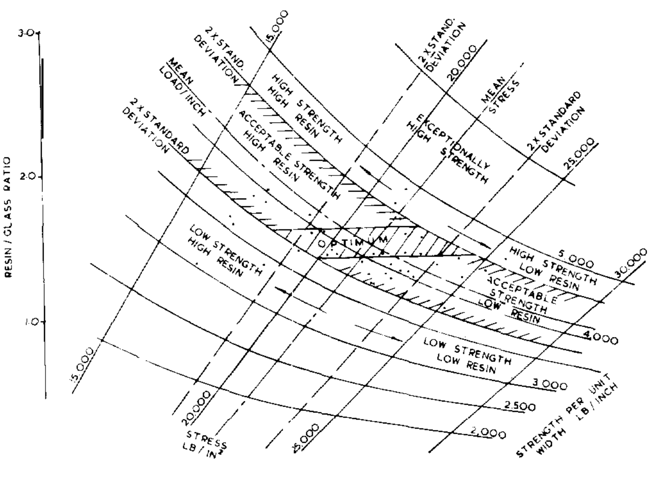


Figure 73. Laminate Strength Comparator

where γ = ultimate tensile stress in laminate
P_{ult} = ultimate load
t_f = equivalent thickness of fibers in laminate
r = resin/glass ratio
γf = specific gravity of glass fibers
γm = specific gravity of resin

The grid assumes that the thickness of glass reinforcement in the laminate remains constant and that the resin content alone varies. The test results are then superimposed on this grid at corresponding carpet coordinates of ultimate stress and ultimate strength per unit width. The position on the grid indicates the quality of the laminate in terms of strength and weight assuming a nominal glass content in the laminate. This indicated theoretical resin/glass ratio is then read off the grid and can be compared with measured values from ash tests. With few exceptions these should all lie within a ± 10% tolerance band. By relating this information back to the test results it is possible to identify the exceptions as being due to variations in glass content, either due to glass cloth weight or operative error.

Labor and Materials Requirements

The following relates specifically to craft hulls constructed from GRP where plug and female molds are built (see Figure 74) the construction of which has been justified on a small batch production basis. This is a very relative term but a production output of one craft a month of HM200 series size has been achieved on a single shift basis and obviously could be increased by nearly a factor of two by employing labor during evenings/night time. The HM527 structure could be turned around in about 3-4 months. Generally speaking the cost of the tooling has amounted to about 15 per cent of the total cost of the prototype craft based on a commercial outfit. The moulds can be maintained to produce of the order of 100 mouldings and with care might exceed this figure.

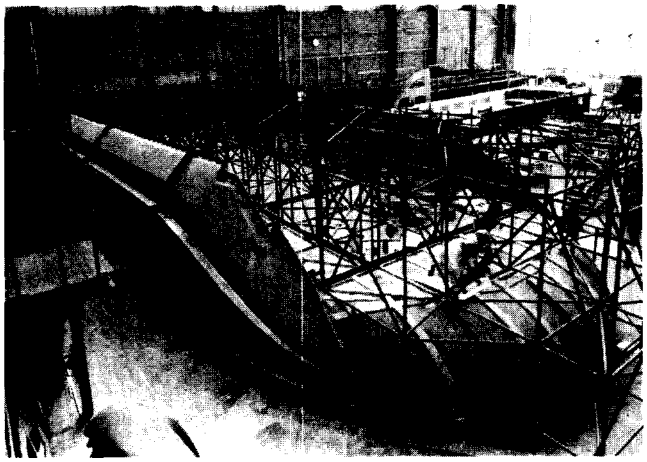


Figure 74. HM527 Series---Hull Mould Being Constructed over the Plug

Stretchability in producing the hull structure in GRP for constant depth sidewalls is relatively easy by using an overhung moulding in the original mold as the plug for the stretch and producing a mold extension around it to be mechanically fastened to the original length mold. HM216, 218 and 221 prototypes were all produced from the same basic hull mould. For craft with tapered side elevation sidewalls the same can be achieved with some adjustment to the gunwale line-this was also adopted in aluminum alloy for the stretch from the BH110 to the SES-200.

A learning curve has to be assumed during the evolution of the production craft from the prototype. For the same design standard and fit out it should be possible to reduce the prototype build hours by about 20-25 percent when final location of seatings and supports have been confirmed and subassembly systems and modules identified.

For craft of limited market potential or for very specific customer requirements, of course, a more direct method of build is appropriate using a skinned framework as a male mold but then requiring significantly more external finishing work. Craft built today using foam sandwich skins adopt this method.

The analysis of production hours is very dependent on the operational role of the craft but for passenger ferry type configurations the following appears to be significant based on trade skills:

Trade	% Total Labor	% Total Materials
Laminators/woodworkers	58-65	27-30
Skirt/seals	1	3 (incl. fabrication)
Painters	4-5	1
Electricians	7-9	6-15
Fitters/plumbers/ sheetmetal details	22-27	50-70

In terms of total basic construction costs, labor amounts to about 59-60 per cent and materials 40-41 per cent.

The structural labor content is about 800-1000 hours per ton of structure (this is also very approximately true on the basis of the total craft build) but this could be reduced significantly by releasing the weight constraint at the expense of direct operating costs per ton (payload) mile maintaining the same speed. The justification of lift power is to provide speed with economy. To compromise this too much is to nullify the benefit of the air cushion and fall into the operational area of the higher speed catamarans or round bilge high speed displacement craft.

Special purpose craft adapted from the basic passenger craft hull lines have involved considerable redesign of internal accommodation and machinery spaces. The Tacoma fireboat versions of HM221 were a successful but very exacting adaptation which involved mechanical and electrical systems from stem to stern. The craft can pump its own weight in water in about one minute! The extra design effort required was equivalent to the design of the original basic hull platform.

This discussion has only scratched the surface of the producibility aspects of SES craft whose hulls are built of glass reinforced plastics. Other composite materials also have their place in varying roles. Their application to larger craft which can benefit from the other advantages of reinforced plastics, particularly in the military arena, have yet to be fully exploited. That they will be is without doubt-a revolution in the acceptance of reinforced plastics for marine vessels has already taken place and will continue to develop to provide robust safe structures requiring minimum maintenance and continued cost effectiveness.

CONCLUSIONS

In conclusion we collectively believe that SES, as a modern ship, can and does economically compete in a myriad of surface ship applications while providing other operational attributes which have yet to be exploited to their fullest potential (1985). Unlike some other revolutionary concepts that evolution has slipped past, we are absolute in the belief that as long as there is a need to move on the surface of our oceans that SES can and will become better utilized.

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APPENDIX

WING-IN-GROUND-EFFECT VEHICLES

INTRODUCTION

Jane's Defence Weekly [1] and the *International Defense Review* [2] have recently published reports that the Soviet Union is about to test a power-augmented-ram wing-in-ground-effect vehicle as a platform for antiship missiles (Figure 1). Except for several relatively small research efforts, there is no similar developmental program currently underway in the United States. However, a discussion of modern ships and craft would not be complete without mention of wing-in-ground-effect vehicles. Hence, the purpose of this article is to briefly describe this type of vehicle, explain the basic technology involved, discuss its attributes and limitations, assess its performance characteristics, and summarize potential military applications.

Early in this century it was noted that a wing operating in close proximity to the ground exhibits a reduction in induced drag, which increases its lift/drag ratio [3]. For several decades this phenomenon, called the wing-in-ground-effect (WIG), was studied because it complicated the takeoff and landing of low wing aircraft.

In the early 1960s, a joint Army and Navy program was initiated to study the feasibility of designing a vehicle which would provide exceptional performance by cruising in ground effect over the ocean [4]. It was found that a vehicle flying in ground effect achieves a lift/drag ratio which is about twice that of a conventional aircraft. These studies also showed that, to keep wave impact loads at acceptably low levels during takeoff and landing, a WIG vehicle needs a low stall speed. This requires a low wing loading, which results in a low cruise speed. The low wing loading requirement results in designs with a high structural weight/gross weight ratio. Unfortunately, a high structural weight fraction, combined with a low cruise speed, results in vehicles with relatively poor performance.

During the 1970s, several small experimental WIG vehicles were designed and tested in a coastal sea environment. A conventional WIG vehicle was designed by Lippisch [5]. This vehicle was tested extensively in West Germany. Another West German WIG vehicle, designed by G. Jorg, incorporated a tandem wing concept [6]. A major advantage of this design is its apparent intrinsic ability to fly in a contour mode over the ocean surface, with waves of irregular height. Both of these vehicles demonstrated the practical aspects of WIG flight. However, both vehicles had high structural weight fractions and an undesirably high takeoff power/cruise power ratio.

PAR-WIG TECHNOLOGY

During the 1970s, the power-augmented-ram (PAR) phenomenon was discovered, which significantly enhanced the performance of the WIG concept [7]. As shown in Figure 2, this phenomenon involves directing the efflux from forward mounted propulsion engines under the wings, with the efflux nearly stagnated under the wings by use of endplates and a trailing-edge flap. At low speeds, a static pressure rise occurs under the wings, which lifts the vehicle out of the water, The use of this phenomenon is called the power-augmented-ram wing-in-ground-effect (PAR-WIG).

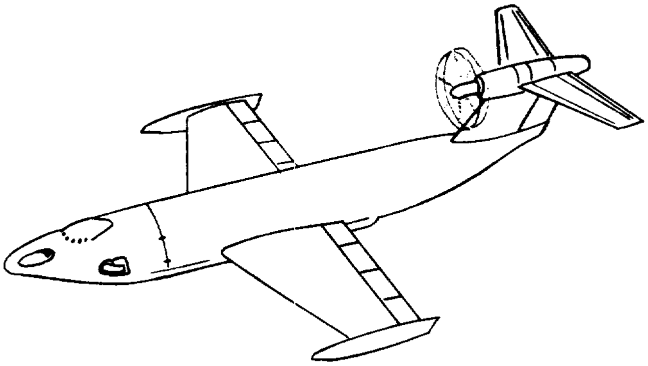


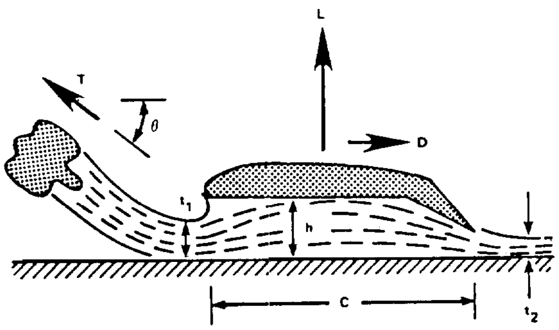
Figure 1. Soviet PAR-WIG (*Janes Defence Weekly)*

Early NASA and U.S. Navy tests demonstrated that the PAR concept can be used to assist the takeoff and landing of a WIG vehicle [8,9]. Use of the concept also allows a significant reduction in the structural weight/gross weight ratio. This reduction is achieved because the static lift generated by the PAR system greatly decreases the hydrodynamic loads during takeoff and landing and because a higher wing loading can be achieved.

The PAR-WIG concept also allows a decrease in the thrust/weight ratio necessary for take off. It is estimated that a typical PAR-WIG can take off and accelerate to cruise speed with a thrust/weight ratio of only about 0.20; whereas, a conventional seaplane requires a ratio of at least 0.35. A PAR-WIG, therefore, will not have as much excessive thrust as a seaplane when airborne at high cruise speeds. After the vehicle is airborne, only limited thrust is required to cruise at low speeds. Many PAR-WIG designs, therefore, have separate cruise power plants and lift power plants, which can also be used for boost speeds.

The longitudinal stability and control of a PAR-WIG with low aspect ratio wings has been examined analytically [10]. These analyses, and NASA data, show that longitudinal stability can be achieved by the use of a horizontal stabilizer with. a high aspect ratio, located out of ground effect. The tandem wing WIG design has also demonstrated good longitudinal stability and control using two wings, both in ground effect, but not having the same angle of attack. However, the addition of PAR to this design has not yet been attempted.

Two different types of PAR-WIGs have been developed, as shown in Figure 3 [11]. They are distinguished by different ways of integrating the cushion into the airframe and different ways of integrating the thrust required for developing a cushion and the thrust required for acceleration and cruise.



WHERE:

e = Propulsion engine angle

t_1 = Incoming jet thickness

h = Wing height

t_2 = Trailing edge gap

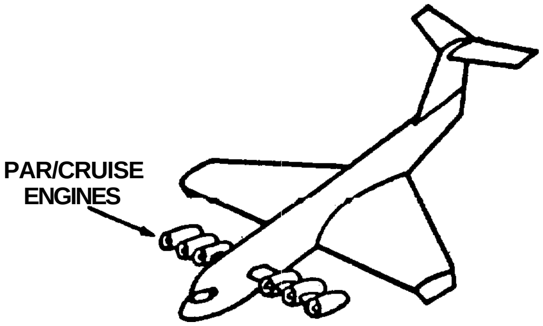
C = Wing chord

T = Thrust

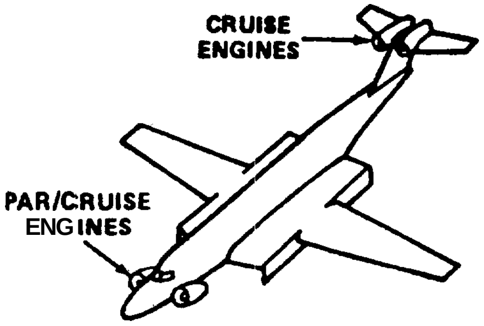
L = Lift

D = Drag

Figure 2. Power-Augmented-Ram Concept



TYPE 1



TYPE 2

Figure 3. PAR-WIG Design Concepts

Using the entire wing as the ceiling for the cushion, Type 1, has the advantage that the endplates and flaps required also serve a useful purpose in cruise flight. Locating the propulsion engines so as to achieve a good distribution of the PAR flux requires a wing with a low aspect ratio of **between about 2.0 and 3.0.**

Another arrangement, Type 2, uses the extended root of the wing, i.e., with leading edge and trailing edge extensions plus the fuselage as the ceiling for the cushion. This arrangement allows for relatively easy placement of the engines for lift power. With this type of configuration, the designer can optimize the aspect ratio of the wing and possibly achieve a design capable of flying out-of-ground effect.

PAR propulsion engines can be dual-purpose and can provide all or part of the required cruise power, or they can be used only during takeoff and landing. In the latter case, it is possible to use extremely light, compact afterburning turbojets, similar to VSTOL "lift engines", for the PAR system, with the main propulsion engine(s) optimized for cruise.

ATTRIBUTES AND LIMITATIONS

Figure 4 compares the empty weight/gross weight ratio of conventional aircraft to PAR-WIGs with low aspect ratio wings. As shown, the ratio is estimated to be less than 0.30, which is much less than that of a conventional aircraft because of the:

- Use of low aspect ratio, highly loaded, thick wings;
- Requirement for less installed thrust;
- Lack of landing gear; and,
- Reduced hydrodynamic loads.

The empty weight of a vehicle includes the airframe structure, propulsion plant, and control systems. The gross weight includes the addition of weapons and sensors; associated support systems, such as, personnel support, electrical plant, and other auxiliary systems; and variable load items, such as. fuel and ammunition. A

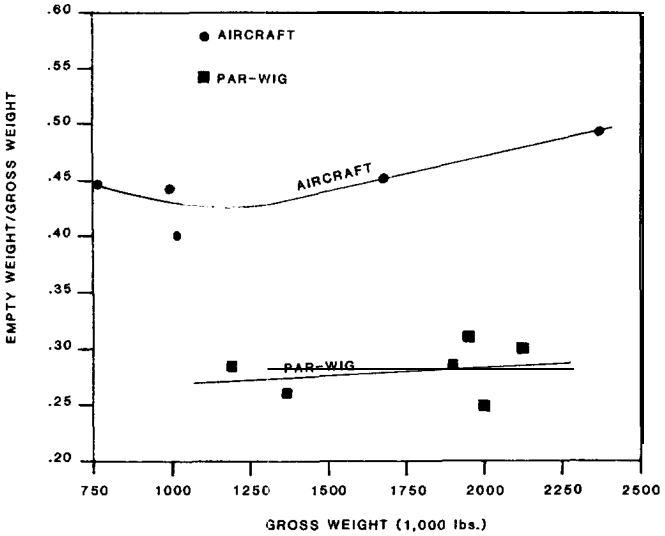


Figure 4. Empty-Weight/Gross-Weight Ratio.

vehicle's payload, therefore, represents the difference between gross and empty weight.

The low empty weight/gross weight ratio of a PAR-WIG is particularly noteworthy when compared to a conventional seaplane. The seaplane has a high structural weight fraction because of the increased fuselage structure required to absorb water impact loads during takeoff and landing. The empty weight/gross weight ratio of a PAR-WIG with high aspect ratio wings, i.e., that could probably fly out of ground effect, is estimated to increase from 0.30 to 0.35, which is still 30% less than a conventional aircraft.

The PAR-WIG, therefore, has two significant attributes:

- A low empty weight/gross weight ratio, and
- A high lift/drag ratio.

These attributes provide a PAR-WIG with exceptional performance as compared to a conventional aircraft, particularly in terms of its:

- Range or endurance, and
- Payload/gross weight ratio.

When flying in ground effect, the degree to which induced drag is reduced is a function of how close a wing is to a horizontal solid surface. The parameter $h/\sqrt{S}$, where h is the flying height, and S is the wing area, is a factor which can be used to determine the benefit of the increased lift/drag (L/D) ratio which occurs when flying in ground effect. For a PAR-WIG with low aspect ratio wings, $h/\sqrt{S}$ should be 0.06 or less when flying in ground effect; this will provide about twice the L/D ratio of a conventional aircraft.

The flying height, h. is a function of the sea state which can be expected in an operational area. If it is assumed that:

- A PAR-WIG does not adjust its altitude with changes in the sea surface: and
- The structure of a PAR-WIG cannot be designed to withstand high impact loads without having to increase the structural weight fraction excessively;

then h must be selected so that the wing endplates clear the water surface, as shown in Figure 5. Thus, if efficient operation in ground effect in moderate sea states is desired, the clearance requirement will be relatively high, which, in turn, will require a large wing area and a large vehicle. For example, if it is desired to operate efficiently one day out of two, year round, in the North Atlantic, the significant wave height (H 1/3) will be 6 feet and the height of the one-thousandth largest wave will be 12 feet. Based on this clearance requirement, the minimum wing area would be 10,000 square feet. Assuming a wing loading of 200 pounds/square feet, the minimum gross weight would be about 900 tons. In other words, given these design constraints, a PAR-WIG will have to be very large for open ocean operation. Under these assumptions, small PAR-WIGs are not practical.

Thus, the primary limitation of a single wing PAR-WIG is the apparent relationship between its size and its seakeeping performance. However, if the concept can be adapted to the Jorg tandlem wing design, this relationship may be decoupled, because of the reported ability of the tandem wing to fly in a contour mode over the ocean surface. It is also thought that the present estimate of the seakeeping performance of PAR-WIGs is conservative. These are areas of WIG performance that require additional research and testing.

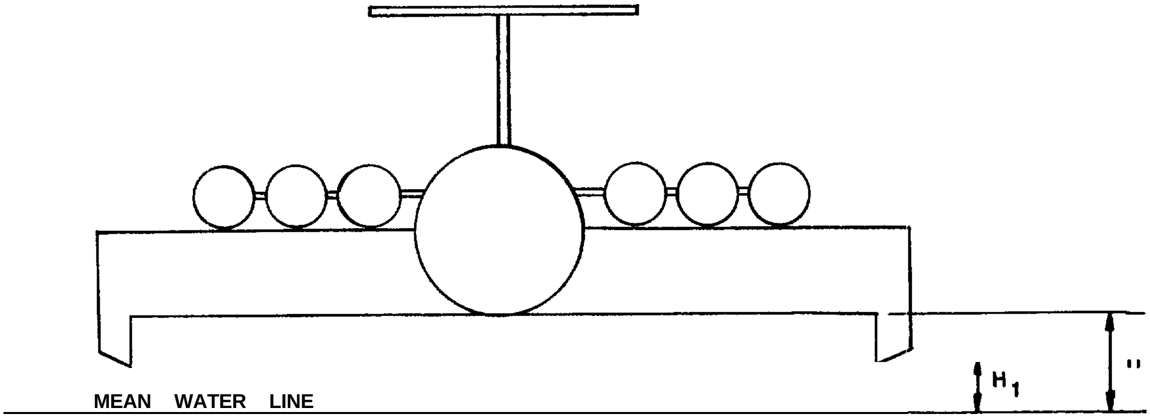
ASSESSMENT OF PERFORMANCE

A PAR-WIG has unusual characteristics compared to a conventional ship or aircraft. A conventional ship can continue operations for a lengthy period of time when operating at relatively slow speeds. However, at 30 knots, most corvette size ships have a range of about 1,000 miles, which allows about 30 hours of continuous high speed operation. By comparison, existing PAR-WIGs cannot operate at slow speeds; they can, however, land and loiter. PAR-WIGs can also operate for periods of 30 hours or more at speeds of about 200 knots.

A PAR-WIG has a payload/gross weight ratio of about 0.70. The payload of a corvette is about 0.55 of its gross weight, i.e., full load displacement. The payload weight of a corvette includes weapons and sensors, weapon and sensor support systems, and all variable load items, such as ammunition, fuel, and potable water.

A PAR-WIG and a conventional surface ship of similar size appear to have generally similar operational seakeeping limitations. However, while a 1,000-ton corvette would not be able to perform a military mission in sea state 5 or higher, it could survive in higher sea states; whereas, a PAR-WIG could not.

In terms of the weight of fuel consumed per pound of payload delivered over one mile, a corvette is far less efficient than a PAR-WIG, when the corvette is operating at high ship speeds. A corvette's efficiency is comparable to a PAR-WIG at low ship speed.



$$H_1 = \frac{\text{Avg. of } 1/3 - \text{ highest wave height}}{2}$$

$$H_2 = \frac{\text{111000 highest wave height}}{2}$$

Figure 5. Seakeeping Clearance Requirement

Currently, the size of a conventional aircraft is limited by the length of available runways. A conventional aircraft generally has less range than a PAR-WIG. primarily because of its higher empty weight/gross weight ratio. A conventional aircraft also carries relatively less payload then a PAR-WIG. It also has the highest unit cost and requires the most fuel per ton-mile of cargo delivered of any of the three types of vehicles discussed, i.e., PAR-WIGS, ships, and aircraft.

A PAR-WIG, therefore, has several significant performance attributes:

- A maximum speed which is more than 10 times greater than that of ships, and only slightly less than conventional aircraft;
- A payload weight fraction competitive to a similar size ship;
- An endurance comparable to a corvette at high ship speeds; and,
- Seakeeping performance comparable to a similar size ship.

It also has a significant operational limitation. It cannot loiter for long periods at low speeds, as can a surface ship. Therefore, as currently configured, a PAR-WIG cannot operate in a mission profile similar to a conventional ship, unless it operates in a sprint-drift mode by alighting in the ocean periodically.

POTENTIAL MILITARY APPLICATIONS

A PAR-WIG, which combines an ability to cruise efficiently in ground effect with the ability to take off and land on a cushion, lends itself to several potential military applications. However, the only large PAR-WIGs currently in advanced development are in the Soviet Union.

The PAR-WIG is not restricted in size, has a seakeeping capability and a payload weight fraction comparable to similar size ships, has a dash speed capability. and has the ability to loiter afloat in the open ocean. Among the potential military applications for the PAR-WIG are:

- Amphibious operations,
- Logistical support of forward deployed forces,
- Antisubmarine warfare.
- Surface strike warfare, and
- As a strategic weapons carrier.

For example, it is estimated that a 900-ton PAR-WIG, carrying four Trident missiles, [12] could be periodically relocated 100 miles or more to a new location every four hours, while operating in an area 1,000 miles from its home base for a period of up to four days, in sea state 3 conditions. It is also estimated that one 900-ton PAR-WIG could deliver more cargo further than three 300-ton C-5 aircraft over the same period of time, without requiring a forward airstrip, while using about 60% less fuel, in sea state 5 conditions.

It is estimated that a 900-ton PAR-WIG could carry a powerful low frequency dipping sonar, sonobuoys, heavy antisubmarine weapons, self-defense weapons and sensors, have a dash speed of 400 knots, and a mission endurance of five days, assuming 50% loiter operations. Such an antisubmarine capability could be an effective counter to the next generation of super-quiet nuclear submarines.

The viability of the PAR-WIG depends on several major technical questions which, as yet, remain unresolved in the West, including whether:

- A PAR-WIG can operate at an $h/\sqrt{S}$ of 0.06 or less;
- The resulting wave impact loads, ride quality, and handling quality are acceptable in various land and sea conditions;
- Unique component development, e.g., flaps and end-plates, is feasible;
- Seakeeping performance is acceptable; and,
- On-off cushion transition is possible.

Given the apparent success of the Soviet Union's PAR-WIG program, it is estimated that these technical questions can be answered satisfactorily. The high payload carrying capability of the PAR-WIG, along with its high speed, high fuel efficiency, ability to operate independent of airfields, unrestricted size, and ability to alight in the ocean and loiter, all combine to offer military planners with unique operational capabilities and innovative tactical uses that are obviously waiting to be exploited.

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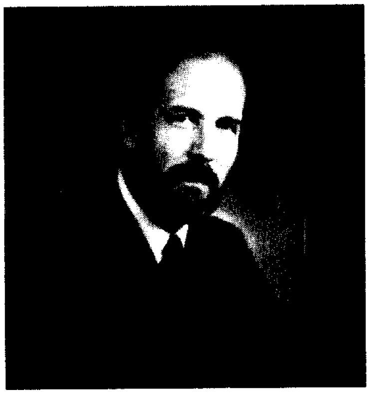
CHAPTER VII

AIR CUSHION CRAFT



THE EDITOR

__David Lavis__ was educated in Exmouth and Exeter, Devon, England. He began his professional career in air cushion vehicles with Saunders-Roe on the Isle of Wight in 1959. Initially, as a student apprentice, Mr. Lavis worked on many aspects of air cushion vehicle research, design, and construction. In 1966, he received a master of science degree from Cranfield Institute of Technology. A year later he joined Bell Aerosystems, Buffalo. New York and was engaged in the early design work for the SES-100B and the AALC **Jeff(B).** *Mr. Lavis then joined the Aerojet General Corporation (AGC) in Sacramento and in 1972, he was appointed manager of technology for the AGC. SES Division, who were at that time testing the SES-IOOA and conducting the early design work for the 2KSES and AALC Jeff(A). Mr. Lavis has continued to support the U.S. Navy advanced ship programs. In 1977, together with Mr. E.G.U. Band, he formed Band, Lavis & Associates, Inc. of Severna Park, Maryland, a company specializing in advanced marine technology*

INTRODUCTION

It has been a quarter of a century since the first man-carrying air cushion craft was launched, and five more years since Sir Christopher Cockerell, the British inventor, started his early experiments. From this common heritage, two distinct types of vessel have evolved: the rigid-side-wall surface effect ship (SES), and the fully-amphibious air cushion vehicle (ACV), the subject of this section.

What Cockerell and others accomplished was to demonstrate that a vehicle could ride on a cushion of air in close proximity to the ground. Since the resistance to forward motion of an air cushion was low, high speeds could be obtained over land or water with relatively low propulsive power. Power, however, was required to replenish air that leaked frorn the cushion, and this power increased in proportion to the obstacle height or wave clearance height of the vehicle. Fortunately, the problem of gaining adequate clearance height with acceptable power levels was solved by the introduction of the flexible skirt. The skirt, made from neoprene or natural rubber impregnated into a nylon weave, was shaped to impede the leakage of cushion air while allowing the hard structure of the hull to ride well clear of the water or ground. In this way the expenditure of lift power was greatly reduced, friction drag was largely eliminated, the probability of water (or ground) impact loads was reduced so that relatively light structure could be used, and. most importantly, the amphibious capability of the vehicle was preserved. With this development, serious practical uses for ACVs became possible.

To many, the progress achieved with amphibious ACVs since these early days has been impressive. To others, it has been painfully slow. With the introduction of the flexible skirt, development was, initially, very rapid. It led the way to the evolution of the worldwide industry. from the introduction of large 300-ton fast passenger-car ferries, moving over two million passengers a year, (Figure 1) to the construction of much larger 850-ton hoverbarges for use in support of civil engineering projects. Despite high acquisition and operating costs, these ACVs demonstrated the economic viability of the concept. However, the military exploitation of the ACV was comparatively slow, at least in the Western World. This was the result, undoubtedly, of the ever present gap between the advancing technology and the peacetime operational need, the desire for minimum risk, and the consequential, inordinate length of time required to push innovation through the procurement cycle. In the United Kingdom (U.K.), for example, nearly all of the 50 or so military or paramilitary ACVs built in the last 20 years were constructed in small quantities for overseas customers. The Royal Navy bought a few craft and borrowed others, for extensive trials, particularly with respect to mine warfare. The U.K., however, has not yet reached a decision to form an ACV squadron. In the U.S., after extensive experimental programs, both the Army and Navy are now building ACVs in significant quantities. In contrast, the Soviet military have had, for several years, an active fleet of at least 6.5 ACVs, developed primarily for amphibious warfare.

ACVs have been built., or operated, in most major countries of the world. The principal centers of construction are shown in Figure 2 along with an illustration of the chronological order of development and the most significant craft built in each case. To this list can be added the recent progress made in the Peoples Republic of China and in Spain. From this collective experience many valuable lessons have been learned. To summarize this experience and provide a measure of the technical state of development, a number of leading authorities in ACV design, construction. and operation, in industry and government, from the U.S. and from overseas, have contributed to the major sections of this chapter.

John Chaplin, vice-president of engineering of Bell Aerospace Textron's New Orleans operations has a long and distinguished career in the development of ACVs starting with his involvement with the SRN-1 at Saunders Roe Ltd. in 1957. He has been with Bell since 1962 with major responsibility for both ACV and SES programs. In this chapter, Mr. Chaplin has contributed his valuable

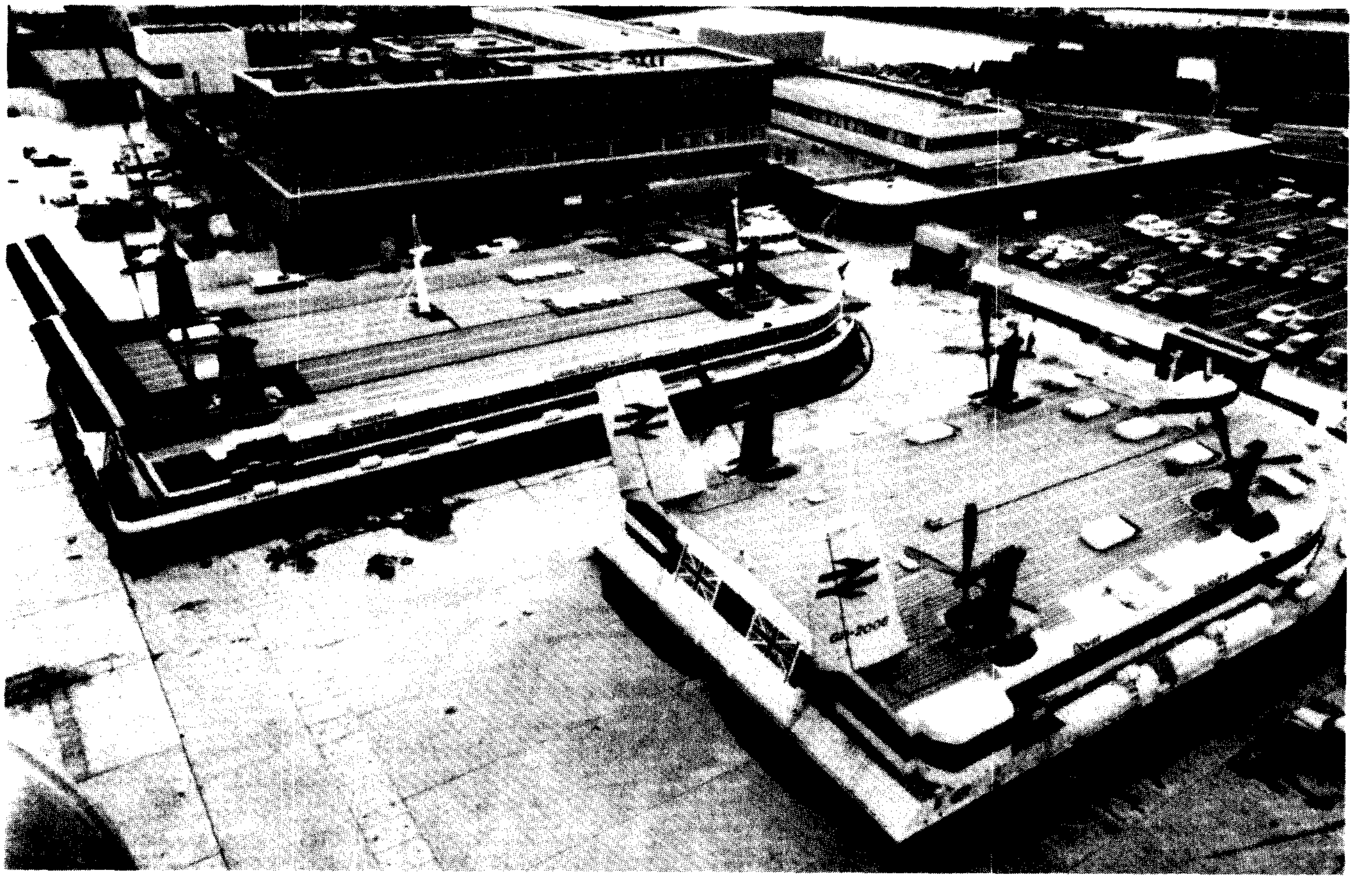


Figure 1. The SR.N4 Mk3, *Princess Anne,* Alongside the SR.N4 Mkl, *Princess Margaret,* at the Unfinished Dover Hoverport in 1978. (Courtesy of *High-Speed Surface Craft,* June 1984).

insight regarding the state of ACV technology, and the accomplishments which have been achieved in designing for improved producibility. improved supportability, and in the reduction in cost of U.S. military craft.

Raymond Wheeler was chief designer of the SR.N4 and is now technical director of British Hovercraft Corporation where he has worked throughout his professional career. Mr. Wheeler has written an excellent review of worldwide commercial ACV passenger and car ferries and has discussed the many advantages of using ACVs in the mine warfare role. His discussion has been based on the experience gained by extensive trials conducted in the United Kingdom. Mr. Wheeler also gives an important assessment of the producibility and supportability of commercial ACVs with emphasis on how construction and operating costs can be, and have been, reduced in recent years.

The impressive employment of ACVs by the Soviet military is addressed in a perceptive article by Stephen Dibbern of the U.S. Army Foreign Science and Technology Center. He has worked since 1970 on analysis of foreign ACVs in conjunction with the U.S. Army, Navy, and Coast Guard, as well as other agencies and commercial ACV developers in the U.S., U.K., and Canada. Mr. Dibbern provides valuable input in an area normally characterized by a scarcity of information.

Discussion of the use of ACVs in amphibious warfare and other military logistics functions has benefited from informative articles provided by a number of leading authorities. Capt. Charles Piersall, USN, and Richard Kenefick have shared some of their knowledge and experiences in connection with the landing craft air cushion (LCAC) development and acquisition. Capt. Piersall has been head of the Naval Sea Systems Command's Amphibious Warfare and Strategic Sealift Programs (PMS-377) since 1978. Dick Kenefick is LCAC acquisition manager in F'MS-377, and has been involved in U.S. Navy ACV development for the past 12 years. Augmenting information on the Navy's program, Thomas Smith writes about the activities of the U.S. Army in the logistics-over-the-shore (LOTS) program and its employment of ACVs. He is well qualified in this subject, having been involved in the development, operational testing, and production of the LACV-30 since 1976. Mr. Smith is currently ACV project manager for the LAC-30 and LAMP-H programs in the Amphibians and Watercraft Office of the U.S. Army Troop Support Command.

ACVs are also of considerable interest to the Canadian Coast Guard. John McGrath provides some of the reasons for this interest in his discussion of their employment on the West Coast of Canada. Mr. McGrath is with the Canadian Coast Guard Hovercraft Unit in Vancouver, British

Columbia. He has had a long career in ACV operations and has been largely responsible for their success in performing a number of coast guard functions.

The unique multiterrain features of the ACV make their employment in Arctic areas very attractive. Their utility in this environment was well demonstrated in a recent experience with the U.S. Navy test craft AALC *Jeff(A).* Wilfred Eggington and Jack Edwards have provided a most interesting account of the *Jeff(A)'s* use in support of an oil exploration project in the Beaufort Sea. Wilf Eggington is president of RMI, Inc. and has had a long involvement in ACV development, having held responsible positions at Saunders Roe, Vickers Armstrong, Bell Aerospace, Aerojet General, Litton, and Rohr Industries. Dr. Edwards is director, ACV programs at RMI. and has been associated with the development of advanced marine vehicles at RMI since 1977. His most recent experience involves the direction of design and shipyard supervision of a heavy lift ACV for use in the Arctic and in the direction of the Jeff(A) Arctic demonstration program.

Other applications of ACVs in the Arctic are discussed by Jeffrey Benson. Mr. Benson has been actively involved in U.S. Navy ACV programs since 1972. For eight years he was AALC program manager, first at NAVSEA and later at DTNSRDC from 1978-1981. He managed the successful transition of AALC R&D to the follow-on LCAC acquisition. Mr. Benson is now head of the Surface Ship Division in the Ship Systems Integration Department at DTNSRDC.

Applications of ACVs are also treated by other well-known contributors. Colin Faulkner and Reginald Page have provided an input on heavy lift applications. Mr. Faulkner started in ACV development with Saunders Roe and Westland Aircraft. At British Hovercraft Corporation, he was head of the Product Management Team that marketed the initial growth of ACV development. Subsequently, Mr. Faulkner worked for both Bell and Aerojet in a similar capacity and is now manager of marine systems at Aerojet TechSystems Company in Sacramento, California. Reginald Page began his career in ACV development in 1961 with Hovercraft Development, Ltd. and

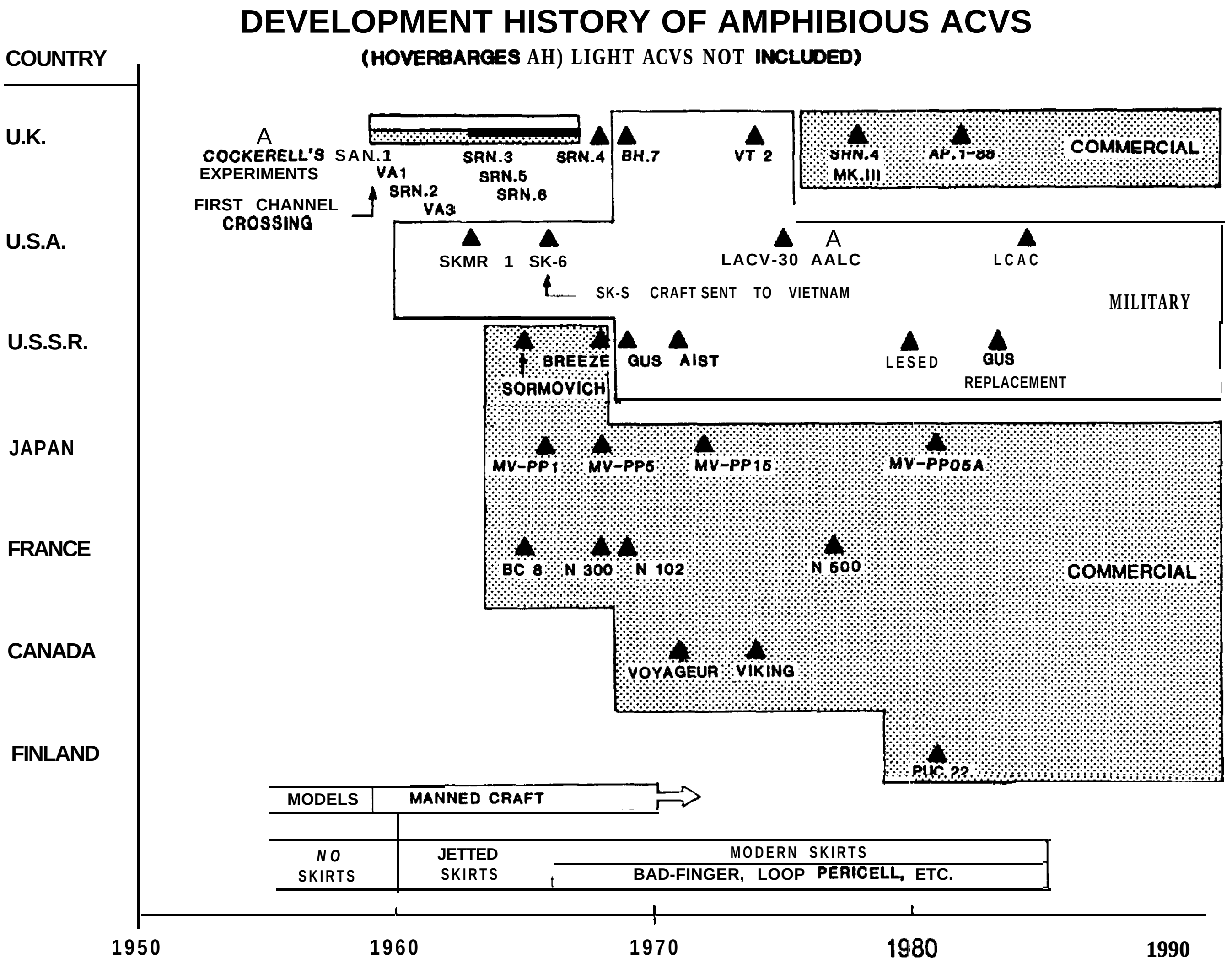


Figure 2. Development History of Amphibious ACVs.

later worked in the U.S. with Bell and Aerojet where he made significant contributions to skirt and seal design. At present he is a program manager at Aerojet Tech-Systems Company working on the Army's LAMP-H program.

Another contributor to the discussion of other ACV commercial and military applications is John Offutt. Since 1972, Mr. Offutt has been deeply involved in the AALC and LCAC development and has made important contributions to the success of this program. At present, he is head of the ACV and SES Group in the Ship Systems Integration Department at DTNSRDC.

Truly, this is an impressive roster of knowledgeable individuals with extensive background and experience in the development and application of air cushion vehicles. Their contributions in making this a comprehensive and timely review are gratefully acknowledged.

VEHICLE DESCRIPTION

An ACV can be defined as a surface vehicle having its complete weight supported by a cushion of pressurized air. Air must be supplied continuously to this cushion to maintain the supporting pressure against the imperfect sealing of the cushion periphery formed by the flexible skirt, as illustrated, schematically, in Figure 3. The skirt is configured in such a way that, when inflated by the fan, it retains the cushion beneath the vehicle both when it is stationary and when it is underway. The functions of the cushion are two-fold: one is to minimize resistance to forward motion, and the other is to provide a soft suspension for traversing rough seas or rough land surfaces.

The pressure of the air cushion is very low. Typically, the pressure is in the range from 0.2 to 0.7 psi for high-speed ACVs and from 0.7 to 1.2 psi for slow, heavy-lift hoverbarges. As a consequence, ACVs can operate over many surfaces which are normally denied to standard wheeled or tracked vehicles.

Lift power is proportional to the product of cushion pressure and cushion airflow rate. It is inversely proportional to the efficiency with which the air can be delivered to the cushion. The power required to supply air to the cushion varies from approximately 5 h.p. per ton of displacement for slow hoverbarges to approximately 25 h.p. per ton for high speed craft.

As the lift power is reduced, cushion airflow and the hovergap (Figure 3) are also reduced and vehicle drag is increased. This results from an increase in the drag of the skirt in contact with the surface. As such, if the vehicle is to maintain speed, the thrust, and hence the propulsion power, must be increased. Lift and propulsion power are, therefore, normally traded, one against the other, until a minimum total power is found.

The optimum hovergap varies with the sea state or terrain being traversed and need not increase in proportion to vehicle size. Thus, as ACVs become larger their lift systems become progressively more efficient (i.e., they need less power per unit vehicle weight).

The designer of an ACV usually has considerable freedom of choice in the selection of craft layout. While most automobiles today look very alike, the same certainly cannot be said of ACVs. This is a consequence, primarily, of the low cushion pressure and the very large planform area per unit displacement available for payload, machinery, and other essential accommodations and equipment. For example, the ratio of payload deck area to overall planform area for a single deck ACV is typically in the range from 0.4 to 0.85. Also, the beam of an ACV is generally half its length or more, thus providing additional flexibility for different arrangements. Fortunately, the ratio of disposable load (i.e., the payload plus fuel load) to all-up weight of an ACV can also be high, usually over 0.5. Therefore, high payload area and weight. for an ACV, go hand in hand. Although a high disposable load fraction is desirable, it can usually be achieved only by using very lightweight. and hence

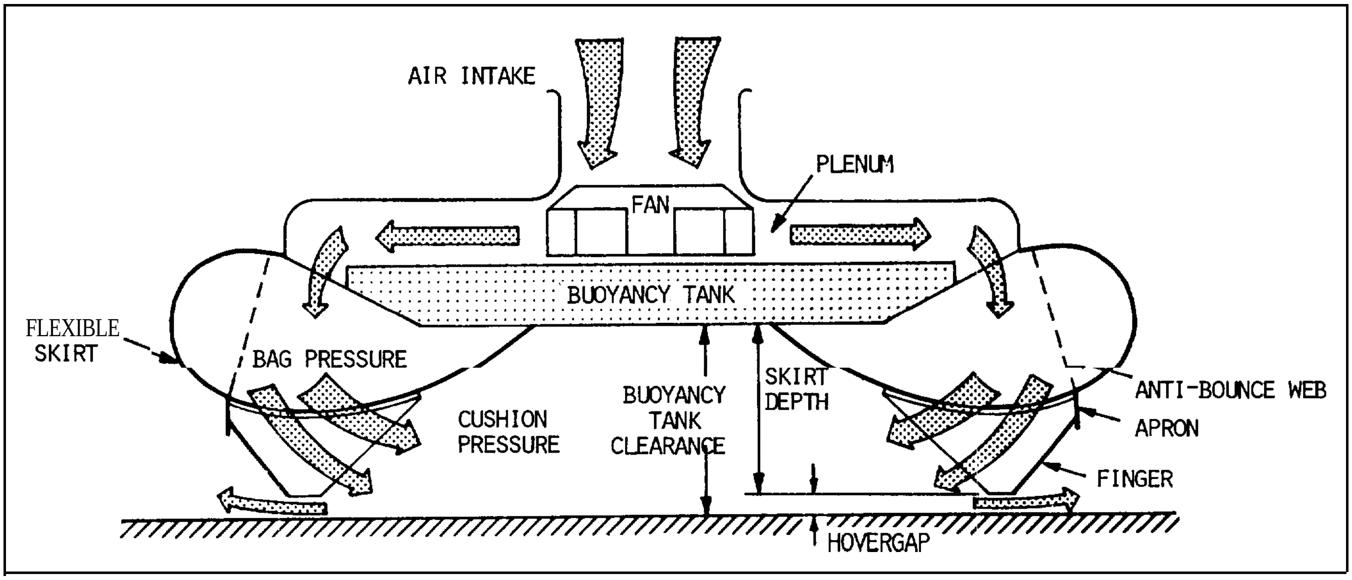


Figure 3. Illustration of Airflow Through an ACV.

expensive, hull structure and propulsion systems. Thus, high percentage disposable load must often be compromised by the need for high overall economic performance.

In addition to craft layout, there is also usually considerable freedom of choice for the various essential subsystems of ACVs. Propulsive thrust, for example, is sometimes provided by marine screws, but more often by aircraft-type propellers. when amphibious operation is necessary. Invariably, marine-screws are more efficient than airscrews, for normal ACV speeds. Although the low-speed efficiency of airscrews can be increased by installing them within shrouds, there is often an installation limit on how large the propeller(s) can be. The smaller the limit, the higher the disc loading, and the lower the efficiency.

Some amphibious ACVs have been propelled successfully by low-noise-level airjets using the same source of air that supplies the air cushion. Other (slow-moving) ACVs have been propelled by hydraulically driven and retractable wheels with large treads and paddle wheels attached for improved water mobility.

Usually the installed thrust is determined by one or more of the following requirements:

a) to climb an overland slope of a specified gradient,
b) to traverse the hump in the overwater drag curve with a specified forward acceleration, and
c) to cruise at a particular speed, above hump speed, in a specified sea state.

Gas turbine engines are usually the choice for prime movers (at least for large ACVs) because of their superior power-to-weight ratio. Alternatively, high-speed diesel engines have been used for their overall economy, particularly for small to medium size ACVs. The lift-air supply fans and the propulsors are either powered separately or geared together in integrated machinery sets. This latter approach, combined with variable-pitch propellers, enables the craft operator to trade off lift and propulsion power when he is required to adjust to changing conditions. Thus, often one engine can be used in place of two, and less total installed power is required to meet the individual peak demands of lift and propulsion.

Fan design is another area of flexibility in ACV design. A number of different fan designs are available for producing the cushion airflow; they include various types of centrifugal, mixed-flow, and axial fans. The most common selection is the centrifugal fan, either mounted within an air distribution plenum, Figure 3, or mounted within a spiral volute, Figure 4.

Maneuvering control can also be achieved in many ways: by rudders in the propeller slipstream, by airjets issuing either from side ports (e.g., puff ports) or from swivelling nozzles fed from the lift-air supply fans, or by differential propeller thrust. Propellers are sometimes pylon-mounted with freedom to rotate in azimuth and often have controllable- and reversible-pitch blades for additional control. Craft trim can be controlled by the transfer of fuel, by aircraft-type elevators placed in the propeller slipstream, or by a skirt shift, or lift, mechanism which controls the location of the skirt hemline relative to the hull. Often a combination of these maneuvering and trim control methods are used.

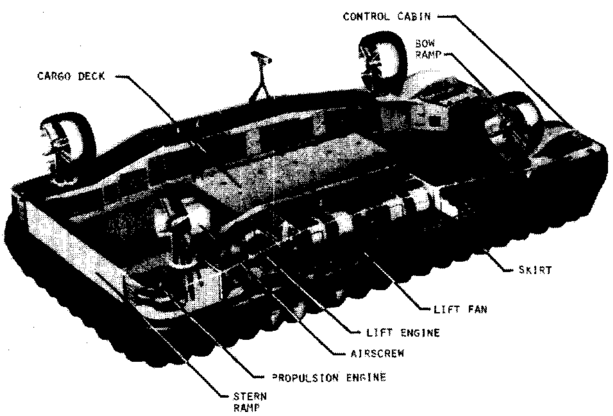


Figure 4. Illustration of U.S. Navy's AALC Jeff(A).

A typical ACV is shown in Figure 4. Its hull is a simple aluminum-alloy raft, the upper side of which forms a cargo deck. The machinery is arranged in the two superstructures on either side of the cargo deck. In this configuration, the propulsors are powered separately by their own gas-turbine engines, and the four lift fans on each side are powered by two more engines (six in all). Steering is provided by rotating the ducted airscrews on their pylons about vertical axes or by differential control of propeller-blade pitch. The skirt system selected in this case is a loop-pericell arrangement, although the majority of modern ACVs use some form of the bag and finger skirt. Both arrangements are illustrated in Figure 5.

Skirt depth, hence buoyancy tank clearance, (Figure 3) is typically 20% of the cushion beam or less to ensure adequate roll stability when underway. To provide additional stability for a bag-finger skirt, longitudinal and transverse fabric seals are usually installed beneath the hull. These are not shown in Figure 3, but can be seen in Figure 5B. For the loop-pericell skirt, Figure 5A, such seals have been found to be unnecessary and are omitted since they are difficult to inspect and maintain.

The wide beam, raft-like hull also provides considerable buoyancy and intact stability when the craft is off-cushion over water. Watertight subdivisions internally provide stability for the damaged case, and landing pads or rails are located beneath the hull for parking on land.

In general, the design of an ACV *will* emphasize the need for efficient and low-weight subsystems, such as the structure and the propulsion and lift machinery, without neglect of construction and life-cycle cost. Many possible variations of machinery layout and component selection exist, so that it is essential that this part of the design be developed in a rational manner. The geometry of an ACV is often limited by considerations of its own outer envelope (as in the case of the AALC and LCAC, which must fit inside the well decks of existing landing ships). and/or considerations of the size and type of the payload that it must carry (buses, automobiles and trailers in the case of the SR.N4; battle tanks, USMC vehicles and weapons in the case of the AALC and LCAC). The struc-

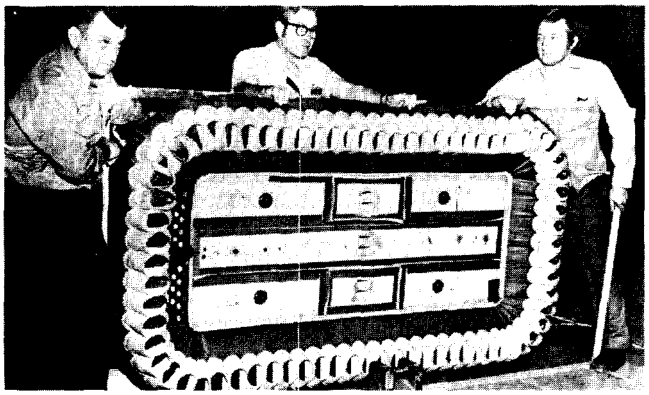


Figure 5A. Loop-Pericell Skirt as Used on AALC *Jeff(A)*, Shown Here on a 7/100-Scale Model.

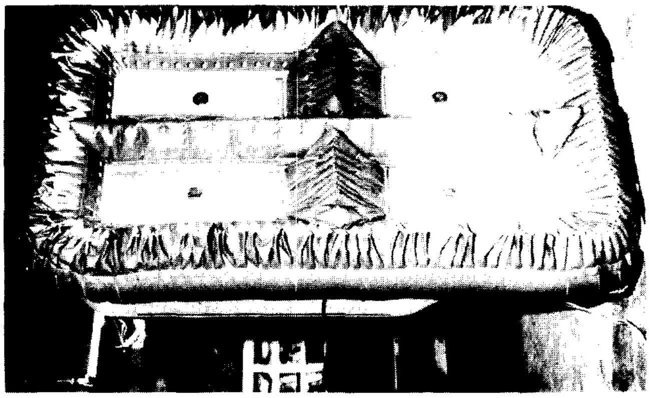


Figure 5B. Bag-Finger Skirt as Used on AALC Jeff(B), Shown Here on a 1/12-Scale Model.

ture usually has a simple. box-like form which lends itself to modularization for ease of transportation. Many of the structural scantlings are often determined by the minimum thickness of aluminum plating that can be accepted by commercial welding practice and by the local loads. Local loads are caused by vehicular cargo or payload rather than by the seakeeping loads that are used to design much of the structure of conventional ships.

SPECIAL ATTRIBUTES AND LIMITATIONS

ACVs can be designed for very high speeds. In calm conditions the speed of an ACV can generally be higher than for other forms of marine transport (e.g., 50 kts for the 101-passenger AP.l-88 and 70 kts for the 300-ton SR.N4 Mk.3 shown in Figure 6). Payload capacity can also be high, as can the fraction of deck area to total planform area, thus making the ACV suitable for carrying a wide variety of cargo.

However, the most valuable attribute of an ACV is the fact that it is amphibious; it can operate effectively in deep water, and in shallow water, in the surf zone, over mud and marsh land, over solid or broken ice, within the dry or wet well of a landing ship, or overland, within obvious limitations of terrain roughness. The advantages of this capability in certain military applications, such as amphibious assault, riverine warfare, and Arctic operations, are self-evident. In commercial applications, the success of the SR.N4 operation, for example, has been due, in no small way, to Hoverlloyd's effective utilization of the amphibious capability to shorten the route length and block time by crossing the Goodwin Sands, and to minimize the docking, loading, and turn-around times at the terminals. Current commercial operations with the 88-passenger, AP. l-88, frequently achieve turnaround times of four minutes.

Terminal requirements for ACVs are minimal. Amphibious capability makes the ACV independent of existing facilities, and the basic requirement is a sloping slipway or beach. This may enable the terminal to be located in the most advantageous position relative to the existing local infrastructure of car parks, rail heads, airports, etc., (see Figure 7). It also facilitates the inauguration of new routes between areas not already serviced by marine transport links.

Other advantages of air cushion vehicles are equally significant. Passengers not only benefit from the more frequent service than the typical ferry would allow, but they also benefit from quicker processing through customs and immigration. Another important factor has been the ability of the large ACV to operate outside the established deep water ports, and thus, avoid the associated shipping congestion. Experience has shown that existing harbors, which need not be used by ACVs, often have the worst sea conditions of the route at the entrance to the breakwaters. These conditions can cause signifi-

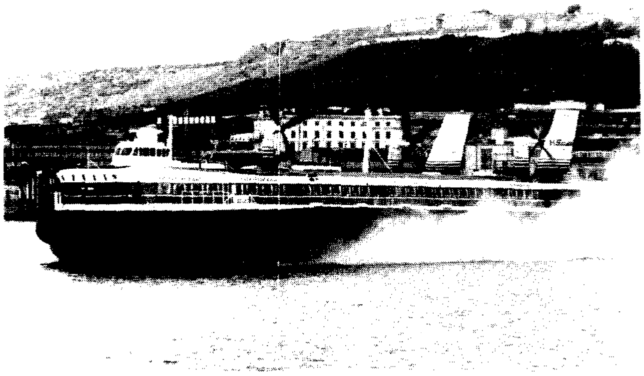


Figure 6. BHC SR.N4 Mk.3 Passenger/Car Hovercraft.

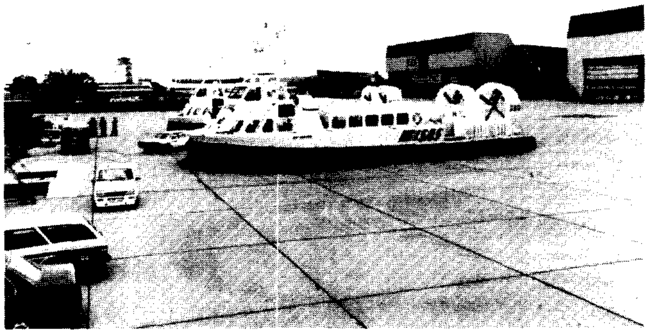


Figure 7. The BHC AP.l-88 at Airport Terminal.

cant delays if the traffic to the port is heavy. They can even cancel all port operations before the individual craft or ship limits are reached.

The superiority that ACVs have over standard ships under certain circumstances is largely the result of the separation of the hard structure of the vehicle from the water surface. This reduces the probability of water impact loads so that light structure can be used. It also renders the ACV relatively immune to underwater explosions with consequent enhancement of its military worth.

Other features that are important to military applications are the ACV's very low underwater acoustic, magnetic, and pressure signatures; attributes that make it particularly suitable for mine countermeasure work. Magnetic signatures are low because of the minimum use of ferromagnetic structures and components in ACV construction. Low pressure signatures are a direct result of the low cushion pressure, and low acoustic signatures exist because of the presence of the air cushion and the absence of subsurface propulsion or controls.

Along with this list of ACV attributes are certain inherent limitations that must be recognized. Although much as been accomplished over the years to remove these limitations, there remains a continuing effort to minimize their severity.

High wear rate of the flexible skirt is one example. With today's technology, the achievable life of a typical skirt bag is less than 3000 operating hours, and the life of the fingers is usually no more than 400 hours.

The cushion can also throw up considerable quantities of sand or saltwater spray, particularly if the cushion pressure is high and no spray-suppression skirt is installed. This can impair the vision of the craft operator. It can also cause severe erosion of propeller and lift-fan blades if the blades are required to run at high tip speeds and their leading edges are not well protected. Engine life can also be limited by the ingestion of sand, seawater spray, and salt-laden air unless fairly elaborate combustion-air inlet filtration systems are used.

High levels of airborne noise have also been a problem with airscrews and lift fans having blades running at high tip speeds. Shrouding the propeller within a duct and sharing the thrust (or airflow) between a larger number of slower speed propellers (or lift fans) has been the only practical solution achieved to date.

Another limitation of ACVs has been the difficulty in achieving precise maneuvering and control, particularly when operating on slopes over land. This problem has been overcome but only at the expense of using more sophisticated controls such as the pylon-mounted propellers on the SR.N4 and the AALC *Jeff(A)* (Figures 1 and 4), or the swivelling bow thrusters on the LCAC and the AP.1-88 (Figures 19 and 7).

Finally, the cost of ACV construction and operation has been high. However, efforts to remedy this situation have been impressive. As explained towards the end of this chapter by Ray Wheeler, the development of more efficient skirt systems has permitted a transition away from the use of high-cost aircraft-type hull construction and machinery. towards a more marine-engineering based industry.

In the late 1970s, for example, the gas turbine-powered SR.N4 Mk.2, which used <aircraft-type hull construction, had a total power/weight ratio of the order of 68 HP/ton. The development, on this craft, of the low pressure ratio, high response skirt, enalbled the SR.N4 Mk.2 to be stretched by 55 ft, increasing the AUW from 200 to 300 long tons, and the payload by 80% for only a small increase in power [1]. The reduction in total power/weight ratio to about 51 HP/ton is illustrated in Figure 8.

To reduce cost, the new generation craft (such as the AP. l-88) utilized this increase in efficiency in a different way. sacrificing the potential payload increase for the opportunity of using lower cost but heavier power plants and less labor intensive, welded, aluminum-alloy structures.

The AP.l-88 was built to replace the aircraft-type constructed, BHC SR.N6 Mk.1S, shown in Figure 9. The large reduction in build cost and operating cost achieved by using marine structures and diesel engines, on the AP. l-88, is graphically illustrated in Figure 10 and 11 [2].

The message is clear. The key to successful ACV development will continue to depend on minimizing cost and on the selective application to missions that will most benefit from its unique capabilities. The ACV is not a highly efficient, long-range, cruise form of transport, but rather a moderately efficient, medium-to-short-range, highly mobile, and highly flexible amphibious system with a significant work capacity. It is capable of development to gross weights of over 1000 tons [3], and it will provide heavy lift capabilities in undeveloped or marginal areas, such as the northern tundra, far beyond the limits of other surface vehicles. Short range ferry applications will continue. These applications will exist, however, only where the full advantage of the ACV amphibious capability can be utilized for terminal optimization and location, shallow water routes, and the crossing of obstacles such as sand bars.

While there will continue to be a requirement for improved performance and efficiency, this must not come at the expense of ruggedness, reliability, or ease of maintenance. Some of the features of ACVs built in the 1970s that are problems to the operators today are the result of, or a legacy of, earlier excessive design emphasis on the maximum vehicle performance and efficiency.

These and other attributes and limitations of today's ACVs are discussed further in the following sections of this chapter. In particular, the concluding sections on the "State of Technology" and on the "Producibility and Supportability" of ACVs, concentrate, in more detail, upon the limitations of ACVs and what has been accomplished to overcome them.

CURRENT AND FIJTURE APPLICATIONS

COMMERCIAL FERRIES

The world's first commercial ACV service began in the United Kingdom on the 20th July 1962, across the Estu-

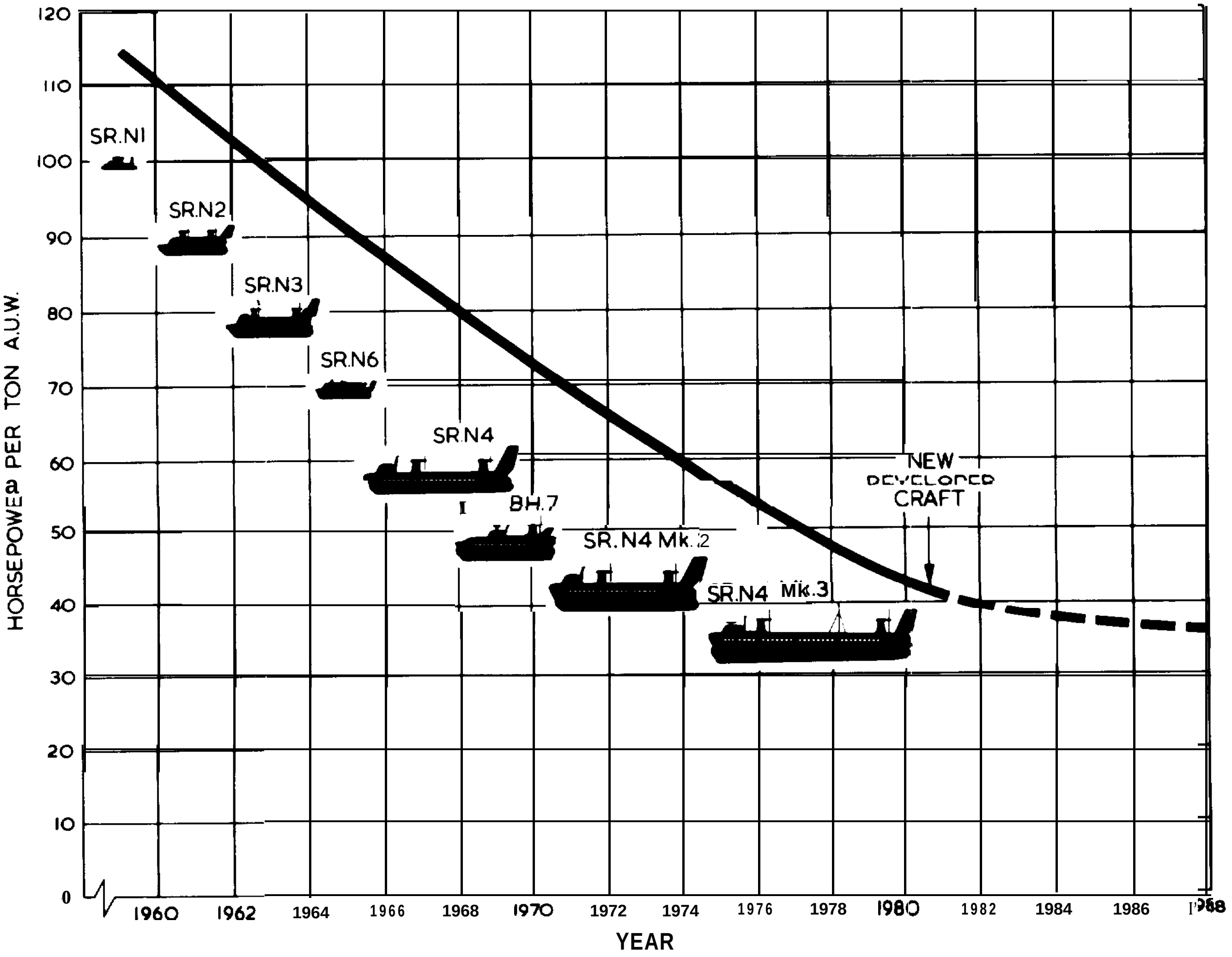


Figure 8. Improvement in Power to Weight Ratio Achieved by BHC Craft.

ary of the River Dee, between Rhyl and Wallasey for a period of eight weeks. It utilized the 24-seat Vickers VA3 and was intended to evaluate the performance of the craft in the passenger carrying role and to assess customer reaction. Some 3,760 fare-paying passengers were carried and valuable lessons were learned. Other early experimental and route proving services were operated by Westland in association with Southdown Motors, across the Solent between Ryde and Southsea (6 nm) in the

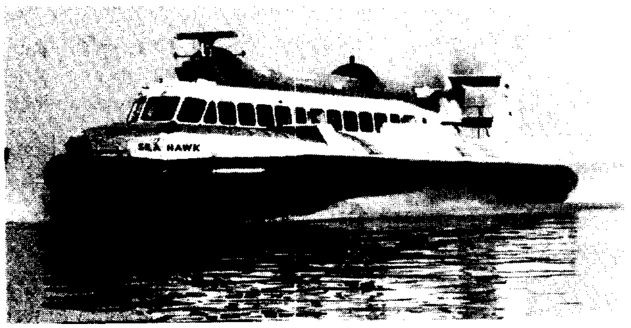


Figure 9. BHC SR.N6 Mk.1S Passenger Hovercraft.

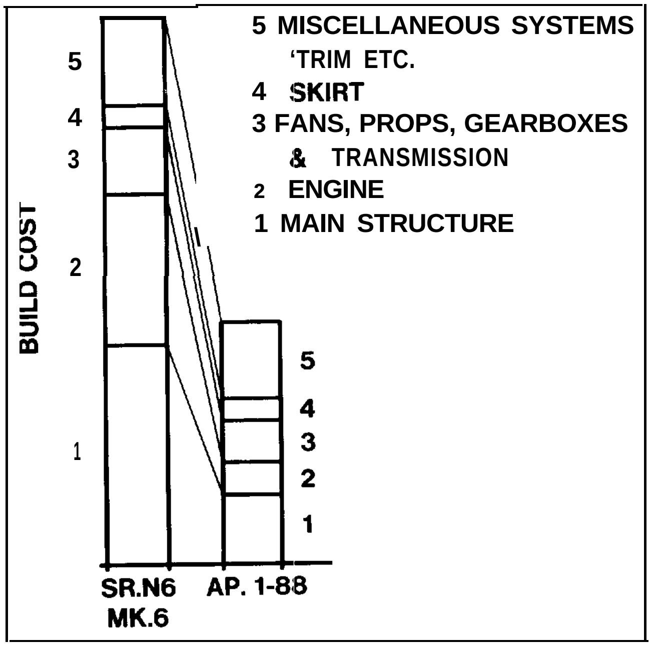


Figure 10. Comparison of Build Costs.

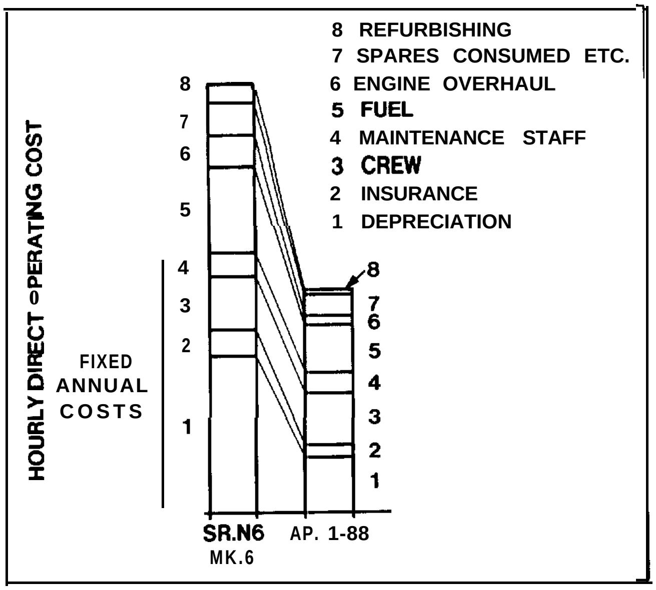


Figure 11. Comparison of Hourly Direct Operating Costs.

summer of 1962, using the 60-seat SR.N2; across the Severn Estuary from Weston-Super-Mare to Penarth (12 nm) in the summer of 1963, in association with P & A Cambell, again using the SR.N2 craft; and Ryde to Southsea (4 nm) for six weeks in June and July 1964 by Hovertransport, Ltd. using two craft, the SR.N2 and an 18-seat SR.N.5. This latter service is still in existence, operated by Hovertravel, Ltd. using the AP.1-88 craft.

Serious commercial operations first became feasible with the availability of the 38-passenger SR.N6 Mk.1. This craft entered service in 1966 across the Solent (Ryde to Southsea, and Cowes to Southampton). In the summer, it operated only across the English Channel to obtain operating experience. Worldwide ACV ferry service operations between 1966 and 1983 are summarized in Figure 12. This figure is based on published information and excludes operations in the USSR and China [4]. While it is believed that commercial use is made of ACVs in these countries, particularly on rivers, little specific information is available. Figures 13 to 17 show some of the craft listed in Figure 12.

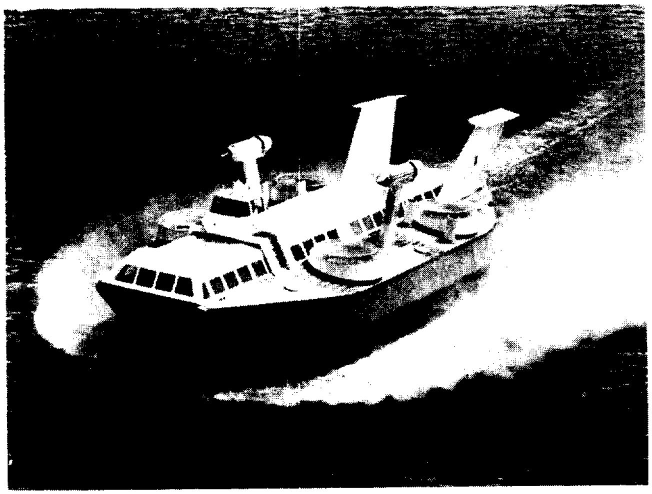


Figure 13. Sedam N300.

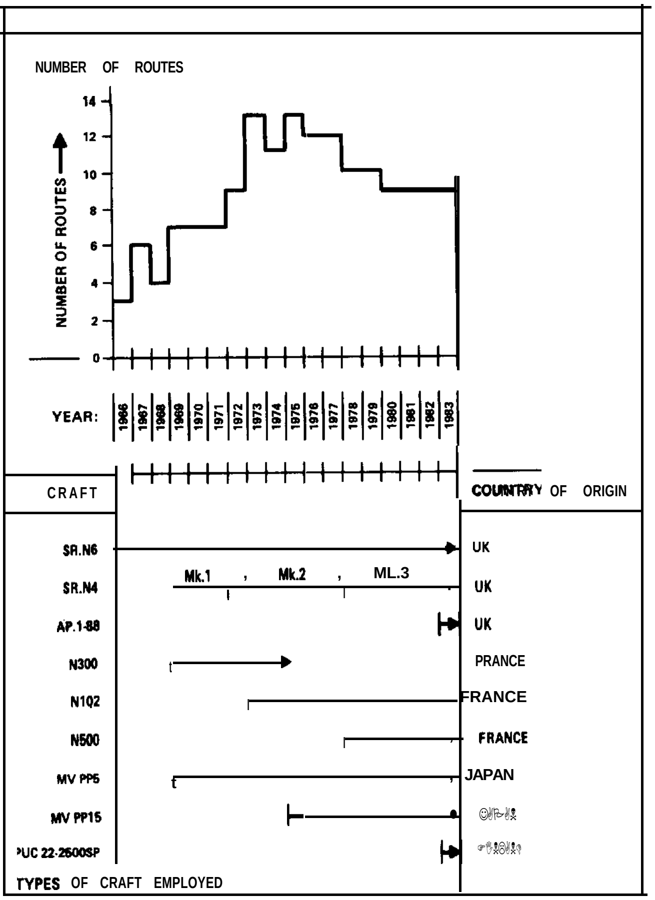


Figure 12. Summary of Worldwide ACV Ferry Service Operations, 1966-1983.

Since 1966 approximately 16 routes can be identified that were sustained for longer than one year, although some of them were seasonal operations only. Of these routes eight were, according to the information available, still in operation in 1983: three in the U.K., one in France, and four in Japan. One new route was commenced in 1983 in Finland, making a total of nine routes in operation that year.

It is clear from Figure 12 that there was a slow but steady net increase in the number of routes to approxi-

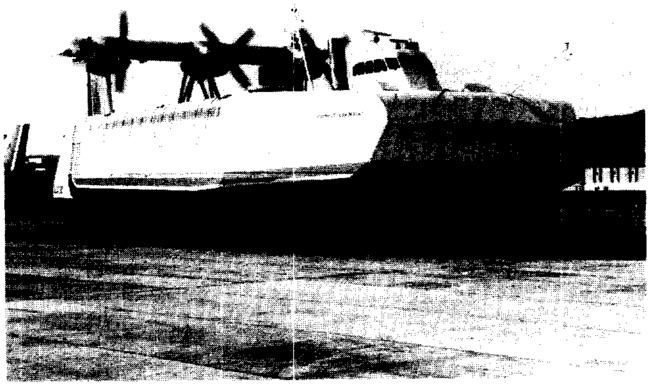


Figure 14. Sedam N500.

Table 1. Craft Leading Particulars

CRAFT	SR.N6 Mk.1S	AP.1-88 (PROD.)	SR.N4 Mk.2	SR.N4 Mk.3	N500	N102	MV PP5 Mk.2	MV PP15	PUC 22-2500SP
COUNTRY OF MANUFACTURE	UK	UK	UK	UK	FRANCE	FRANCE	JAPAN	JAPAN	FINLAND
MANUFACTURER	BHC	BHC	BHC	BHC	SEDAM	SEDAM	MITSUI	MITSUI	WARTSILA
POWER PLANT	1 GAS TURBINE	4 DIESEL	4 GAS TURBINES	4 GAS TURBINES	5 GAS TURBINES	1 GAS TURBINE	1 GAS TURBINE	2 GAS TURBINES	4 DIESEL
APPROX. HORSEPOWER	1000	4 x 428	4 x 3400	4 x 3800	5 x 3000	565 or 700	1050	2 x 1100	4 x 870
APPROX. AUW (tons)	10	38	200	300	285	4	19	50	89
PASSENGERS	58	101	282	418	418	13	76	115	50
CARS	–	–	37	60	65	–	–	–	16
APPROX. MAX. SPEED (kt)	52	50	70	70	70	55	52	65	30

mately 13 in the eight years up until the international fuel crisis of 1974, when the cost of fuel drastically increased. Between 1974 and 1982 only three new routes were established (all in Japan), and two of these had been discontinued by 1978. However, all the craft involved (see Figure 12 and Table 1) were gas-turbine-powered craft with comparatively high fuel consumption. It is significant that, as far as is known, the only new routes to be inaugurated since 1978 have both employed diesel-powered craft. These are the Finnish PUC22-Larus (Figure 17) operating in the Finnish Archipelago in 1983, and the AP.l-88 service (commenced in June 1984) across the Oresund between Sweden and Denmark (Malmø to Kastrup).

It is also noteworthy that. with the exception of the last mentioned AP.l-88 service, all routes since 1966 have been operated within (or to and from) the country of origin of the craft concerned. This is probably, at least in part, a reflection of the difficulty of obtaining acceptance of the ACV as a passenger ferry by classification societies outside the country of origin. The AP. l-88 is probably the first ACV to satisfy the IMO code as interpreted by a foreign country.

With the exception of the two cross channel routes (Dover-Boulogne and Ramsgate-Calais) employing SR.N4 and N500 combined passenger/vehicle ferries, all services until 1983 were passenger only. However, the PUC22-2500SP, which, as previously mentioned, entered service in 1983, has a vehicle carrying capability.

The most immediately evident feature of commercial ACV operation over the last 18 years is the comparatively small number of routes in existence. However, the three longest established routes, namely the cross channel car/passenger ferries and the cross Solent (Ryde to Southsea) passenger service have been extremely successful. For example, Hoverlloyd performance, according to Calais Chamber of Commerce data, was 13.5 percent of the car and 14 percent of the passenger traffic through Calais in

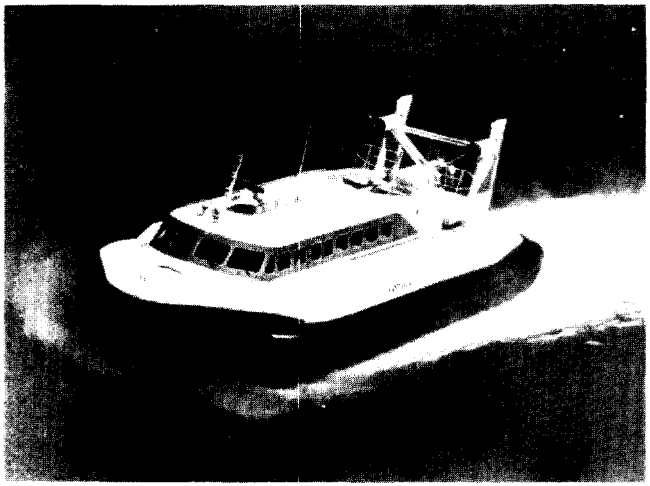


Figure 15. Mitsui PP5.

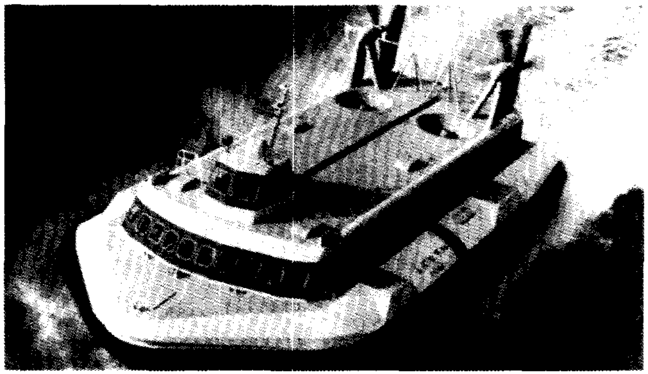


Figure 16. Mitsui PP15.

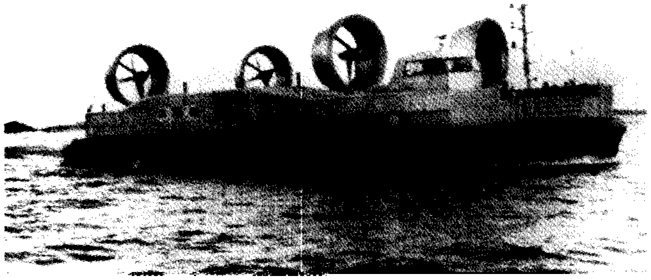


Figure 17. Diesel-Powered Wartsila PUC22-Larus.

1969, increasing to 17.4 percent and 20 percent respectively in 1970. In 1974 Hoverlloyd carried 7.9 percent of all vehicles and 9.7 percent of all passenger traffic between the United Kingdom and the ports of France and Belgium. Seaspeed claimed 30 percent of the traffic between Dover and Boulogne, with load factors of 64 percent passengers and 79 percent cars between January and October. 1975. In 1977, Hoverlloyd was reported to have made 1.4M pounds sterling profit carrying l.lM passengers and 211,000 vehicles on their 4 SR.N4 Mk.2 craft. At the end of 1973 Hoverlloyd announced a serviceability rate of 99.09 percent for the previous year, with weather cancellation rates of only 1.49 percent of planned flights [5].

More recently. average load factors during the first nine months of AP. l-88 Hovertravel operations across the Solent in 1983 were of the order of 55 percent with only I percent cancellation due to weather [1]. In one peak summer month, during operation with only one 88-seat craft. an average of nearly 2,500 passengers a day was achieved (see Figure 18).

Future Trends

From the discussion in the previous paragraphs, it could be concluded that the number of ACV ferry routes worldwide using gas-turbine-powered craft reached a peak at the time of the 1974 fuel crisis. The arrest of the subsequent slow decline in the number of routes has roughly coincided with the development of diesel-powered craft in the last two years or so. At the time of writing two types of diesel-powered craft are in operational service and it is known that three other diesel powered craft (all 36-40 passenger vehicles) are in the prototype stage in the U.K.

Any further expansion of the ACV ferry market will depend on the availability of low cost, more efficient craft to meet the new economic restraints. At the same time, these craft must be able to satisfy international maritime licensing regulations without prejudicing their economic viability. Such craft have finally become available and have entered commercial service.

U.S. NAVY AND MARINE CORPS AMPHIBIANS

The effective transfer of men and material from embarked shipping to shore during an amphibious landing has always been hampered by the limitations of conventional landing craft. Use of an air cushion vehicle in this role overcomes these traditional restrictions and promises to have a dramatic impact on future amphibious operations.

There are only two methods of transporting, offloading, and sustaining the men and supplies of a large occupying force: by use of a port where mooring and handling facilities are available or by amphibious assault.

The harbor approach usually is beset with dangers. A disagreeable owner is likely to have extensive defenses, including mines, in the area, thus making a surprise frontal assault difficult. Attempts to reduce the defenses in advance make an alerted enemy a certainty.

The problems of securing usable port facilities force the consideration of an amphibious assault. Although the concept permits the option of selecting a more lightly defended site, amphibious assault carries its own set of limitations: the necessary men and materiel must be transported from ship to shore by use of highly specialized equipment, over unpredictable seas, to a shore site of often uncertain character. It is not surprising, therefore, that studies of amphibious assaults throughout history show many limited successes and frequent failures. At Gallipoli, the British mounted the ". . . greatest and most unfortunate combined operation of military history . ." [6]. This disaster understandably led many military leaders to dismiss for years any consideration of an amphibious assault. However, the U.S. Marines had met with success in several Caribbean and Pacific amphibious operations. This encouraged development of a body of amphibious doctrine and tactics during the 1930s that was to prove crucial to the success of World War II.

The transition of military force from sea transport to shore operations-both the initial assault and effective resupply-always has been and still is the fundamental problem in an amphibious assault. The root cause is the inescapable means of effecting this transfer of men and materiel: the landing craft. Current landing craft differ little from World War II design and must be launched from close-in ships, exposing high-value amphibious assault ships to direct enemy fire and mines. The landing craft are slow-moving, easy targets, and their use is limited to landing sites possessing favorable shore gradient, current, and surf conditions. Poor trafficability/egress at the critical beach interface often has proved to be a dreadful operational impediment. The necessity for advance force operations to reduce the threat posed by fixed defenses to these close-in ship and boat operations reduces the potential for tactical surprise.

We certainly have numerous illustrations of the problem, e.g.

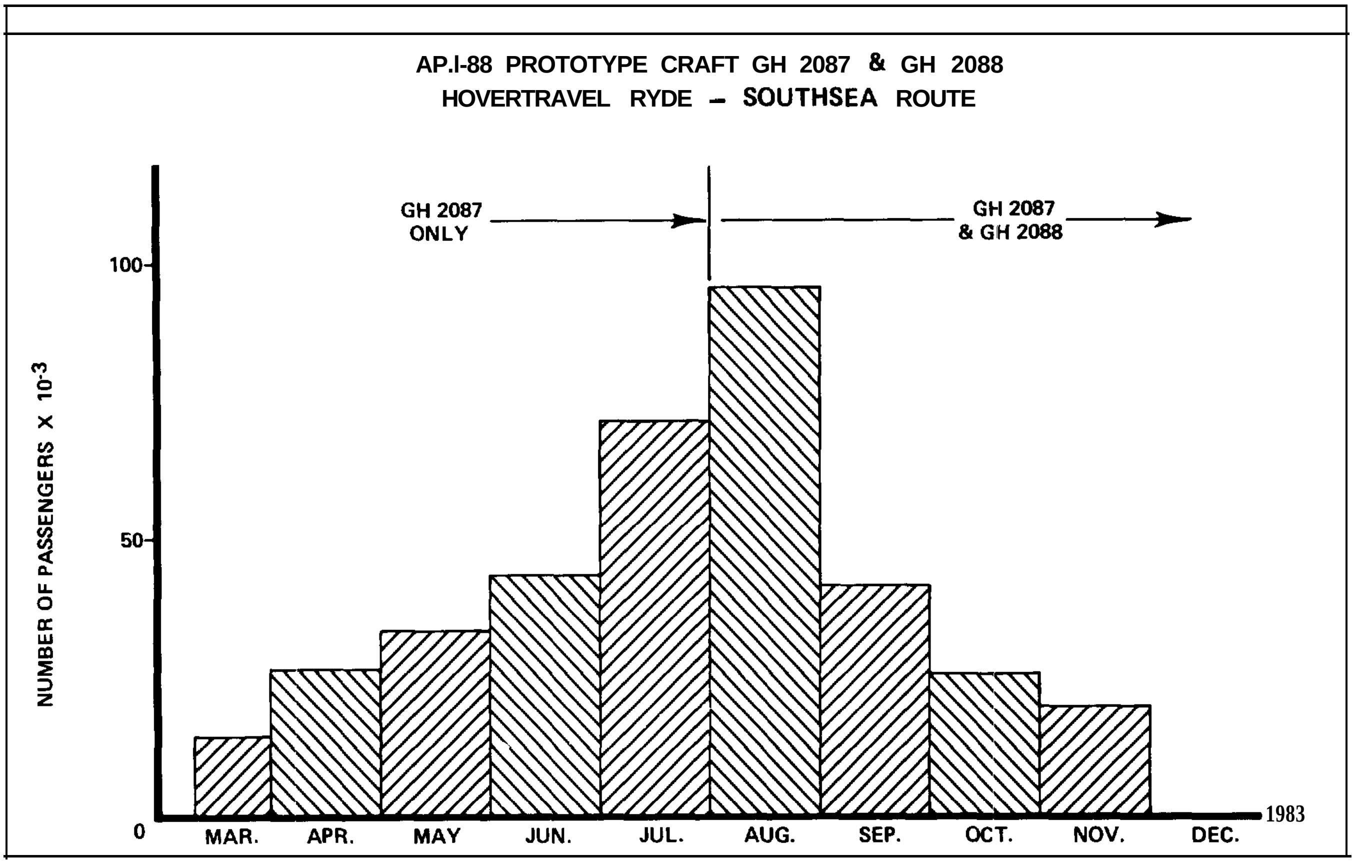


Figure 18. Passengers Carried: Monthly Breakdown for 1983.

In World War II

During the Guadalcanal campaign a classic pile-up of materiel occurred at the beach-an exposed and tenuously held area. Assault ships and craft were compelled to leave the vicinity by enemy forces. During this absence, the main island could not be supported even though the securely-held island of Tulagi (25 miles away) could have served as a base if suitable craft had been available.

In recapturing New Guinea, General McArthur successfully used the "back and fill" approach-trying a landing, but, if resistance was encountered, retreating to sea and moving to another beach until a lightly defended one was found. A good tactic but limited by the mobility of landing craft.

On several occasions, attempts to leapfrog to the rear of the enemy by sea-in Sicily and in the Anzio landing-were often frustrated or limited by slow-moving craft assets.

Figure 19. The First LCAC at the Naval Coastal Systems Center (NCSC), Panama City, Florida, Where It Is Undergoing Test and Trials Prior to Moving to Its Operational Base in 1986.

Figure 20. The Cumbersome Beach-Landing Craft Interface, Well-Illustrated by an Embarkation Scene at Guadalcanal.

Figure 21. An LST and LCM Stranded by Low Tide at Incbon. In Such Conditions, Efficient Transfer is Only Possible at High-Tide Periods.

In Korea

At Inchon, the long tidal range required LSTs to remain beached and exposed between high tides. Men and material had to move long distances over marshy terrain.

An attempted encirclement of Koreans at Wonsan failed because slow craft allowed time for the enemy to escape.

More recently

In the Falklands, the initial landing was made 50 miles from Port Stanley. Resupply during the overland trek was a continuing problem, because much of the march was on marshy terrain (many heavy helicopters, a resupply alternative, had been lost in the sinking of the *Atlantic Conveyer*). Disembarkment of troops at Fitzroy exposed two ships to fatal air strikes upon loss of cloud cover, with heavy casualties.

In Grenada, no beach landings were possible during the initial assault because of heavy surf. Troops were landed by helicopter, one company at a time.

Although improvements to amphibious vehicles and development of assault helicopters have enhanced greatly the landing force flexibility and mobility, the preponderance of combat and cotnbat service-support materiel still must be transported ashore by landing craft. Since World War II and Korea, the continuing interest and support of the Marines in improving our amphibious warfare capability has been in large measure responsible for the initiation and support of the Navy's amphibious assault landing craft (AALC) advanced development R & D program.

The AALC program objective was to develop a family of advanced landing craft to improve movement of men and materiel during an amphibious assault. Early in the program the requirements of overall amphibious lift, ship availability, technical aspects, and funding, as well as operational limits imposed by current landing craft, were examined at length. The studies concluded that the most promising concept was that which would use an air cushion vehicle (ACV) as the new-generation landing craft. ACVs would permit assaults at high speed, with an inherent ability to traverse most beaches and shore terrain. In addition, the ACV appeared. capable of carrying the heaviest item of equipment in the Marine Air Ground Task Force (MAGTF) and of providing rapid load/off-load capability.

Upon selection of the ACV as best candidate, emphasis was placed on making the new craft compatible with existing amphibious ships and fleet assets. Amphibious ship considerations limited the proposed ACV size to a beam 47-48 feet, length 90 feet, and height 23 feet. The weight of the M-60 tank retriever dictated that craft payload be 60 tons. The principal design characteristic resulting from these constraints was a relatively high cushion density (Figure 22) which required examination of an unexplored regime in an otherwise well-understood body of ACV technology.

Contracts for two ACVs, to be known as *Jeff* craft, were awarded in 1970. In general, important design specifications were made stringent enough to ensure that follow-on craft design requirements would fall within confirmed construction and performance boundaries; an approach that proved sound when the follow-on acquisition program, the landing craft, air cushion (LCAC), was begun.

One *Jeff* craft became available in 1978, the other a year later, and both have undergone an extensive series of tests and trials. Craft operations and maintenance have been performed by Navy personnel, and a series of operational demonstrations were performed for the Navy's Operational Test and Evaluation Force beginning in 1979.

During the operational demonstrations, over-water and overland trials were conducted under a variety of conditions and payloads. Typical Marine Corps equipment was loaded and off-loaded to determine cycle times and to identify any interface areas of concern. Various equipment up to and including the M-60 main battle tank were carried, on-cushion, at design speeds. The heart of the operational demonstration was a series of interface trials with a landing ship dock; well-deck entries and exits were conducted under wet and dry well conditions, both at anchor and underway.

The first operational demonstration was successful, and the report of the Commander, Operational Test and Evaluation Force, recommending initiation of a follow-on ACV program was very encouraging. The positive results were a critical factor in obtaining approval to begin LCAC acquisition.

On 15 February 1980, a presentation to the Ship Acquisition and Improvement Panel, chaired by the Deputy Chief of Naval Operations for Surface Warfare, reported the results of *Jeff* craft testing. The panel approved the LCAC requirements and the plans for a system design/specification competition.

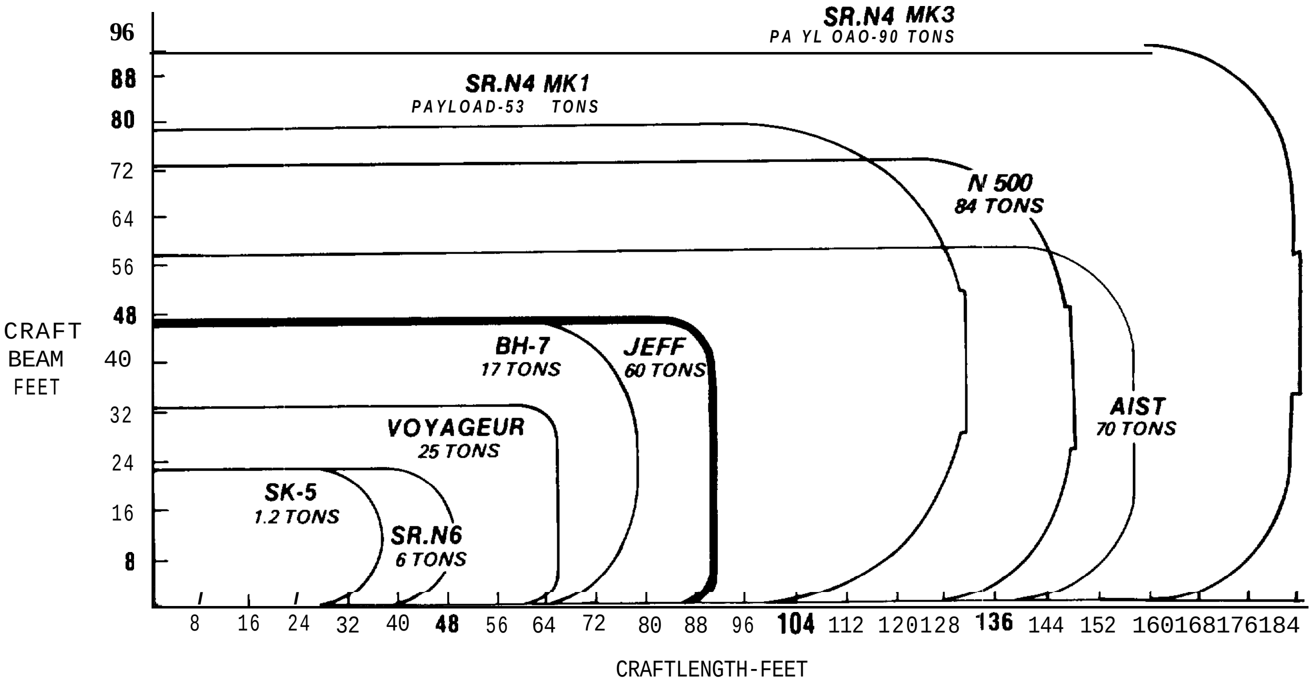


Figure 22. Deck Area and Payload of Operational ACVs and *Jeff* Craft.

On 20 February 1980, a request for proposal to perform the LCAC system design/specification was issued by the Naval Sea Systems Command. On the basis of the responses, two contractors were selected and awarded a contract to prepare competitive designs. In October 1980, the competition was in progress and because of the success of the *Jeff* craft, the Deputy Secretary of Defense directed that the Navy's LCAC program be presented for a production decision.

Grappling with craft procurement proved every bit as challenging as grappling with design. An ACV is a mixture of ship and aircraft requirements that is weight critical. As a result, a lead production program of 12 craft (3-3-6) leading to a full production rate of 12 craft/year was presented to the Secretary of the Navy and approved on 21 December 1981. A contract for detail design and procurement of long lead material also containing options for lead production was awarded on 5 June 1981 to the winner of the system design competition; Bell Aerospace, Textron. Roll-out of the first LCAC (Figure 19) occurred on 2 May 1984, and testing began in the summer of 1984. The Amphibious Warfare and Strategic Sealift Program Office (PMS-377) is seeking to establish a second source supplier of the LCAC to provide a long-term competitive environment as well as industrial base expansion. The first phase candidates have been selected.

The first operating site will be in use in 1986 on the West Coast at Camp Pendleton, and fleet operations with the first six craft will commence. In the meantime, PMS-377 is assuring that all new amphibious well-deck ships, such as the LSD-I and LHD-1 classes, are designed to accept LCACs. PMS-377 is also exploring the use of the ACV in other missions such as medical evacuations, coastal/surf zone minesweeping, Arctic operations and mobile support base.

In order to gain valuable Arctic data, PMS-377 leased the *Jeff(A)* to RMI, Inc. in 1983 for use in the Arctic. The results of this effort are discussed in a later section. With the expanded role of strategic sealift, PMS-377 has been working with the U.S. Army program manager for watercraft to insure a solid technology transfer as well as lessons learned between the two services.

In other related efforts, the need exists for a craft suitable for general cargo offload as a replacement for the LCU, and various alternatives are being examined. Although a surface effect craft in this role may prove feasible, a fully-skirted ACV, well-deck compatible and capable of LCU payloads, is clearly the preferred candidate at the present time. Since the LCAC has made am-

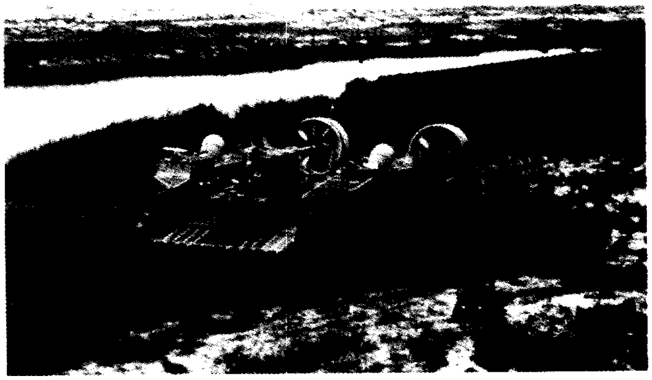


Figure 23. Scene during *Jeff* Craft Operational Demonstration.

phibious assaults possible over most of the world's beaches, logic supports selection of a craft capable of general cargo offload over these same beach areas.

The LCAC transcends the limitations imposed by current craft: it can carry heavy loads with high speed and maneuverability, it can be launched from over-the-horizon. and it can operate, by riding on a cushion of air, less dependently on water, surf, and beach conditions. In short, the LCAC adds a new dimension to amphibious warfare. As the operational constraints imposed by slow-moving landing craft are removed and the capabilities of the LCAC are better understood through use, we can expect radical innovations in amphibious warfare tactics and operations.

U.S. ARMY CRAFT

As the primary land-based force in the event of armed conflict, the Army has an extremely critical need for large quantities of resupply cargo. During long engagements, airlift to makeshif't, friendly, or captured airstrips, or sealift to established ports, can adequately handle much of the resupply. However, in the early phases of conflict, a significant amount of cargo must be provided by sea and taken across the shoreline when ports are not available. This scenario is called logistics over-the-shore (LOTS).

The LOTS mission invollves the movement of cargo (to include personnel, containers, break-bulk, and vehicles) in three distinct phases: discharging of cargo/containerships offshore and at anchor, transportation of cargo to and across the shoreline, and delivery of cargo to an inland marshalling area. A graphical depiction can be seen in Figure 24. The LOTS mission for the Army has historically been satisfied by a mix of wheeled amphibians and displacement craft. The existing Army amphibian and watercraft fleet designed to fulfill the LOTS mission consists of six primary components:

- Heavy Boat Company-consisting of landing craft utility (LCU-1466, 1600 classes)
- Medium Boat Company-consisting of landing craft, mechanized (LCM-8)
- Medium Lighter Company-consisting of lighter, air cushion vehicle. 30 Ton (LACV-30)
- LARC LX Platoon
- Terminal Service Company (Container)—consisting of a container discharge facility which can move up to 4.000 tons per day

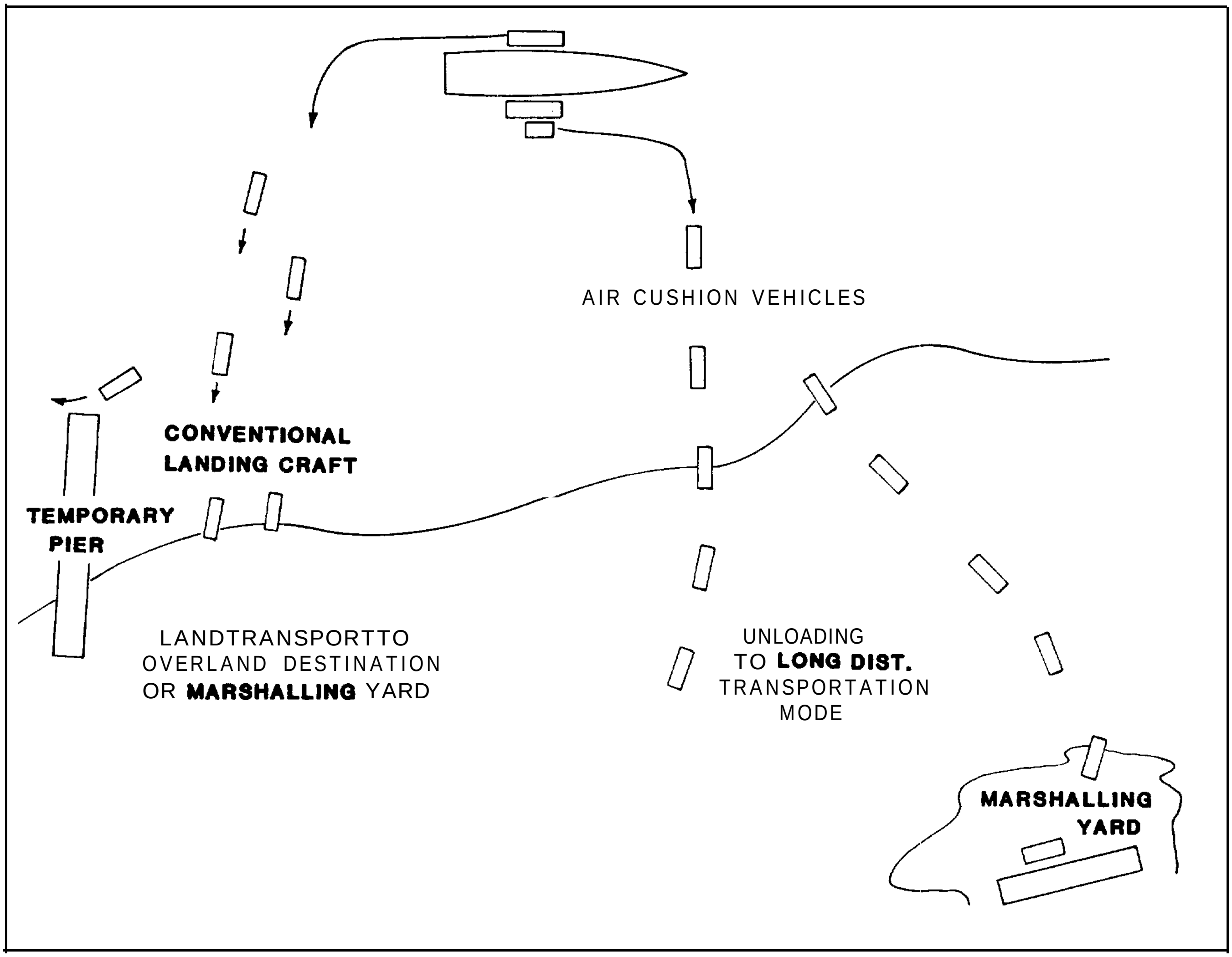


Figure 24. LOTS Scenario.

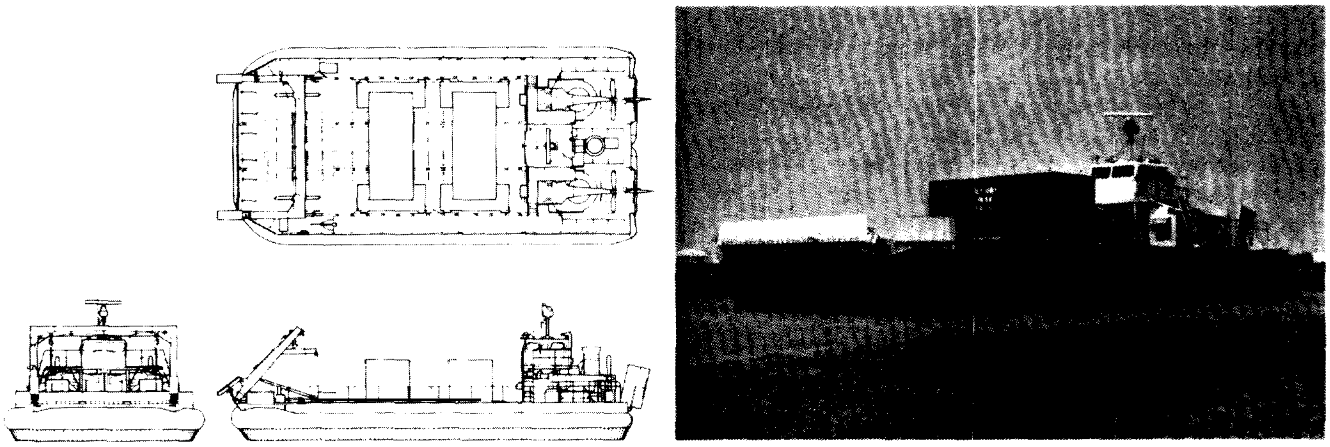


Figure 25. U.S. Army LACV-30.

- Terminal Service Company (Breakbulk)-handles non-containerized cargo, up to 1,000 tons per day.

Recent efforts to coordinate LOTS developments with the Navy have established Army requirements for roll-on/roll-off (RO/RO) discharge facilities. elevated and powered causeways, and side-loadable warping tugs. It should be noted that these shallow draft lighters cannot operate in all scenarios, particularly in extreme offshore gradients. For this reason, the Army has maintained the wheeled amphibian fleet until the advent of the air cushion vehicle.

Changing shipping methods (predominately containerships of 1000 to 2000 container capacity) requiring faster movement and rapid turnaround have made the wheeled amphibian obsolete. With the publication of the Trans-Hydro study in 1973, the Army requirement for an amphibious air cushion lighter was born. By June 1974, a required operational capability (ROC) document was approved by the Department of the Army for a 20- to 30-ton payload, 40-knot. fully amphibious air cushion vehicle, designated the lighter, air cushion vehicle, 30-ton payldad (LACV-30). In 1975, the Army bought two prototype LACV-30s for development and operational testing. The craft were type classified standard for acceptance into the Army in September 1978. Another major outgrowth of the study is the lighter, amphibian heavy-lift (LAMP-H) which is currently in the early development phase.

Not envisioned during the Trans-Hydro study, however, were the developments in Southwest Asia (SWA). The primary requirement for LOTS in the near term can only be the Rapid Deployment Joint Task Force (RDJTF), established in 1977. The concept is centered around a mobile task force that could be deployed in an extremely short time to nearly any world-wide location. Realizing the logistics burden that SWA operations would require and the fact that supplies must be transported by sea, serious consideration has been given to determining the most cost-effective method to assure cargo delivery. Further, the lack of port facilities in that theater dictates particular emphasis on Logistics Over-the-Shore.

Early Army Operations

Although the Army experience with the LACV-30 goes back to the mid- to late seventies, the LACV-30 was not the first ACV used by the Army. In the mid to late sixties, the Army operated three small ACVs in Southeast Asia, primarily as patrol and (evacuation vehicles. There was never much of a LOTS requirement in that area because fixed ports generally existed. The ACVs were designated as SK-5 by the supplier, Bell Aerospace, who provided the craft as a modification of the British Hovercraft SRN.5. The ACVs performed well (as did three additional SK-5s run by the Navy for a total of over 10,000 operating hours), and proved to be an extremely valuable asset to the services during the Vietnam conflict.

Lighter, Air-Cushion Vehicle, 30-Ton (LACV-30)

Deployment of the LACV-30 officially began in 1981 with the delivery of the first production craft to Ft. Story. The operational unit was formed as the 331st Transportation Co. (ACV) in September 1982, and became fully equipped with twelve LACV-30s in June 1983.

The LACV-30 is a military adaptation of Bell Aerospace Textron's commercial *Voyageur*. The *Voyageur* has been used successfully by the Canadian Coast Guard for years, operating in the northern Great Lakes. The major improvement areas of the LACV-30 are an air-management system, 12-foot longitudinal stretch, improved propellers, upgraded engines, surf fence, swing crane for self-unloading capability, load-spreader pallets, airconditioning, and several other minor systems. The main structure is built from 6000 series corrosion resistant aluminum, hollow core panels and plates that are welded to form individual modules. The LACV-30 consists of 15 different sections, including structural and power modules, side decks, landing pads. skirts, and cabin. The key LACV-30 characteristics are presented in Figure 25. The craft is powered by two Pratt & Whitney ST6T-76 twin pack gas-turbine engines rated at 1800 SHP each, driving three-bladed, 9-ft diameter, Hamilton Standard variable pitch propellers. Skirt inflation is accomplished by

Figure 26. LACV-30 Operations at Fort Story, VA.

means of a right angle gearbox driving British Hovercraft Corporation 7-ft diameter lift fans. A Solar 140 SHP gas turbine drives the auxiliary power unit.

The logistics support system for the LACV-30 is centered on a two level maintenance philosophy, organizational and depot. The organizational level encompasses crew assignments, organization, and direct and general support. Depot level maintenance requirements consist primarily of complete end item, major component repair, or overhaul. The modular nature of the LACV-30 lends itself well to this philosophy. The supply concept utilized is the standard Army requisitioning procedure. However, the standard organic supply system has been augmented by a contractor operated "bond room" or central supply depot. This facility, located at Ft. Story, has procured, repaired, stored. and issued all required LACV-30 parts since its inception in early 1981. Phase-out is scheduled for September 1984 as the organic Army system nears total readiness.

The 331st Transportation Company is comprised of three platoons of four craft each and all the necessary ground support equipment to provide full organizational level support. The company requires 198 personnel; nearly one-half are the actual crews and one-third are devoted to maintenance. Of the 198 personnel, there are six officers, one warrant officer, and 191 enlisted. A second company (the 8th Transportation Company) is scheduled to begin operations in late 1984 at Ft. Story. Figure 26 is a photograph of the LACV-30 operations area at Ft. Story.

The LACV-30 has been subjected to arduous testing since the first prototype acquisition. The initial development and operational tests were performed in widely varying locations and under extreme conditions. Technical performance operations were conducted at Aberdeen Proving Ground, Maryland and Ft. Story, Virginia; cold chamber testing to - 40°C at Eglin AFB, Florida; surf transition capability (to 8 ft) demonstrated at Camp Pendleton, California: and icebreaking exercises (up to 47 inches thick) on the Illinois River near Peoria, Illinois. The LACV-30 and its integration into the LOTS mission were successfully demonstrated in joint LOTS (J-LOTS) exercises in 1977 and 1984. During the exercises the LACV-30 averaged over 90 percent availability and proved to be a valuable addition to the Army inventory. As a result of the strenuous test and evaluation programs, the Army has concluded that the LACV-30:

- has met or exceeded all essential established requirements
- is the most cost-effective craft in the Army inventory
- can be easily transported to the operational theater

The LACV-30 fulfills a major need in the Army LOTS environment, but there remain requirements that the LACV-30 cannot meet. The transportation of heavy, outsize cargo quickly exceeds, the LACV-30 lift capability, and, therefore, dictates further exploration of the unique capability of air cushion technology. This requirement was foreseen in the Trans-Hydro study, but was not defined until Headquarters, Department of the Army, approved the letter of agreement (LOA) for the LAMP-H on 24 May 1982.

Lighter, Amphibian Heavy Lift (LAMP-H)

The LAMP-H is required to transport heavy equipment, LOTS support equipment, the M-l tank, tracked and wheeled vehicles, 20- to 40-foot containers, and general cargo. It will be an air cushion lighter, intended to replace the LARC-LX by providing greater productivity with fewer lighters. The LOA requires the new lighter to be an air cushion vehicle, but permits sufficient latitude in concept selection to permit a self-powered or barge-type vehicle. The primary characteristics of the LAMP-H are :

● Payload	-can transport 80 to 100 short tons of cargo -possess sufficient deck area to accommodate four 20- or three 40-foot containers -possess an open cargo deck capable of supporting high loads imposed by heavy equipment and tracked and wheeled vehicles -be equipped with recessed tiedown points -possess an integral bow ramp and be compatible with RO/RO vessel discharge systems
● Performance	-traverse minimum gradient of 1 in 17 rise --clear ground obstacles of 3 feet height --traverse ditches/trenches of 10 feet in diameter and 9 feet deep —have an endurance of five hours as a self-propelled craft; 18 hours as a barge
● Logistics	-possess maximum commonality of components and parts with existing DOD craft -be designed for ease of maintenance and supportability -have energy consumption and efficiency as a major consideration

The craft will be utilized in much the same manner as the LACV-30: LOTS (ship-to-shore and shore-to-shore), port support, coastal, inland waterway, interisland, riverine, and miscellaneous amphibious operations. The percentage of time devoted to each of the above tasks has been targeted by the LOA as:

LOTS (Ship-to-Shore, Shore-to-Shore)		80%
Outsized Cargo, Heavy Equipment, Tracked & Wheeled Vehicles	60%	
Containers	35%	
General Cargo	4%	
Personnel & Medevac	1%	
	100%	
Port Support, IWW. Coastal, Inter Island		16%
Riverine		3%
Amphibious Operations		1%
		100%

In response to requirements stated in the LOA, the Army has evaluated four candidate LAMP-H concepts; modified U.S. Navy landing craft air cushion (LCAC), modified British Hovercraft SRN.4 hoverferry, air cushion barge, and modified U.S. Army LACV-30. Each concept was evaluated and compared in areas of cost, payload, transportability, development time, RMA estimates, system performance, and several other factors. The concept favored in the Belvoir Research and Development Center study is a combination of all four candidates, proposing a barge-type vehicle with a modular steel hull, 125- 150 ton payload, diesel power, and large open-deck area. The craft would require some external means of propulsion across the shore line and on land, probably winched across. the shore by a line and thereafter towed by a land-based vehicle. The next step in the LAMP-H acquisition cycle is the approval of the ROC document, the draft of which will be circulated in late 1984.

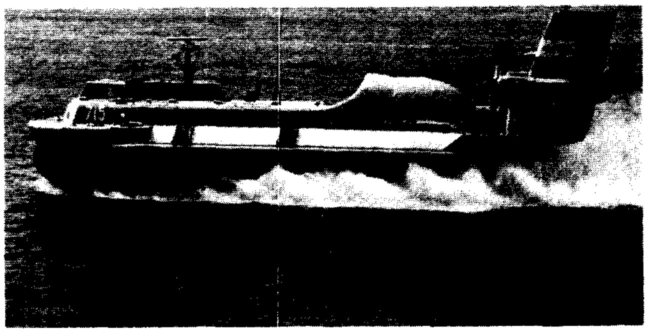


Figure 27. Gus at Speed. The Soviet Navy's First Production ACV.

Other Army ACV Applications

Although the primary ACV operations for the Army are the logistics-oriented LACV-30 and LAMP-H, there are two other on-going smaller projects. In December 1982, the Army National Guard in Alaska took delivery of a small ACV for test and evaluation purposes. The craft, a *Corsair* manufactured by Air Cushion Technologies International. Inc., was tested during 1983 in medevac, scout, and logistics roles in the areas of Bethel and Sitka, Alaska. The craft is 11 feet, 8 inches wide, 28 feet, 6 inches long, 8 feet. 9 inches high off-cushion, and weighs 5300 pounds empty. It is capable of clearing 16 inch vertical obstacles. transporting a net 2000 pounds of cargo (including up to eight passengers), and cruising at 30 to 35 knots. At a normal fuel consumption of 12 gallons per hour, the craft has an effective range of 280 miles. It is powered by a Ford eight-cylinder marine engine for propulsion, a Ford four-cylinder industrial engine for lift, and has a Suzuki 1.5-kw auxiliary power plant. The evaluation program was completed in 1984, with future procurements dependent on the outcome. The Army also has a requirement for passenger ferry service in the Pacific islands and would use air cushion vehicles to replace a function previously fulfilled by fixed-wing aircraft. The ACVs would be competitively procured, capable of carrying 75 to 100 passengers, and be designed for high reliability and low operation and support costs.

The Army is committed to a wide range of air cushion vehicle programs. and convinced that the ACV has a definite role in logistics and tactical applications. The Army's current inventory of fifteen craft will grow to thirty within three years, providing a critical capability to the Army and a source of valuable operational data to all the services.

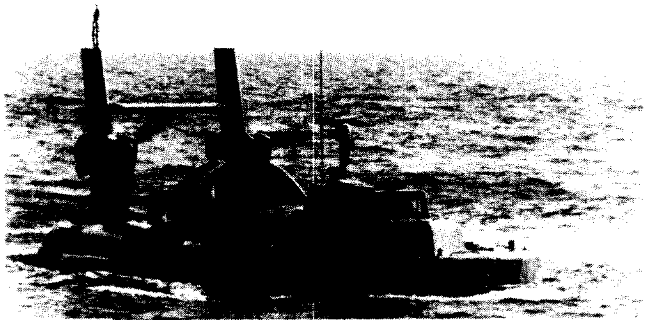


Figure 28. Gus Off-Cushion during a Baltic Exercise.

Gus Class
(Est.)

Length (m)	21
Width(m)	7.5
Powerplant:	
kW	575
Type	TVD-IO gas turbine
No.	3
Payload	one platoon
Maximum weight (kg)	27.000
Maximum speed (knots)	50

SOVIET MILITARY CRAFT

Developments in the Soviet Union using the air cushion principle are divided into three primary categories: the fully-skirted, amphibious ACV, including heavy-lift hoverbarges; the sidewall surface effect ship; and the wing-in-ground effect vehicle *(Ekranolet).* The Soviet sidewall SES are mostly riverine and coastal commercial craft, but the majority of Soviet amphibious ACVs are military. The *Ekranolet* has been developed in such secrecy as to leave no doubt concerning its military nature. This category is discussed separately in the previous chapter.

The first Soviet military amphibious ACV was a 15-ton experimental machine, powered by radial aircraft engines. It was displayed at the Leningrad Navy Day parade in 1967. Two years later the first truly modern Soviet military ACV, code-named Gus, was built. Gus was first shown publicly in 1979 and had a production period of more than ten years. This ACV (Figures 27 and 28) was powered by three TVD-IO gas turbine engines rated at 575 kW each. Two of these engines drove 3-meter diameter propellers for forward propulsion, and the third engine drove an axial lift fan in the rear body of the craft. Axial lift fans seem to have been favored by the Soviets for all of their ACVs in contrast with the British and U.S. preference for radial fans. The skirt of Gus was also interesting, in that it appeared to be a copy of the British Hovercraft Corporation bag-and-finger design. Used primarily by the Naval Infantry (the Soviet equivalent of the U.S. Marines), *Gus* performed riverine patrol, small unit troop insertions, and amphibious assault, carrying a platoon of troops at speeds up to 50 knots. It was a competent machine, but suffered a number of teething problems, The most serious appeared to be related to engine air filtration. Simple banks of mesh barrier filters were used in the first versions; later versions used a conduit running to the plenum chamber to collect partially prefiltered air as is done in some types of British craft. The number of filtration schemes tried has appeared to be almost as large as the number of craft.

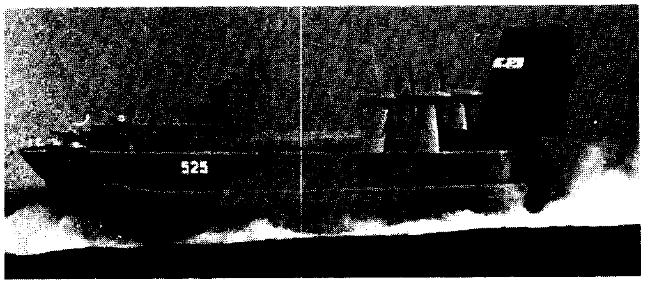


Figure 29. *Aist* Underway in Baltic Exercise.

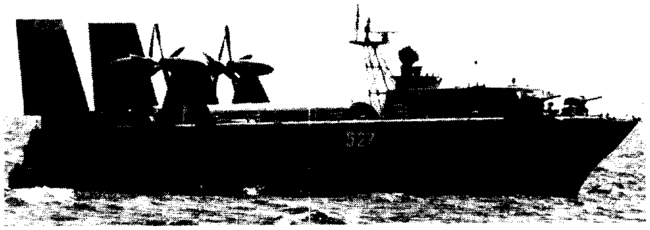


Figure 30. *Aist* Anchored in Baltic Off East Germany.

Soon after Gus, a second, much larger, machine appeared called *Aist. Aist* (Figures 29 and 30) is almost 48 meters long, 17 meters wide, and at the time of its launch in 1970, was the largest self-propelled ACV in the world. It weighs about 270 tons with a 100- to 120-ton payload and a full length roll-on, roll-off well deck. Its propulsion arrangement is unusual. Four 6-meter diameter propellers are mounted in front of two large aerodynamic rudders. Each propeller is mounted on an A-frame pylon. The propellers are contrarotating and are arranged in tandem pairs. *Aist* is armed with a pair of radar directed, general-purpose, twin 30-mm gun turrets for defensive armament. *Aist* has two gas turbine engines, each driving a pair of axial lift fans, and a pair of propellers. It is believed to use the NK-12 gas turbine used on the TU-114 and AN-22 transports at a power rating somewhat less than the aircraft rating of 9000 kW (possibly 7500 kW each) giving a maximum forward speed of approximately

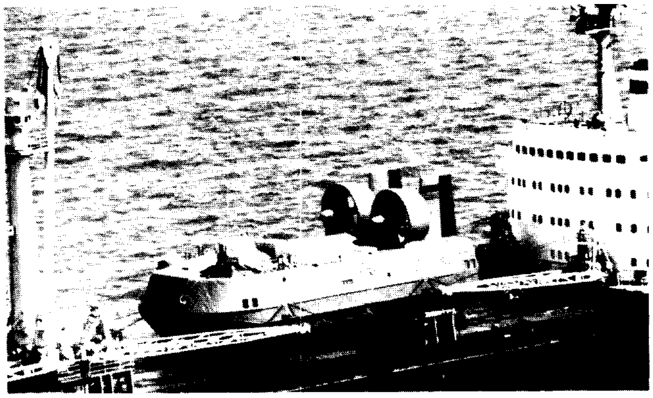


Figure 31. *Lebed* as Deck Cargo. It is Also Compatible with Some LASH Ships.

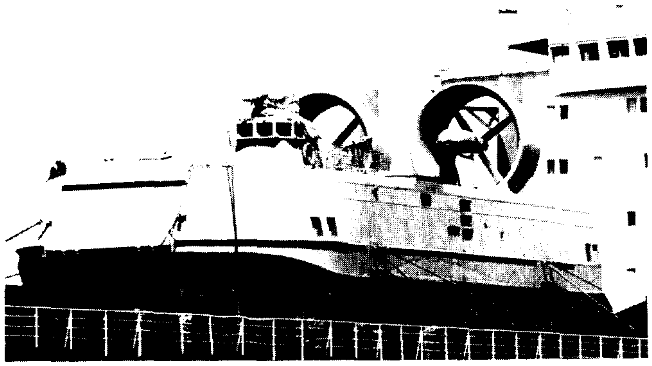


Figure 32. Lebed Being Shipped as Deck Cargo.

Aist Class
(Est.)

Length(m)	4X
Width (m)	17
Powerplant:	
kW	7500?
Type	NK-12 gas turbine
No.	2
Payload (kg)	100.000-200.000 ?
Maximum weight (kg)	270,000 ?
Maximum speed (knots)	70 ?

Lebed Class
(Est.)

Length (m)	25
Width (m)	II
Powerplant:	
Type	gas turbine
No.	*2*
Payload (kg)	45-50,000 ?
Maximum weight (kg)	120.000 ?
Maximum speed (knots)	60-70 ?

60 knots. Hull construction appears to be conventional shipyard work with virtually no aircraft-type construction. Welded plate (probably marine aluminum alloy) is used extensively.

Published material has given a list of various interior areas and amenities in *Aist* which include: a command or conning cabin in which the captain actually handles the flight controls (this is the only "ship" in the Soviet Navy in which this is the case), a full-length vehicle bay for two tanks or four armored personnel carriers, troop compartments on each side of the vehicle bay, crew areas with bunks and a galley, two engine rooms, and an engineer's control room. The press has also described a simulator to aid in training operators and crew for this type of vehicle.

Similar press material describes the advantages of air cushion assault to include a dramatic decrease in the time the craft is exposed to enemy fire (half an hour for a normal landing craft, compared to a few minutes for an ACV), and the ACV's ability to penetrate inland "beyond the enemy's first line of defense."

The latest major unit of ACVs to be built by the Soviet military is the *Lebed* class (Figures 31 and 32). The *Lebed* is approximately 11 meters wide and 25 meters long. It has a full-length central well deck, 4.8 meters wide, plus a bow ramp for vehicle access. Lift is provided by two axial lift fans mounted on the side decks. The propulsion units consist of two 3.6-meter-diameter ducted propellers, mounted aft, one on each side. Behind each is a large aerodynamic rudder. With two large rudders, puff ports, and differential propeller-pitch, control of this craft should be very good. It should also be efficient, compared with most Soviet ACVs, and relatively quiet. The payload for the *Lebed* class is probably in the area of 45 to 50 tons, making it capable of carrying all major Soviet group equipment including tanks in an over-the-beach assault role. Most of *Lebed* appears to be of riveted construction as opposed to the *Aist* which is welded. The center well deck is covered, having only personnel doors on the rear. The skirt on the *Lebed* is a bag-and-finger design which appears identical to British Hovercraft Corporation designs including the piano-hinge hangers and bolt fasteners.

The *Lebed* has been observed operating from the flooded well deck of the new amphibious warfare ship the *Ivan Rogov* (Figure 33). The *Rogov* carries a number of general purpose helicopters in addition to troops and armored vehicles.

The potential for Soviet amphibious logistics was recently increased with the purchase from Wartsila of Fin-

Figure 33. *Ivan Rogov* Amphibious Warfare Ship Showing Two Lebed Emerging from Well Deck.

land of a large number of 40-ton-payload air cushion barges. The Soviets bought a number of icebreaking cargo ships from the Finns for use in the Far North, and each is being delivered with an air cushion barge for cargo handling in areas without port facilities or over ice. As most Soviet cargo ships are built to handle military cargo (high deck loads, etc.), it may be assumed that, in wartime, the cargo ship/air cushion barge combination could significantly aid them in logistics over-the-shore operations (LOTS).

For a country that disbanded its marines after World War II, and until a few years ago had no amphibious capability other than in the enclosed waters of the Baltic. the addition of the *Rogov* is quite a change. To be sure, one unit of this class will not alter the world balance of power, but the technology is clearly there. So too is the momentum.

The Soviet military has shown three basic applications of their ACVs:

1) Riverine and coastal patrol with insertion of small troop units. This involves the Gus class.
2) Amphibious assault to secure the narrow routes of egress from their naval bases such as the strategic Danish Straits and the Dardanelles. This involves the use of the *Aisr* class. which has a reasonable range, but cannot be transported by a mother ship.
3) And lastly. offensive amphibious assault on a highly mobile worldwide basis using their naval infantry as the tool of their foreign policy. This involves the *Lebed* class in conjunction with the *Ivan Rogov class of* amphibious warfare ships.

The primary operating areas for the Soviet Naval Infantry ACV forces are on the Baltic. the Black Sea, in the Soviet Far East, and in the Far North.

Since 1977, the Soviets have had yearly exercises in the Baltic Sea emphasizing larger and larger numbers of air cushion vehicles for mechanized assault. Early tactics simply used the ACVs for flanking movements; however, more recent years have seen more and more use for frontal assault. All three classes of vehicles have been used in these exercises.

The introduction of three classes of ACV into their amphibious inventory has given them an unmatched capability to land men, weapons. and cargo at speeds unheard of in amphibious warfare. While it is obvious that we in the West have the technology to produce such craft, the Soviets have applied their technology to field the largest, most effective military ACV force in the world.

MINE WARFARE CRAFT

The contemporary inventory of mines is broadly divided under two main headings: the moored mine, secured to a sinker by a length of wire, and the ground or bottom mine, which lies on the seabed until triggered. Mining is relatively cheap and the stock of conventional mines is increasing. With the more sophisticated mines of the future an efficient, reliable, and safe method of dealing with this threat must be found.

Conventional mine warfare vessels are always at risk. Protective measures are expensive, limited in effect, and require frequent monitoring. The amphibious ACV, however, offers the following advantages:

a) ACVs have high transit speeds. This, in addition to other obvious advantages, enables the crew to live ashore and the craft to operate with a much reduced crew.
b) ACVs can cross underwater and shore obstacles.
c) ACVs, by virtue of their air cushion, are virtually immune to underwater explosions as shown by tests against British and United States manned and unmanned ACVs.
d) ACVs have been shown to have inherently low underwater signatures. (magnetic, acoustic, and pressure) and are, thus, unlikely to explode mines. Furthermore, these signatures do not require constant monitoring as do those of ships.
e) Appropriate existing ACV designs can carry. deploy, and operate all existing and projected mine countermeasures equipment.
f) ACVs can be readily converted to accept new equipment or to assume alternative roles because they have large unobstructed working areas generally all on one level.
g) The capital cost of a mine hunting ACV can be up to 50 percent less than that of a conventional vessel.
h) ACVs have the ability to operate from shore bases/beaches, and, if required, to provide a high delivery rate of men, material, and vehicles with the ability to disembark over land.
i) ACVs have low IR and radar signatures.
j) ACVs have the ability to operate from specialist warships and adopted merchant ships.

In addition, trials have proved conclusively that ACVs are substantially more controllable than ships, and are able to make a precise turn much closer to the mine. As a result, the ACV can reduce the ship's normal classification safety range by up to 75 percent making the classification task much easier, particularly when several targets require investigation.

The BH7 Mk.2 Minehunter

The Royal Navy's BH7 Mk.2, is a 60-ton, fully-amphibious ACV about *2.5* meters long, powered by a Rolls-Royce Marine Proteus gas turbine with a maximum rated power of 4500 SHP.

In 1980 British Hovercraft Corporation and Plessey Marine undertook an MCM air cushion vehicle evaluation trial for the U.K. Ministry of Defense. The objective of the trial was to determine the suitability of an ACV as an operational platform for the Plessey 193M hull-mounted sonar.

Prior to this evaluation, the main areas of concern with regard to deploying a hull-mounted sonar were:

(a) The possible interference by air penetration from the craft's cushion into the sonar beam.
(b) The effect5 on the craft's acoustic signature resulting from radiated noise coupling through the transducer.

The evaluation was therefore conducted as a series of acoustic measurements to investigate the acoustic environment beneath the Royal Navy's BH7.

The test systems used on the BH7 for these trials were:

(a) The Plessey 193M sonar transducer.
(b) A standard hydrophore.
(c) A transmission loss rig, which could be positioned at any point beneath the craft to enable detailed acoustic measurements to be performed.

The results of the trials measurements established that:

(a) There was no interference from the ACV cushion.
(b) At low speeds, the transducer self-noise characteristics were similar to a shipborne system.
(c) At higher speeds, the self-noise performance was significantly better. because the craft was not subjected to turbulent water noise from a displacement hull or from stern arc propulsion noise.
(d) The self-noise became unacceptably high once the craft went into the hump speed region.

The trial identified installation siting requirements for a hull-mounted sonar and clearly demonstrated that a 193M sonar could be successfully deployed from an ACV for mine countermeasures clearance and surveillance operations.

In early 1982, British Hovercraft Corporation in conjunction with the Royal Navy, Plessey Marine, and Racal Positioning, extended their MCM investigations by equipping the BH7 Mk.2 with:

(a) a Plessey minehunting/classification sonar, 193M Mod 0
(b) a Speedscan type PMS-75. route survey system
(c) a Racal positioning navigation stack, QX1, and
(d) a Mk.20 plotting table.

All of these systems are in current operation with the Royal Navy, Speedscan being the Sonar 2048 route survey system.

The period, from commencement of design to the successful completion, by the Royal Navy, of harbor and sea acceptance trials, took only nine months. During the evaluation phase of the 193M sonar on the BH7, the equipment was found to be easy to install, with setting-to-work taking only six weeks. In that time, the equipment satisfied all the test requirements of an equivalent shipborne system. For comparison, setting-to-work of a similar ship installation takes between eight to twelve weeks. A 14-foot wide bow door gave easy access to the operational areas, and allowed equipment to be easily installed or removed. The craft operations room was situated in the center of the craft between the craft's main fore and aft internal bulkheads. The Plessey 193M sonar transducer, shielded by its dome, was lowered to its operating position by means of a large tube. In its retracted position it lay inside the craft buoyancy tank.

The minehunting trials, which were conducted in generally unfavorable weather conditions, produced a number of significant results. Utilizing the Racal high definition navigation system, with track information provided to the pilot, the ACV maintained a high degree of track keeping and hover accuracy, showing a considerable improvement over that achieved by displacement hull minehunters.

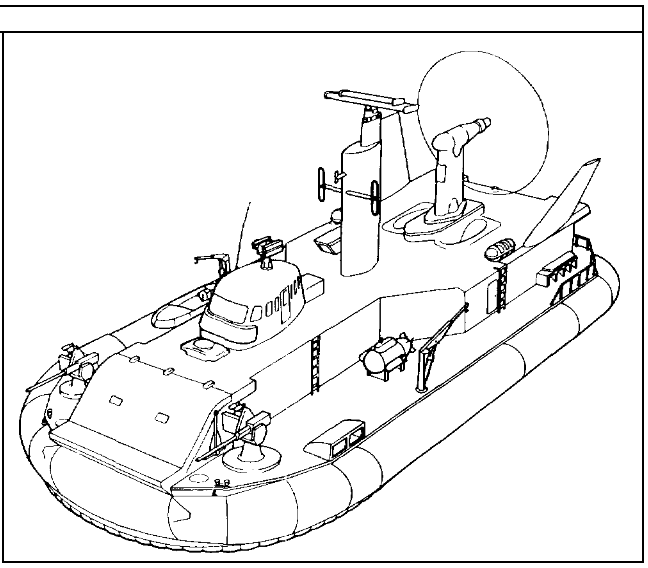


Figure 34. BH7 Mk.20 Hovercraft in Minehunting Role.

The ACV also reacted quickly and accurately to maneuvering instructions; the speed of reaction being enhanced by good maneuvering control and the fact that the pilot was directed by the mine warfare officer on the same intercom circuit as the sonar operators. The pilot, therefore. had a continuous up-to-date operational picture.

In the conventional hunting role using standard minehunting practices in the exercise minefield off Portland, the sonar installed in the ACV achieved its maximum detection and classification performance. It detected mine-like objects that it was able to classify and that were then confirmed by divers. It was noteworthy that during normal minehunting maneuvers there were no sonar blind areas (the ACV is not subjected to the stern arc propulsion noise inherent in conventional ship systems).

Several trial runs were conducted using the sonar in conjunction with Speedlscan, the route-survey equipment, and a satisfactory picture of mine-like objects on the sea bed was obtained at craft speeds up to twice those achieved by conventional MCMVs. The craft was also noise-ranged, and the underwater signature showed no degradation with the sonar tube in the water.

BH7 MK.20

The BH7 Mk.20, Figure 34, is a development design of the Royal Navy's BH7 Mk.2, and takes full advantage of the latest ACV skirt system technology.

Key features of the design are an all-up-weight in excess of 80 tons, and a Detroit Diesel Allison 570K gas turbine flat-rated to 4500 continuous SHP. This engine has a 25 percent improvement in specific fuel consumption as compared to the original Rolls Royce Proteus engine no longer in production.

The craft is also lengt'hened by five meters to increase seakeeping and payload capacity. These improvements more than double its payload carrying capability relative to the standard BH7. The waterspeed performance of the Mk.20 is four times as fast in calm conditions and twice as fast in high sea states as a conventional mine countermeasures ship. High ambient temperatures do not affect performance since the engine is powerful enough to be flat-rated regardless of intake temperature.

Internally there is ample space for an operations room, a magazine for the mine disposal weapon charges, and accommodation for the off-duty members of the crew of twenty.

Typically, for a sector 150 nm from base, the BH7 Mk.20 will have a minehunting endurance of around 12½ hours, making the total sortie time approximately 20 hours. The more lightly equipped route surveillance craft will have a time on station of between 15 and 23 hours.

In addition, the higher speeds of the ACV to perform the route surveillance or fast exploratory task, compared with the conventional MCMV, will mean that the ACV requires less time on station to complete a given task.

As an alternative to the hull-mounted sonar, channels, once surveyed and cleared, can be continuously monitored at high speeds, using a towed sidescan sonar (such as the Westinghouse AN/AQS-14) to make comparative records of the sea bed.

A further important advantage of the ACV is that it can fully utilize potentially new high speed sonars and their associated automatic data processing equipment. This results from the craft's high speed capability together with the fact that its underwater acoustic signature does not increase with increase in forward speed.

SR.N4

A mine countermeasures version of the 300-ton SR.N4 Mk.3 has also been tested. This larger craft offers enhanced seakeeping performance and endurance comparable to BH7. It can carry all existing and proposed minehunting, classification, disposal, and sweeping equipment, similar to that fitted to the Royal Navy's *Hunt* class and that proposed for the single role minehunter ships. The SR.N4 trials were successfully conducted by the Royal Navy to assess minesweeping operations, controllability and track-keeping, motion characteristics, and the measurement of underwater signatures.

Alternative Roles

Mine sweeping is also possible with BH7 Mk.20 using elements of the United States Navy Mark 103 wire, and the Mark 104 acoustic sweeps. Both of these sweeps have been towed behind BH7 by the Royal Navy. The craft can also tow, but not carry, the Mark 106 combined magnetic and acoustic sweep. When not being used in a mine countermeasure role, the Mk.20 can function equally well as a mine layer, carrying 20 mines.

Unlike conventional ships, ACVs can be readily converted to other roles as circumstances demand. Roles such as fast attack and logistic support are facilitated by the ACV's spacious, single level, unrestricted working area and by the ability to fit the equipment and accommodation in self-contained modules, installed or removed through the craft's large bow door.

Both the BH7 and the SR.N4 have clearly demonstrated the advantages to be gained in using ACVs in the mine countermeasures roles. Similar successful work conducted in the United States, using the AALC *Jeff(A)* and *Jeff(B)*, adds further confirmation to the fact that ACVs can provide an important contribution to this increasingly important mission area.

ARCTIC OPERATIONS WITH *JEFF(A)*

For almost twenty years, air cushion vehicles (ACVs) have operated in the cold (climate environments of Northern Europe and North America. From the St. Lawrence River to the Beaufort Sea, the North American cold climate experience has included approximately 6000 hours of operations over land, as well as on ice and in open water. From this experience many lessons have been learned.

North American experience with ACVs in cold climates has been achieved with a variety of vehicles including SK-5, SR.N5, SR.N6, *Voyageur*, LACV-30, *Mackace*, ACT-100, hoverlift craft, CC-7, *Jeff(A)*, and others. Northern European operations have been less quantified, but notable among them are the operations of the BH-7 in Sweden and the PUC-22 *Larus* in Finland. Adding to the total would: be the Russian experience. A large percentage of the total North American operating hours have been spent gathering design data or demonstrating the suitability of ACVs to perform given transport or logistics tasks. 'Technical feasibility for ACV operation in cold regions has been amply demonstrated. Almost all the ACVs used for transport demonstration were capable of operating in temperatures of -40°F, and of carrying heavy loads over snow-covered ice and terrain inaccessible to other types of surface transport.

Arctic environmental characteristics have a major impact on craft design and operation. Terrain and weather, including temperature, visibility, wind, and precipitation, affect air cushion vehicle operation. ACVs, in return. have an impact on the environment, affecting vegetation and terrain, birds, mammals, and fish. The latter categories are statutory in nature, and, based on the relatively small amount of data available. are all minimally impacted by ACVs.

While not completely representative of all cold climate operating regions, the American and Canadian Beaufort Sea region possesses most of the salient features that characterize the Arctic. In winter, most Beaufort Sea coastal weather stations report easterly winds with an average velocity of about 10-14 knots. Winds of 30-50 knots are common in winter, and winds well over 100 knots have been recorded, with the highest wind speeds coming from the west.

Temperatures in the Beaufort coastal area are fairly constant within seasons. In summer, the typical range is from 30 to 48°F, with a maximum of 75°F. In winter, the typical range is from −24 to −6°F, with a minimum of 49°F.

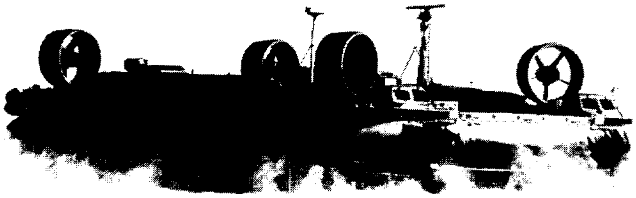


Figure 35. *Jeff(A)* at Prudboe Bay.

Winds superimposed on these low temperatures produce wind chill temperatures consistently below the danger zone for personnel working outdoors. The danger zone (in which exposed flesh may freeze within one minute) is considered to be when equivalent wind-chill temperatures are below – 20°F.

The average annual precipitation of the Beaufort Sea coastal area is only five inches, with most of the precipitation along the North Slope coastline falling as rain, primarily in July and August. Snow typically covers the ground from October through May. but it can fall during any month of the year. The average annual snowfall is about three feet or less.

Surface contour, both onshore and offshore. also impacts the operation of ACVs in a cold climate. On shore, in regions contiguous to the Beaufort Sea, the tundra tends to have relatively gentle slopes, but long grasses, hummocks, sharp cuts, deep pits, and river areas present obstacles to ACV navigation. Ice, with rubble fields and ridges, makes circumnavigation an absolute must. Rubble piles, especially around shore, and natural or man-made islands can reach heights of thirty to forty feet. Ice ridges. vertical extrusions of ice formed by the compressive force of large ice sheets moving together, are another obstacle to be overcome in the Arctic. Navigation around or through holes punched in ridges is the only route available, forcing ACV point-to-point navigation to follow the path of least resistance.

In the Arctic, visibility over ice is often seriously limited. Fog, ice fog, and wind-blown powdered snow can produce zero visibility. Darkness can be a factor with or without these conditions. High intensity lighting and navigation systems that improve visibility are essential. For fixed routes, navigational grids can be established and these have been found to be very effective.

The most recent Arctic operating experience of any duration has been achieved by *Jeff(A)*, a U. S Navy ACV. leased by RMI, Inc., and time chartered to Sohio Alaska Petroleum Company. The purpose of the operation was both to provide ACV design engineering data and to provide logistics support for offshore drilling operations in the Beaufort Sea. The craft was winterized by RMI at Prudhoe Bay, Alaska, through the incorporation of 36 engineering changes primarily oriented at incorporating heating or insulation on critical craft systems. The operating term began November 1, 1983, and was completed July 5, 1984. Three engineering test series (one in November, one in March and one in July '84) were directed at gathering craft performance data-maneuvering, ridge crossing ability, drag and thrust, ice-breaking and towing capability, above- and below-ice acoustic characteristics, and transit over broken ice.

Table 2. *Jeff(A)* **Arctic Program Fact Sheet.**

PROGRAM	MILESTONES
1 June 1983	*Jeff(A)* Leased from U.S. Navy by RMI and Time Chartered to SAPC.
16 August 1983	RMI Winterization of *Jeff(A)* Begins.
5 November 1983	*Jeff(A)* Arctic Test Program Begins.
7 December 1983	First Run to Mukluk Island.
11 January 1984	RMI Arctic Cargo Service for SAPC Begins
8 February 1984	Total Cargo Carried by *Jeff(A)* Exceeds One Million Pounds.
13 February 1984	*Jeff(A)* Accomplishes Single Lift of 102 Tons.
21 February 1984	Two Runs to Mukluk Island-294,000 Pounds of Total Cargo.
21 March 1984	Mid-Winter Test Program Begins.
14 April 1984	*Jeff(A)* Spring Lay-Up Begins.
30 June 1984	Break-up- Period Demonstration Begins.
4 July 1984	First Third-Party Charter Cargo Run.
6 July 1984	Preparation for Return Shipment to Navy

The *Jeff(A)* experience combined the requisite elements of successful Arctic programs: facilities, personnel. and equipment. Figure 35 shows the craft in flight over the ice in Prudhoe Bay.

Prior to and during craft modification, an operational base camp was established at East Dock in Prudhoe Bay. The base camp consisted of a 160' x 80' hangar. a 2000 square foot maintenance building, an office structure, and diesel-fueled electrical generators and heaters for all buildings. Adjacent to the *Jeff(A)* operating camp was Sohio's East Dock Exploration Camp, which provided housing for the operating crew. The work environment provided by the camp was extremely good. A heated work area large enough to house the entire craft allowed maintenance and craft modifications to be carried out effectively. Access to the machinery spaces would have been difficult without a shirtsleeve environment. Whereas it appears that previous programs operated essentially without the heated shelter, maintenance effectiveness was substantially improved, and complex systems were more easily worked on.

Table 2 lists the *Jeff(A)* Arctic program milestones and operational highlights:

In January of 1984, *Jeff(A)* initiated cargo service in support of Sohio's Mukluk Island drilling activity. The base of operation was Milne Point on the southeastern end of Harrison Bay in Alaska. A number of round trips were made to Mukluk Island hauling a variety of cargo such as cranes, trucks, backhoes, portable buildings, drilling pipe, and drilling mud. Each of the loads presented loading and unloading problems, but, with the use of bow and stern ramps and the over-the-side crane loading all the cargo, up to 1.75M pounds was handled with only modest start-up problems. Utilization of "Micro-Lan" laminated planking for dunnage enhanced craft deck loading and minimized damage resulting from handling of skid-mounted loads. ACVs in Arctic service, to be compatible with the established logistics base, need to accomodate both crane and RO-RO cargo-handling methods.

The track to Mukluk Island was an "L" shaped route to minimize transit over rubble and, therefore, enhance transit time. The 41.7 n. mile route was marked with radar and light reflective markers. Each of the Firth-style fiberglass markers was mounted on a twenty-foot high aluminum tripod. The installed height of the radar reflectors protected them from curious polar bears and enhanced visibility. Despite this precaution, several were lost. Because of the ease of detection either with radar or by use of high intensity spotlights, trail following was quite readily accomplished, except in periods of poor visibility. An alternative navigation system was also used. A prepositioned six-tower microwave system. customarily used for precise navigation and survey work, was adapted to track the craft at the relatively high rate of speed, and to display on a monitor, craft position, speed, and bearing. The system, though limited in range, proved very effective both as a primary or back-up navigation method. Because of low temperatures, buildup of static electricity, and localized magnetic anomalies, it was virtually impossible to keep the radars (two on the craft), Syledis navigation system, and compass working all the time. The lesson from this is to design in navigational redundancy for craft anticipated to perform in the Arctic during winter periods. Because of location, Sat-Nav and Loran-C did not provide adequate coverage.

In addition to having a marked effect on navigational gear, temperature and build-up of static electricity tended to have a severe impact on all the electrical and electronic equipment on the craft: power conversion apparatus, computer-based data logging equipment, electronic fuel controls, and communication gear were all disabled at one time or another. Diligent grounding for electronic equipment, use of antistatic mats, addition of wick-type static discharges attached to craft structure exterior, and use of grounding chains attached to the understructure all helped to alleviate the static build-up problems.

Communications were still somewhat problematical for similar reasons due to difficulties encountered with other electronic gear. Back-up communication equipment is a must. Good antenna function, power output, and frequency control enhance communications.

Little has to be done in the way of material substitution aside from adjustments in viscosity properties of various fuels and lubricants; changes in elastomeric material composition for applications such as "O" rings, gaskets, etc.; attention to control of heat rejection; and the craft skirt system. Insofar as the elastomers are concerned, increasing low temperature ductility is the overriding consideration. The skirt system especially benefits from being fabricated of natural rubber. Ozone present in the Arctic aggravates the material in the long-term, but the flexibility of natural rubber, even at cold temperatures, increases life adequately to overcome this problem. Skirt damage, not wear, is the largest cost factor. Skirt system designs that mitigate snagging and facilitate repair or replacement, even at low temperatures when elastomeric materials tend to be stiff, are a distinct requirement for Arctic operation.

The aluminum structrue of *Jeff(A)* performed extremely well, handling the heaviest of transported loads (102 tons) without much difficulty. The only metallic material difficulties arose from bolting materials, where the ductility was reduced at the low operating temperatures and bolts failed. Once the engine fuel control and operating problems were solved and one set of power-turbine bearings were replaced on the Avco-Lycoming TF-40 engine, the engine performed very well. Because of the very low ambient temperature, the engine delivered substantial power even at low throttle settings. This situation and the tendency to run at very high craft speeds led to a control system change which allowed the propeller-blade pitch to be selected at any power-turbine speed instead of the two parameters being coupled. This resulted in running at lower power-turbine speed over a range of blade angles and in reducing craft speed and fuel flow.

Propeller problems in the area of failed shear pins were attributed to engine overslhoot difficulties related to malfunctioning fuel control. These problems were readily cured once operational fuel controls were obtained and installed. Propeller seal problems were straightened out once proper parts were available. Ice buildup as a consequence of ice skidding was not a problem.

The overall Arctic performance of a more than seven year old craft, the Jeff(A), originally designed to run in southerly climates. was truly commendable, especially since relatively few cold weather modifications had to be made. With a strong, structural foundation and the developed wisdom of keeping things warm (or at least not letting them get really cold), with the use of compliant or low viscosity materials at the operating temperature and the contending to a draw with static electricity buildups, craft performance became more than satisfactory. Clearly, the ACV is a viable transport alternative in the Arctic.

ARCTIC APPLICATIONS

Arctic missions for amphibious ACVs are a totally logical and natural application of available technology. Although this fact is generally recognized. to date there has not been a commensurate requirement in the Arctic region. However, acceptance of an Arctic ACV concept may be imminent because of recent changes in U.S. policy.

Several types of vehicle or platform can perform Arctic operations including aircraft and surface vehicles. Each of these classes of vehicle is faced with the difficult environmental problems due to extremely cold temperatures, ice, high winds, and low visibility. Some environmental problems are unique for each type of vehicle, and must be solved individually, while for other problems, a more generic solution will serve all equally well. Additionally, it is desirable that all vehicles that operate in the Arctic be capable of operating both independently as well as in coordination with each other.

The operational flexibility of most types of platform in the Arctic region is limited.

Aircraft. for example, are severely constrained by the environment in the Arctic. Basing in cold regions, low visibility, and navigation anomalies all tend to reduce their effectiveness.

Of all available surface platforms, ACVs have the greatest potential for success in the Arctic. Experience with ACVs has shown that, besides their capability to operate over a wide variety of surfaces (water, land, swamp, ice, tundra, etc). their low footprint pressures permit them to operate with minimal adverse effect on the environment. They can hover at low speed, loiter, float. or operate at high speed. They have been shown to have a high payload fraction, a low underwater acoustic signature, and low pressure and magnetic signatures. A recent study indicates that ACVs may provide an excellent platform for any or all of the following generalized roles and tasks that may need to be accomplished in the Arctic region:

- SAR: Search and rescue operations.
- Support: Provide logistic support. Support ice camp operations.
- Defense: Conduct limited self-defense.
- Other: Perform hydrographic surveys and environmental monitoring.

While all of the above generalized roles are feasible and realistic, the most probable near-term opportunities will involve ACVs in support operations in the Arctic. The tempo of activity in the Arctic is increasing, however, adequate support for these operations is still not readily available or easily provided. It is this area of Arctic support operations that ACVs may be most immediately suited and cost effective.

OTHER ARCTIC MISSIONS

Surveying

ACVs could be used to survey ice characteristics. Ice thickness surveys could be effectively and efficiently conducted by ACVs. Iceberg characteristics could also be surveyed by ACVs. ACV surveys could also identify hummocks that might interfere with operations, especially in shallow water. The location of such hazards would be very useful for routing and optimizing operations in the region. The endurance of ACVs coupled with their low footprint pressure, high maneuverability, and ability to loiter and/or set down (to take measurements or samples) makes them ideally suitable for this role.

Navigational Aid Deployment

ACVs could be directed to specific locations to implant transponders or other navigational aids or devices. ACVs could preposition the navigational aids and retrieve them after the assignment.

Search and Rescue

A vehicle experiencing difficulty while operating in the Arctic can hope for little if any assistance today. ACVs operating in the Arctic could provide valuable and much needed support and emergency assistance. The capability and flexibility of an ACV's payload is such that it could be readily fitted out with the means for locating and assisting a vehicle in distress, including the capability to rescue the crew.

Ice Camp Support

ACVs are a natural choice as the vehicle to support Arctic ice camps. The United States has experience with ice camps varying in size from three to almost 100 individuals. Ice camps can operate at the same location for short intervals of just several hours or for extended periods of a year or more. Ice camps are typically set up by airlifting people and equipment by helicopter or fixed-wing aircraft. Requirements for landing strip preparation, ice thickness, surface conditions, and environmental constraints on flight operations (light, visibility, wind, icing, etc.) can severely restrict camp deployment, resupply, disassembly, and backhaul. Since 2/3 to 314 of the 4000 pounds per person typically deployed to a scientific ice camp is backhauled, the availability of a fulltime logistics ACV would significantly increase the flexibility and efficiency of these activities. ACVs supporting such operations could operate from, or between, ice camps which are logistically autonomous because of the ACVs.

ACVs have a place both in near term and in long range Arctic roles. The Arctic operational area encompasses 3.9 million square miles of land, tundra, open water, ice and marginal ice, all of which are natural operating environments for ACVs (Figure 36). In recent studies, three basic options were considered in evaluating the utility of ACVs to demonstrate their effectiveness under various Arctic conditions. These are summarized in Table 3.

One option involves the use of a number of "Small ACVs and Fixed Support Sites." This option required about 20 small ACVs. Supporting this operation would be 20 to 30 fixed-maintenance and replenishment sites. The advantage of using a small ACV with fixed support sites is that this could build upon proven technology and performance, thus allowing for a rapid introduction with little technical risk. The main disadvantages of this approach are that it calls for the use of less than optimal

Table 3. Alternative Arctic Hovercraft Concepts.

OPERATIONAL HIGHLIGHTS	
Cumulative Operating Time (1 November-5 July)	305 hours
Cumulative Cargo Carried (I November-5 July)	I ,820,000 pounds
Heaviest Single Load	102 tons
Craft Operational Availability (1 January-5 July	90 percent
Highest Sustained Operating Speed	SO knots
Shortest One-Way Transit Time to Mukluk (41.7 N.Miles)	I hour 17 min.
Shortest Round-Trip Transit Time to Mukluk (83.4 N.Miles)	2 hours 41 min.

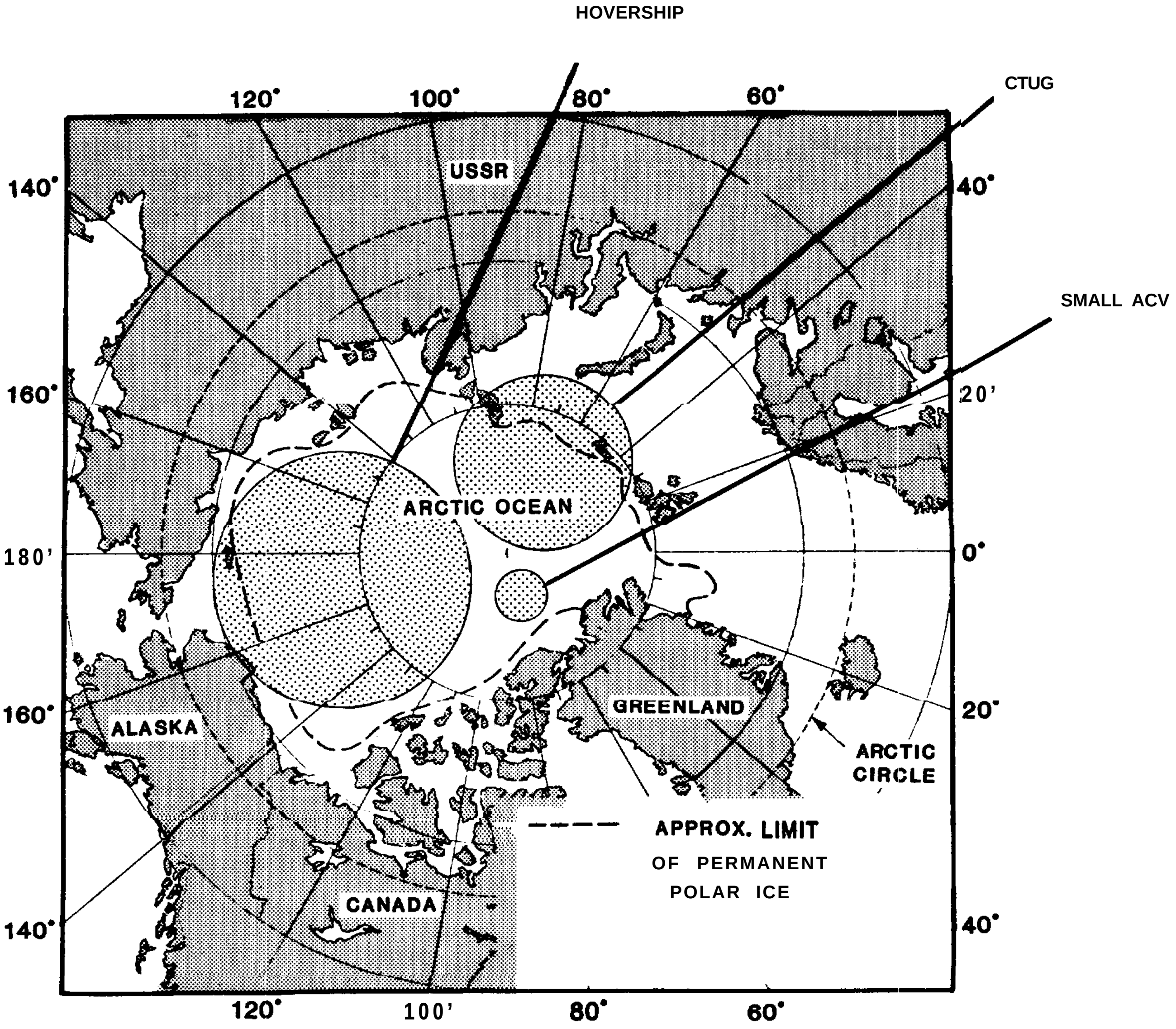


Figure 36. Arctic Hovercraft Operational Area.

Arctic ACVs and a large number of units, support sites, and personnel.

A second option for the use of ACVs in Arctic operations involves the use of about eight "Large Arctic Hoverships." These large ships would be self-supporting over a 30-day cycle and would require only a home port. The large Arctic hovership concept was derived from work done in the early 1970s under the Arctic SEV program. The advantage of this approach is that a new, fully capable, Arctic hovership would be designed, developed, and placed in service to meet specific planned and projected Arctic needs. The disadvantages of using large Arctic hoverships are their costs, their long development cycle, and the risks associated with a new design of a large ACV.

A third and more balanced approach involves what was termed "Ctug and Hoverbarges." First envisioned and postulated by James Schuler, this innovative concept envisions the use of ACVs for both mobile basing and operational units. Approximately eight medium-sized, Arctic-configured, multipurpose ACVs (Ctugs) would be required to adequately cover the Arctic region with 16 to 24 multipurpose air cushion barges (hoverbarges). The Ctug is an operational platform that also has the capability to tow hoverbarges to selected operating sites. The hoverbarges act as local operating bases providing the support required by the Ctugs in the field. (Figure 37).

The Ctug/hoverbarge concept has been investigated and found to be feasible and attractive from a theoretical performance point of view (Figure 38). The coupling of the hoverbarge to the Ctug effectively provides a high length-to-beam vehicle suitable for lower speed and long endurance, while the uncoupled Ctug is a more suitable platform for higher speed operations.

The use of Ctugs and hoverbarges to support Arctic assignments builds upon proven operations and hovercraft technology. It eliminates the need for fixed-support

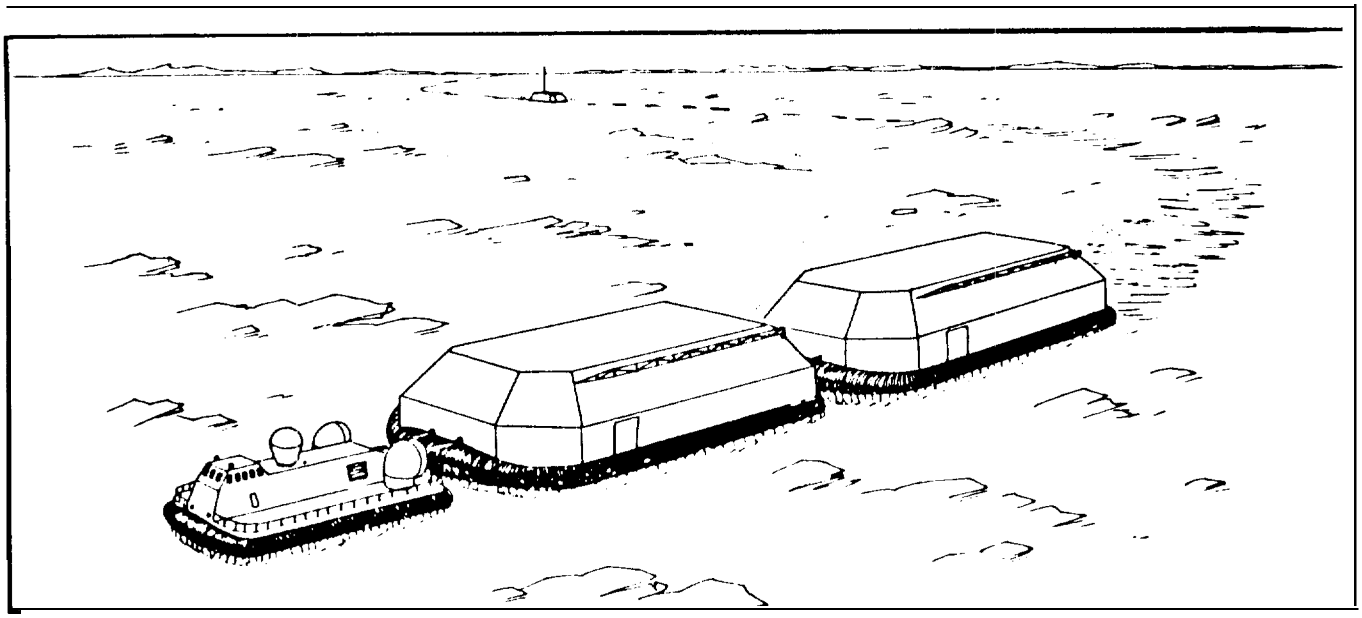


Figure 37. Ctug and Hoverbarges.

bases, and provides a highly mobile and flexible system. The risks and costs of its development and deployment are minimal. The disadvantage of the Ctug and hoverbarge approach is that it is less independent than the full mission capabilities available in a large Arctic hovership. The Ctug and hoverbarge concept also involves somewhat more complexity (and thus risk) than that associated with the use of many small hovercraft and fixed support sites.

The U.S. Government can be expected to use R&D as necessary to explore current and projected Arctic requirements. ACVs will be required to operate for extended periods of time over smooth and rough ice, open water, and tundra. Once the unique match between technical "push" and operational "pull" of ACVs is recognized, the technical feasibility and utility inherent in this approach is certain to make Arctic ACVs a reality.

CANADIAN COAST GUARD CRAFT

Conscientious mariners spend lifetimes staying well away from areas where the ACV excels. The fundamental benefit of the ACV is its ability to function at greatest efficiency in areas where vessels are endangered. Normal vessels are limited to navigable waters-the ACV achieves optimum performance in mudflats, shoal water, cliff areas, high currents, whirlpools, and ice-affected channels.

Canadian Coast Guard ACVs have been operating for the past fifteen years in these environments, and have accumulated many thousands of operating hours. Over five thousand SAR operations have been successfully completed and the operational crews are convinced that the ACV is the ideal vehicle for many jobs in coastal waters.

The ACV uses radar as a complete navigation system and derives maximum safe benefit from good radar operation. The ACV and radar are totally compatible. Radar indicates where an ACV can safely operate since below surface obstacles do not affect the amphibious vehicle. Night operations pose no unusual problems to trained crews, and full speeds are maintained in darkness.

Speeds in excess of fifty knots are routinely achieved, and high block speeds result in large areas of search coverage within a given tirne; an ACV can cover an area approximately ten times larger than a vessel of fifteen knots. This capability is extremely valuable because greater benefit is derived from skilled personnel, such as medical or dive teams, and levels of service for given areas are sustained at less cost.

The multitasking of coast guard ACVs allows work to be done without the use of specialized equipment. The search and rescue (SAR) commitment is not compromised when work is carried out on beacons, buoys, and lightstations, and the SAR crews benefit from increased operational exposure. Roles such as vessel inspections, fishery patrols. pollution prevention and cleanup, surveying, and surveillance are all easily handled by ACVs. At all times, in event of SAR requirement, the operational flexibility of the vehicle ensures quick response to the incident.

Adverse weather conditions affect speeds to the point where fifty knot winds and ten-foot seas reduce full-power speeds to an average of approximately fifteen knots. However, crews have found that, during heavy weather, greater speeds and more comfortable rides are achieved by staying in shallows. or within the surf line where the location of the SAR incident permits such transits to be made.

Maintenance of an ACV group can best be carried out at a centralized facility, and, with a properly organized program, high serviceability and reliability factors are realized. Breakdowns have been few and far between. Routine defects are promptly resolved. Regular maintenance checks are scheduled, and each vehicle requires approximately six weeks of dedicated refit for each operational year.

Substations can be easily created since no docks or moorage are required. An ACV SAR substation has been

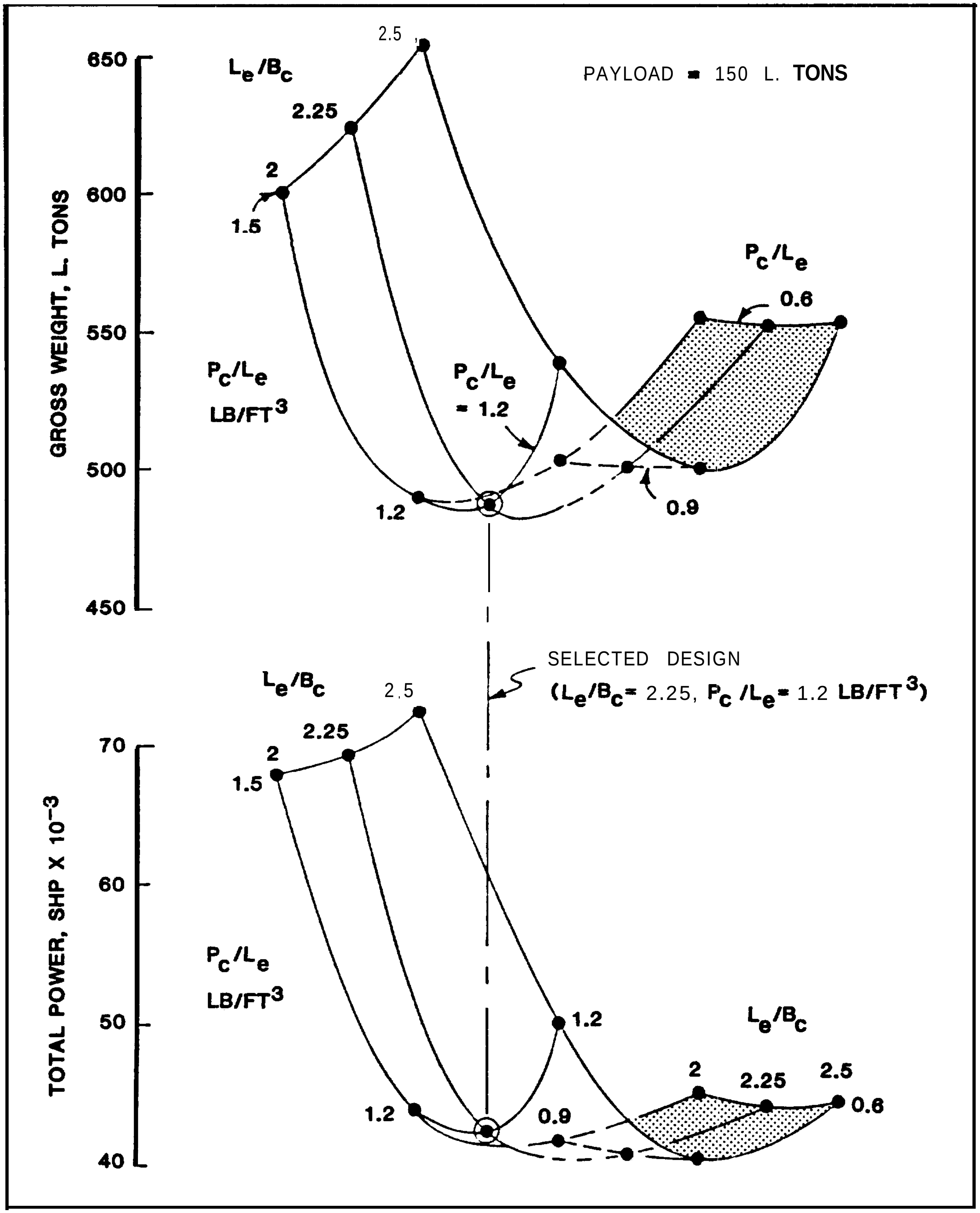


Figure 38. Parametric Design Study Results for Ctug.

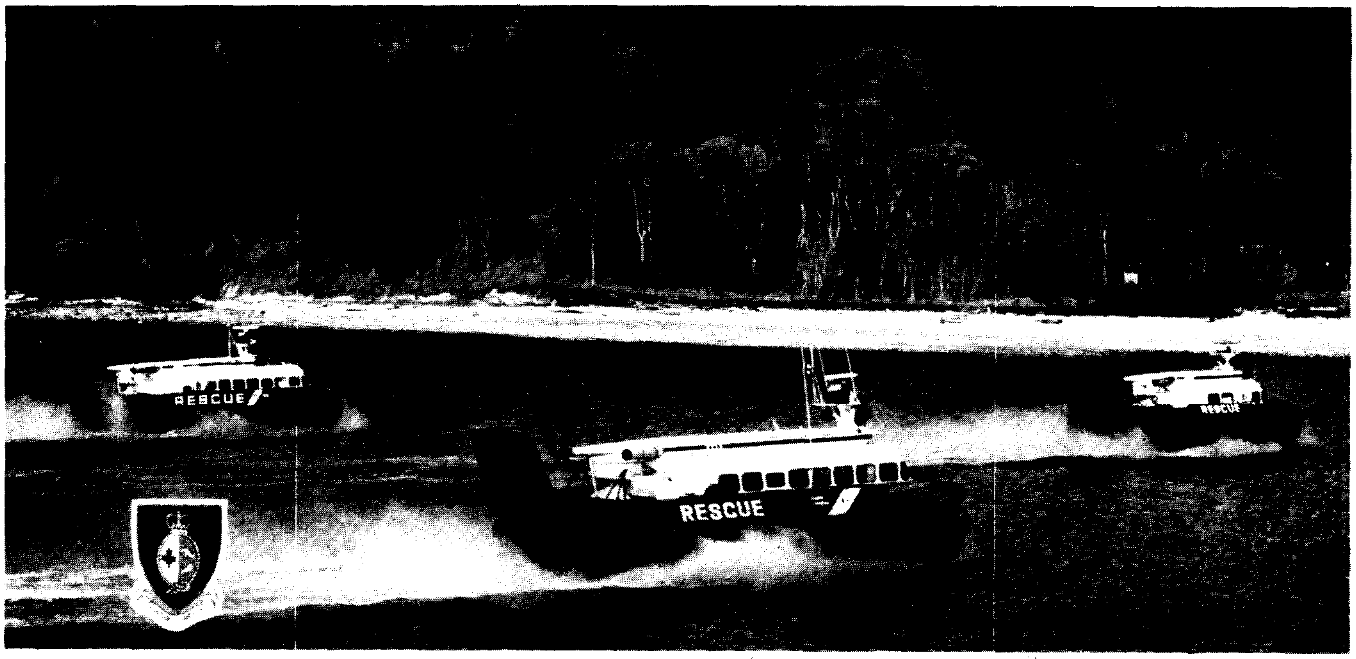


Figure 39. Canadian Coast Guard West Coast SR.N5 and SR.N6 ACVs.

installed in Parksville. B.C. with the basic requirements being a trailer, concrete pad. fuel bay, and telephone. The vehicle dedicated to the substation returns to the central facility for skirt inspection and engine checks once every two months.

The icing on the cake for the users of this versatile vehicle materialized when it was discovered that the ACV is a highly efficient icebreaker, with the ice in blocked harbors being broken up and cleared without ice compression damage to the hulls of fishing vessels and pleasure craft. Twelve inches of ice and above has been broken by a fifty-foot, ten-ton ACV cruising at fourteen knots.

Trials of a conventional vessel compared to an ACV indicated that greater towing power was achieved using waterscrew compared to airscrew propulsion, but the ACV could tow at higher speeds. Towing is limited as a matter of policy, yet, where towing will quickly resolve an incident, small vessels can be towed at speeds of up to thirty knots. Apart from an exhilarating ride for the pleasure craft owner, the ACV is not removed from other service for any length of time, and the incident is rapidly

Table 4. Worldwide AC'V Applications during the Year 1983.

TABLE 4

WORLD-WIDE ACV APPLICATIONS DURING THE YEAR 1983

COUNTRY	NO. CRAFT	PRINCIPAL USES
AUSTRALIA	1	AGRICULTURAL
BAHRAIN	1	COAST GUARD
CANADA	13	COAST GUARD, MILITARY, CIVIL FERRY
CHINA	3	MILITARY, CIVIL FERRY
DENMARK	2	CIVIL FERRY
EGYPT	3	COASTAL DEFENSE, PATROL & MINE LAYING
FINLAND	15	CIVIL FERRY, ARCTIC LOTS
FRANCE	4	CIVIL FERRY, ASW, COASTAL PATROL
IRAN	14	MILITARY LOGISTICS, PATROL, MISSILE BOATS
IRAQ	6	MILITARY PATROL
ISRAEL	2	MILITARY LOGISTIC SUPPORT
JAPAN	13	CIVIL FERRY
NEW ZEALAND	2	AIRCRAFT CRASH RESCUE
NIGERIA	6	HARBOR POLICE, PIRACY CONTROL, OIL EXPLORATION
PAKISTAN	2	COAST GUARD PATROL & INTERDICTION
SAUDI ARABIA	16	PATROL, CONTRABAND CONTROL, SAR
SPAIN	1	MILITARY R&D
USSR	65	AMPHIBIOUS ASSAULT k COASTAL PATROL
USSR'	1116	OIL. EXPLORATION, LOGGING, SURVEYING
UK	18	MCM, CIVIL FERRY, AIRCRAFT RECOVERY, CHARTER, FREIGHTER
USA	18	ARMY LOTS, AMPHIBOUS ASSAULT, ICE: BREAKING, OIL EXPLORATION
ZAIRE	1	MILITARY UTILITY
HOVERBARGES		

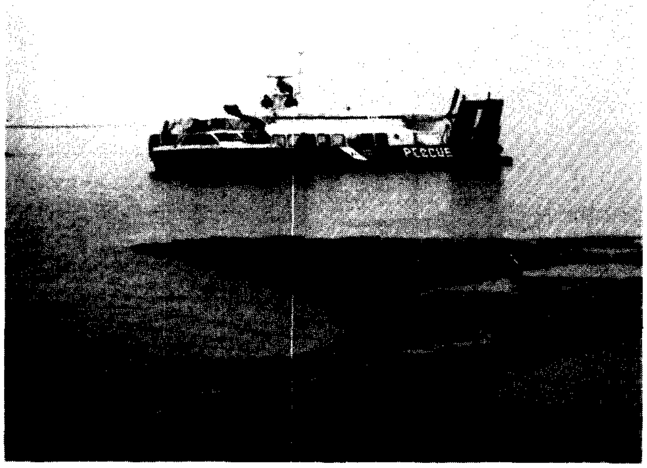


Figure 40. Shallow Water Rescue.

Figure 41. Quick Transfer Ashore.

resolved. Larger vessels up to eighty feet have been towed at speeds up to twelve knots.

Enthusiasm is often suspect; however, it has often been said that the best way to judge a vehicle is to talk to the crews. It is paradoxical that decisions are often made by people well removed from the operational scene, and unfortunate that few opportunities exist which allow observers to participate in SAR patrols on an ACV. Levels of service can be improved by using inexpensive amphibious speeds. Capabilities should not be limited by imagination, and greater efforts should be made to closely look at ACV potential in an operational role.

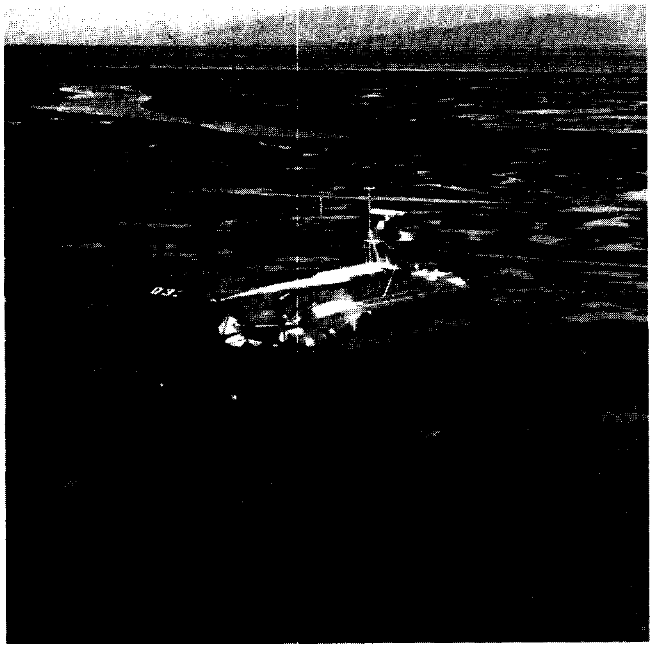


Figure 42. SR.N6 Over Mud Flats.

Figure 43. SR.N5 Tending Electric Buoy.

OTHER APPLICATIONS

Air cushion vehicles have been used over the past two decades in a very wide variety of applications in addition to those already discussed. Military and paramilitary activities have included: drug interdiction, law enforcement, logistic support, fishery protection, reconnaissance, coastal patrol, picket-boat duties, surveillance, and commando operations. Civil activities have included: casualty evacuation, flood relief, logistics, airport crash rescue, harbor support, firefighting, hydrographical, seismographical, gravity and geological surveying. postal services, and agricultural spraying operations.

At the present time, based on a review of Reference [4], there are approximately 200 large-to-medium-size ACVs in operation throughout the world providing a variety of different services. Of these at least 65 are in service with the Soviet military, 18 are in operation in the UK, 18 in the USA, 16 in Saudi Arabia, 14 in Iran and the remainder distributed among 16 other countries as shown in Table 4. In addition, there are approximately 1120 hoverbarges most of which are employed in Soviet Siberia and Afghanistan.

These applications have been particularly successful when advantage has been taken of the ACV's amphibious capability. In many of these cases. successful operations could not have been achieved in any other way. The ACV has demonstrated a capability to traverse shallows, surf, mud flats, marshes, swamps, coral reefs, estuaries, deltas, sandbars, shingle, rapids, weed or tree infested rivers. tundra, ice, and snow. No other conventional marine craft, or land vehicle, can match this. In many of these environments, water is too shallow for all but the smallest of conventional craft. while tortuous channels often make navigation difficult and journeys circuitous.

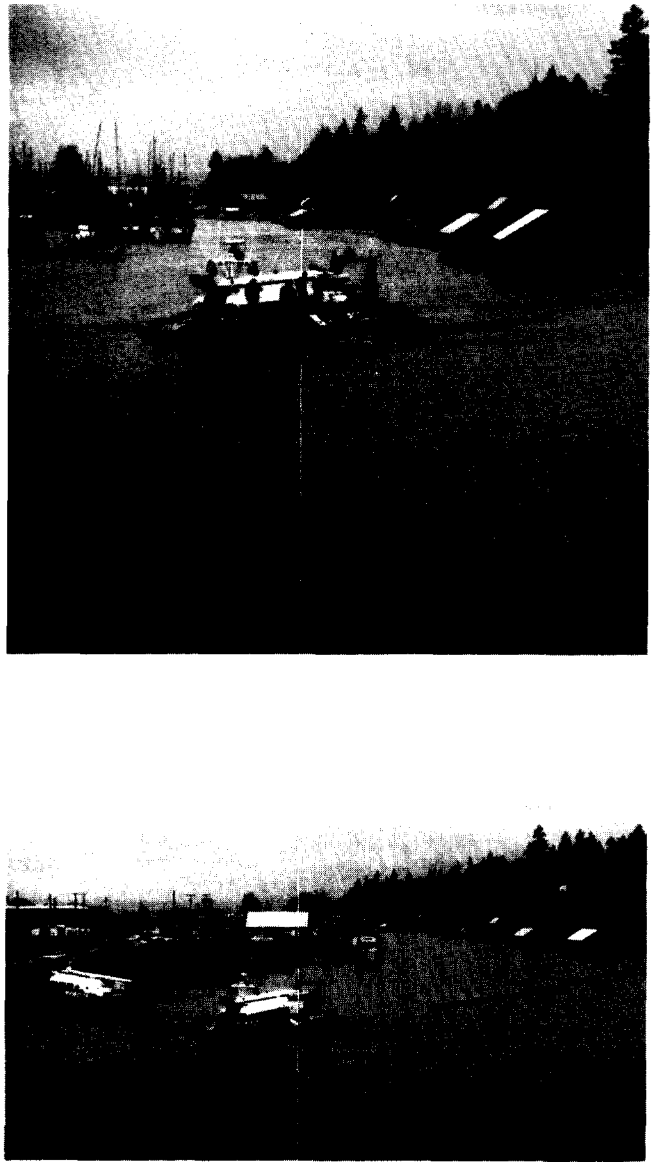


Figure 44. SR.N6 Laying Inflatable Pollution-Control Boom.

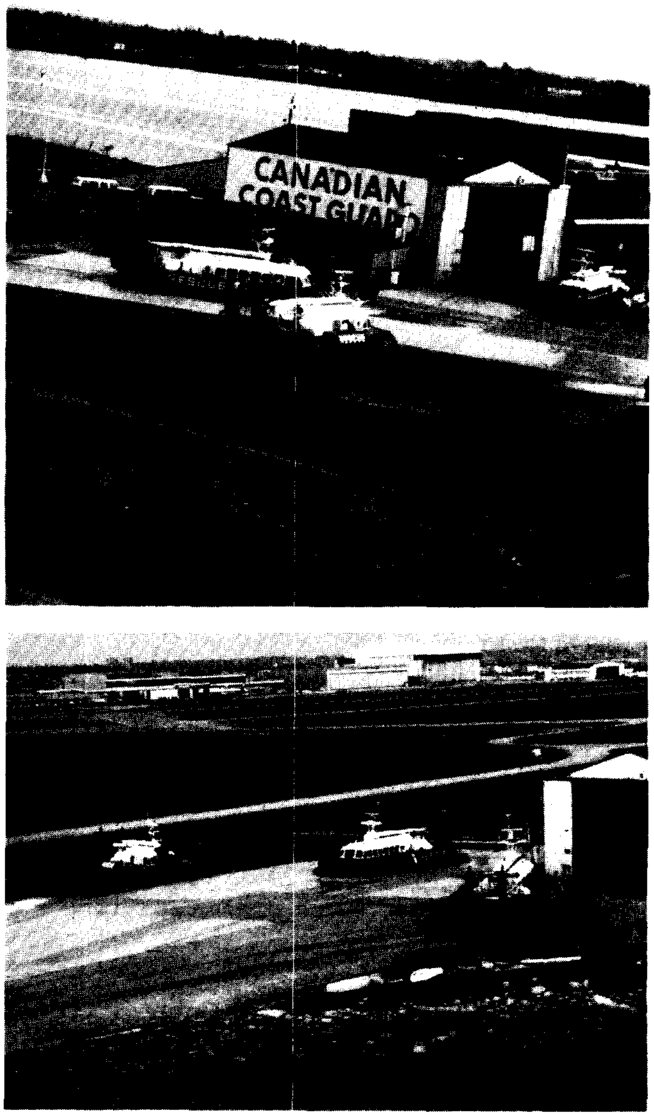


Figure 45. Canadian Coast Guard ACV Base Adjacent to Vancouver Airport.

There have been between 2000 and 3000 self-propelled ACVs of various types in (existence over the years. These have included about 400 large and medium size craft; the remainder are made up of relatively small privately-used craft.

Summaries of significant ACV operations not addressed previously in this chapter are as follows:

Coastal Patrol

One of the most successful ACV patrol operations has been that conducted by the Saudi Arabian Coast Guard and Frontier Force since 1971 using SR.N6s equipped with machine guns and capable of speeds of 50 knots. An initial fleet of eight of these craft, later increased to sixteen, operate from bases in Jeddah and El Aziziyah [4] (Figure 47). Their primary mission has been drug interdiction. Patrols along the 300-mile Arabian Gulf and 1000-mile Red Sea coasts were initially limited by the SR.N6's restricted range. However, the subsequent use of extended range fuel tanks and the installation of fuel dumps at remote intermediate bases along the coast have permitted the SR.N6 to patrol for periods of up to ten days [7].

Similar ACV patrol operations have been successfully conducted by other countries including India, Iran, Pakistan, Egypt, Iraq, Oman, and Hong Kong. Six SR.N5 Mk 6Cs, for example, were purchased by the Iraqi Navy in 1982 and are now being operated out of Basra on internal security duties. Each craft can carry 5.5 fully-equipped troops. Because much of the local area in the Tigris Euphrates valley is covered with tall water reeds, ACVs are the only practical vehicles available.

Egypt has operated three SR.N6s since 1976 on patrol and fast mine laying duties out of a base at Abukir. Iran has acquired eight SR.N6s since 1968 as well as 6 larger

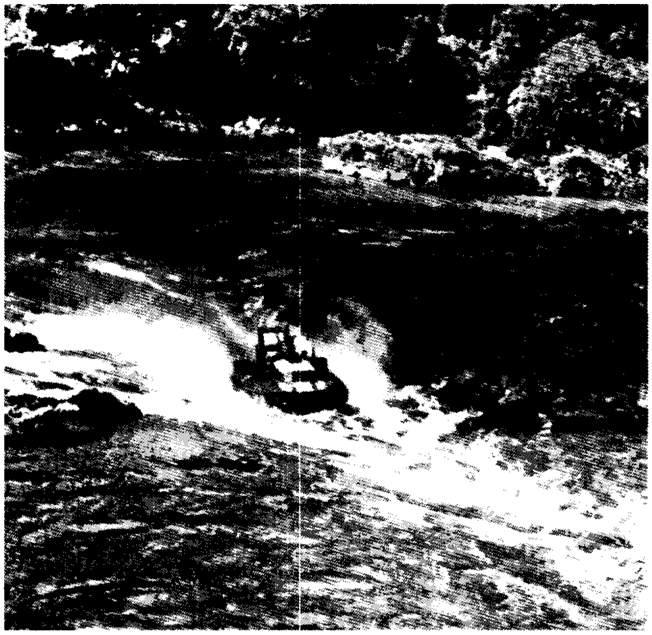


Figure 46. SR.N5 Operated by U.K. Army Team Negotiating Rapids in Borneo, 1965. [7]

BH7s, two of which are capable of carrying 175 fully-equipped troops, and the other four are equipped as fast missile-patrol craft.

Coastal Surveying

Because of their high speed, productivity, and ability to traverse shallow water, mud, and land, ACVs have been employed on numerous occasions for hydrographic, geological, and seismic survey work, as shown, for example, in Figure 48. Hoverwork Ltd., a British company formed in 1966, has conducted survey work in 15 different countries. Table 5, extracted from Reference [4], identifies some of their work conducted primarily with SR.N6s in support of the oil industry.

Several smaller craft (e.g., the air vehicles *Tiger* and *Pindair Skima* 12) have also been used very sucessfully for estuary mud sampling, and general area surveying over marginal terrain. In all cases, the ACV has demonstrated a unique ability to survey coastal areas much faster and more economically than is possible with traditional methods.

Aircraft Crash Rescue

Since 1970, the New Zealand Department of Transportation has successfully employed an SR.N6 for aircraft crash-rescue work over the mud flats and tidal waters around the Auckland International Airport at Mangere. By late 1981, the craft had logged over 4000 hours in general search and rescue operations and was supplemented in 1982 with the delivery of a smaller craft, a *Pindair Skima* 12. The smaller craft is used to transport life rafts to the scene, while the SR.N6 is employed in getting to the scene quickly with medical and firefighting equipment and personnel This operation, and the Canadian Coast Guard operations at Vancouver Airport, are the only sustained ACV crash-rescue services known, although there have been several trial operations in other countries including the U.K., Colombia, South America, Saudi Arabia. Aden, and Libya. An ACV on the partially frozen but fast flowing waters of the Potomac River in January 1983 would have provided invaluable assistance to the rescue of passengers on the ill-fated Air Florida passenger jet which crashed into the river after takeoff from Washington National Airport.

Military Versatility

Recent trends have seen successful ACVs being offered and used in more than one version to meet a variety of roles. The BH7 and AP.1–88 are examples which can be readily reconfigured to versions capable of logistic support, amphibious assault, police and customs operations, counterinsurgency, minelaying, MCM support. or fast missile attack roles. Because of the large deck space available on the LCAC, for example, several alternative missions have appeared feasible and include using the craft for troop transport, medical evacuation (MEDEVAC), mobile hospital, MCM, ASW, mobile sup-

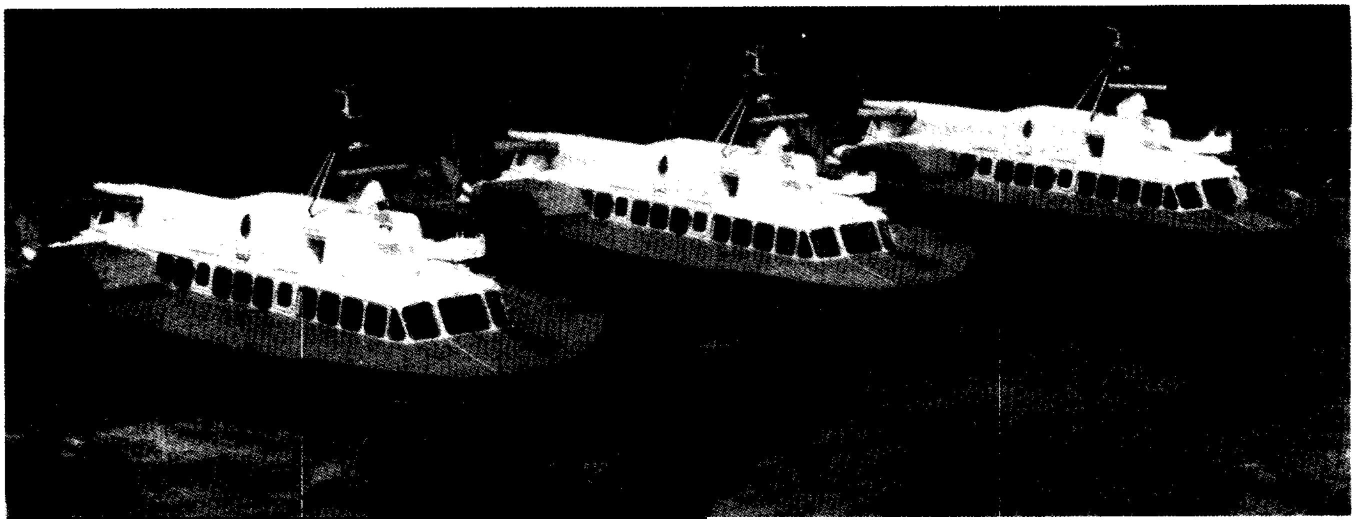


Figure 47. Three of Sixteen SR.N6s Delivered to Saudi Arabia (1971-82). [7].

Table 5. Examples of Hoverwork Coastal Surveying Operations. [4]

YEAR	LOCATION	TYPE OF OPERATION	TYPE OF TERRAIN
1969	HOLLAND-THE WADDENZEE	SEISMIC SURVEY	SHALLOW TIDAL AREAS
1969-70	ABU DHABI	SEISMIC SURVEY	VERY SHALLOW WATER AND CORAL REEFS
1970	BAHRAIN	GRAVITY SURVEY	SHALLOW WATER AND CORAL REEFS
1971	HOLLAND - DOLLARD BAY	SERVICE DRILLING RIG	SHALLOW TIDAL AREA. 3 MILES OF SAND TO CROSS AT LOW WATER
1971	ARCTIC CIRCLE	LOGISTICS	LEADS OF PACK ICE, SHALLOW WATER AND PLATEAU OF ROCK WITH DEPTHS FROM 0.5 TO 6 FEET
1971	U.K. - NORTH SEA HAISBRO & LEMAN BANKS	SEISMIC SURVEY	SHALLOW WATER, SAND BANKS, TIDAL STREAMS. AREA STREWN WITH WRECKS. IMPRACTICAL TO USE BOATS.
1972	TUNISIA - SFAX	SEISMIC SURVEY	VERY SHALLOW WATER AND SHORELINE LAND WORK
	NORTH WEST TERRITORIES, CANADA	SEISMIC SURVEY	SHALLOW WATER, ICE
1973	U.K. - MAPLIN SANDS	GEOLOGICAL SURVEY FOR LONDON'S THIRD AIRPORT	TIDAL SANDS, SHALLOW WATER
1974-76	SAUDI ARABIA	SEISMIC SURVEY	SHALLOW WATER, REEFS, UNCHARTED AREAS
1975	U.K. - THE WASH	TRANSPORTATION OF MEN AND MATERIALS	TIDAL AREAS, HALF MUD, HALF WATER
1976	U.K.	SEISMIC SURVEY	TIDAL AREA OF LIVERPOO BAY AND BLACKPOOL
1977-80	UNITED ARAB EMIRATES	SEISMIC SURVEY	VERY SHALLOW WATER COMBINED WITH CORAL REEFS AND SAND BARS
1981-82	IRAQ	SEISMIC SURVEY	INLAND LAKES; IN PART MUD BANKS AND REEDS
1983-84	EGYPT - GULF OF SUEZ	SEISMIC SURVEY	VERY SHALLOW WATER, CORAL REEFS AND SAND BARS

port base, mobile command post, helicopter platform, IRBM launcher and missile picket-boat duties.

Light Hovercraft

In terms of sheer numbers and variety, the light hovercraft industry worldwide has been phenomenal. Pindair Ltd., for example, have their small inflatables (Figure 49) operating in 67 countries [4]. Applications of these and other inexpensive craft have included police duties. hovering doctor services, military firing range bomb-disposal duties, construction site personnel carriers, pest control, agricultural spraying activities and oil rig support duties, etc.

An even much larger number of recreational ACVs have been built both commercially and privately. There are at least 24 independent hoverclubs throughout at least 10 countries, while the Hoverclub of America Inc., headquartered in Clinton, Indiana [9], has 12 branches in the U.S. and three more overseas. Hoverclubs exist to encourage the construction and operation of light, recreational ACVs by private individuals, schools, colleges, universities, and other youth groups. In the United Kingdom and the United States, local and national race meetings are held each year at which as many as 60 or more light ACVs compete for championship points. According to *June's Surface Skimmers*, [4], a growing activity within the various hoverclubs has been the pastime of hovercruising which involves traveling by single, or more usually, multiseat light ACVs along rivers, canals, lakes or coastlines, thus offering the ability to explore areas which are not accessible by other means of transport.

By virtue of the numbers of craft involved, it is not surprising that many innovative ideas are explored and valuable experience gained from a very large number of operating hours each year. The ACV industry would do well to monitor this activity closely.

Heavy-Lift Applications

The air cushion barge is an unglamorous, but. nevertheless, very promising application of air-cushion

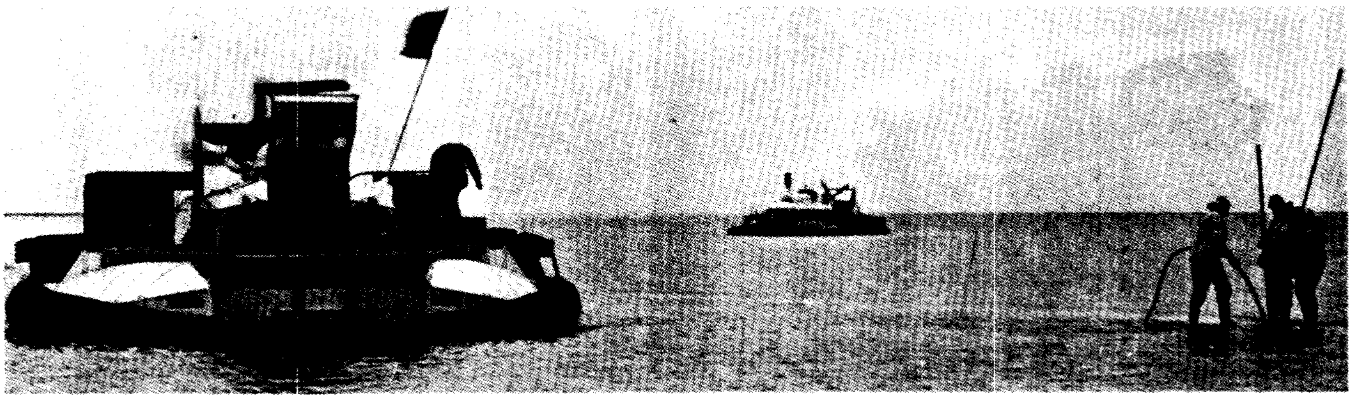


Figure 48. A Bore Hole Being Charged in Shallow Water. [7]

Figure 49. Pindair Inflatable Hovercraft. [10]

technology. A barge trades high payload and simplicity for high speed and complexity. It is best suited to applications requiring movement of large quantities of heavy cargo over relatively short distances. Its basic simplicity makes it particularly attractive for use in intensive operations in remote areas.

Typical applications include ship-to-shore resupply by the TAV-40 (Figure 50) along the Soviet Arctic coastline, and the use of two "Yukon Princess" heavy lift barges (Figure 51) to carry loads across the Yukon for the Alaska pipeline project.

A common thread to applications is that air cushion barges have been utilized as a temporary expediency, often for very short term applications or one time events where there has not been a practical or economic alternative. Most of the opportunities have arisen because of a high cost enterprise being held up due to difficulties of the operating site, weather, or both.

About a dozen different hoverbarges have been built in the West, and many more designed. Generally, they have had very similar features. These are a basic hull platform (often of modular form for ease of transportation), lift machinery packages with fans driven by diesel engines, and a simple segmented skirt of coated fabric. External propulsion has been provided by some form of tug over water, a wheeled or tracked vehicle overland, or a winch. Self-propelled hoverbarges have used outboard marine drives for over water use, and an on-board winch or some combination of wheels, paddles, or tracks for shallows or marginal terrain.

Compared to the high speed air cushion vehicle or hovercraft, barges are simple, low cost, rugged devices which do not demand operating or maintenance skills beyond levels that would typically be available at construction sites, on drill rigs, or on board supply ships.

The concept illustrated in Figure 52 capitalizes on the basic virtues of the barge by offering an approach for ship-to-shore movement of military and commercial cargo where there is no access to deep water port installations. The modular configuration permits assembly alongside, or on board, ship, which it then offloads, moving heavy cargo across the beach to firm ground.

To arrive at a compact, heavy load-carrying system, air cushion barges usually have higher cushion pressures than their high-speed counterparts. This has given them a tremendous ability to break ice, a fact that has been well demonstrated, particularly by the Global Marine ACT-100 (Figure 53).

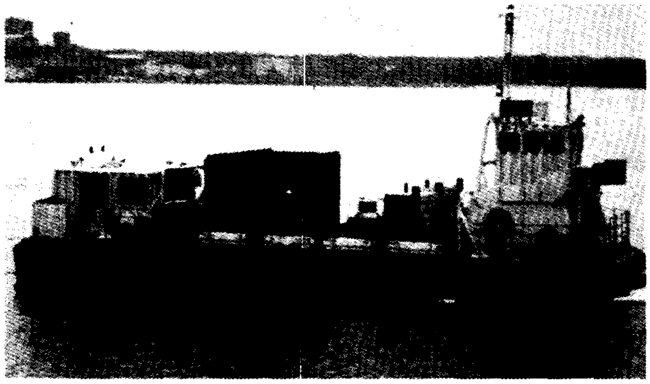


Figure 50. 40-Ton Payload TAV-40 Air Cushion Barge Built by Wartsila of Finland for the Soviets.

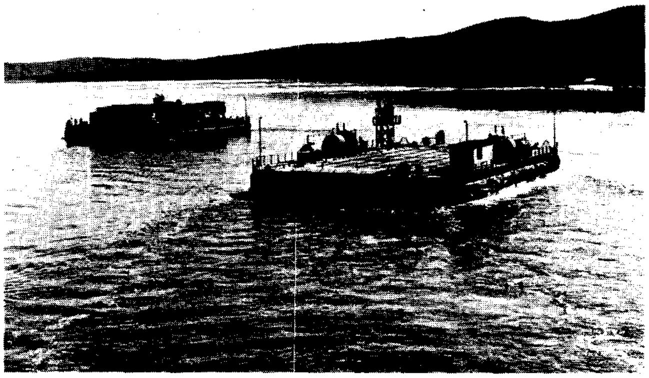


Figure 51. *Yukon Princesses* Carrying Supplies for Alaskan Pipeline Project.

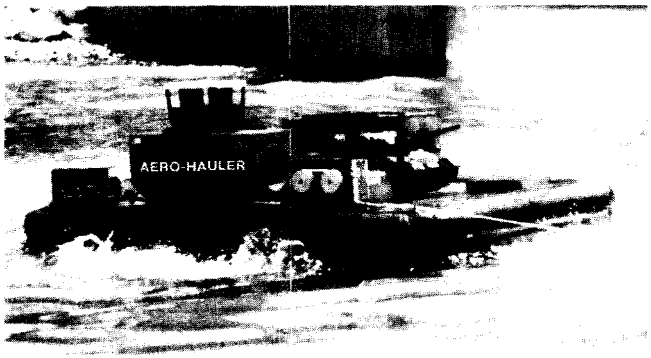


Figure-52. Aerojet *Aero-Hauler* Air Cushion Transporter.

Future applications are likely to follow the trends established by past operations. Oil and gas exploration has, of necessity, moved into more inaccessible regions such as the Arctic. In such areas, where there is no existing infrastructure and operations are intensive but of limited duration, the air cushion barge offers unique advantages. It is a low cost, low risk system which can be readily moved to other locations as needs arise. It demands little, if any, fixed installation, and, if modular, can be redeployed by sea, road, rail, or air. In the Arctic, its ability to break ice could be used to extend the season of summer supply convoys.

In warmer climates there are also undeveloped areas where natural resources exist but are difficult to approach. Air cushion barges could, for example, permit, with minimum environmental impact, the development of many potentially rich wetland areas of the U.S. where other means of transporting construction or drilling equipment are not feasible. Access to wetlands is often made difficult by the need to dredge canals or construct special roads, both of which take time and limit flexibility; neither of which are required for the air cushion barge.

Self-propelled and towed air cushion barges have also been used effectively in the U.K. in support of shoreline construction and civil engineering work over mud flats where excavating, dredging, pile-driving and bridge construction activities have been required.

In these applications, the barge is used to transport material or to hover its raft to the construction site where the lift system is shut down and the raft sits in position while the equipment is used. Often the same engine is used to power the lift system and the on-board equipment.

There are close military parallels to these commercial applications. In particular, post assault logistics-over-the-shore missions call for the movement of large quantities of material from ships offshore across primitive beach sites.

In summary, the air cushion barge has a proved and justifiable place in the transportation spectrum. Remote area, short range movement of heavy loads over shallows, marshes, ice, etc., in support of major industrial or military projects, is its natural role.

According to Reference [8], only a fifth of the world's land surface can be reached by wheeled vehicles and only half of the world's rivers are navigable with about 1/4 of the world's coastlines approachable by boat. Thus, low-cost ACVs are expected to make a major contribution towards improving mobility in these areas.

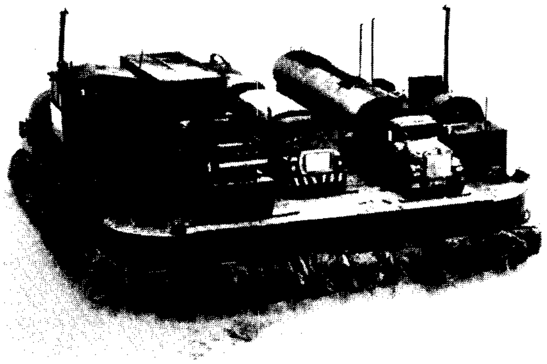


Figure 53. Global Marine ACT-100.

STATE OF TECHNOLOGY

During the evolution of the ACV a number of technological issues have arisen that are unique to this type of vehicle. In this section.. the more significant of these problems are described together with the measures taken to overcome them. The reader is referred to Reference [IO] for a more complete review of ACV technical development.

OVERALL PERFORMANCE

One measure of the overall performance of an ACV is the total HP/ton-knot at cruise speed. Figure 54 summarizes values of this parameter for a range of craft, plotted versus calendar year [11]. As can be seen, there has been a dramatic improvement from approximately 5 HP/ton-knot for the SR.N1 to less than 1 HP/ton-knot for current generation ACVs. This measure of craft efficiency de-

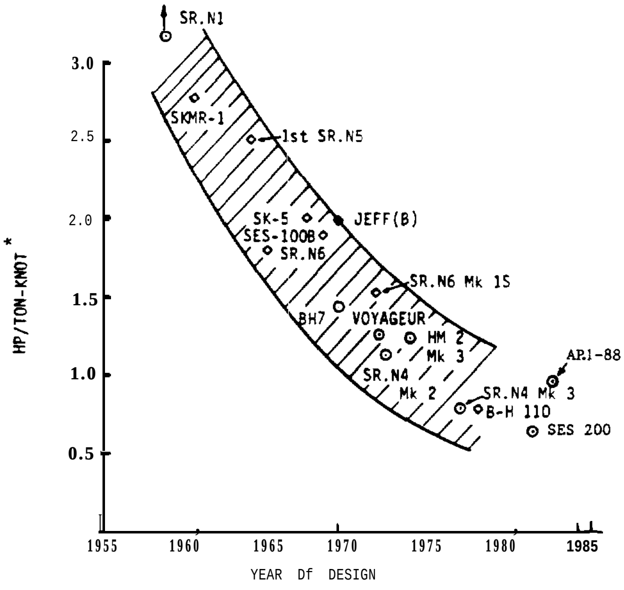


Figure 54. Improvements in ACV/SES Efficiency. (Reference [11].)

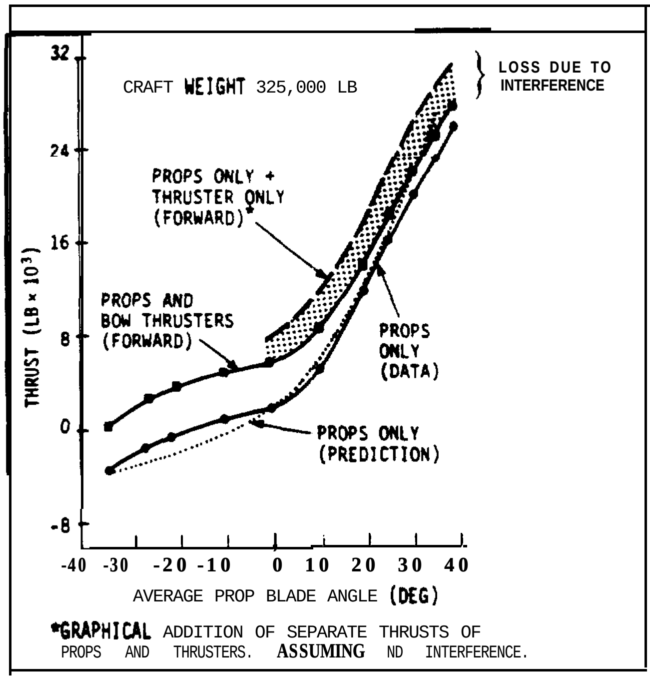


Figure 55. Effect of Propeller-Blade Angle and Bow-Thruster Interference on *Jeff(B)* Total Static Thrust. (Ref. [12].)

pends on the resistance to forward motion and on the efficiencies of the lift and propulsion systems. The historical improvement evident in Figure 55 is due primarily to the following factors:

1) The reduction in lift power possible with current flexible skirt sysems, particularly as compared with the unskirted configurations of the SR.N 1 and SKMR-1.
2) The reduced drag of fingered skirts compared with early jetted-bag configurations.
3) The development of fans and propellers tailored more closely to the operational requirements of ACVs.

Improvements in all of these areas can reasonably be expected to further reduce HP/ton-knot to perhaps 0.4-0.6 over the next 20 years. It is important to realize, however, that other design constraints may prevent the achievement of best efficiency for specific designs. This is particularly the case for the AALC *Jeff(A)*, *Jeff(B)* and LCAC, where dimensional limits result in high cushion density and high disc loading for the propulsion system. It is also worth noting that performance is not always the controlling parameter. Cost effectiveness, as measured by cost per payload ton-mile, is often a more meaningful parameter, and this is influenced not only by cruise performance, but by structural efficiency, engine specific fuel consumption, maintenance costs, and first cost. In recent years, there has been a trend towards the use of diesel engines and more conventional marine practices for hull construction. The design of the AP. 1-88 is a good example of this trend. Every effort was made to reduce initial cost and operating costs, and high speed performance was considered to be of secondary importance, although still relatively high (e.g., 50 knots) by displacement craft standards.

AIRSCREW PROPULSION

Thrust and Interference Effects

ACV propellers can lose efficiency and may suffer vibration problems when used in an installation where the airflow entering the propeller disk is severely non-uniform. Manufacturers of aircraft propellers have paid relatively little attention to this problem compared with the marine propeller industry where wake effects have always been a major consideration. Nearly all propeller-driven aircraft use tractor installations in which the propeller is designed to operate in an essentially uniform airflow. Even the few pusher-prop aircraft have a relatively undisturbed propeller inflow compared with that of most marine propellers. Accordingly, the air propeller performance technology is not geared to dealing with severe wake problems.

When the AALC *Jeff(B)* was being designed, for example, Hamilton Standard, the propeller manufacturer, was given simplified inflow velocity profiles based on model tests in a wind tunnel. In this installation, the propellers were mounted behind a bluff superstructure. It was thought that the propeller ducts, acting as a strong sink, would essentially straighten the flow before it reached the blades. Accordingly, performance predictions were little affected by the stipulated velocity profiles. Later, tests on other models and on full scale craft, in which propeller thrust was measured independently of aerodynamic drag, indicated that superstructure ahead of the propeller has a marked effect on net thrust and on propeller-vibration levels. Static tether tests on *Jeff(A)* and *Jeff(B)* revealed, in each case, a significant difference between predicted and measured thrust values. However, satisfactory craft performance at speed indicated that the problem was less severe when underway.

Undoubtedly. propeller--installation effects remain as a technical issue that requires further attention when considerations are made of craft performance, and perhaps more importantly, when considerations are made of aerodynamically induced propeller vibration, stress, and noise. In addition to the effects of propeller blockage, *Jeff(B)* propellers are subject to interference from the bow-thruster jet efflux, and to a lesser extent by ingestion of the turbine engine exhaust gases. Both of these phenomena, particularly the former, have a direct effect on propeller thrust. The effect of bow-thruster interference can be seen in Figure 55, taken from Reference [12].

To minimize bow-thruster interference with the propellers, the nozzles are aimed upwards and outwards for normal ahead operation. The loss of forward thrust due to the cosine of the tingles of deflection is quite small and is significantly smaller than the loss of propeller thrust which would result from direct impingement of the bow-thruster jet on the propellers.

Bow-Thruster

Figure 56 [12] illustrates the variation of thrust and sideforce with bow-thruster nozzle rotation. The princi-

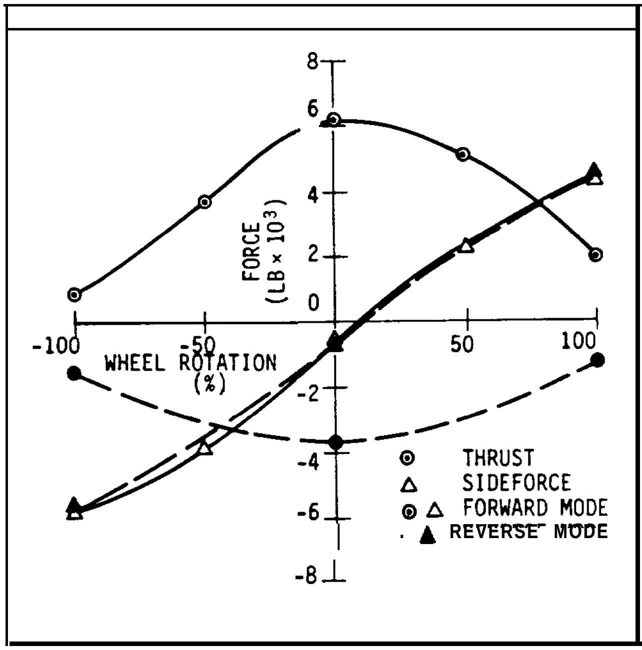


Figure 56. Bow-Thruster Thrust. [12]

pal duty of the bow thrusters on *Jeff(B)*, LCAC, and AP. 1-88 is to provide control force. While the contribution to forward (or reverse) thrust is welcome in enabling the craft to meet its design performance goals, in terms of thrust per horsepower it would be more efficient to put the equivalent horsepower into the propellers.

Erosion Protection

Erosion of ACV propeller blades is caused by the impingement of sand and water particles carried up by the cushion airflow. Blade erosion becomes most troublesome when operating, for extended periods, over a sandy beach. Erosion has been particularly severe for operation of ACVs over beaches in the Gulf of Mexico where the sand is extremely fine and has remarkable abrasive properties. Propeller-blade erosion on Jeff(B), and on LACV *30* or *Voyageur* craft when operating over such beaches, has proved very much more rapid than has been experienced on British hovercraft operating daily over French and English beaches where the sand is often damp and compacted.

The Hamilton Standard solid aluminum blades on the *Jeff(B)* rapidly wear to thin jagged edges near the tips. The addition of polyurethane strip leading-edge guards delays this process, but the leading edge at the propeller tip is soon exposed. There is a limit to the mass that can be added to the propeller for erosion protection without adversely affecting the propeller-blade dynamics.

The Dowty Rotol propeller for the LCAC has a composite fiberglass construction. It is provided with replaceable stainless steel, bolt-on, leading-edge guards and polyurethane coating over the rest of the blade. These guards, which have had extensive service on British hovercraft in commercial service, lasted only minutes over Florida beaches. After extensive research and experimentation, satisfactory guard life can be obtained with a thick molded polyurethane "nose" on the leading edge. When this nose is worn away, the guards are replaced—an operation quickly and easily performed in the field.

Research continues to find better ways to protect both solid aluminum and composite blades from the effects of sand and spray. Nickel plating, and electrodeposited or sprayed-on hard coatings have been tried with mixed success. Present efforts include fitting precision-molded, ceramic leading-edge strips that have proved to show negligible wear. Many practical problems remain to be overcome before a fully satisfactory protection system evolves. The use of antispray skirts, which minimize the amount of spray as well as the amount of sand particles in the air, appears to be one solution that is showing great promise. This will be discussed later in this section.

LIFT AIR SUPPLY FANS

Structural Limits

Most ACVs have centrifugal fan rotors mounted within a plenum or within a spiral volute. Centrifugal fans are simple, rugged, relatively inexpensive, and easy to install. They are capable of high efficiency, but more importantly, they are free of surge problems. Stall, if it occurs, is virtually unnoticeable. The relatively flat pressure-flow characteristic near the peak efficiency operating point makes for a less severe ride problem than would be obtained with axial fans. Axial fans must operate, in most cases, on the steep part of the pressure-flow characteristic to avoid the surge line. However, there is a practical limit to the pressure ratio that can be obtained with single-stage centrifugal fans. So far, this limit has not been reached by ACVs. Pressures over 300 psf are conceivable for the type of aluminum centrifugal fans in use at the present time, whereas peak pressures of less than half this amount are required by most ACVs.

Figure 57, from Reference [13], indicates some design limits for several materials. So far, consideration of anything but aluminum alloys has not been necessary. Commercially available centrifugal fans have proved to be generally unsuitable for military and passenger ACV service. Such fans are optimized for high efficiency with cheap construction and, to meet these goals, low tip speeds are used with low blade angles resulting in low pressures. For higher pressures, radial blading may be used with blades of narrow span resulting in low capability for a given diameter. Commercial designs are not weight effective since weight is rarely a major consideration in an industrial application. Similarly, bulk is often unimportant.

For effective ACV use, special compact, lightweight, centrifugal fan rotors have been developed. The SR.N4 and AALC *Jeff(B)* fan rotors, for example, represent an intermediate stage in the evolution of practical designs for ACV use. Starting with a well-known, high-efficiency, commercial design, rotors with higher blade angles were developed to meet high pressure requirements with sufficient strength while still retaining high flow capacity. Aerospace technology was applied to the design

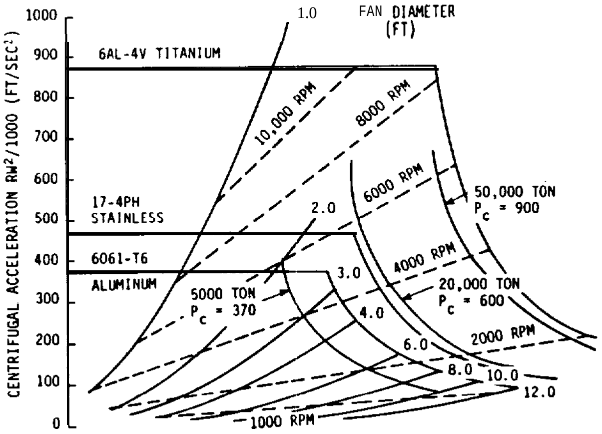


Figure 57. Centrifugal Fan Design Limits. [13]

of the lightweight. thin-skin blades and their attachments. The result was a very expensive fan.

Next, narrower-blade, high capacity fan rotors were developed and these were much less expensive to produce. This type of rotor was used on the BH-I 10 SES and on the LCAC. It continues to be refined and has been used with both hollow and solid blades and with both welded and mechanically fastened construction methods.

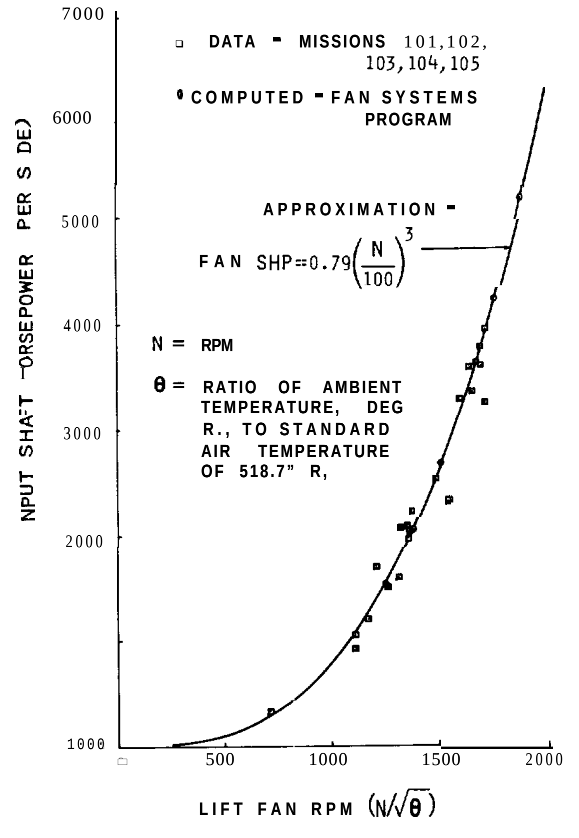


Figure 58. AALC *Jeff(B)* Predicted and Measured Fan Power. [14]

Mixed-flow fans represent an intermediate step between centrifugal and axial flow fans. Cast rotor, mixed-flow fans were used on the *Jeff(A)* and were seriously considered for the LCAC. Some problems of producibility and vibration were encountered, but, undoubtedly. this type of fan has potential for further development for large craft of the future. Figure 58 [14] shows some computed and observed fan-power data for the ***Jeff(B).***

Erosion Protection

Lift fans are subject to erosion from sand and water spray, but to a lesser extent than air propellers. The ***Jeff(B)*** fans with their thin-skin construction suffered blade damage, particularly of the leading edges near the centerplate where the change of air direction is greatest. Coating the blades with a rubber material proved to be a satisfactory solution. While solid extruded blades such as those of the LCAC are less vulnerable to erosion damage, it is advisable to protect this type of blade also by the use of polyurethane or similar material to ensure long life and continued structural integrity.

DRAG

The characteristic shape of the resistance vs. craft speed curve for an ACV operating overwater is similar to curves for other high-speed marine vehicles, but unlike the curve for a conventional displacement craft. Figure 59, reproduced from Figure 12 of Reference [12], shows predicted and experimentally determined drag for a typical ACV, the AALC ***Jeff(B).*** Total drag for an air-propelled ACV such as the ***Jeff(B)*** is comprised of four components: external aerodynamic drag, momentum drag of the lift system air, cushion wavemaking drag, and skirt or seal-system contact drag. Wavemaking drag reaches maximum values at the secondary and primary hump speeds. as shown in Figure 59, and declines at high speeds. Skirt drag is a significant drag component, especially at higher speeds and in waves. Aerodynamic drag is also a significant component of total drag for the case shown because of the relatively blunt shape of the ***Jeff(B)*** hull and superstructure and the ambient wind condition (25-kt headwind in Figure 59).

Experimentally derived drag levels for the ***Jeff(B),*** shown in Figure 59, are generally somewhat below predictions based on model tests. The full-scale drag data points are derived from test measurements using predicted propulsion thrust characteristics. There is some evidence from static thrust measurements that actual ***Jeff(B)*** thrust is somewhat less than predicted, as discussed earlier in this section. Thus, the actual craft drag values might be even lower than indicated here.

When an ACV operates overland, the drag mechanisms are somewhat different from overwater operations. Cushion wavemaking drag is absent. The nature of skirt drag is different overland-and is similar to dry friction. Aerodynamic and momentum drag components are essentially identical to that which would be obtained overwater at the same air speed, craft weight, etc.

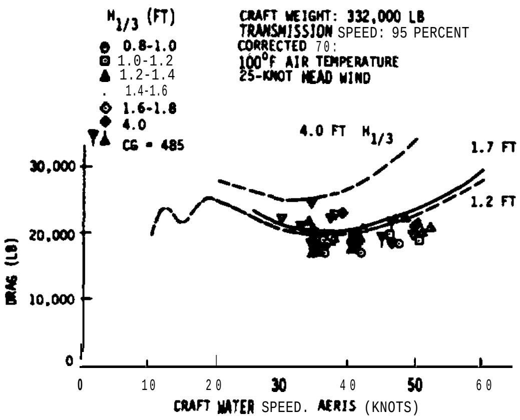


Figure 59. ***Jeff(B)*** **Drag Overwater (Experimental Drag and Predictions Versus Forward Speed and Sea State at 95-Percent Transmission Speed). [12]**

Drag data derived from *Jeff(B)* tests overland are shown in Figure 60, reproduced from Figure 23 [12]. In this case, full-scale derived drag levels are higher than the prediction because of the low lift flow at which the craft was operated relative to the lift flow assumed for prediction.

Cushion System

Skirt Configurations

By far the most successful and widely used skirt configuration has been the bag/finger arrangement, illustrated in Figure 61. The highly compliant fingers provide a responsive, low drag cushion seal, while the bag acts as an air distribution duct and provides increased restoring moments at large pitch or roll attitudes. Additionally, this skirt provides a high level of redundancy in that the failure of individual fingers is largely compensated by expansion of the adjacent units.

The depth of the bag/finger type of seal is generally limited by the roll and pitch stability requirements, particularly with respect to plow-in, as discussed later. For a tapered skirt configuration, where the clearance of the bow is greater by some 25 percent than the clearance at the stern, it appears that stern clearance is the critical dimension. The main advantage of a deeper skirt is improved obstacle and wave clearance, but the ability to utilize this clearance is highly dependent on the pitch characteristics of the vehicle. Excessive pitching of an ACV, as it crosses a series of waves, can cancel the benefit from the increased clearance height. In some military applications, the overall height of the ACV will be important. For example, in the LCAC program, there is the requirement for stowage in the LPD and LSD. A secondary factor is the total drag of the vehicle; while hydrodynamic drag is most significant, the aerodynamic drag of an ACV, such as *Jeff(B)*, will increase at a rate of 450 pounds per foot of skirt depth when traveling at 50 knots into a 25-knot headwind.

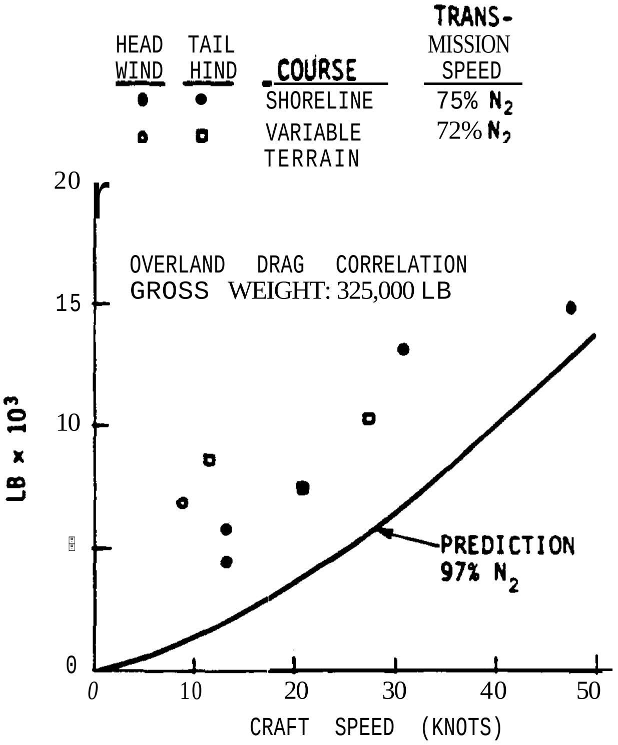


Figure 60. ***Jeff(B)*** **Drag Overland. [12]**

The ratio of finger depth to bag depth is another important design choice. Increasing the depth of the finger reduces the rough water drag, but with a penalty of reduced stability and, generally, reduced cushion area. The development trend has been from the original 30 percent fingers to the present 50 percent, with some continuing research into the feasibility of 60 to 70 percent.

The cushion plenum may be subdivided by stability seals to increase roll or pitch stiffness. Most commonly, this is achieved with a longitudinal "keel" on the centerline, and a lateral seal close to amidship. This arrangement results in four, approximately rectangular, cushion compartments. Frequently the forward section of the keel

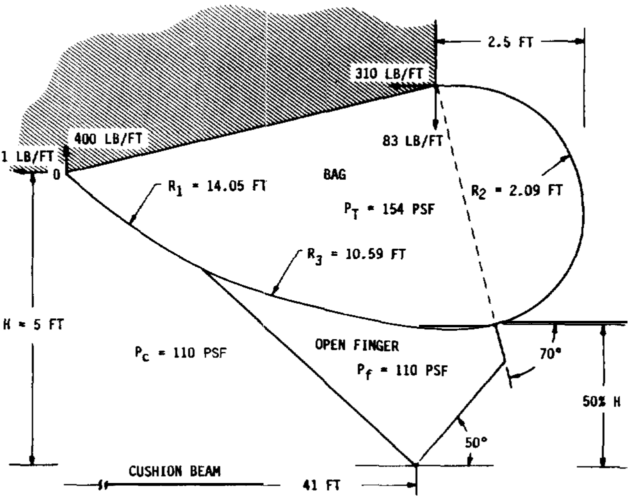


Figure 61. Cross Section of *Jeff(B)* Side Seal Having 41-Foot Cushion Beam and 50 Percent Finger. [11]

is omitted to save cost and weight at the expense of some roll stiffness. Alternative skirt configurations have found limited application to date. Some of these are summarized below:

a) All-fingered skirts with no bag are frequently used for low speed, heavy lift platforms and on small recreational ACVs. The principal advantages of this arrangement are simplicity and ease of maintenance.
b) The French cell-type skirts (Figures 13 and 14) offer high initial stability at the expense of drag and complexity in the air distribution system within the hard structure. A variation in which cells are attached to a peripheral bag. as with the Jeff(A) loop-pericell skirt (Figure 5A), offers the advantage of high craft stability without compartmentation seals. The only full-scale experience to date, however, has indicated higher lift-power requirements and higher drag than the bag-finger configuration.
c) Single or multiple lobe-bag skirts were used as stern seals on both ACV and S ES, but are now only found on SES configurations. Some small recreational vehicles have used single bags around the entire periphery, but this arrangement has proved less successful than fingers or bag/finger skirts.

Skirt Design Criteria

One of the most complex areas in the development of flexible skirts and seals has been the determination of the design criteria and loads to be used. The present ability to design operational seal systems for vehicles of 200 to 300 tons gross weight and to confidently project feasible applications up to 2000 tons is the result of operational experience. empirical analysis, fundamental research, and mathematical simulation. There are several operational conditions that must be considered in the predictions of the loads in the seal system. These conditions include overpressure, drag due to contact with the water surface, loads due to liftoff with the seal system filled with water, and loads due to the fingers contacting or scooping the water surface. Also, the loads generated through the recovery of the seal system after deflection by the waves (the snap back or reinflation snatch loads) must be considered. The behavior of a flexible membrane in response to the motions of a random sea is an extremely complex situation. A satisfactory design depends as much on engineering and operational experience as on the fundamental analysis techniques. Based on this experience, both Bell Aerospace Textron and British Hovercraft Corporation have developed strain energy methods of predicting the reinflation snatch loads. These methods have been deliberately conservative, a fact that has been proved by experience. Data from both ACV and SES bow-seal operation have indicated that even in high sea states and at high speed, the measured loads in the bow-seal material are generally less than 50 percent of the original calculated load. Sophisticated finite element methods are now available for the calculation of bag loads and of load distribution within the inflated structure.

The requirements for finger material are generally for a material strength lower than that for the main bag, but with more emphasis on the ability of the fabric-elastomer bonding to stand up to the high repetitive accelerations caused by the flagellation of the finger extremities as they pass at high speed over rough water. There is, at present, no direct method of calculating these loads, but laboratory testing techniques have been developed and correlated with operational experience.

Flexible Materials

The ability to design the ACV's cushion system so that a reasonable operational reliability and maintainability level can be achieved has been one of the most challenging aspects of their development. A key factor in this has been the selection of seal material and the detail design techniques. With the present level of technology, the achievable seal life for a vehicle such as the LCAC is 2000 to 3000 hours for the bag and 200 to 400 hours for the fingers with the lowest life being at the stern corners of the cushion.

Indicated desirable mechanical properties for seal materials include:

a) Sufficient flexibility to provide good energy absorption and wave following in sea states
b) Sufficient "stiffness" to resist flutter in normal operation
c) Good damping characteristics to attenuate flutter in sea states
d) Sufficient tear and tear fatigue strength to resist peak loads
e) Resistance to flagellation damage at free edges
f) Resistance to cracking or delamination in cyclic flex or buckling
g) Resistance to other modes of damage (e.g., impact abrasion), which may become important as seal life is improved or as seal dynamics are changed.

The list of desirable mechanical properties is in part contradictory; for example, the preparation of the fabric, which is necessary to insure good adhesion of the elastomer, reduces the tear strength of the fabric. Material choices have to be based on trade-off studies conducted as materials and dynamics information accumulates.

The best candidate materials for a typical 100- to 200-ton ACV have certain common characteristics essential for a potentially superior seal material: weight 50 to 90 oz/sq.yd; coating adhesion above 40 lb/in, preferably 90 lb/in; sea water resistance, preferably inert; tear strength greater than 50 lb/in; and tensile strength greater than 500 lb/in. The indicated need for high coating adhesion strength is in accord with the primary observed failure mode, which is delamination at the fabric coating bond line. High weight aids in moderating the severe flapping or flagellation that develops at the edges of the seal while high tear and tensile strength are needed to resist crack initiation and propagation. Nylon fabrics coated with Neoprene or natural rubber are used in almost all the present operating ACVs.

MANEUVERING

The provision of adequate control forces on an ACV requires special attention in the conceptual design phase if the craft maneuverability and handling qualities are to be acceptable. The isolation of the air cushion effectively eliminates the surface reaction available to conventional land vehicles and greatly reduces the hydrodynamic forces used by other marine vehicles.

The primary source of control forces on an ACV is aerodynamic and this can be provided by utilizing the propulsion system and/or the lift system. The principal methods of generating forces and moments are summarized below:

1) Rear mounted fins with rudders for yaw control.
2) Differential propulsor thrust for yaw control.
3) Swiveling bow thrusters as on AALC Jeff(B), LCAC, and AP. l-88 for yaw, sideforce, amd speed control.
4) Single or multiple swiveling propellers as on SR.N3, BH7, AALC *Jeff(A)* and the SR.N4 for yaw, sideforce, and speed control.
5) Puff ports for low speed sideforce and yaw control (SR.N.5, SR.N6, SK-5, *Voyageur,* LACV-30).
6) Propulsive thrust from the lift system utilizing multiple rudders in the jets for yaw and also reverse thrust buckets (SR.N5, SR.N6, SK-5).
7) Skirt lift for roll, yaw, and sideforce control.

These systems are often used in combination: for example, longitudinal, lateral, and yaw control forces on the AALC *Jeff(B)* are obtained by the following means:

1) Variable prop pitch (forward and reverse) on two ducted propellers located at the stern.
2) Twin rudders that operate in unison in the slipstream of each ducted propeller.
3) Twin bow thrusters located forward of the LCG with full 360-degree rotation.

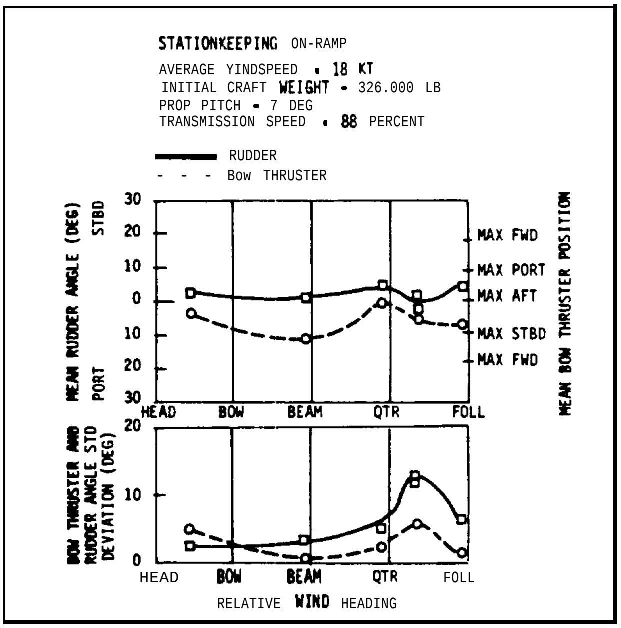


Figure 62. Jeff(B) Stationkeeping On-Ramp for a Range of Relative Wind Headings. [12]

Maneuvering requirements for ACVs are stated in terms of the craft's capability to maintain position **and** heading while hovering overland/overwater in winds from various directions. This capability requires a control device that has almost full 360-degree rotation. Turn rates at steady speed, slope climbing, track transfer, acceleration, and deceleration characteristics are other design requirements.

Jeff(B) stationkeeping data as a function of relative wind direction are shown in Figure 62 [12]. Windspeed was between 17 and 18 knots on the ramp. No problems were experienced in trying to maintain craft station and heading in these conditions at any of the wind headings investigated. The greatest demand on the craft and craft operator appears to exist when operating in winds from a direction between directly astern and off the stern quarter.

Figure 63 shows *Jeff(B)* data in which a number of high-speed steady turns were made overwater with nominally 20 degrees of both thrust control and a range of associated rudder angles to turn in the same direction. Turn rates achieved ranged from 1 to *3* degrees per second in both directions for turns performed at craft speeds ranging from 20 to 45 knots. Actual bow-thruster angles employed were mainly between 15 and 3.5 degrees. In general, the craft rolls and yaws into the turn.

STABILITY

No widely accepted stability standards for amphibious ACVs exist for operation underway at high speed. Adequate stability, over the years, has been judged, for each craft, principally from the experience of model and full-scale testing. As a result of this background, some basic design guidelines have evolved and these are discussed below:

Static Stability

The level of pitch and roll static stiffness as measured during overland hovering tests, or during underway calm-

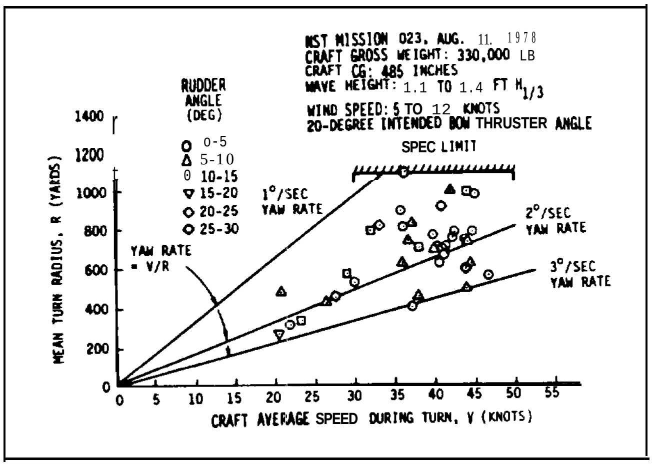


Figure 63. *Jeff(B)* Turn Radius Versus Craft Forward Speed. [12]

water tests, has appeared as the only measure of stability with some universal recognition. This is apparently because the measurement of pitch and roll static stiffness is relatively easy to achieve. Although in itself it conveys little regarding the craft's ultimate ability to resist a capsize, the possible lack of stiffness can be used as an indication of potential problems if values are outside of present day experience.

The pitch and roll stiffness of an ACV is typically expressed as the percentage shift in center of cushion pressure which results from a 1 degree change in roll (or pitch) angle qualified by the linear range over which it is applicable and is written as:

$$\hat{K} = \text{percent c.p. shift/degree} = \left(\frac{M}{WL} \times 100\right)$$

where M = moment to incline the craft through 1 degree
W = craft weight
L = cushion reference length (length or beam).

This, of course, is similar to the metacentric height (GM) used for assessing the initial stiffness of displacement ships. The transverse metacentric height. for example, can be expressed as:

$$GM_T = \frac{K}{W \sin \phi} = \hat{K} \frac{(57.3)}{100} L$$

where K = righting moment for a small angle of roll ϕ
W = ship displacement
L = cushion beam (B, in this case)
$\hat{K}$ = percent c.p. shift/degree (expressed, in this case. as a percent of B).

Pitch and roll stiffness for an ACV can be fairly nonlinear. The range of applicability of quoted stiffness values is usually of the order of ± 3". Some ACVs that have operated satisfactorily are unstable in pitch and/or roll for small angles (e.g., ±0.5°), in which case, the stiffness is averaged over the range of + 0.5" to + 3" and − 0.5 to − 3".

It has become recognized that small, highly maneuverable ACVs, can be satisfactorily designed with overland roll stiffness values of 0.5 percent B/deg or higher and with overland pitch stiffness values of twice this value. ACV stiffness while underway overwater, will, in general, be a little lower than values measured overland, although at high speed, pitch stiffness, in the bow-down condition, can diminish to very small values as discussed later. For large commercial ACVs, British Hovercraft Corporation (BHC) has recommended [15] roll-stiffness values above 1 percent c.p. shift per degree (with pitch values of about twice these values).

The choice of stiffness should also recognize the range of C.G. shift required of the craft. Most craft have been considered satisfactory if transverse C.G. shifts of 3 percent to 9 percent of the cushion beam can be sustained prior to significant skirt tuck-under [15]. The actual shift value depends upon the particular design and should provide a safe margin over the worst possible combinations of upsetting moments including control-force moments, wind moments, wave action, and maximum likely actual C.G. offset. During design, one of the most important parameters is the C.G.-height-to-cushion beam ratio. C.G. height has a destabilizing effect proportional to roll or pitch angle. For example, the larger the C.G. height in relation to beam, the larger will be the destabilizing moments in relation to fixed stabilizing moments (relative to roll angle) during turning maneuvers. Thus, in general, the larger the C.G. height the larger the pitch and roll stiffness should be.

Figure 64 [16] shows for several existing ACVs (and SES) roll stiffness values for corresponding values of cushion height to cushion beam ratio. When comparing various designs, cushion height (taken as the wet deck clearance height) is generally in approximate fixed proportion to C.G. height.

With cushion height instead of C.G. height as the principal parameter, Figure 64 shows ACV overland roll-stiffness values ranging from 0.5 to 1.8 percent c.p. shift per degree, all with cushion-height-to-beam ratios on the safe side of the British Civil Aviation Authority (CAA) recommended limit of 0.2 [17]. Excluding the SR. N5 and SR.N6 craft, earlier versions of which have in fact capsized, Figure 64 shows a slight trend towards a need for higher roll stiffness with craft of higher cushion-height-to-beam ratios. This is indicated by the envelope (curve) for ACVs of known stiffness which have not capsized in operation. The selection of roll stiffness values equal to or greater than those indicated by the envelope of current day experience on Figure 64 could be considered very safe practice, with adequate margin, since all vehicles (below the line) have behaved satisfactorily. However, as indicated earlier. although adequate stiffness is considered necessary, it is an insufficient measure of overall craft stability.

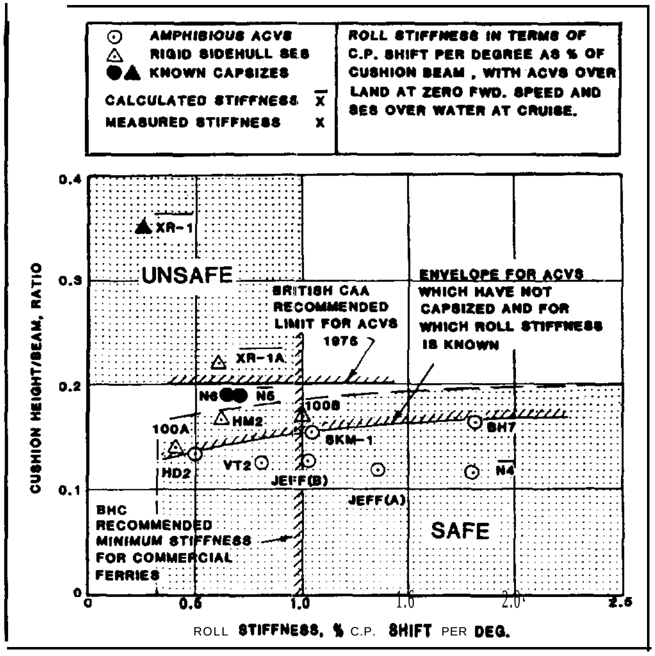


Figure 64. Roll Stiffness, in Relation to Cushion Height to Beam Ratio for Various Existing ACVs.[16]

Dynamic Stability

A primary concern for ACV dynamic stability underway has been the provision for adequate resistance to skirt tuck-under and plow-in. Plow-in is a craft pitch-down event which can occur in smooth or rough water. It is accentuated by operation at high speed, especially with off-set C.G. locations and reduced cushion airflow rate and low bag pressure. Plow-in is due to greater than normal skirt contact with the water. This additional contact will increase the drag forces acting on the skirt and will cause the skirt hemline to “tuck-under”. This will tend to distort the bow skirt (support) bag rearwards, thus moving the center of area of the cushion aft to cause a loss in available aerostatic restoring moment. This loss in restoring moment causes further bow-down and/or rolling attitude; and hence, further skirt immersion and drag. The plow-in is characterized by a rapid deceleration combined with large bow-down (4” or greater) and/or roll attitude with a tendency for directional instability and the development of large, sometimes, uncontrolled angles of yaw. The danger is that at some time during this maneuver, relatively high speed beam-on (pure sideways) motion can occur. Since the available restoring moments in roll are less than in pitch, the destabilizing moments described above can create extreme angles of roll, causing hard structure contact and the possibility of an eventual capsize in roll.

To prevent skirt tuck-under and plow-in, the bow and side skirts are designed to resist the tendency to deform horizontally under load. ‘This is controlled in design by the choice of skirt inflation pressures and geometry. For a given design, operational limits are usually placed on the allowable offset C.G. location, forward speed, sideslip angle, and cushion airflow rate combinations.

Figure 65 shows a typical tuck-under inception boundary for a bow skirt as a function of forward speed and C.G. location as derived from full-scale trials [12]. These full-scale results are compared with results of testing a 1/12th-scale model that had essentially the same skirt geometry. It is apparent, from the comparison of Figure 65, that the model-test technique, or scale effects, resulted in the prediction of a far more optimistic C.G. shift capability than was achieved at full scale. The purpose for presenting Figure 65 is to illustrate the potential danger of relying on predictions based exclusively on model-scale data.

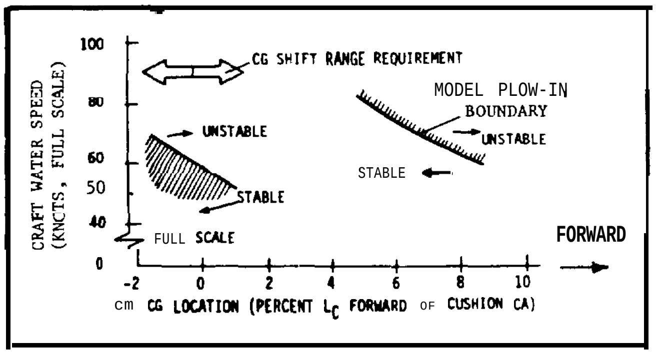


Figure 65. Comparison of Model and Full-Scale, Pitch-Stability Boundary, Water Speed Versus Center of Gravity. [12]

Once the plow-in boundary of a craft has been established, from either full-scale test results, or from adjusted model-scale test results, operation within the boundary will avoid skirt tuck-under and craft plow-in during normal zero-sideslip operation.

During turning maneuvers, however, relatively large sideslip angles can occur. If the maneuver is made at high speed and the sideslip angle and velocity are high, then a danger of side-skirt tuck--under can exist. Thus, regulatory authorities have, in the past, imposed operational speed-sideslip angle boundaries for commercial craft as illustrated for the SR.N5 in Figure 66, [17]. This type of restriction was first introduced by BHC, and is still in use for all British commercial ACVs.

ENGINE COMBUSTION AIR FILTRATION

Early ACVs, such as the British SR.N2, SR.N3, SR.N5, and the U.S. built SKMR-1, utilized simple filtration systems for the engine inlet air. Air was taken from cushion air ducting and passed through a single stage agglomerator-type filter that removed the larger water droplets, but was relatively inefficient in removing dust particles and fine mist. Such filtration systems were reasonably successful when the craft usage was confined to operation over fresh water, but when operating over salt water or sand, even for a limited time. engine performance deteriorated rapidly. Ingested sand rapidly eroded compressor and turbine vanes. Ingested salt water produced salt buildup on compressor blades and long term sulfidation degradation of components in the gas-turbine hot section. Considerable effort was devoted to developing a satisfactory filtration system. Various types of filters were tested in different combinations to obtain a system that could reduce salt and dust to safe levels. even

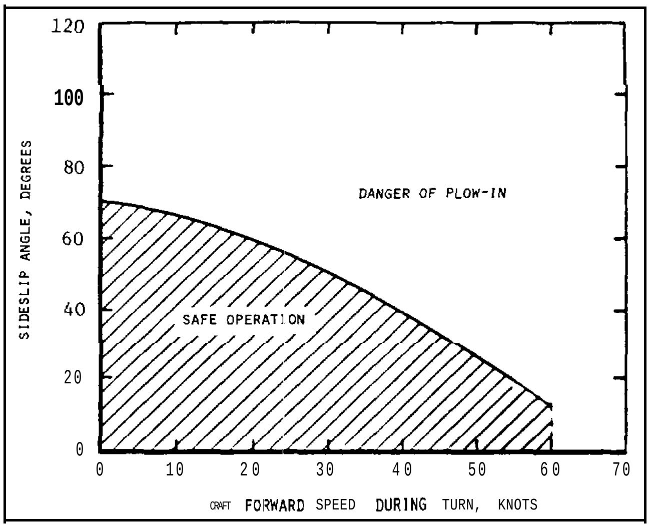


Figure 66. SR.N5 Speed-Sideslip Boundary. [17]

when the air entering the inlet contained high levels of salt water, or sand and **dust.**

Air filtration systems developed for the LACV-30 and LCAC are shown in Figures 67 and 68 [18, 22]. The LCAC system was developed from a combination of laboratory tests at NAPC (Trenton) and NAVSSES (Phil) and from tests of various filter configurations on the *Jeff(B)* [19, 22]. Both the LCAC and the LACV-30 utilize a mesh screen as a first stage to collect debris, such as grass, that would clog the main filter stages. The additional stages consist of hook-vane type water separators; swirl-tube-type inertial filters, which remove dust particles and water droplets; agglomerator-type filters, which coalesce mist into water droplets that can then be removed; and barrier-type filters, which remove microscopic dust and salt particles.

Such filtration systems have proved to be effective in removing the dust **and** salt even from highly contaminated air. Significant efforts have also been directed toward reducing the spray and dust content of the air before it enters the filtration system. Spray suppressors of various designs have been tested in both model and full scale. Extensive full-scale testing of spray suppressors on LACV-30 and *Jeff(A)* are discussed in References [18]and [20], respectively. The spray suppressors (Figure 69), installed and tested on the LACV-30 and *Jeff(A)*, in each case significantly reduced the amount of spray and sand reaching the deck level. A more advanced spray suppressor (Figure 70D) was also tested on Jeff(A), and further improvement in spray reduction was achieved. A spray-suppressor skirt for the LCAC has also been designed and tested at model scale, and is being installed on the full-scale craft.

NOISE

The airborne noise produced by an ACV has been a problem, and remains an item of prime consideration in design. The major noise producing elements on an ACV are the engines, propellers, and lift fans. ACVs generally utilize gas turbine engines, which generate high noise levels over a wide range of frequencies (32 Hz to 8 KHz

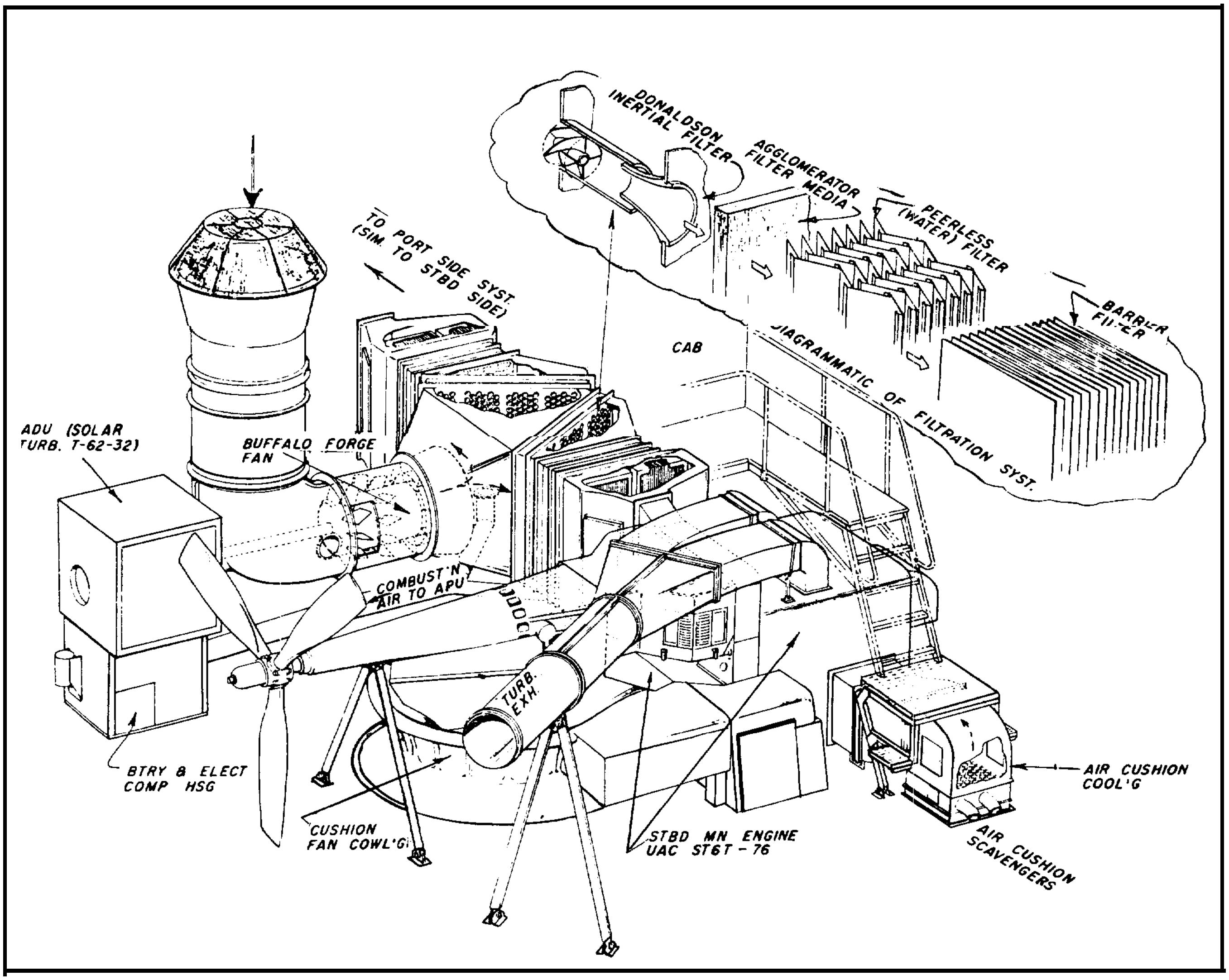


Figure 67. LACV-30 Engine Air-Management System. [18]

octave-bands). A considerable reduction in noise can be obtained with engine inlet and exhaust silencers if space is available for such devices. However, the multistage inlet air filtration systems will, themselves, provide a significant reduction in noise from the inlets.

Early ACVs utilized aircraft propellers operating at tip speeds exceeding 900 ft/sec and earned a reputation for high noise levels both internally and externally. Numerous investigations into the propeller noise problem concluded that for nonshrouded propellers, the parameters that reduced sound levels were: an increase in the number of blades, a decrease in blade-tip speed, and a decrease in horsepower absorbed by the propeller. Furthermore, reductions in sound levels of as much as one-half could be realized for shrouded propellers as compared to a free propeller of the same diameter, provided the flow remained unseparated.

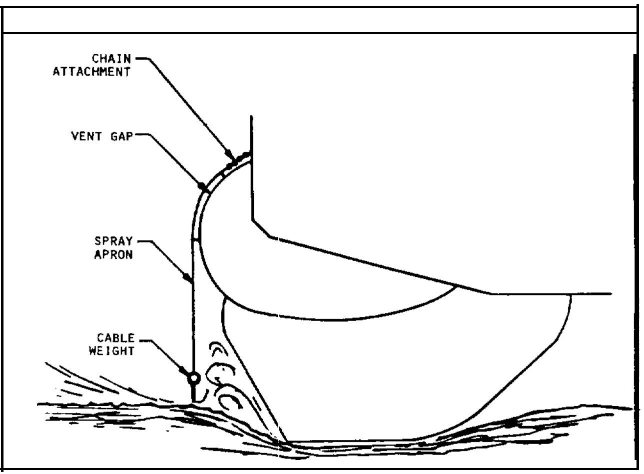


Figure 69. Original *Jeff (A)* Spray Apron. [20]

The lift-fan installation in the craft requires provisions for inducing the flow into the fan without undue disturbance of the inlet air and also for ducting to deliver the exhaust air to the cushion or seals. As the fan inlets or plenum are open to atmosphere, care must be exercised to assure that noise criteria for the on-deck and surrounding area are not exceeded. Furthermore, if the fan-exhaust flow ducts are adjacent to crew living areas, sufficient duct treatment or fan silencing must be provided in the acoustic design. Typically, centrifugal fan rotors used in ACV/SES applications range from approximately 4 feet to 7 feet in diameter and have tip speeds generally in the

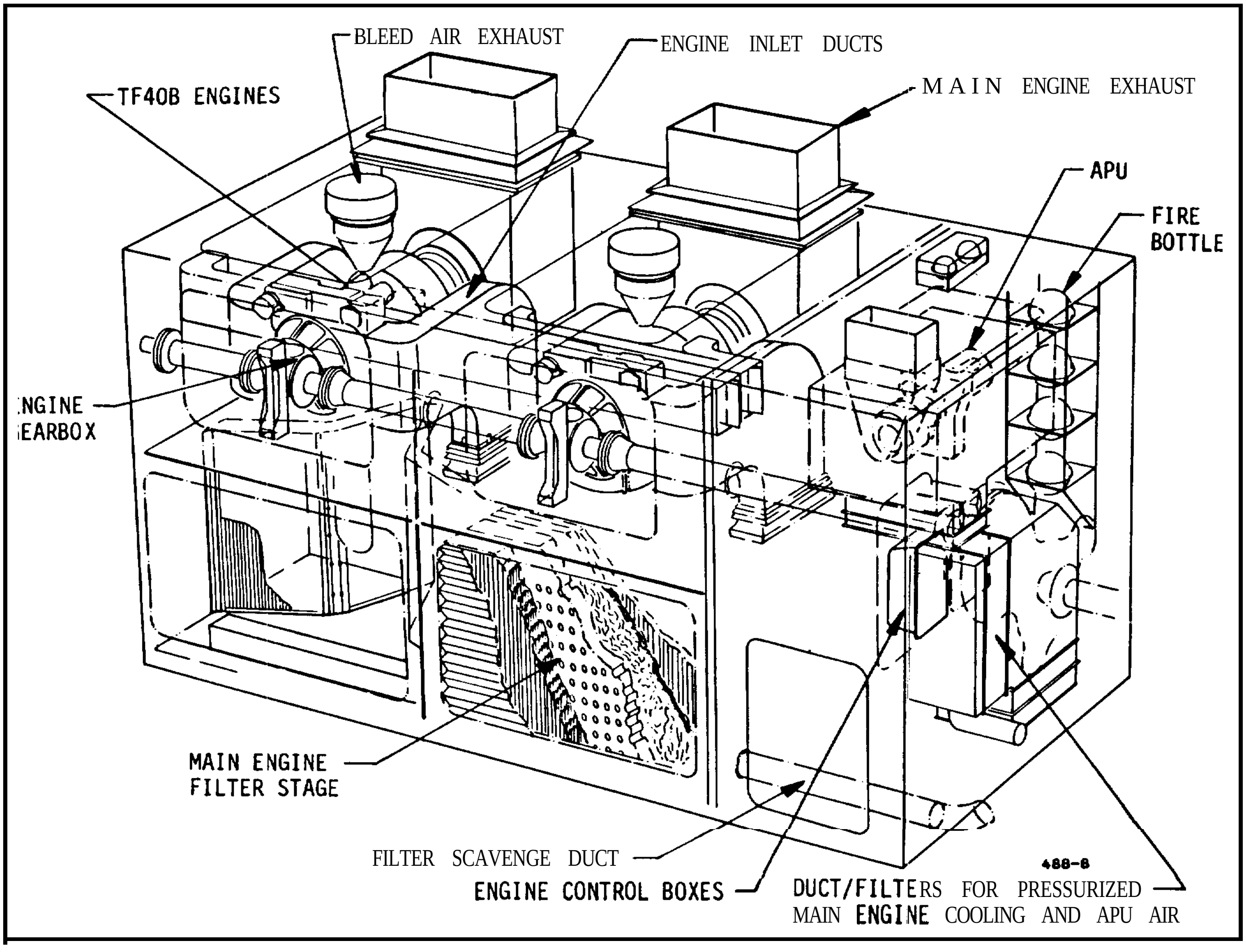


Figure 68. LCAC Engine and Air-Filtration Installation. [22]

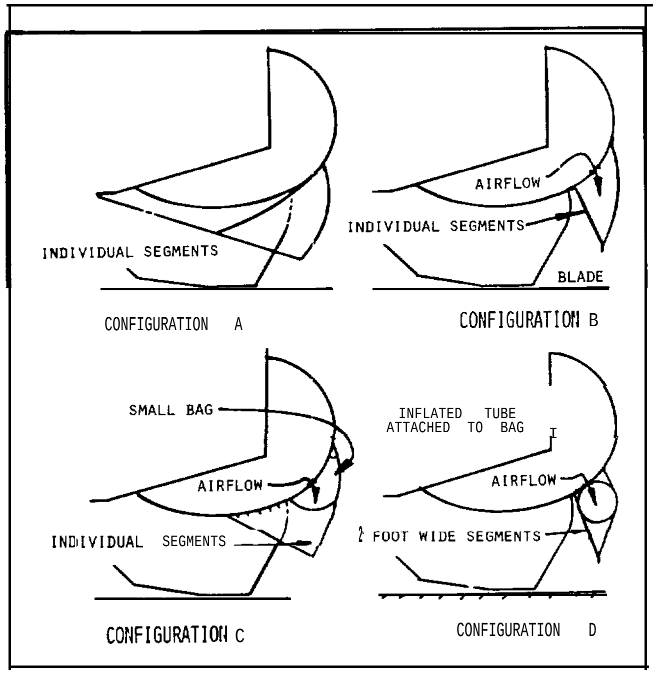
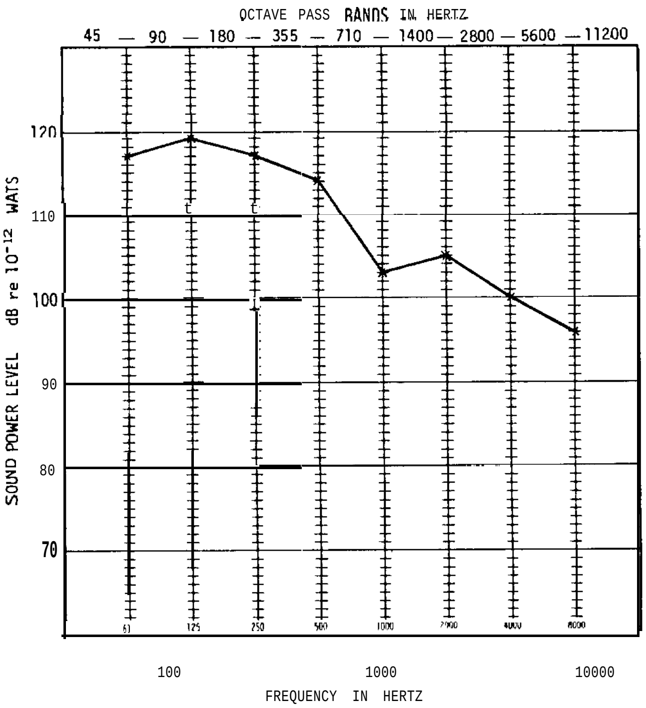


Figure 70. Jeff *(A)* Spray-Apron Development. [20]

350-550 ft/sec region. The acoustic signature of a representative ACV fan is shown in Figure 71, [21]. The overall spectrum of this signature is seen to be dominated by low-frequency noise.



FAN SIZE: 44 IN. DIA

FLOW RATE: 38,000 CFM

Figure 71. Typical Sound Plower Levels of ACV Centrifugal Fans. [21]

PROTECTION FROM THE MARINE ENVIRONMENT

ACVs designed to operate in a saltwater environment require that special precautions be taken to protect them from corrosion damage. The environment is especially severe because of the spray generated by the ACV itself, even when it is operating in calm water. Spray can be minimized by operating at low lift-power settings and by use of spray-suppressor skirts, but cannot be completely eliminated.

To prevent saltwater corrosion, the following techniques have proved successful [22]. Corrosion-resistant materials should be used throughout the craft. The hull structure should be made either of corrosion-resistant aluminum alloy of the 5000 or 6000 series or of fiberglass. When aluminum alloy is used, faying surfaces, which cause crevice corrosion, should be eliminated whenever possible. The use of dissimilar metals should be avoided, but, if they must be used, dissimilar metals should be wet assembled using an acceptable insulating compound.

Corrosion resistant materials should also be used for components in craft auxiliary, electrical, outfitting, and propulsion support systems. This is especially true for any components exposed to the weather. Acceptable materials are hard anodized series 5000 or 6000 aluminum alloy or 300 series (except 303) stainless steel. Electrical connectors should be black anodized aluminum, and electronic boxes should be an approved NEMA type.

It is important that fan bearings, propeller-hub components, and other exposed rotating machinery parts be adequately sealed to prevent dust or water ingestion. Exposed shafting and couplings. if made of ferrous metal for strength reasons, must be adequately protected by means of epoxy paints or other corrosion-resistant coatings. Fans and propellers must be made from corrosion-resistant materials and may require erosion protection as described previously.

MACHINERY VIBRATION

Vibrations generated by machinery can cause damage to the machinery, fatigue of craft structure, and discomfort to passengers or crew. Experience with the *Jeff(A)* and *Jeff(B)* has shown that vibrations can cause equipment and structural problems resulting in the craft being out of service for long periods of time. This experience has also shown that vibration problems can be avoided or eliminated.

Both ***Jeff*** craft have relatively complex (but different) machinery systems with multiple gas-turbine engines, lift fans, ducted air propellers, gearboxes. shafts, couplings, and auxiliary power units. Because the *Jeff(A)* and the *Jeff(B)* are prototype craft, vibrations have been monitored at many locations. and statistical trends of vibrations versus time in service have been maintained. Therefore, these two craft have provided very valuable vibration experience, with sufficient data so that measured vibration levels and characteristics could be generally correlated with mechanical problems believed to be caused by vibrations.

On these *Jeff* craft, there have been no reported problems of high vibration levels that have had a significant effect on human performance. However, a number of mechanical problems encountered have been attributed to vibrations:

1) Cracks in lift-fan blades and fan structure
2) Damage to internal components of a gearbox
3) Large random motions of propulsors (ducted propellers) and high propeller stresses
4) Fatigue cracks in propulsor shrouds
5) Fatigue cracks in lift-fan volutes
6) Propeller unbalance
7) Damage to hydraulic lines and fittings.

This experience has dramatically illustrated that vibrations can cause very real and serious problems on ACVs. However, these craft have also demonstrated that with careful design, monitoring of machinery vibrations, and a good maintenance program, the effects of machinery vibrations on craft operations (and availability) can be reduced to an insignificant level.

The following steps are recommended to minimize vibration problems in future craft:

1) Dynamic analyses of machinery and structure during all design phases
2) Monitoring of vibrations and torques in machinery, at least during initial craft trials
3) The development of vibration standards applicable to air cushion vehicles. (The MIL-STD-167 criteria for ships may not be suitable for ACVs).

PRODUCIBILITY AND SUPPORTABILITY

COMMERCIAL ACVs

The development of fully amphibious ACVs began within companies experienced in building aircraft. This was not surprising since skirt systems were relatively inefficient, and fan and air distribution systems suffered from small size and lack of knowledge. The need to keep the weight of the early craft to a minimum was all important.

The use of comparatively low cushion pressures was analogous to the use of low wing loadings on early aircraft. This produced a similar need for low-density, large-area structures, and a power plant with high power/weight ratios relative to more conventional marine craft.

Even when, quite early in the development of ACVs, cushion pressures were more than doubled to around 70 psf, aircraft-type structures were retained in order to maximize payload. The power employed, coupled with the use of first-generation turbo-shaft engines, meant that fuel weight was high.

Then, during the 1970s, came the development of the efficient, low pressure-ratio, responsive skirt system. This skirt was pioneered on the SR.N4 Mk.3 cross channel ferry, and its lower drag and lower demand for lift power when applied to other craft, permitted the escape from high cost "aircraft technology" into the more competitive "marine engineering" environment. This, and other developments which have occurred to improve commercial ACV producibility and supportability, are reviewed below.

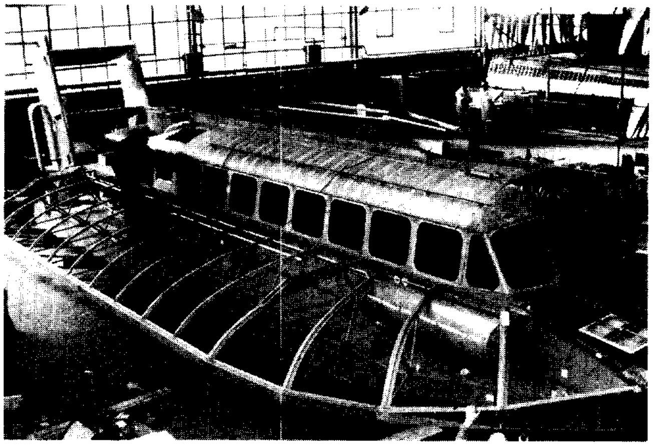


Figure 72. SR.N6 Structure.

Production Techniques and Processes-Early Craft:

All the early amphibious ACVs used lightweight skin and stringer design in aircraft-type alloys. However, the Saunders Roe SR.N2 and SR.N3 ACVs employed a certain amount of Redux bonding, particularly in the buoyancy tank construction, where it was used to attach stringers and frame booms to the webs. The use of Redux bonding was extended in the next Saunders-Roe craft to be designed, i.e., the SR .N5/SR.N6 family, but even so, the structure was complicated with a considerable amount of very thin plating and mechanical attachments, (Figure 72). The plating on the rounded outer decks was as thin as 26 gauge (0.5 mm) (Figure 73). Redux bonding had the important advantages of low cost relative to riveting, watertightness, and very high corrosion resistance.

For the next generation of hovercraft (SR.N4/BH7), highgrade alloys were retained, but extensive use was made of sandwich panels for buoyancy tank and deck construction. This method of production utilized 8 ft x 4 ft panels of a simple nature that could, if required, be made strong enough to carry the wheel loads of cars and

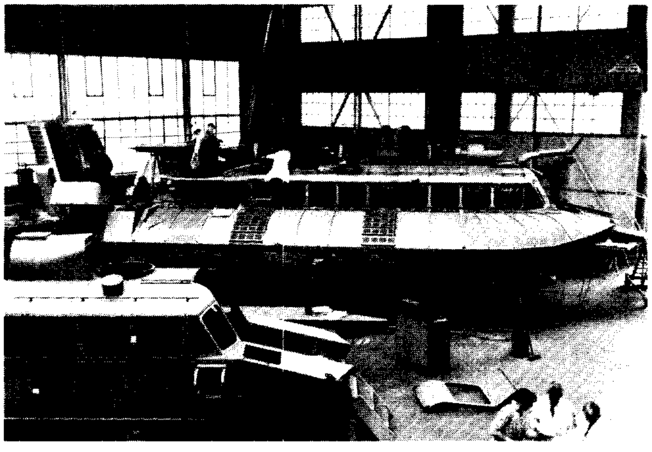


Figure 73. SR.N6 Outer Deck Plating.

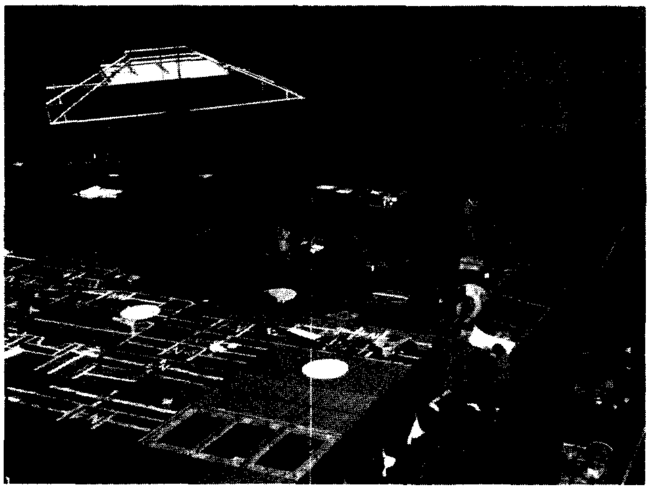


Figure 74. **SR.N4** Buoyancy Tank Construction.

coaches. Although thin-skinned, these honeycomb-cored panels gave excellent service; some of the craft having been in operation for more than 16 years (Figures 74 & 75).

However, edge grain balsa was used as the core for deck panels and some vertical bulkheads on the BH7, and this proved unsatisfactory, particularly in hot climates where the slightest damage to an outer skin allowed salt water to enter, leading to extensive corrosion.

Another form of construction that proved highly successful was the use of large GRP-skinned sandwich panels with a core of rigid PVC. These panels were used to construct the bow of the BH7, which also carried large amounts of fuel internally, (Figure 76). The largest panel made was the SR.N6 cabin floor, which measures 8 ft x 40 ft x 3 inches thick.

Although a great deal had been done to simplify this type of contruction, the structure still remained expensive to produce. A large number of components were involved, and all of them had to be rigorously cleaned and painted. Mechanical fastening was extensive, and sealing and corrosion protection had to be carefully done. All of this was labor intensive.

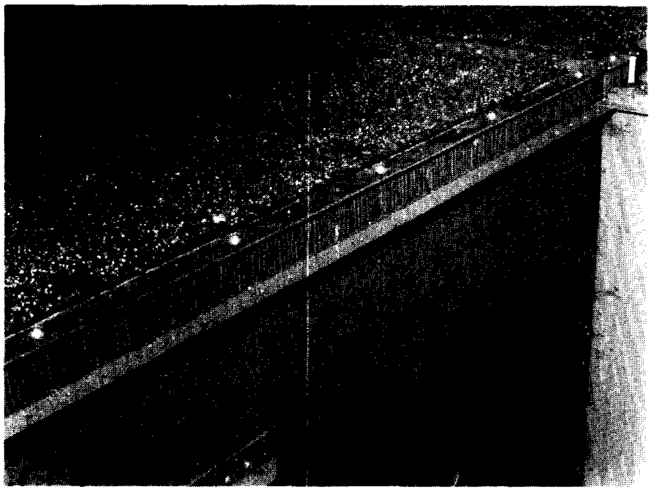


Figure 75. SR.N4 Honeycomb Panel.

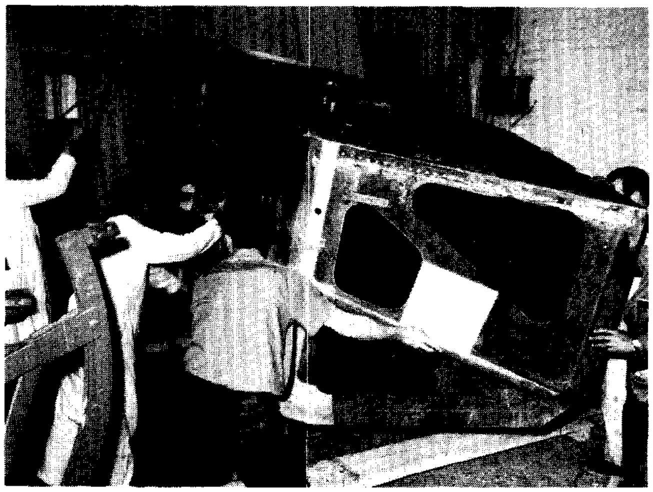


Figure 76. BH7 Bow Component in GRP.

The emphasis on weight control *was* also significant in the machinery used on the craft. All Saunders-Roe/BHC craft after the SR.N1 were gas turbine powered with integrated lift and propulsion systems intended to ensure maximum use of power available. The transmission involved speed reductions, division of power, and changes of direction in order to drive both lift fans and propellers from the high-speed turbine output. This involved expensive gearboxes and transmission components (see Figures 77 & 78). Because of the amphibious nature of the ACV, maneuvering control relied on vectored thrust or air jet-supplied from the cushion. To achieve this, variable-pitch propellers developed from aircraft types were used. For the SR.N4 & BH7, rotating pylons were used with a total weight of over two tons (Figure 79). All these systems require the additional complexity of a hydraulic system.

The result was a purchase price, maintenance cost, and running cost above what the civil market would bear, particularly after the escalation of fuel costs in the 1970s.

Development of AP. I-88

Late in 1979, British Hovercraft decided to replace the SR.N6 with a new family of passenger/utility craft.

The criteria for the design were:

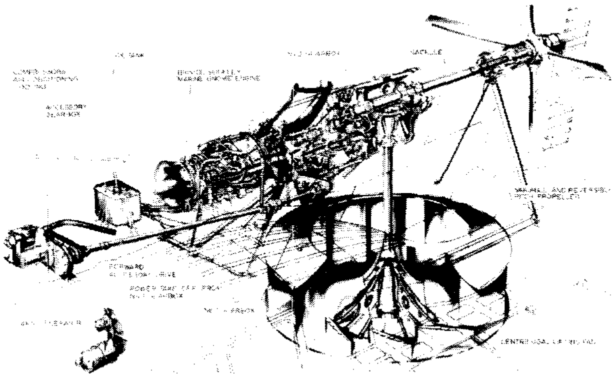


Figure 77. SR.N5/6 Transmission.

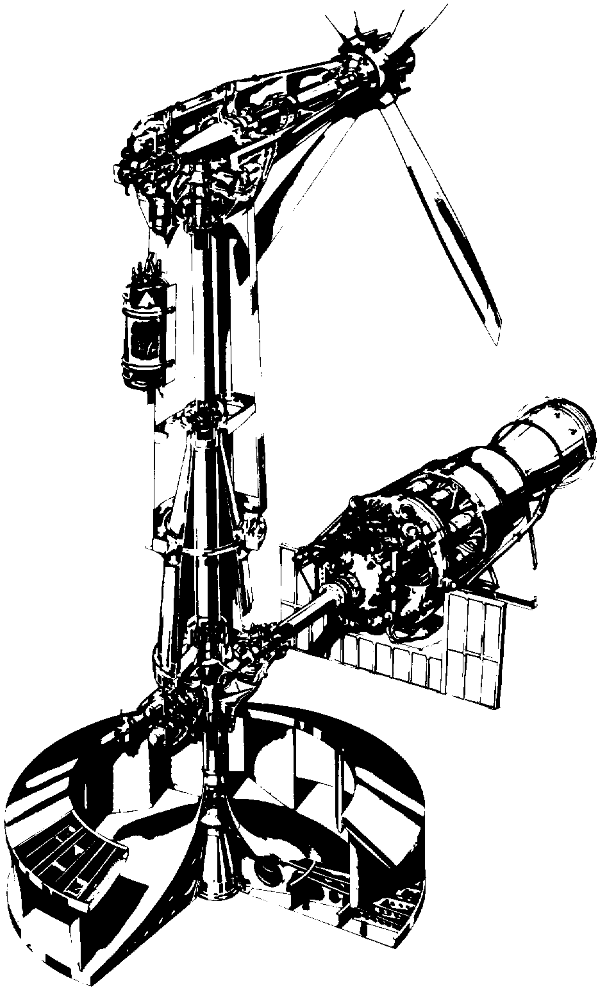


Figure 78. SR.N4/BH7 Transmission.

1) Production cost per passenger seat place to be 1/2 SR.N6 value.
2) Operational cost per passenger mile to be 1/2 SR.N6 value
3) External noise levels to be considerably reduced
4) Passenger comfort to be improved.

This meant a drastic review of the whole design and construction philosophy. From the cost point of view the following choices were clearly indicated:

a) The extensive use of automatic welded structures to reduce the constructional cost:
b) The use of diesel engines to cut both initial and operating costs.

These changes could be contemplated with the attendant increase in weight because of the development in skirt technology over the previous decade; in particular, the low pressure, responsive skirt, first introduced in the design of the SR.N4 Mk.3 (Figure 80).

On that craft the potential reduction of both cushion power loss and overwave drag was used to permit a stretch of some 50 ft of the SR.N4 Mk.2 design, increasing payload by 80 percent for a very small increase in power.

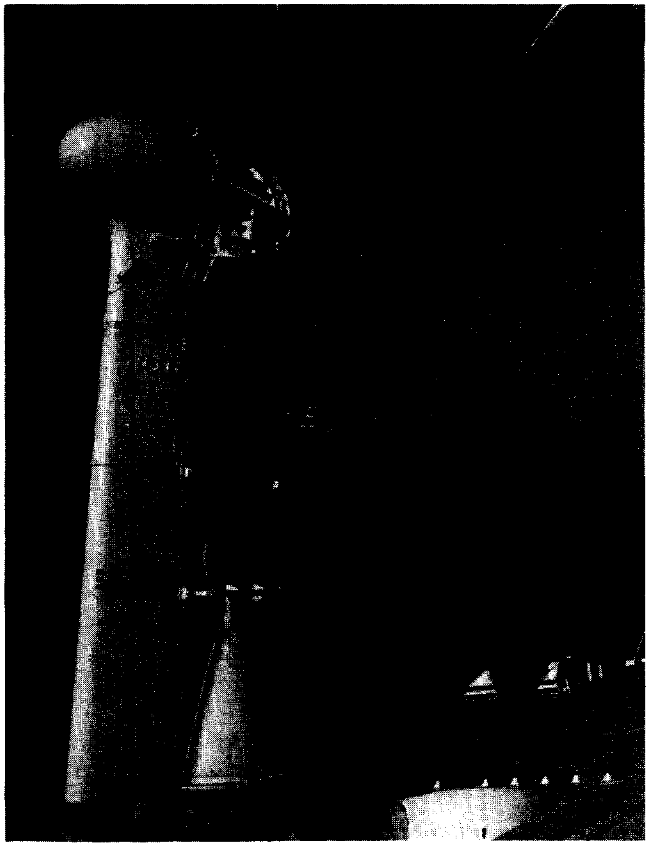


Figure 79. SR.N4 Propeller Pylon.

The AP.1-88 design employed the efficiency gain available in the new skirt to permit the use of heavier structure and power plant rather than to increase payload. The result was a craft with a welded light-alloy structure, similar to that of conventional marine craft, powered by lightweight, aircooled diesel engines (Figure 81).

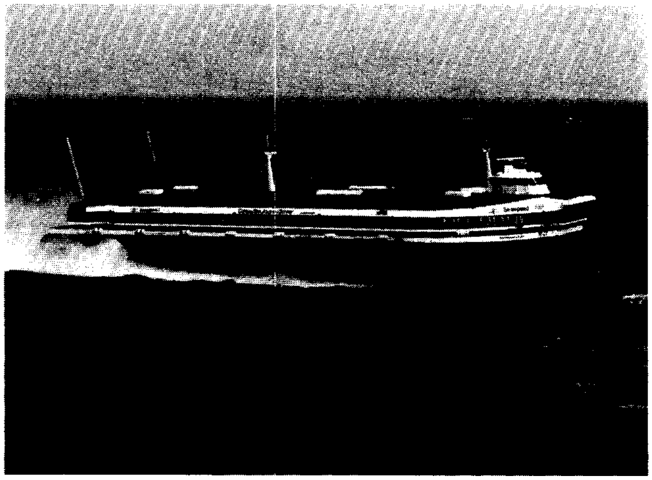


Figure 80. Super 4 (SR.N4 Mk3).

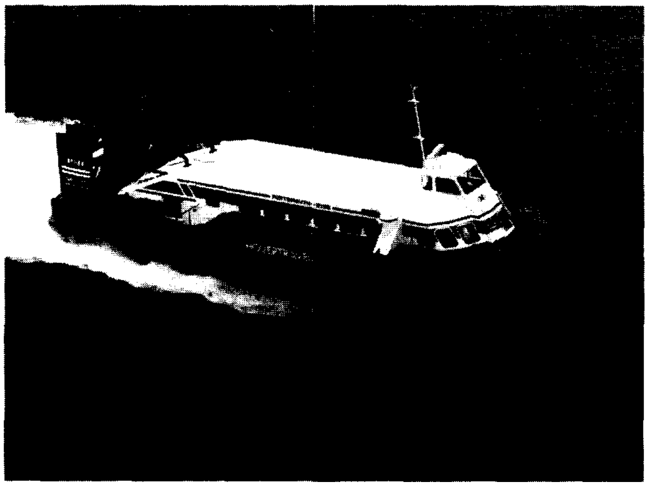


Figure 81. AP.1-88/80.

Structural Design

To reduce labor costs of the craft, the number of components. and therefore the amount of welding, was minimized by the extensive use of large, light alloy extrusions. Areas involved included the buoyancy tank frames, the top and bottom plating, and the roof frames. The only significant area of the structure that was not welded was the corrugated roof panelling, which was not thick enough to weld satisfactorily. In order to reduce heat distortions, machine MIG (metal arc inert gas shielded) welding was used extensively. Where this was not possible, either manual MIG or TIG (tungsten arc inert gas shielded) was used on thicknesses down to 2 mm.

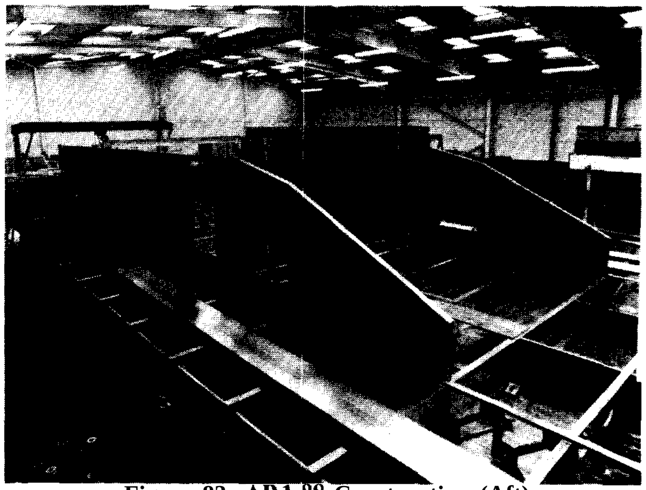


Figure 83. AP.1-88 Construction (Aft).

Use was made of electric seam and spot welding for doors and hatches that were mainly of 1 mm thick material. The bow and side structure used drawn tube, 76 mm diameter, as the gunwales and stringers. Figure 82 shows the basic structure; Figures 83 and 84, the craft under construction; and Figure 85, the interior of the passenger cabin.

The result of using this type of construction is that the structure weight per unit cushion area is approximately twice that of an SR.N6.

Machinery

The cost and complexity of the lift and propulsion systems were also drastically reduced. The use of air-cooled

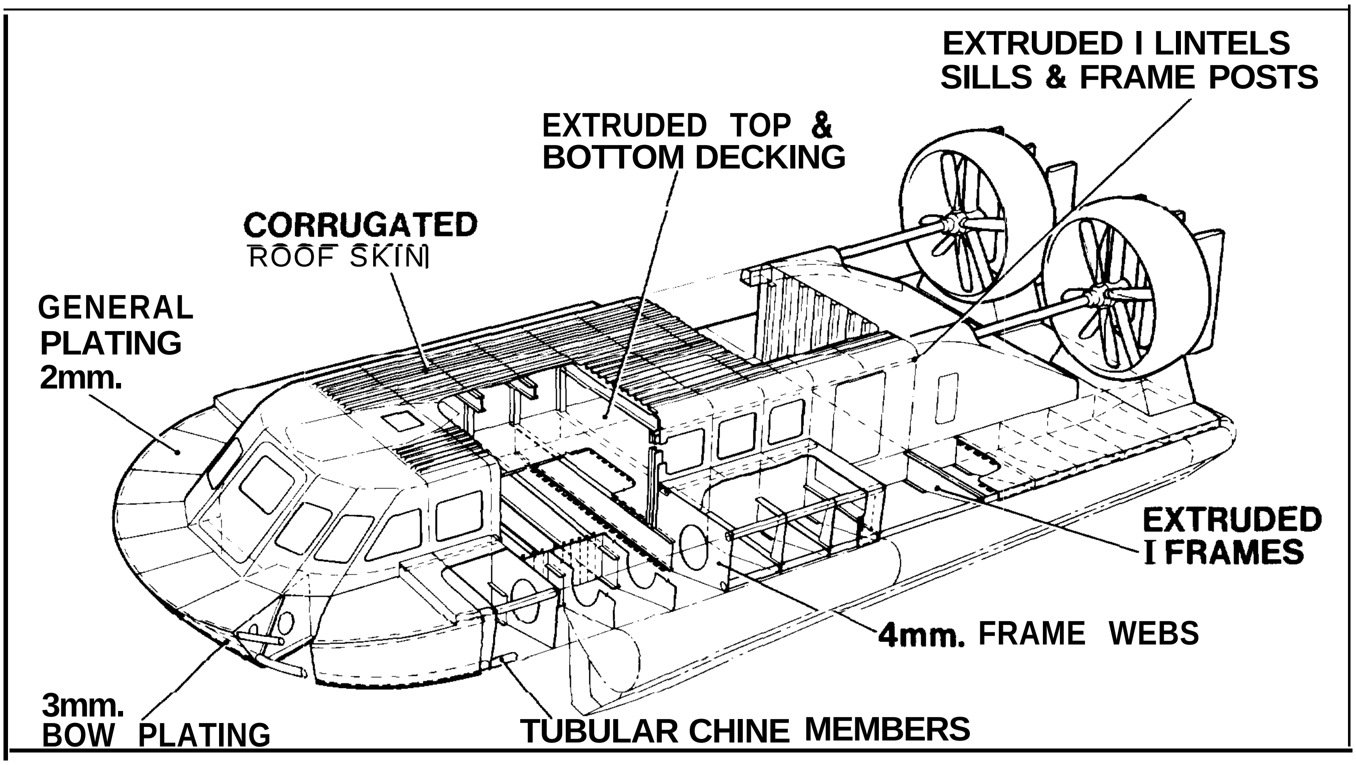


Figure 82. AP.1-88 Structure.

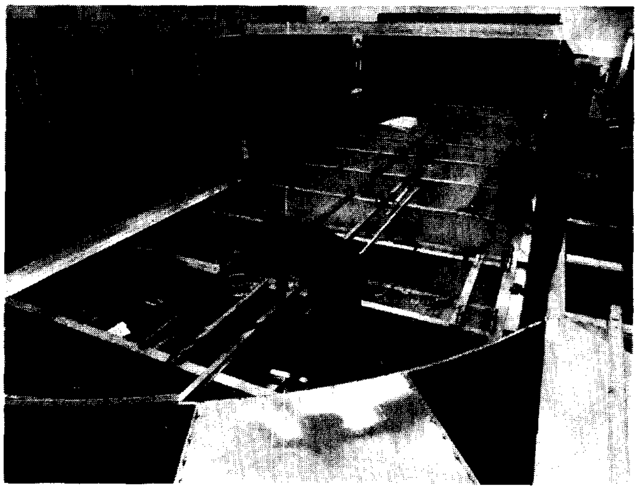


Figure 84. AP.1-88 Construction (Forward).

diesel engines. for example, reduced the initial cost of the power plant to some 15 percent of the cost of an SR.N6 gas turbine power plant. Moreover, the lower output speed of the diesel permitted the lift fans to be directly driven without a reduction gear, greatly simplifying the layout of the system and enabling it to be housed in the side structure, partially below the level of the buoyancy tank. This resulted in a lowering of the craft CG.

Similarly, the propeller-to-engine speed ratio was only 0.6. This permitted the use of a toothed belt without any other speed reduction device, not only reducing the cost of the installation, but greatly simplifying the setting-up procedures and tolerances required.

The absence of gearboxes provided further simplification. There are no pumped lubrication systems on the craft except those associated and integrated with the engines. All bearings are grease-lubricated with the exception of those supporting the propeller, which runs in an oil bath.

A further major departure from previous convention was the use of a fixed-pitch propeller. From a production point of view, the absence of the control mechanism, normally electrohydraulic, with all its associated pumps, tanks, filters, and pipe work, greatly simplified the craft. The lengthy setting up procedures and complex trials associated with the approvals of a variable-pitch propeller were thus eliminated. The propeller design chosen, produced by Hoffmann, consisted of an aluminum-alloy hub with wooden blades coated in glass and carbon reinforced plastic.

While the financial savings incurred by the use of a fixed-pitch propeller are large (costs are one-fifth that of variable-pitch propellers), the AP.1-88 is more complex because it uses propeller ducts. This use arises from the need to minimize external noise and provide extra thrust for adequate hump performance (Figure 86).

Finally, at the expense of some weight, wherever possible, commercially available components are used. While this has led to some quality problems, the saving in manufacturing time and cost has been considerable.

Systems

The same philosophy of simplicity to reduce cost has been applied to the craft systems.

Control is by means of rudders in the propeller slip stream (Figure 86) and by bow thrusters. It was apparent that rudder hinge moments would be too great for manual operation so a small hydraulic power-assist system, based on automotive equipment, was used. Elevators, which give some degree of craft pitch control, are manually operated, and both systems use Bowdenflex cables to simplify the control runs.

As in all BHC craft, the fuel system also doubles as a ballast system to provide craft trim control, and the basic principles have not altered significantly. Changes have been made in that the fuel is contained in welded aluminum cylindrical tanks, and the small-diameter fuel feed lines are steel. Aluminum alloy is retained for the larger diameter ballast and ventilation pipes.

The need to meet marine specifications and requirements had an adverse effect on the electrical system. "Earth return" systems were not acceptable to marine authorities, and the amount of cabling was therefore

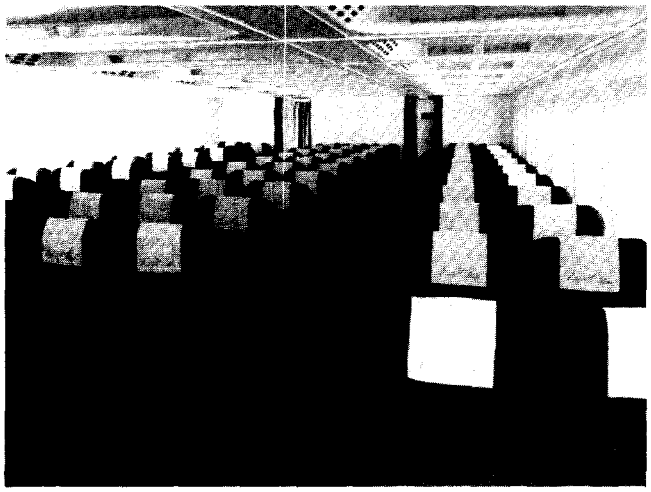


Figure 85. AP.1-88 Passenger Cabin.

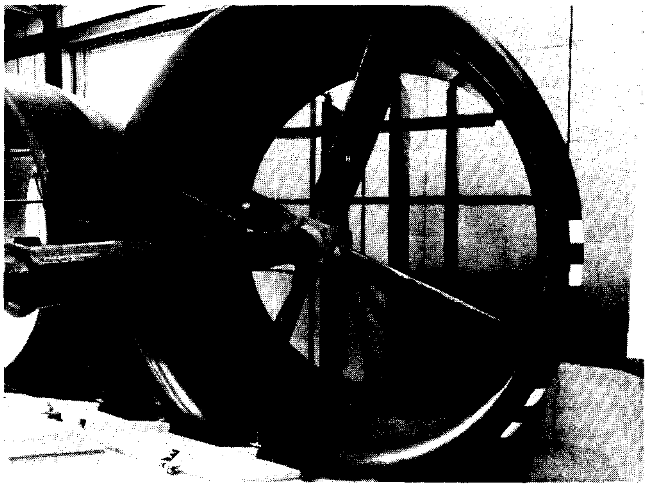


Figure 86. AP.1-88 Propellers and Ducts.

nearly doubled. The use of multiple engines, however, means that power supplies can be reliable without the use of an auxiliary power unit.

Cost Savings

To give an indication of the cost savings involved, the labor content of design and production of the AP.l-88 and the latest version of the SR.N6 have been compared on the basis of man hours/seat place. Using this criterion, the AP.l-88, 80-seat craft design labor cost was 52 percent less than that of SR.N6. The production craft, when allowance is made for the contribution of the prototype, gives a figure of 36 percent. The difference is largely due to the changes required for a foreign government.

Similarly, the AP. l-88 100-seat craft are already showing, on the basis of seat place, 20 percent and 50 percent less man hours required for manufacture of the third and tenth craft as compared to the SR.N6. Furthermore, many of the aircraft skills required for SR.N6 are not needed. and the craft can be built in a normally competent boatyard familar with high-speed craft.

Supportability

While the simplicity of the machinery together with the use of commercially available equipment have been instrumental in reducing first cost, cost reduction is even more significant on the operational side. This can be illustrated by the following facts.

The servicing schedule for SR.N6 has some 80 separate routine servicing items. while the number for the AP.l-88, a significantly larger machine, is only 20. Overhaul costs, particularly of engine and propeller, have formed a significant proportion of the direct operating cost on previous ACVs. The overhaul life of the Deutz diesel used in the AP.l-88 is predicted at 8000 hours, compared with the best achieved on the SR.N6 Gnome gas turbine of 2000 hours. The net result is a reduction of engine overhaul cost per operating hour to 25 percent.

A similar pattern is evident on the propeller. The AP. l-88 propeller has an unlimited retirement life. While the current overhaul life for the blades is two years, this period is primarily a development check and will be extended. The SR.N6 propeller has an overhaul life of 2250 hours, and a blade retirement life of 4500 hours. These figures, to some extent, represent an obsolescent propeller and one governed by aircraft design. Nevertheless, they are indicative of the differences in complexity. The saving on propeller overhaul cost is approximately 80 percent.

Operational Experience

The first two AP.1-88/80 craft went into service in the spring and summer of 1983. By June 1984, they had totaled nearly four thousand operating hours. The AP.1-88/100 craft, 004 and 005, started the Malmo to Kastrup run on 16 June 1984 after a short period of intensive training. Operational costs are not yet available from the AP.1-88/80 operation, and at the time of writing insufficient data had been obtained from Denmark. However, indications are that the cost savings anticipated in the original design are being achieved.

MILITARY ACVS

The requirements for the producibility of military ACVs are basically similar to those for commercial ACVs; the primary objective is the optimum compromise between cost and weight. Cost reductions are usually best achieved by following conventional shipyard design and construction methods, while weight reduction, on the other hand, is best met with the technologies of aircraft manufacturing. Using existing production facilities, either shipyard or aircraft factories are adaptable to the production of military ACVs. This is because, in most cases, the total production requirement does not justify the investment in new facilities. There is always a danger, however, that if the production of ACVs is mixed with the manufacture of other products, ACV production will tend to drift towards the basic production system. For a shipyard, this would mean increasing weight, and, for an aircraft facility, increasing cost. If the production quantities are significant enough, as they are with the U.S. Navy LCAC program, for example, then a facility can be built to meet the exact requirements of ACV production. This has occurred with the Bell Halter facility, as discussed later.

There are additional requirements affecting the producibility of military ACVs that do not exist to the same degree in the commercial world. These are associated with the integrated logistics support (ILS) and the reliability, maintainability and availability (RMA) requirements of the military. Without exception, almost all of these requirements result in increased cost, increased support analyses and documentation, increased manufacturing, and increased procurement for spares.

The basic hull structure of a military ACV is not the main culprit in cost increase. The structure is under the direct control of the ACV designer and is generally almost completely designed to meet the specific requirements of the ACV application. The cost impact is a direct result of the equipment and systems that must be selected from already existing items developed and produced for application in the marine or aircraft world. Much of the availabile marine equipment, if produced to military specifications, is for conventional large warships and too heavy for ACVs. The cost to modify and reduce weight is significant. Small marine equipment is generally only available for commercial use, and here the cost increase results from modifying and qualifying equipment to meet military specifications. Aircraft equipment available for ACV applications is lightweight and often already meets military specifications. It may, however, require considerable modification, marinization, or protection to qualify for operation in the marine environment. When the market potential for new equipment is sufficiently high, the producers will often make the required investment to manufacture or qualify their existing products or systems to meet specific applications. Unfortunately, the market is small compared to that of conventional ships or aircraft. As a result, the additional cost to modify, develop, and qualify equipment for ACV applications must be borne by the actual AC'V military programs.

The following is a review of the U.S. Navy LCAC program, an example of the present day state of the art with respect to producibility and supportability.

The LCAC, shown in Figure 87, is of aluminum-alloy construction, since it is weight sensitive, and powered by four gas-turbine engines that drive two aircraft-type propellers for propulsion and four centrifugal fans for lift air. A bag-finger skirt of natural rubber-coated fabric surrounds the craft to retain the air cushion. Powerful controls are provided by propeller differential pitch, four aircraft-type rudders, and two swiveling bow thrusters. The propellers are ducted to increase low-speed thrust, and reverse pitch is provided for reverse motion of the craft.

Plans for the LCAC include equipping the fleet with a substantial number of these vehicles and achieving a production rate of one per month. While recurring structural cost is important, structural weight is also crucial, as it is with all airborne craft. The structural design has been a compromise between structural weight and producibility. At the same time. the need to transport Marine Corps equipment (including heavy construction vehicles, tank recovery vehicles, etc.) with a craft that is reliable in the severe marine environment, while still meeting certain maintainability goals, has been met.

The LCAC hull structure is shown in Figure 88. The hull is fabricated from 5456 aluminum plate and extrusion and consists of a buoyancy box and attached superstructure modules for personnel, machinery, and equipment. The buoyancy box is a raft-like structure 4 l/2 feet deep, 81 feet long. and 44 feet wide. It consists of nineteen transverse bulkheads, three longitudinal bulkheads, two sidewalls. a main deck, and a wet deck. The entire structure is a welded assembly, and all stiffening is on 9-inch centers.

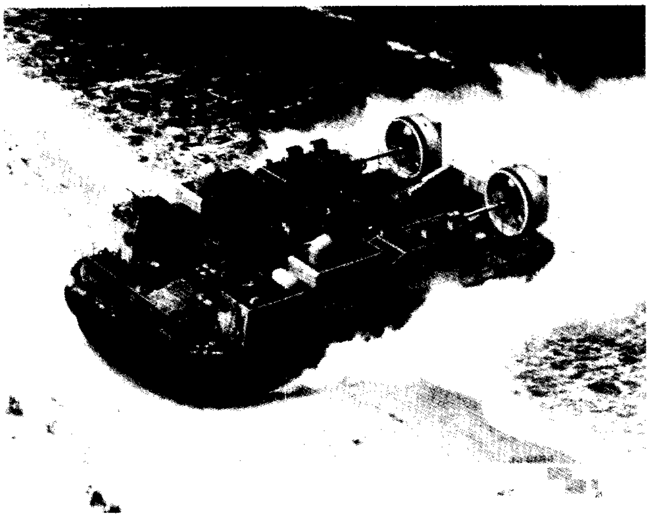


Figure 87. Artist Illustration of LCAC.

The transverse bulkheads, fabricated from 0. l-inch plate with vertical flat bar stiffeners, are spaced typically on 4 l/2-foot centers, with additional partial bulkheads in the region of the fan volutes. The longitudinal bulkheads are on 12-foot, 9-inch centers, with the center bulkhead on the craft centerline. All bulkheads have reinforced openings and hatches for access.

The main deck includes the 28-foot-wide cargo deck and the machinery decks, which extend 8 feet on either side. The cargo deck is of 3/8-inch plate, heavily stiffened to sustain the loads produced by any wheeled or tracked vehicle used by the U.S. Marine Corps, including the M-l and M-60 tanks. The cargo deck also contains four longitudinal rails that have sockets on 12-inch centers for cargo tiedown.

The machinery decks on either side of the cargo deck are of l/S-inch plate stiffened with 3-inch-deep stiffeners. These decks contain foundations for the various superstructure modules, each of which is attached at four points. The wet deck, which forms the lower surface of the buoyancy box, is externally stiffened with extruded channel stiffeners. Four large aluminum castings, each 17 feet long, 12 inches wide, and 12 inches deep, are inset into the wet deck; these act as landing rails for the craft. The wet deck also contains openings for air feed from the fans and openings to the cushion and stability seals. These openings are reinforced to carry hull girder bending and torsion loads. Attached to the buoyancy box is the control module, which houses the crew and electronics gear; the personnel module, which houses troops; two engine modules; two fan modules; and the bow and stern ramps for loading and unloading vehicles.

The superstructure modules are also constructed of tee-stiffened plate, with generally vertical stiffening, to take advantage of internal floors and decks to support stiffeners. Numerous openings are built into the engine-module structure for engine access, engine exhaust, engine combustion air, compartment cooling air, etc.

The structural design philosophy was driven by the need to minimize initial cost, weight, and life-cycle cost.

The major structural consideration in minimizing initial fabrication cost was the use of all-welded construction. Welded construction involves significantly fewer manhours than mechanically-fastened construction; some quantitative data will be given later. In addition, welded construction lends itself more readily to automated fabrication, particularly if the structure is designed initially with that in mind. For this reason, the LCAC structure has been designed with (emphasis on longitudinally-stiffened flat panels, which are compatible with automated welding with a vacuum table, automated stiffener loading equipment, and automated stiffener tracking welding heads. Following this approach has resulted in 70-percent of the welds being made mechanically and only 30-percent manually.

Extensive use has also been made of extrusions to obtain efficient shapes and to combine multiple functions, all with the same objective: avoiding costly machined or formed parts.

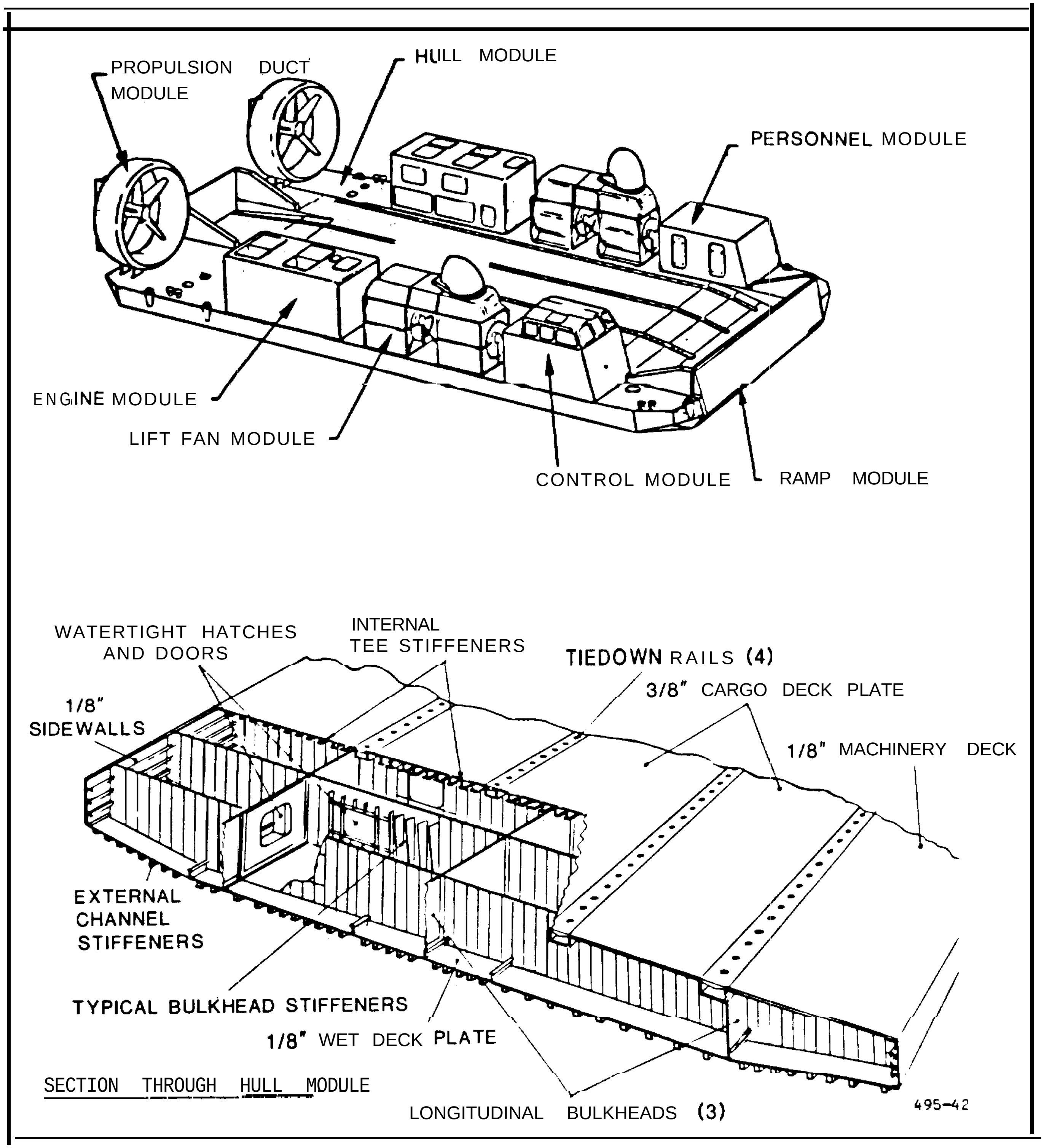


Figure 88. LCAC Hull Structure Arrangement.

Structural life-cycle cost has been minimized by characteristics that maximize structural reliability and minimize the manhours required for maintenance. For the structure, the principal consideration in maximizing reliability and minimizing maintenance, is corrosion. Problems of corrosion have been minimized by the use of corrosion-resistant aluminum alloys, specifically 5456 and 5086 marine alloys; the almost complete avoidance of mechanical fastenings and dissimilar metals; and elimination of exposed faying surfaces, in order to avoid crevice corrosion. The corrosion resistance of the 5000-series aluminum alloys is well (established. Furthermore, they require no paint or anodic treatment.

Only hatch attachments and ramp hinges have mechanical fastenings. This minimizes dissimilar-metal effects and also avoids corrosion under aluminum rivet heads, which has developed ***on Jeff(B).*** Exposed faying surfaces exist only in a few small voids, where access is not possible and must be closed from the exterior, and a limited number of fillet welds that, because of access limitations, can be welded only on one side. All voids can be easily inspected for corrosion, and satisfactory weld penetration criteria have been established for single-sided fillet welds.

Life-cycle cost is also minimized by welded construction, since all of the structure is repairable by welding. Welded construction minimizes the number of tools and types of equipment required for maintenance, the number of skills required, and the variety of materials and parts that must be stocked. Only a few thicknesses of plate and a selection of extrusions are required for almost any structural repair. A limited number of castings are used in the structure in the interest of minimizing cost. Castings can also be repaired by welding, although slightly more skill is required than for repair of wrought material.

Finally, life-cycle cost is minimized by establishing a maximum time between structural inspections. This time is based on fracture mechanics analysis in which generous assumptions are made regarding the size of a crack that might go undetected in an inspection. Limited regions of the structure, where the local strength is critical and redundancy is not present, are inspected each year, while the remainder of the structure is inspected every two years.

The LCAC is intended to be produced at a rate that precludes the use of conventional field fit and hand assembly methods. In addition, a target recurring cost was set that demanded a fabrication approach with low labor content. These requirements were approached for the LCAC by the following methods:

1) Extensive use of flat, longitudinally stiffened panels, to permit automated welding,
2) Modularization of all superstructure components,
3) Complete detailing of all structural parts,
4) Minimum use of machined fittings or parts in the structure,
5) Maximum use of extruded sections.

All of the decks, sideplating, and superstructure plating are constructed from flat plating stiffened with extruded stiffeners. These stiffened plates are welded with equipment designed and built for this purpose. This equipment includes a vacuum table to hold the plating flat and a carriage that is programmed to traverse laterally and longitudinally across the panel. The carriage is fitted with equipment to automatically position and hold the stiffeners and then weld them in position. Figure 89 shows the automatic welding equipment in operation.

Plating flatness tolerances are particularly critical on this craft, except as they affect assembly of details and subassemblies. However, plating flatness is easily maintained by the relatively closely spaced stiffening and by the automated welding of plating stiffening on a vacuum table.

Other fixtures that are used for assemblies and subassemblies include the hull assembly fixture shown in Figure 90. This fixture is equipped with a semiautomatic traversing welding gantry so that the individual deck panels, already provided with stiffeners, can be welded together. Other elements that are welded in with this equipment include four large rails that run the full length of the cargo deck and have sockets every 12 inches for vehicle tiedown.

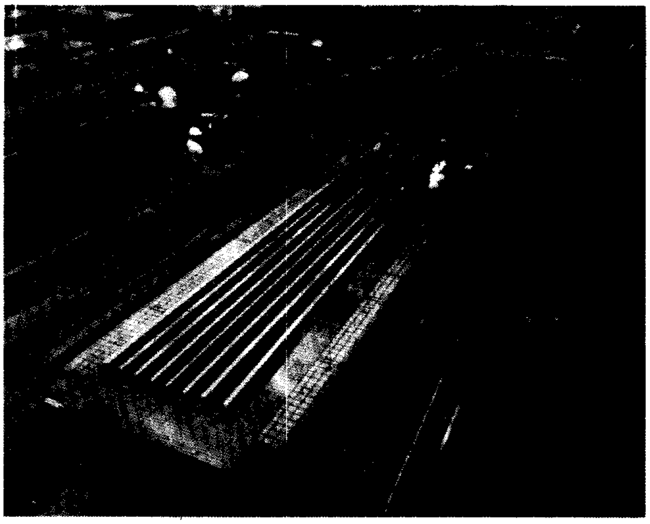


Figure 89. LCAC Automatic Welding Equipment.

The hull assembly fixture is actually an assembly line with three work stations suited to different assembly functions. The first station welds up the main deck; the second installs transverse frames. the longitudinal bulkhead, and the four corner assemblies, previously assembled on other fixtures; the third station installs the wet deck, associated landing rails, and skirt attachment extrusions. Separation of these stations not only permits the application of tooling, for the specific assembly steps, but also provides for the application of more manpower than could be used with a single fixture. A specially designed rail system is built into the assembly fixture to lift the hull slightly and move it from one station to the next.

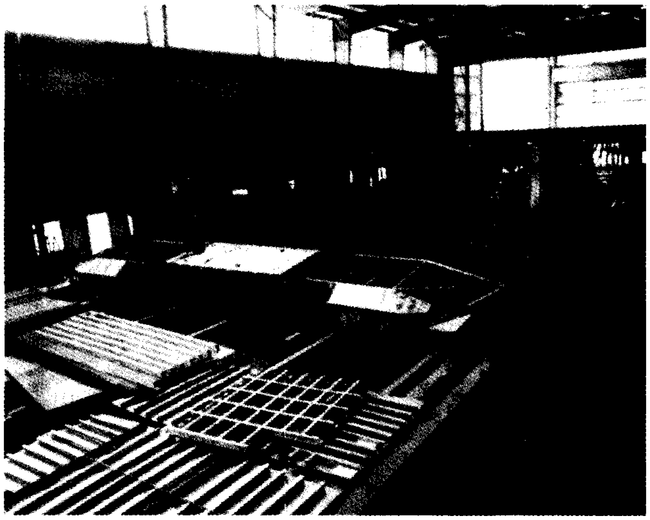


Figure 90. LCAC Hull Assembly Fixture.

Modularization of the superstructure also permits these components to be assembled and completely fitted with vehicle systems, such as the fuel system, the lubrication system, the electrical system, etc., without impeding the hull assembly. Multiple assembly fixtures are provided for these components, depending on their complexity and the amount of manpower that can be applied to each, so that superstructure assembly can keep pace with the hull assembly line. For instance, five parallel control-module assembly fixtures are provided, since this component contains extensive amounts of electrical wiring, and space limitations prevent the application of a large amount of assembly manpower at any one time. Similarly, four engine-module fixtures are provided. These modules are fully equipped with engines and transmission systems, all finally aligned before they are placed on the hull.

Separation of the superstructure into modules has also produced structural benefits. For instance, the modules are isolated from hull girder bending. Although this might seem to be undesirable, because it produces a hull that is only a relatively shallow box, this proves not to be so. By using only the hull as the primary hull girder, the massive cargo-deck structure, which is designed to carry heavy cargo, is also made to contribute to hull stiffness. If the superstructure were a part of the hull girder, the cargo deck would be near the girder neutral axis and relatively ineffective for resisting overall bending loads. Hull vibration modes and frequencies have been calculated to ensure no resonance with wave-induced or machinery-induced excitation forces. Response of the hull to transient wave impact loadings has been considered in the hull-bending moments, stresses, and fatigue analysis.

In addition, when the superstructure is part of the hull girder, the superstructure becomes the main shear carrying member of the hull because of its depth. This creates larger bending moments in the transverse hull frames, with appropriate weight penalties, and requires heavy reinforcement of the many openings in the superstructure that are necessary for access, air intakes, exhaust openings, etc.

This superstructure scheme is taken to the point where each module is essentially a four-point attachment to the hull, with built-in tolerance and shimming provisions for proper alignment and positioning. Therefore, final assembly of the modules to the hull and connection of systems and services is rapid.

To minimize machining, extensive use has been made of extrusions, with many special shapes being created. Tapering of members has been used extensively where it involved only the shape cut from a flat plate, but tapering by more costly machining has been used more carefully, and only where significant benefits result.

SUMMARY

This chapter has reviewed the most important technical issues, recent developments, and applications of amphibious ACVs. The chapter has shown that much has been accomplished in recent years to simplify design, to streamline production, and to reduce ACV acquisition and life-cycle cost. With few exceptions, ACV technology is mature. and we are now entering an exciting era of renewed ACV activity. 'The company of U.S. Army LACV-30 lighters at Fort Story, Virginia, will soon be increased to a total of 26 craft; the first of an initial batch of U.S. Navy assault landing craft, LCACs, are undergoing trials at Panama City, Florida; the U.S. Army is gearing up to procure a new family of heavy-lift hoverbarges. and the low cost BHC AP.1-88 is paving the way for a revival in the ACV commercial ferry industry.

It is clear that the key to the success of the ACV will continue to be the exploitation of the many advantages of its amphibious capability. The few problems that remain are minor for most applications. They include the undesirable high rates of propeller-blade erosion and skirt wear and remain the subject of on going development.

The success of the ACV can be attributed to developments in technology which have provided improved efficiency, improved controllability and reduced operating costs. Advances in skirt design, lift fan and propeller design. the development of bow thrusters, and all-welded marine aluminum hulls, have all contributed significantly to this success.

In the past. ACVs have been expensive largely due to machinery costs. Gas turbine engines, controllable pitch propellers, and high-speed lightweight transmissions are all expensive. The BHC AP.1-88, which utilizes air-cooled diesel engines, fixed-pitch propellers, and a toothed-belt drive is an example of an approach to a much less expensive ACV[1]. Trends such as these plus continued improvements in basic technology will ensure the future growth in use of these versatile craft.

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