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THE OPEN OCEAN HYDROFOIL SHIP: WILL IT COME OF AGE?

by

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Abstract of

THE OPEN OCEAN HYDROFOIL SHIP: WILL IT COME OF AGE?

Problems encountered during development of the hydrofoil ship have restricted exploitation of its unique characteristics in an open ocean environment. An examination of pertinent physical and technical constraints is undertaken to assess their impact upon the future. The focus of this examination is centered upon the evolution of the fully submerged foil type ship during the past decade with emphasis upon the commitment directed toward its development by the United States government. The developmental process induced by this commitment is found to be impeded by physical and technical factors, but organizational and traditional constraints are also instrumental in retarding progress. Recent successes indicate a reversal of past trends and suggest that the ocean going hydrofoil ship may soon add another dimension to surface water-borne transportation.

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CHAPTER I

INTRODUCTION

The Problem.

> It is an interesting fact of life that since man first straddled the log with a paddle and made a very limited speed by using this vehicle, that we have only progressed to speeds approximately 40 knots in the development of surface ships.[1]

This remark was made over a decade ago by Rear Admiral Ralph K. James, USN, then Chief of the Bureau of Ships of the United States Navy, in testimony before a special investigating subcommittee on science and astronautics. The fact that this statement remains essentially valid today is extraordinary, particularly after a decade of unprecedented technological advancement which culminated with man's journey to the moon.

Alexander Graham Bell, in the year 1918, set a speed record of 70.8 miles per hour in an 11,000 pound motor boat equipped with devices known as hydrofoils.[2] The tantalizing prospect of these devices providing the quantum jump in technology to revolutionize surface ships has inspired considerable speculation and some sporadic developmental activity for over half a century. It has only been during the last decade, however, that a concerted effort has been directed specifically toward developing a high speed hydrofoil ship for use on the open ocean. The thrust behind this development has been provided principally by the United States Navy, with the Canadians engaging in a complementary program.[3] Hook offers this explanation for the American involvement:

> The American share in hydrofoil history has been largely influenced by geography; a glance at the map reveals an absence of offshore islands, straits, or other passages suitable for fast ferry services; so interest in sea-going types has been concentrated almost entirely on their suitability for naval purposes.[4]

Technical problems, unfortunately, have emerged during construction of operational hydrofoil ships for use in the open ocean environment that have restricted exploitation of their unique characteristics. The squadrons of U.S. hydrofoil ships that Admiral James undoubtedly envisioned do not yet roam the open oceans.

Need for the Study. Literature on hydrofoils abounds with the words "craft" or "boat" in contrast to "ship" when referring to a vessel supported on foils. This connotes something quite small and almost immediately implies certain inherent performance limitations. Hook further states:

> It is probably on the matter of size that there are the most misconceptions regarding hydrofoil craft and this is clearly because we are trained from childhood to think of ships as colossi, the image of the "Queens" coming immediately to mind. But the navigational problems that had led man to this by degrees are all based on waves and their domination by mere mass and mere length.[5]

The hydrofoil craft is an entirely different vehicle with characteristics, in many ways, contrary to those of conventional surface ships. Unfortunately, it appears that the majority of literature on hydrofoils represents a dialogue between individuals within the hydrofoil community and, as a consequence, the "craft's" unique capabilities and limitations are not widely known.

Vice Admiral B.B. Schofield, RN (Ret.), in a recent prognosis of tomorrow's warships, strongly advocated that in the future full advantage be made of small ships. He further suggested that small ships may provide the best counter to a hostile missile threat.[6] The oceangoing hydrofoil ship is an ideal candidate for employment in this environment, and a better understanding of its potential could possibly provide another dimension to naval strategy.

<u>Purpose</u>. The purpose of this paper is to examine the physical and technical factors which have significantly

hindered the development of the oceangoing hydrofoil ship during the last decade. An attempt will be made to identify critical accomplishments and problems in order to clarify their present status and to assess their prospects for the future.

Scope and Limitations. The scope of this study is limited to the physical and technical aspects of oceangoing hydrofoil development in the United States over the past decade. Major limitations include the necessary deletion of classified material and the exclusion of socio-economic and political variables.

Summary. An overview of hydrofoil background information is presented in Chapter II. This is followed by a brief look at the commitment directed toward their development. Chapter IV summarizes the expectations and actual realizations of the United States program. Major physical limitations and technical constraints are enumerated in Chapter V. Trends for the future and concluding remarks are contained in Chapters VI and VII respectively.

CHAPTER II

BACKGROUND

The Hydrofoil Concept. A surface ship moving through the water encounteres resistances to its motion which are in the form of friction and residual effects, principally comprised of wave-making resistance. The total resistance is overcome by the propelling force of a marine propeller, a sail, or other such device. At low speeds the ship's propulsive power is expended primarily in overcoming frictional effects, but as the vessel's speed increases, correspondingly more power is required to overcome the effects of wave-making resistance.[1]

A vessel equipped with devices known as hydrofoils has two modes in which it can operate. While at rest or at slow speeds its hull floats upon the water and it performs as any conventional ship. At some higher speed, however, the hydrofoils have the capability to lift and support the hull clear of the water,[2] where it escapes the major portion of the penalties imposed by resistance. With the marked drop in resistance the vessel can continue to increase speed until the limit of installed power is reached.

What Are Hydrofoils?

> In essence, a hydrofoil is a wing that "flies" through water and is completely analogous to the airfoil used for aircraft in that it provides lift to the supported craft. Thus, as the water flows over the top of the foil shape, a negative pressure occurs. A positive one occurs on the bottom due to angle of incidence. The foil will then rise and lift whatever it supports, providing that sufficient speed is attained. Hence, a vessel traveling on hydrofoils is actually flying, since its entire hull will be clear of the water surface.[3]

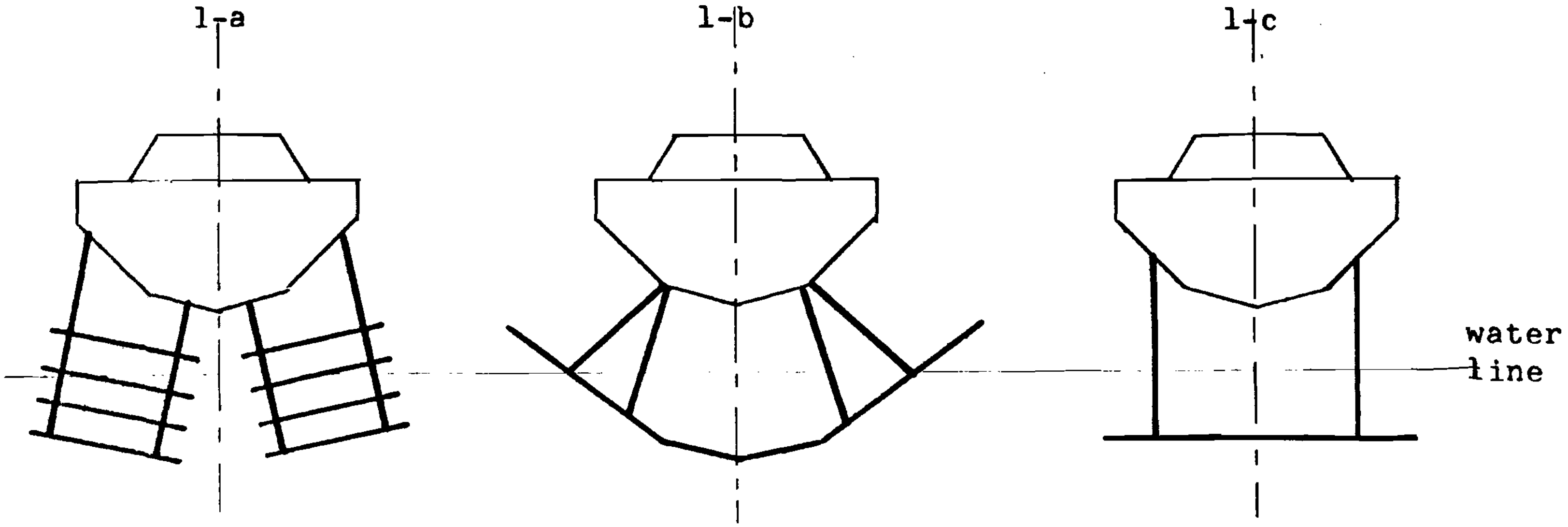
The size of a hydrofoil shape needed to support a given load is a function of its geometry, velocity through the water, and the density of the water through which it travels. Since, however, the density of water is about 800 times greater than that of air, a hydrofoil would be only a fraction of the size of an airplane wing lifting the same weight at equal speeds. Simplified calculations contained in Appendix I illustrate that a typical hydrofoil shape with an area of less than one square foot could support a craft of 1200 pounds traveling at a velocity of 30 knots.

Basic Hydrofoil Configurations. The hydrofoil speed boat used by Alexander Graham Bell was attached to a series of foils arranged on supports or struts similar to a venetian window blind, or a ladder. As this arrangement accelerated through the water the upper most foils were successively lifted out of the water until a state of equilibrium was reached; i.e. the area of immersed foils produced sufficient lift to support the craft at a particular speed. This configuration, generally known as the "ladder" type (Figure 1-a) is considered of limited utility since at low speeds, with the hull in the conventional mode, the mass of this arrangement below the water surface compounds resistance problems. At higher speeds those foils lifted clear of the water serve little useful purpose and represent additional weight to be supported.[4]

A more suitable and less cumbersome arrangement is the "surface piercing" or "Vee foil" system in which the foil itself pierces the air-water interface. This arrangement, illustrated in Figure 1-b, is in its simple form a vee-shaped foil attached to the ship by supporting struts. It can be designed to possess inherent stability since lift will vary with the depth of submergence. To illustrate, a downward movement of the bow will increase the area of the foil beneath the water and will, therefore, develop additional lift to restore normal trim. Similarly, a roll experienced to one side is accomplished with increased foil immersion on that side. Again, a counter-balancing force is produced to right the vessel.[5] This type of response is fixed by the basic design and behavior in a

FIGURE 1

BASIC HYDROFOIL CONFIGURATIONS



LADDER TYPE FOILS

SURFACE PIERCING
or
VEE FOILS

FULLY SUBMERGED
FOILS

Source: Abstracted from U.S. Congress, House of Representatives, Special Investigating Subcommittee of the Committee on Science and Astronautics, *Hydrofoil Development*, Hearing (Washington, D.C.: U.S. Gov't. Print. Off., 1960), p. 10.

heavy sea can become erratic. The simplicity of this system has, however, attracted considerable attention for use on vessels in calm seas or sheltered waters.

Another configuration, even less massive, is known as the "fully submerged" foil system (Figure 1-c). In this arrangement the entire foil is completely below the surface of the water and is attached to the hull by struts. Little if any inherent stability is realized by this arrangement. In the condition where the hull is supported on the moving foil, the vessel behaves in a manner much like an airplane and stability is generally achieved through use of movable control surfaces similar to those on aircraft. Because of the depth of the foil, this system is less likely to be affected by wave action and, hence, offers the potential for operations in heavy seas.[6]

Other distinctions in basic foil configurations can be made. As an example, one could categorize the various systems by the distribution of foil area with respect to the center of gravity of the hull. Another categorization could relate to the characteristics of the individual foil.

Potential Advantages. The ability of any vessel to attain high speed may prove valuable in itself, but it may also lose much of its significance if this capability exists only in calm water and is achieved through large expenditures of power. Figure 2 represents a typical power-speed relationship for a hydrofoil craft and a conventional displacement hull and is illustrative of the higher cruise speed potential of the hydrofoil. One cannot help but be impressed at the increased range of speeds available to the hydrofoil without expending additional power, once the hull is lifted clear of the water. Equally impressive is the fact that hydrofoil ships, in theory, can be designed to operate comfortably at higher speeds under conditions which force conventional ships to reduce speed to accommodate high seas.

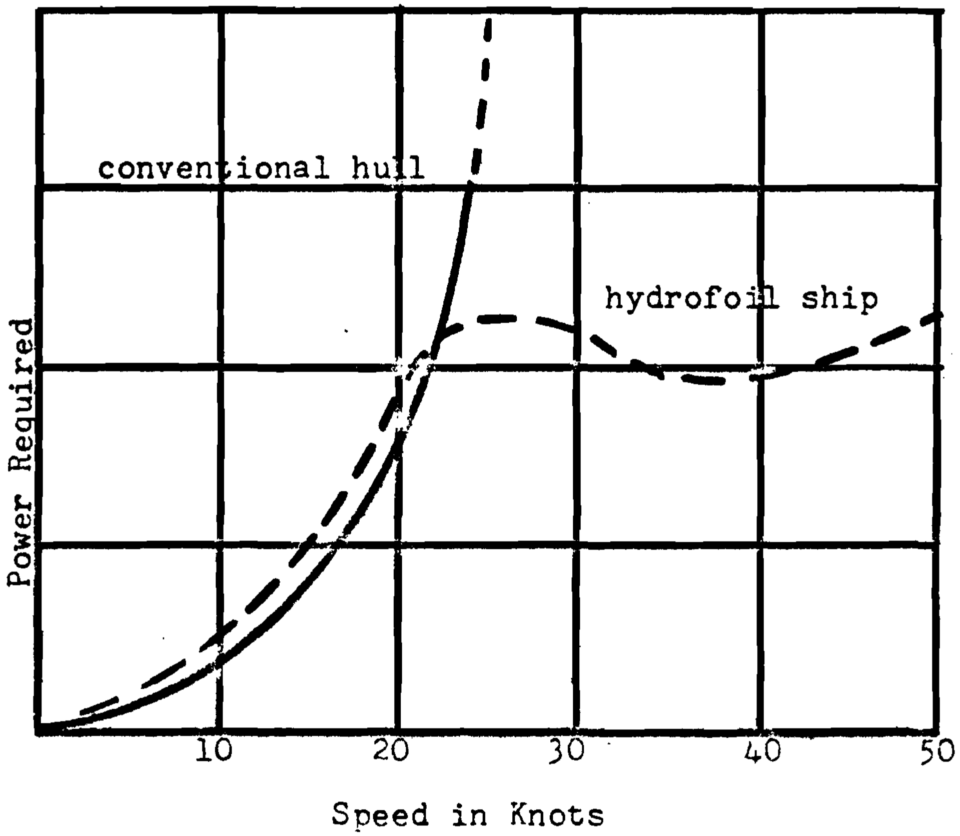
The foregoing merely suggests that hydrofoil craft are more effective and exhibit greater efficiency than do conventional ships. Gayer and Wennegal used more specific criteria for comparison of transportation systems in their studies of hydrofoil vessels.[7] They investigated the capabilities of various transportation systems to carry a useful load (payload) and compared the incurred costs in terms of power and displacement. For this purpose the following criteria for evaluation were defined:

$$\text{Productivity} = \frac{\text{useful load x speed}}{\text{displacement}}$$

$$\text{Transport efficiency} = \frac{\text{useful load x speed}}{\text{power-requirement}}$$

FIGURE 2

TYPICAL POWER-SPEED RELATIONSHIP FOR A HYDROFOIL CRAFT AND A CONVENTIONAL HULL

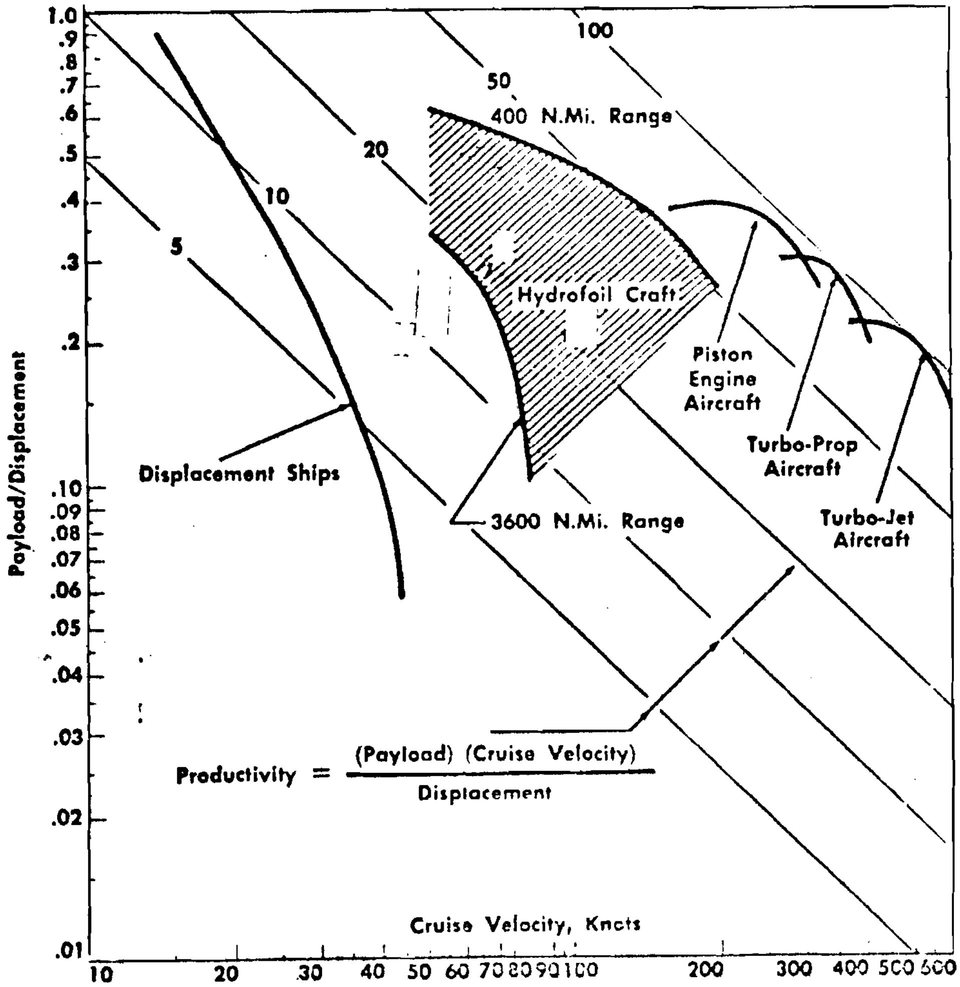


Source: Abstracted from E.K. Sullivan and James A. Higging, *Test and Trials of HS Denison* (Washington, D.C.: Maritime Administration, Office of Research and Development, April 1963), p. 19. and Thomas C. Gillmer, *Fundamentals of Construction and Stability of Naval Ships* (Annapolis, Md.: U.S. Naval Institute, 1956), p. 104.

As reflected in Figures 3 and 4, it was concluded that there is a speed region which exists between that of displacement hulls and aircraft, wherein the hydrofoil ship can operate productively at high transport efficiencies.[8] Subsequent evaluation of operating hydrofoil ships of advanced design have demonstrated twice the transport efficiencies of comparable conventional ships.[9] Thus, it can be seen that a hydrofoil ship has the potential to offer higher cruise speed, better passenger comfort, and higher transport efficiencies over conventional ships of comparable size. Moreover, these advantages may be realized while operating in a high sea state environment.

FIGURE 3

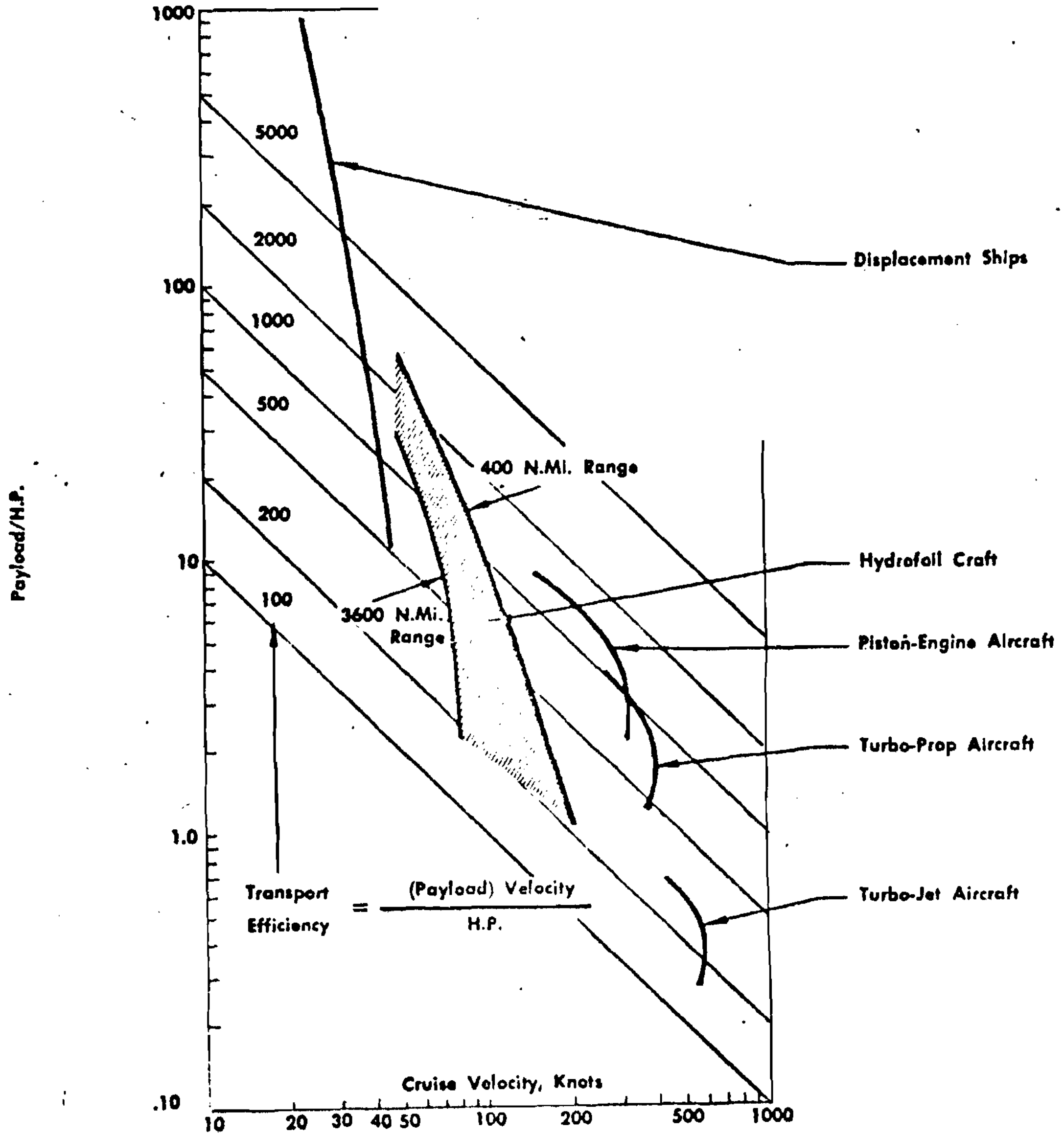
HYDROFOIL PRODUCTIVITY COMPARISONS WITH OTHER VEHICLES



Source: L.A. Geyer and G.J. Wennagel, "A Feasibility Study of Hydrofoil Seacraft," Quarterly Transactions. The Society of Naval Architects and Marine Engineers, October 1957, p. 705.

FIGURE 4

HYDROFOIL TRANSPORT EFFICIENCY
COMPARISONS WITH OTHER VEHICLES



Source: L.A. Geyer and G.J. Wennagel, "A Feasibility Study of Hydrofoil Seacraft," Quarterly Transactions. The Society of Naval Architects and Marine Engineers, October 1957, p. 706.

CHAPTER III

COMMITMENT

Current Use--Commercial. In light of the potential advantages offered by hydrofoils, it is somewhat surprising to discover that it was not until January 1961 that a small, sixty-passenger foreign-built hydrofoil named the "Flying Fish" was put into operation carrying passengers between Bellingham, Washington and Victoria, B.C.[1] The first operation of a hydrofoil boat approved by the Coast Guard for commercial use in the United States did not occur until September 1962. This was a twenty-four passenger boat named the "Albatross", which was capable of attaining speeds up to 40 miles per hour.[2] Today, four such craft are operating regularly in New York City on a commuter service between upper Manhattan and Wall Street and between New Jersey and Wall Street.[3] With the exception of several additional small hydrofoils engaged in providing sightseeing services, only five larger commercial craft (seating 50-125 passengers) regularly operate in the United States and these serve the Virgin Islands and on the West Coast, between San Diego and Mexico.[4] All five of the larger craft are foreign built and three of these are of Soviet design.[5]

In Europe, the U.S.S.R., and Asia, the situation is quite different and commercial hydrofoil boats have been in actual operation for the past 18 years. While there are several foreign producers of hydrofoil boats, the Supramar Corporation of Luzerne, Switzerland, has been in continuous production of such craft for this entire 18 year period and has 130 craft in operation around the world.[6] While over 30 hydrofoils provide regular service in Asia, several hundred hydrofoil ferries are in operation on the rivers and lakes of the Soviet Union.[7]

With few exceptions, all commercial hydrofoil craft in operation today are relatively small (between 20 and 165 tons displacement), equipped with the simple rigid surface piercing foils, and provide essentially passenger services in relatively calm seas or inland waterways.[8]

Current Use--Military. Since 1966, the People's Republic of China has been building 45 ton, 70 foot hydrofoil torpedo boats called the "White Swans". They are estimated to have between 50 or 60 of these in operational status. In addition, they have several larger (80 foot) hydrofoil boats equipped with rapid firing, twin-mounted cannon fore and aft.[9] The Albanian Navy reportedly has about 12 hydrofoil torpedo boats similar to the "White Swans". All these craft are sea-state limited, but are capable of speeds of about 55 knots under calm conditions.[10]

The Soviet Union also began building surface piercing hydrofoil boats for military use in the mid 1960's. It is believed that they possess about 25 such vehicles capable of attaining speeds up to 50 knots. These boats each displace about 80 tons and are about 90 feet in length, and are used by the Soviet Frontier Police in the Baltic, Black, and Caspian sea areas.[11]

The United States Navy currently is operating two 70 foot, 57 ton hydrofoil gunboats, the Flagstaff (PGH-1) and the Tucumcari (PGH-2). In addition, two large hydrofoils, the 115 foot, 120 ton Highpoint (PCH-1) and the 212 foot, 320 ton Plainview (AGEH-1) are engaged in experimental projects.

With the exception of some isolated applications of small hydrofoils for law enforcement duties in Asia, the only other known operational military hydrofoil is the Canadian 151 foot, 200 ton prototype Bras d'Or (FHE-400). The hydrofoils of the United States and Canada were designed for high sea state operations.[12]

Need. Literature on development of hydrofoil craft generally presupposes that a need, in fact, exists for such vehicles. Commercially, this need is not perceived as being evident.

Currently in the conduct of international commerce, about two billion tons of freight are transported via ship. Of this amount, approximately 55% consists of bulk oil with an additional 20% being coal, ores, and grains which move by specialized carriers.[13] The productivity and transport efficiencies of these bulk carriers and the remaining cargo carriers have been improved by increasing their payload capacity and reverting to economies of size. This can be illustrated by the following:

> The Universe Ireland, the first 312,000 d.w.t. tanker built, is used to transport crude oil from Kuwait to an oil corporation's new terminal at Bantry Bay in Ireland, *via* the Cape of Good Hope. This is a round-trip of 37,670 km (23,400 miles), which is 20,930 km (13,000 miles) longer than the route *via* the Suez Canal. The operating cost per ton, however, is estimated to be half of what it would be through the Suez Canal with a 50,000 d.w.t. tanker.[14]

Similar economies are realized during construction of bulk carriers. In 1965 the cost of construction was found to be $125.00 per ton of capacity, while in 1969 a 250-300,000 d.w.t ship was estimated to cost about $75.00 per dead weight ton (U.S. prices at least 50% higher).[15]

Table I, listing tankers of the world constructed during the last decade, indicates the tendency of shippers to capitalize on the economics of larger size. It is interesting to note that 20.4% of the world's tanker

TABLE I

SIZE AND CONSTRUCTION ANALYSIS OF WORLD TANKER FLEET
(As of 1 January 1970)

SIZE GROUP (TONS D.W.)	NUMBER CONSTRUCTED DURING PERIOD 1961-1965	1966-1969
200,000 and above	0	63 (note 1)
100,00 - 199,000	16	119 (note 2)
70,000 - 99,000	133	213
50,000 - 69,000	260	55
35,000 - 49,000	125	29
25,000 - 34,000	50	9
20,000 - 24,999	49	57
15,000 - 19,999	37	25
6,000 - 14,999	32	35
TOTAL	702	605 (note 3)

Notes:

1. These 63 ships total 14,045,760 D.W. Tons and represent 9.7% of the world tanker capacity.
2. These 119 ships total 15,424,079 D.W. Tons and represent 10.7% of the world's tanker capacity.
3. As of 1 January 1970 there were 3416 operating tankers totaling 144,191,750 D.W. Tons.

Source: Abstracted from H. Clarkson and Company Limited, The Tanker Register 1970 (London, England, 1970).

tonage was constructed during the period 1966 through 1969. Thus, the tendency in waterborne commerce has been clearly in the direction toward mammoth vessels operating economically at conventional speeds.

Conversely, in the area of international travel, speed has become a critical factor. Whereas a large ocean liner may require a crew of about 1000 to accommodate 2000 passengers for a period of days, an airliner carrying 250 passengers on a similar trip for a few hours can operate with a crew of a dozen or so employees and thereby realize considerably better passenger-to-employee utilization. Large liners are no longer considered competitive with aircraft in the international travel business.[16] Obviously similar considerations, in 1968, caused Baron H. Von Schertel, Head of Development of Supramar AG, to conclude:

> Hydrofoil lines will never go in for Atlantic crossings or passages on similar long routes over oceans because of the competition of aeroplanes which on such distances monopolize all advantages of speed and comfort.[17]

Application. It is in the realm of short distance passenger service, at distances substantially less than 200 miles, that the commercial hydrofoil ship appears competitive with conventional ships and aircraft.[18] Here, although air transportation is faster, the time saved in flight may not compensate for other factors such as airport congestion.

Hydrofoil craft may also compete with conventional ships in inaccessible locations as in the Soviet Union where geographic conditions are such that networks of rivers and canals offer better access to population centers than many of the poorly maintained roads of the countryside.[19] In 1962 the Soviets reportedly used a hydrofoil to transport fresh vegetables some 2000 miles along the Volga River to Moscow "because of an inadeouate or slow transportation and distribution system".[20] These craft may also prove feasible for isolated applications such as supporting off-shore oil fields[21] or oceanographic research programs.[22]

The military advantages to be realized from exploitation of hydrofoil ships appear promising and there are currently dozens of known missions for them in the United States Navy.[23] Some naval officers foresee the hydrofoil ship in an anti-submarine warfare role while others advocate that they be assigned less demanding tasks, such as exerting limited control of restricted waterways. Regardless of the intended mission, the high speed and sea-keeping potential of the hydrofoil ship in an open ocean environment are the characteristics which most intrigue the military planners. The United States Navy is firmly convinced that large ocean-going hydrofoil ships require the completely submerged foil system with fully automatic controls, and for this reason, has concentrated its developmental efforts in this direction.[24]

United States Investment in the Open Ocean Hydrofoil.

Col. Charles R. Denison of the Maritime Commission of the U.S. Department of Commerce initiated a series of technical and economic studies in 1957 which subsequently indicated that "open ocean hydrofoil ships" up to several thousand tons displacement were feasible.[25] As a result, the Maritime Administration decided to construct a seagoing hydrofoil and, in 1960, a contract in the amount of $5 million was awarded to Dynamics Developments, Inc. (a subsidiary of the Grumman Aircraft Engineering Corporation) for this purpose.[26] This vessel, named H.S. Denison, was launched on 5 June 1962 at Oyster Bay, Long Island. It was 104 feet in length, displaced 95 tons (full load), and was designed to carry 20 passengers at speeds of 60 knots. The foil configuration was a hybrid arrangement with both surface piercing and completely submerged foils.[27]

A contract in the amount of $60,000 was negotiated between the Maritime Administration and Stanford Research Corporation to identify hydrofoil ship trade routes.[28] The areas of the United States that offered the greatest promise of economic success were found to include the Great Lakes, Hawaii, Puget Sound, New York City, Nantucket Sound, Miami-Nassau, and the islands off California.[29] The Grace Lines Inc. was subseouently selected from 30 shipping companies to operate the craft for an 18 month testing period and then commercially exploit the vessel.[30]

At one point the entire Denison project was jeopardized by a lack of funding and the project was rejuvenated only after Grumman Aircraft Engineering Corporation offered to assume $2 million of the project costs and charge the Administration only $1.5 million. General Electric, Alcoa, and approximately 50 other companies reportedly invested the remaining $1.5 million.[31]

During the decade of the 1950's the United States Navy sponsored a number of research and development projects directed toward establishing design criteria for hydrofoils. A small experimental craft named "Sea Legs", built for the U.S. Office of Naval Research through a joint effort of Gibbs and Cox, Inc. and the MIT Flight Control Laboratory,[32] provided the first convincing demonstration of the advantages of the fully submerged foil system augmented with automatic controls. This 29 foot, 5 ton boat was capable of operating comfortably at high speeds in seas up to five feet.[33] By 1960 sufficient data had been accumulated to indicate that large, fully submerged foil craft were feasible and this marked the start of an accelerated open-ocean hydrofoil development program for the U.S. Navy. FY 1960 ship construction funds were provided for the design and construction of a 110 ton hydrofoil patrol craft (PCH-1) with a fully submerged foil system. A $2,082,200 contract was awarded to the Boeing Company for this purpose and construction commenced in January 1961.[34]

Six months later the U.S. Navy Bureau of Ships awarded the Boeing Company another $1.5 million contract to construct a 15 ton, twin-hulled craft to be used as a fully instrumented test vehicle for development of advanced, high speed foils. The craft, named "Fresh 1", was equipped with a turbo-fan jet engine capable of propelling the vehicle for foilborne speeds of 100 knots.[35]

This was followed in October 1961 by a U.S. Navy contract for a 300 ton, 212 foot hydrofoil ship. The contract was a two phase award. The initial phase, design and planning, was awarded to the Grumman Aircraft Engineering Corporation in the sum of $1,597,781.[36] This phase was completed in May of 1963 and detailed design and construction responsibility was awarded to the Puget Sound Bridge and Dry Dock Company, a subsidiary of the Lockheed Shipbuilding and Construction Company, in June of 1963. This phase of the contract was in the amount of $11,795,000 and had an additional requirement which specified that provision be made for installing additional power and conversion to higher speed foils with minimum "modification to the ship".[37]

Mr. William I. Niedermair, a former director of research of the Maritime Administration, embarked on a venture in early 1963 to construct and operate a commercial, fully submerged hydrofoil ship. He founded Northwest

Hydrofoil Lines Inc. and contracted with the Maryland Shipbuilding and Drydock Company of Baltimore to build a 40 ton craft capable of carrying 75 passengers on a route between Victoria, B.C. and Seattle, Washington. Appropriately, the craft was named "Victoria". The craft was designed by Gibbs and Cox Inc., New York Naval Architects, and was expected to operate in sea-state four (see Appendix II) and cost about $750,000. Application for financial assistance was made under Title XI of the Merchant Marine Act of 1936, and both the General Electric Company and the Maryland Shipbuilding Company reportedly agreed to absorb some of the cost as a contribution to advance the state-of-the-art of hydrofoils.[38]

The Grumman Company, builders of Denison and designer of the Plainview, announced in January 1965 their intention of joining the German shipbuilding concern of Blohm and Voss, to build commercial hydrofoil vessels of the completely submerged foil type. The cost of the craft was undisclosed, but its characteristics were such that a speed of 50 knots was planned, carrying 90 passengers. The craft, named the "Dolphin", was to displace 84 tons, be gas turbine powered, and have a cruising range of 200 miles while foilborne.[39]

Early in 1966 contracts were let for the construction of two high speed hydrofoil gunboats. Of the seven contractors solicited with known experience in design and construction of such craft, only the Grumman Aircraft Engineering Corporation and the Boeing Company responded. A decision was made to procure one boat from each firm and contracts were awarded in April 1966.[40]

Since the Canadian Navy is engaged in a hydrofoil program regarded as complementary to U.S. efforts, mention of their endeavor is considered appropriate. In 1964 the Canadians commenced construction of a 151 foot, 200 ton hydrofoil ship with surface piercing foils designed to attain speeds of about 50 or 60 knots. It was envisioned as a low cost system that could make a "small and many" procurement concept feasible. It must be noted that the choice of the surface piercing foil system would provide an opportunity to test validity of the U.S. Navy's conviction that oceangoing hydrofoils require completely submerged foil systems to achieve acceptable performance in high seas.[41]

CHAPTER IV

EXPECTATIONS AND REALIZATIONS

Denison. By March of 1961, Maritime Administration officials viewed H.S. Denison as a "precursor of larger foil equipped liners that could cross the ocean at high speeds, carrying 300 passengers".[1] Not only were plans available for commercial exploitation of the craft, but ancilliary plans to convert the craft to an 80 knot ship for Navy use were also under consideration.[2] This optimism seemed well founded when, on her maiden foilborne trials (9 June 1962), H.S. Denison achieved speeds up to 59 knots and exceeded rough water design objectives.[3] Enthusiasm for the open ocean hydrofoil rapidly began to wane, however, when less than ten foilborne hours could be accumulated in the succeeding nine months. All thought of commercial ventures for Denison were abandoned and further trials accounted for only about 250 hours of foilborne operation.[4] The craft was subsequently turned over to the U.S. Navy for use on the Pacific Missile Range.[5] Today, Denison is in inactive status at the Puget Sound Naval Shipyard where her components are sometimes "cannibalized" for other projects.[6]

Highpoint. Highpoint (PCH-1) was originally conceived as a state-of-the-art craft and was to go straight from the drawing board into the fleet as an anti-submarine warfare patrol craft.[7] The ship was accepted by the United States Navy in August of 1963 and was manned by an all Navy crew. This obviously reflected the traditional view that conventional new naval ships do not undergo revolutionary changes in design and, hence, require little testing or modification to achieve acceptable levels of reliability and performance. Unfortunately, in the next 13 months Highpoint was only able to operate in the foilborne mode for a period of 53 hours and 41 minutes because of a number of problems (only two hours of this period were spent in conducting rough water evaluations). An extensive rectification effort was initiated and the ship was dry-docked from September 1964 through June 1966.[8] The craft was subsequently transferred to the Naval Ships Research and Development Center for employment as an experimental vehicle. Today, more than seven years after delivery, Highpoint has accumulated less than 600 hours of foilborne operation and extensive trials with integrated fleet units are scheduled for the first time for early spring 1971.[9]

Plainview. Similar disappointment was encountered with Plainview (AGEH-1), the world's largest hydrofoil ship. Although construction of the ship commenced in June of 1963, numerous construction problems delayed delivery to the Navy for almost six years, until March of 1969. Shortly thereafter, a number of additional deficiencies were discovered and <u>Plainview</u> was not accepted by the Navy until March 1970.[10] As of 22 February 1971 the ship had operated foilborne for 25 hours in smooth water only.[11]

<u>Fresh 1</u>. The high speed experimental craft, <u>Fresh 1</u>, was launched in February 1963 and was to be operated by contractor personnel while testing various foil configurations designed to attain speeds significantly in excess of 50 knots. During demonstration trials for the Navy Trial Board on 18 July 1963 the craft lost directional control and upset at a speed of 70 knots. Fortunately, only minor injuries were sustained by those onboard and damage to the craft was minimal. Analysis of the accident revealed that the effectiveness of the control surfaces was reduced at higher speeds by the formation of a vapor cavity in the flow pattern around the foils and stability was eventually lost.[12] The craft was subsequently repaired with modifications to prevent a similar recurrence. Shortly thereafter, however, the Navy withdrew from its objective of developing a 100 knot hydrofoil ship, ostensibly because of reduced research and development funds, and <u>Fresh 1</u> was placed in storage and has not been used to date.[13].

Victoria. The commercial plans of Mr. Niedermair, President of Northwest Hydrofoil Lines, were more enthusiastic and before *Victoria* was half completed he was considering the construction of a fleet of from 50 to 100 hydrofoil vessels.[14] Unfortunately, the *Victoria* venture was operating in troubled waters and *Victoria's* construction costs sky-rocketed from the original estimated $750,000 dollars to 3.5 million dollars. Nevertheless, Mr. Niedermair was pleased with *Victoria's* performance after her launching in 1966,[15] and remained enthusiastic. He reported satisfactory operation in waves of 20 to 25 feet and maintained that floating or partially submerged debris proved no obstacle to the hydrofoil operation.[16] Nevertheless, it was this very debris, for which Puget Sound is notorious, that brought Northwest Hydrofoil Lines to an abrupt halt. On November 20, 1968 *Victoria* struck an unknown object and the foils were "wiped off a foot below the surface, as if cut by a knife". There were no serious injuries reported and watertight integrity was maintained and the craft journeyed 38 miles to Seattle on its auxiliary engines. Damage to the craft was estimated at $250,000. *Victoria* was subsequently purchased by International Hydrofoil Lines and as of early 1970 was not operational.[17]

Dolphin. The commercial venture, *Dolphin*, of Grumman

Aircraft and Engineering Corporation appears more promising. As of early 1970, two craft were built and one was operated commercially by Hydro-Flite Inc. on a daily service between St. Thomas and St. Croix in the U.S. Virgin Islands.[18] This successful Dolphin design reportedly provided the basis for the Grumman response to the U.S. Navy's patrol gunboat hydrofoil requirement.[19]

PGH. The Navy patrol gunboat hydrofoils Flagstaff and Tucumcari evidently represent second generation hydrofoil craft for their speed, maneuverability, and seakeeping characteristics surpass anything currently possessed by the U.S. Navy. Moreover, it has been reported that both these craft have proved more reliable than any vessel of comparable size joining the fleet to date.[20] Operational evaluation of these craft were conducted in the combat zone in Viet Nam during 1969 and verified the dependability of the automatic control systems under severe weather conditions and with less than optimal maintenance conditions.[21] It would appear that these craft represent a rugged, dependable, advanced surface craft that mark a significant achievement in over a decade of painfully slow development. The estimated cost of Tucumcari was $4 million and that of Flagstaff was estimated to be $3.6 million.[22]

CHAPTER V

DEVELOPMENTAL CONSTRAINTS

Physical Limitations. There are definite physical limitations on the size and speed of hydrofoil craft. One such limitation stems from the lift requirements imposed on the foils and has been termed the "cube-square" law. The implications of this law become apparent when the dimensions of the foil system and the ship itself are altered. If the principal dimensions of the ship that the foils support are doubled, the ship's weight can be expected to increase by about a factor of eight. On the other hand, if the principal dimensions of the foils are doubled, keeping all other factors constant, the area which directly influences the generated lift is only increased by a factor of four. Hence, as the entire foil-ship structure grows larger, the foils must become larger in proportion to the hull if sufficient lift is to be developed to sustain foilborne operation.[1] Thus, it can be concluded that hydrofoil ships are weight critical and foil weight could dictate the maximum attainable displacement of the vessel.

The early Maritime Administration feasibility study indicated that displacements of hydrofoil ships up to 3000 tons could be achieved with acceptable performance characteristics.[2] This study, however, assumed extensive use of relatively new titanium alloys in the fabrication of the foil and strut assemblies and evidently did little to assuage the concern over the "cube-square" law as a major developmental constraint.[3]

Oakley, in a subsequent discussion of foil weights, noted that application of fully submerged foil systems in conjunction with high strength materials suggested that, in fact, foil weight would not become prohibitive until large size hydrofoils of several thousand tons displacement were considered.[4] Nevertheless, studies do indicate that relatively small weight savings (approximately 3.5% of total craft displacement), if applied to an equivalent fuel increase, could markedly affect overall performance by increasing the operating ranges by as much as 30%.[5] It thus appears that a continued search for lightweight structural materials for hydrofoils would be justified.

The quest for lightweight structures has resulted in an almost universal acceptance of aluminum alloys in hydrofoil hull construction, and has produced weight reductions of approximately 60% when compared with equivalent steel structures.[6] These aluminum structures must, however, perform in a hostile sea environment which not only impose a variety of repetitive loadings on them, but is corrosive as well. Hence, the selection of alloys is confined to those possessing good fatigue life, strength, and corrosion resistant properties (see Appendix IV).

The weight of propulsion systems and auxiliary machinery will also obviously increase in relation to increased ship size, but other criteria such as cruising range or payload requirements will affect the selection of propulsive machinery. Gas turbines can produce greater power per unit weight and space than can other engines but they have exhibited high fuel consumptions at lower speeds, and are subjected to compressor fouling as a result of ingestion of salt entrained in the atmosphere. Unfortunately, gas turbines are also expensive. The cost of a pair of gas turbines to propel a 40 ton hydrofoil craft was estimated, in 1964, to be about $120,000.[7] Regardless of the machinery chosen, weight of the propulsion system represents approximately 15% of the over-all ship weight. Figure 5, based on a ship's speed of about 50 knots, indicates weight distribution in hydrofoil ships as a function of displacement.

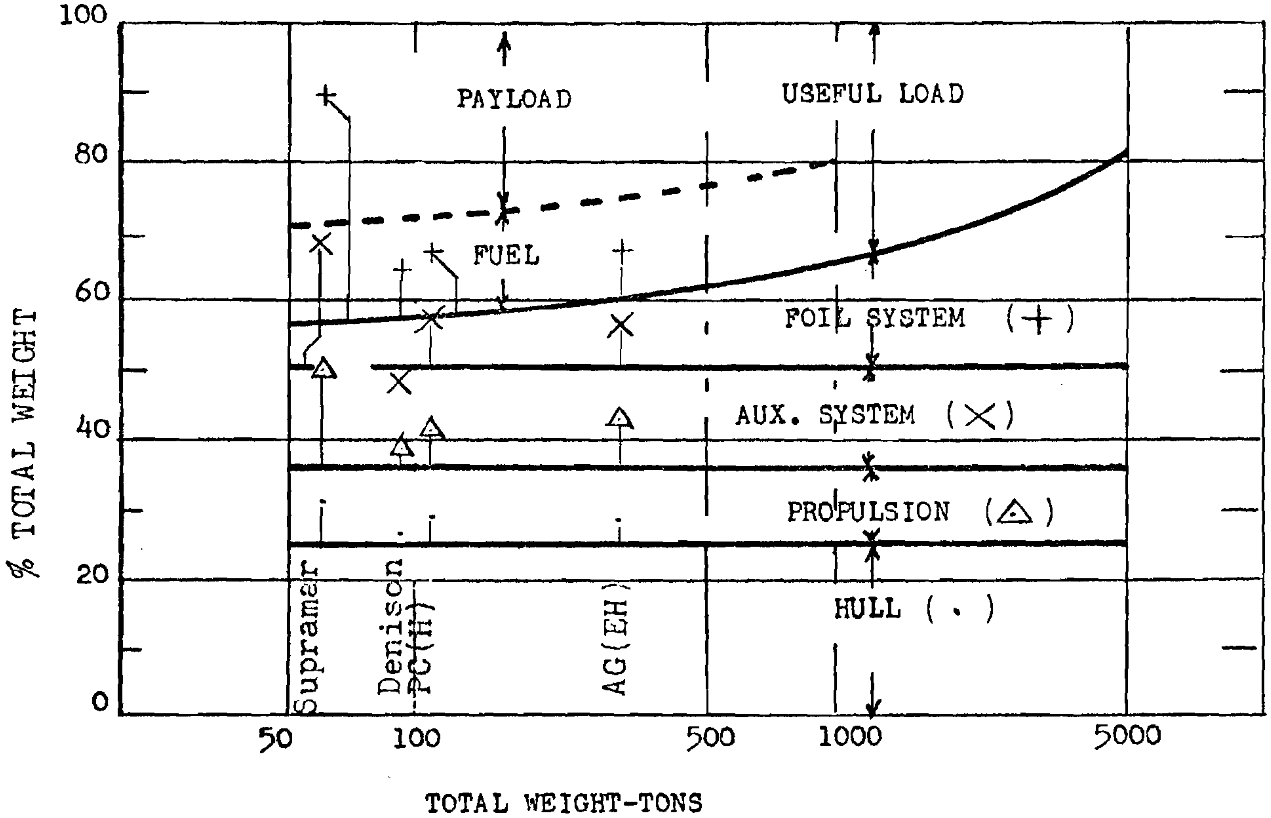
The second major physical limitation relates to the maximum speed attainable by a foil as it passes through the water.

> High velocity flow around struts, foils, and other appendages is attendent with a reduction in local pressure. When the total pressure at a point in a licuid drops below vapor pressure, cavities form and collapse with resulting radical alterations to the flow characteristics.[8]

This flow phenomenon is known as "cavitation" and

FIGURE 5

WEIGHT DISTRIBUTION IN HYDROFOIL SHIPS
AS A FUNCTION OF DISPLACEMENT



Source: Abstracted from Owen H. Oakley, "Hydrofoils--a State of the Art Summary," Proceedings of the National Meeting on Hydrofoil and Air Cushion Vehicles (Washington, D.C.: Institute of the Aerospace Sciences, September 1962), p. 20.

is considered by some to be the Achilles heel of foil design, for in the speed region of 40 to 60 knots it can produce severe pitting and erosion of metal.[9] The presence of cavitation alone is not in itself totally detrimental, for erosion results only when inception and collapse of the vapor cavities alternate in close proximity of the structural material. Thus, a critical speed exists below which cavitation will not occur and erosion will not take place.

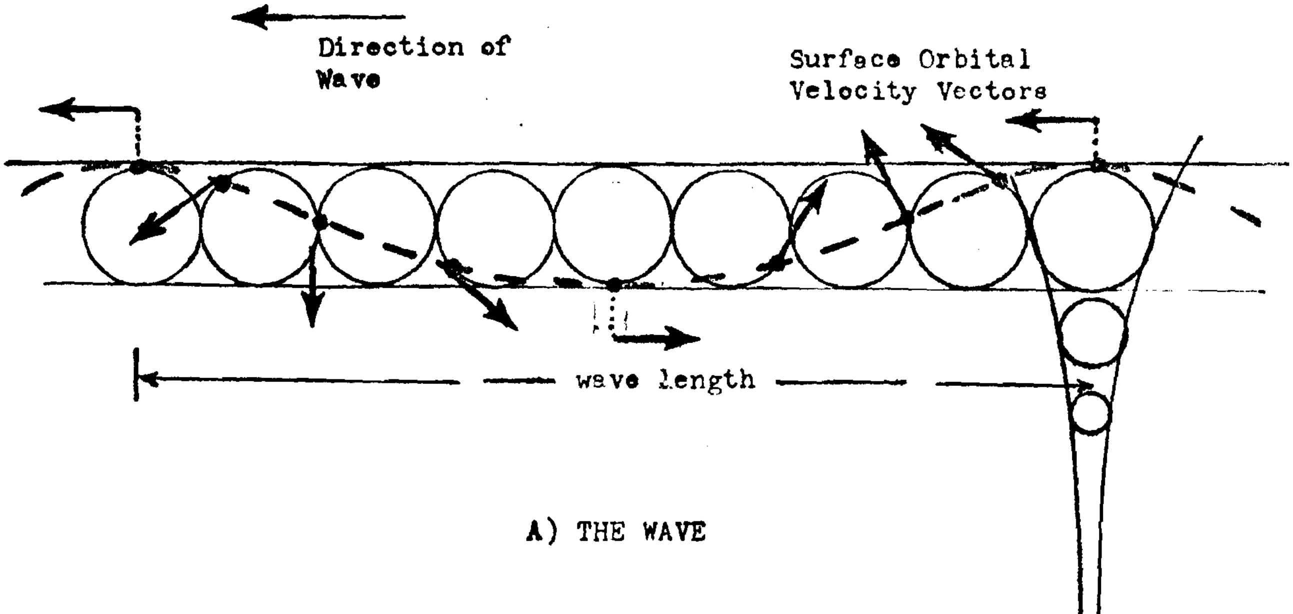
At speeds above about 60 knots, a new design area is entered. Foils with sharp leading edges must be utilized to cause the vapor cavity to be permently developed over the entire upper surface of the foil, with collapse of the cavity occurring well aft of the trailing edge.[10] A distinction, therefore, can be made between sub-cavitating and super-cavitating foil designs, and from the foregoing it would appear that the super-cavitating design would predominate in hydrofoil design. Ellsworth reports:

> There are a number of difficulties with super-cavitating foil designs yet to be satisfactorily resolved. Among these are the high angles of attack needed to reliably generate the cavity, the effects of proximity to the free surfaces, structural strengths of the thin leading edges, the problem of generating high lift at low speeds associated with take-off, and difficulties in achieving reliable and effective control of lift.[11]

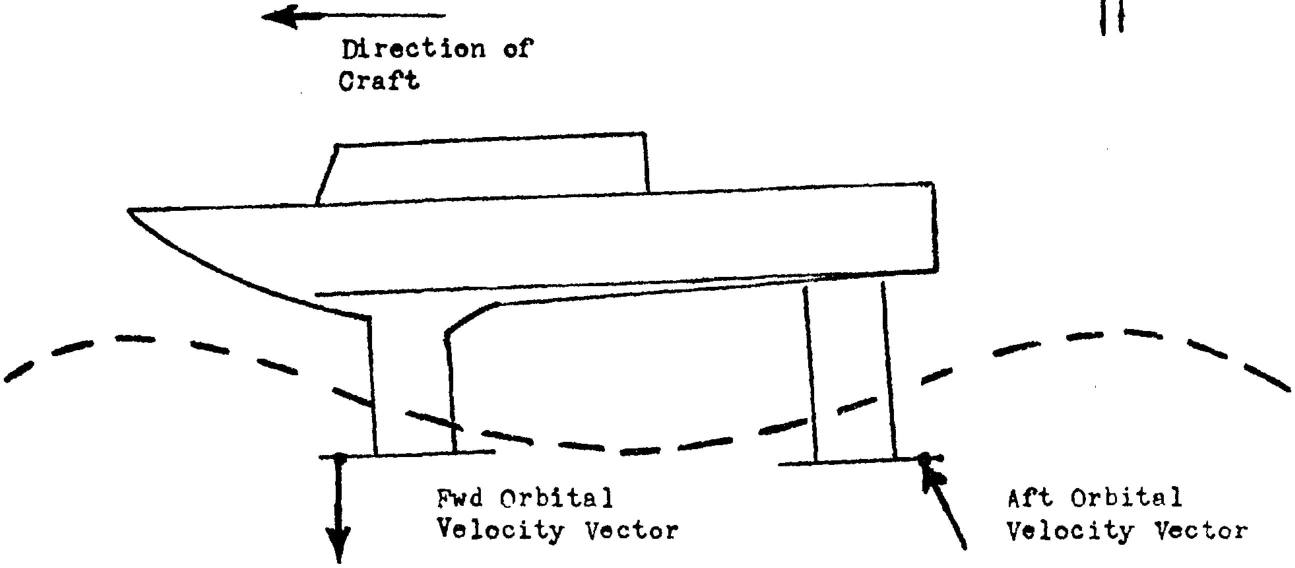
The third major limitation is imposed by the rough and unpredictable surface of the sea. The hydrofoil ship must operate in close proximity to the water surface in a very restricted altitude band. Individual wave action can induce angle of attack changes which radically affect seaway performance. To illustrate, Figure 6 represents the two dimensional cross-section of an ossilatory ocean wave, and depicts the orbital motion of a water particle whose net displacement over one cycle is zero. The direction of this orbital velocity corresponds to the direction of wave motion at the crest but is opposite in the trough. A hydrofoil ship traveling into a wave, head-on, experiences a two-fold effect which results in a positive angle of change. First, the on-coming components of the velocity of the water particles are additive to the ship's translational speed relative to the water and, thereby, generate additional lift; secondly, the vertical components tend to reinforce this lift. The combined effect is more pronounced on the leading foil and the ship responds with a bow-up movement. In effect, the hydrofoil is assisted in remaining foilborne in a head sea. In a following sea, unfortunately, the effect is reversed and a bow-downward movement is encountered and lift may be reduced to the point that the ship can no longer remain foilborne.[12] This is

FIGURE 6

ORBITAL MOTION OF WATER PARTICLES
AND ITS AFFECT ON HYDROFOIL CRAFT



A) THE WAVE



B) THE CRAFT IN A FOLLOWING SEA

Source: Abstracted from R.M. Rose, "Rought Water Performance of the HS Denison," J. Aircraft, Sept-October 1964, p. 275.

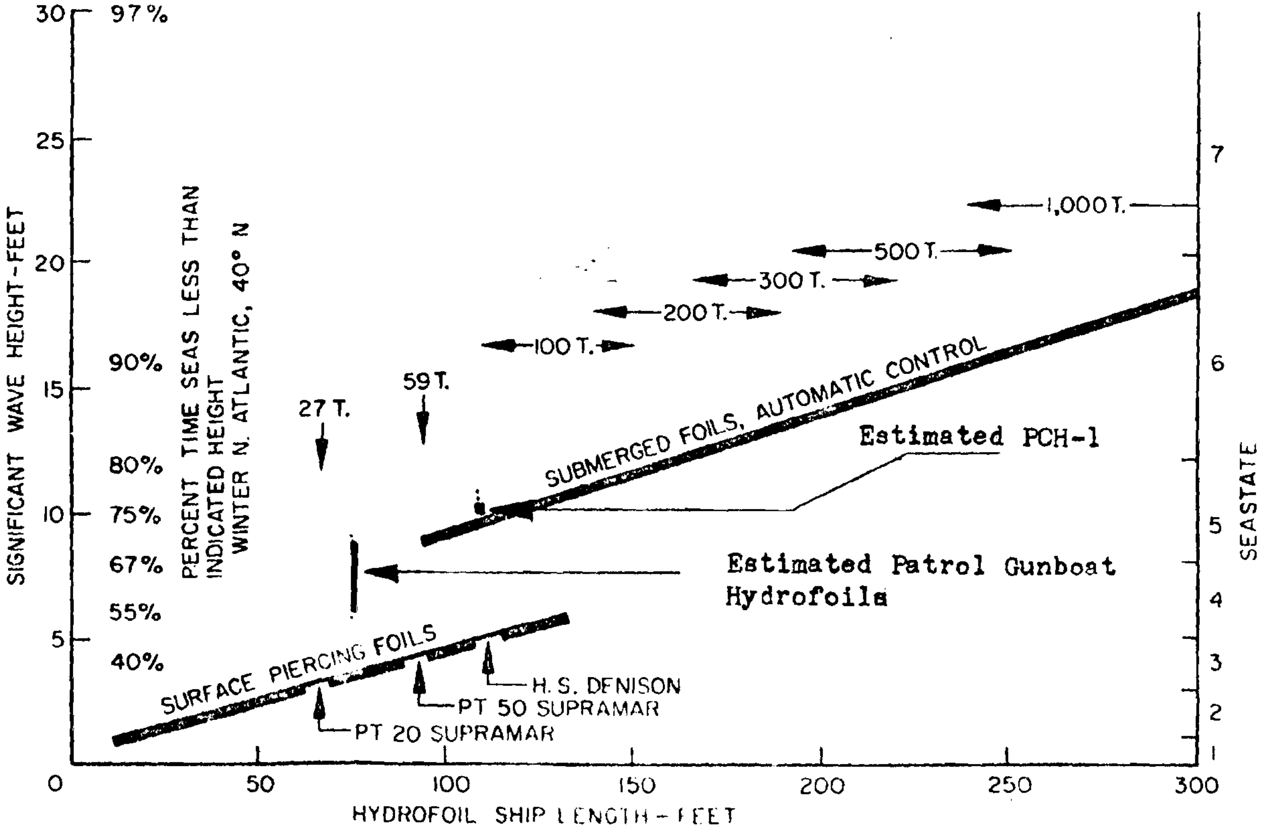
particularly true of vessles with surface piercing foil systems. Von Schertel of the Supramar AG has reported that Supramar boats with surface piercing foils find the "limiting wave height for following seas is three quarters that for head seas".[13]

The performance of the surface piercing type arrangement could be improved by the addition of control surfaces and an automatic control system. The fully submerged foil system of which such surfaces are already a part, however, exhibits less drag and is less affected by wave disturbances. The more appropriate alternative, therefore, appears to be the use of the automatic control system and control surfaces in conjunction with the completely submerged foils.[14] In this arrangement it is also possible to lengthen the struts between the hull and foil assemblies to assist in traversing a selected design wave height. To gain some insight into the comparative high sea state performance characteristics of the surface piercing and submerged foil systems, Figure 7 was abstracted and modified to include a PCH-1 data point[15] and estimated points for PGH-1 and PGH-2.[16]

Technical Limitations. The advantages of the fully submerged foil system could be realized only at the expense of greater complexity. The simplicity of conventional hull design, or even design of solid structures associated with

FIGURE 7

COMPARATIVE SEA STATE PERFORMANCE CHARACTERISTICS



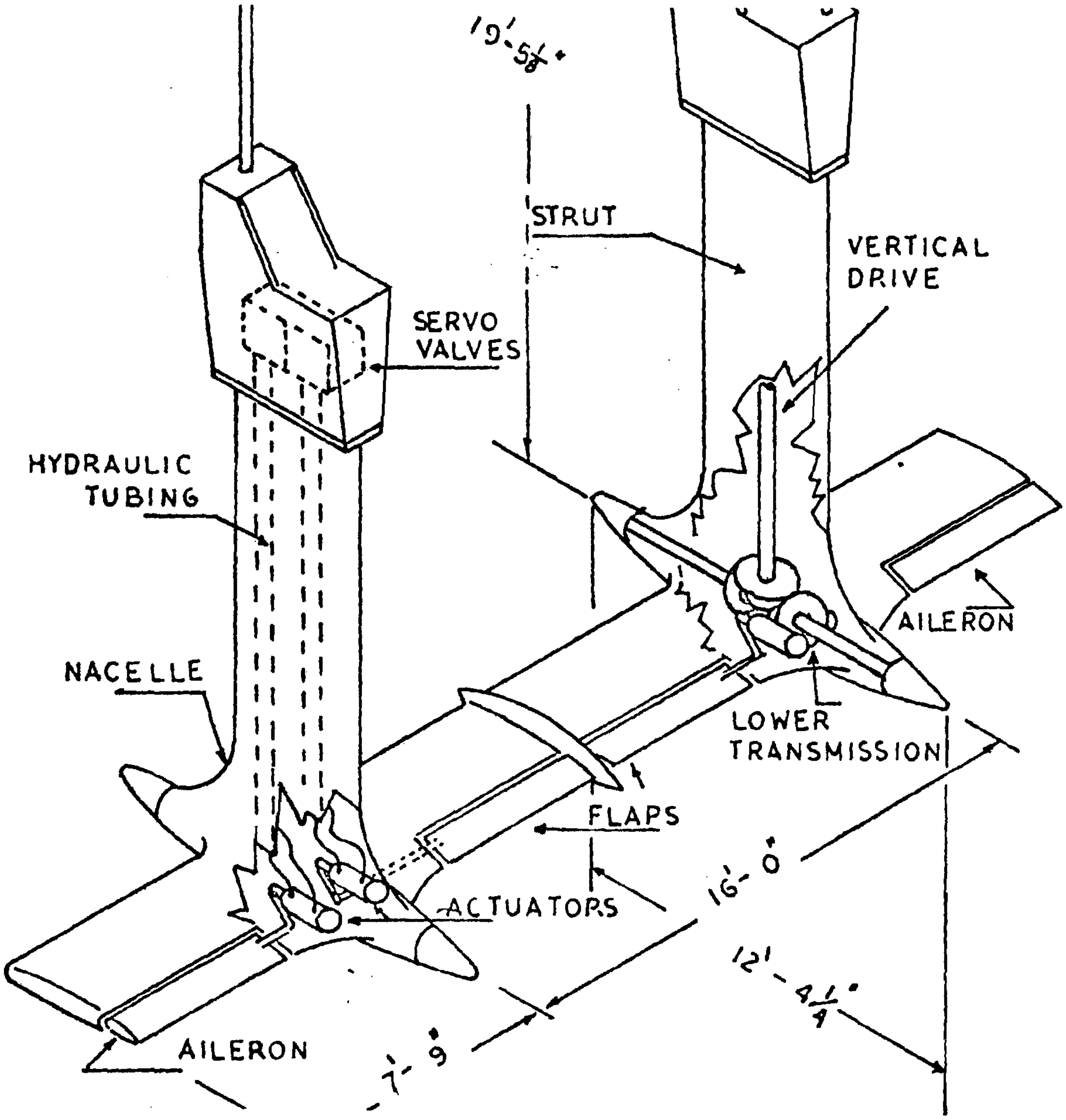
Source: Abstracted from E.K. Sullivan and James A. Higgins, Tests and Trials of HS Denison (Washington, D.C.: Maritime Administration, Office of Research and Development, April 1963), p. 27 and William M. Ellsworth, The U.S. Navy Hydrofoil Developmental Program-A Status Report (Norfolk, Va.: AIAA/SNAME Advance Marine Vehicles Meeting, Paper No. 67-351, May 1967), p. 2.

the surface piercing foils, gave way to structures containing mechanical and electrical components of the propulsion and control systems. Figure 8, a sketch of the aft-foil assembly on PCH-1, is illustrative of these arrangements.

As stated earlier, the foil system on <u>Denison</u> was a hybrid system consisting of two surface piercing foils forward of the center of gravity of the boat, and a single fully submerged foil aft. The aft arrangement was similar to that of PCH-1 in that it housed transmission drive shafts, associated gearing, and control system actuators within the strut assembly. In general, this complexity of arrangement is characteristic of all fully submerged foil systems and it imposes definite constraints on the size and design of the hydrofoil ship and its foil system. Material weight and strength considerations have become critical factors and have forced designers to adopt structural philosophies and construction techniques of the aircraft industry. Unfortunately, shipbuilders, aware of the ranging nature of the seas, have traditionally been conservative and build ships with considerable margins of safety and large structural dimensions for greater strength.[17] This need for, and reluctance to change, design philosophies and construction techniques has been a significant impediment in the development of the hydrofoil ship.

FIGURE 8

PC(H)-1 AFTER FOIL ASSEMBLY



Source: Steven W. McGanka, "Service Evaluation of the Control System Installed Onboard the Hydrofoil Ship Highpoint (PCH-1)," Proceedings (Annapolis, Md.: Ship Control Systems Symposium, USN Marine Engineering Laboratory, November 1966), p.v.-B-10.

Fabrication of Foil Assemblies. The Chief of the Division of Ship Design for the U.S. Maritime Administration stated that the major reasons for construction delays of Denison could be attributed to difficulties in fabrication of the after strut assembly which was some 20 feet long and only about seven inches thick.[18] Fabrication difficulties were encountered even in construction of the surface piercing foils. Variations in the angle of attack along the foil span of the starboard foil were discovered which demanded control system compensation during subsequent foilborne operation. Such compensation reduced the control range and effectiveness of the flaps.[19] Similar problems were discovered in the after foil assembly on PCH-1. Inspection of this assembly after 54 hours of operation indicated gross misalignment of bearing seats as a result of structural warpage and a twist in the after center foil. This necessitated extensive reboring of all bearing seats to correct the misalignment and warpage problems. The after center foil had to be cut cordwise along the ship's centerline and externally flanged.[20]

The foil assemblies supporting the ship at high foilborne speeds are subjected to very high structural loadings.[21] Such loadings compounded by fluctuating seas have caused cracking in the base metal and deflection between sub-assemblies; this resulted in leakage of salt water into the foil assembly. This salt water contamination proved to be one of the major problems retarding operation of both <u>Denison</u> and <u>Highpoint</u>.[22] The salt water would mix with the transmission lubrication oil and form an emulsion that could not be effectively centrifuged to remove impurities and which promoted corrosion of the transmission components and electrical failures.[23]

Salt water contamination of the lubricating system formed the basis for drydocking <u>Highpoint</u> six times between October 1963 and September 1965. On one occasion (25 September 1964), 15 gallons of salt water was found in the starboard transmission system.[24] This problem was eventually resolved on <u>Highpoint</u> by installing off-the-shelf face type seals for the propeller shafts.[25]

<u>Propellers</u>. The marine propeller itself emerged as a troublesome problem source. On <u>Denison</u>, a single, stainless steel propeller of supercavitating design was mounted on the stern strut and provided thrust for foilborne operation. The first propeller used (DTMB 37670) was found to contain a number of surface cracks due to improper weld repairs of faulty castings. An interim two-bladed propeller was installed and failed due to metal fatigue, after four hours of foilborne operation at a ship speed of 57 knots. As a result, blade thickness on the original design was increased but now became susceptible to local cavitation

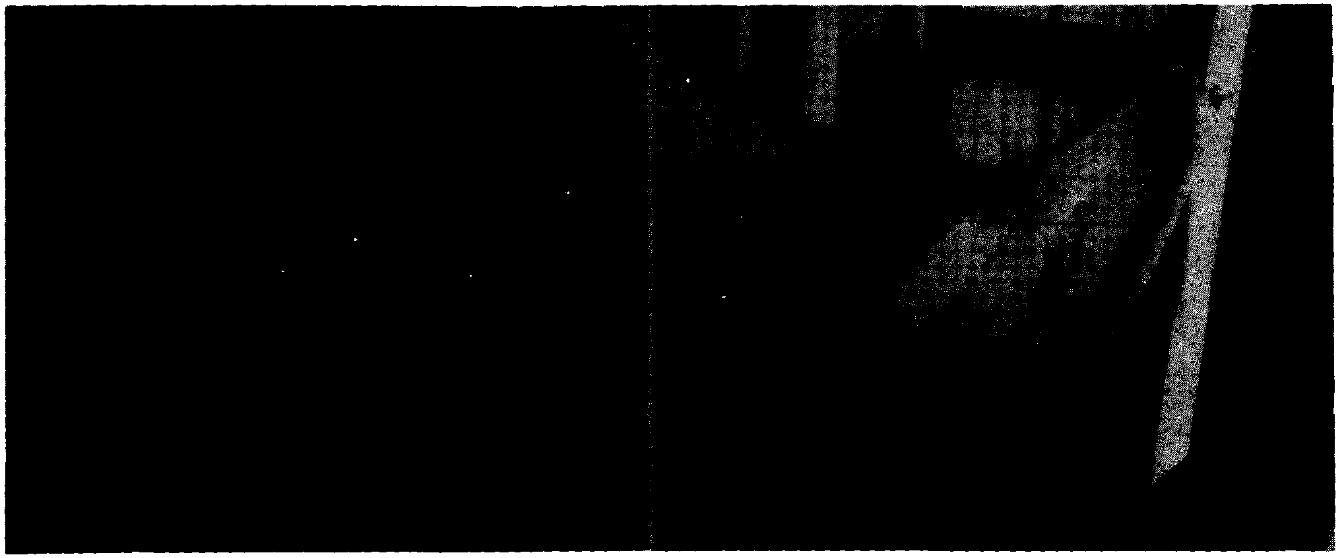
erosion. After about 132 hours of foilborne operation and various minor design modification, a new titanium propeller was machined to the original design. Unfortunately, the problem of cavitation erosion was never eliminated before <u>Denison's</u> operations were terminated.

Although subcavitating propeller designs were employed similar problems were encountered on <u>Highpoint</u>. Tip vortices from the forward foilborne propellers were impinging on the after propellers and resulted in extensive erosion and limited operating life to about 20 hours at maximum speed. Figure 9 illustrates the extent of damage after slightly over 10 hours of high speed, foilborne operations were achieved. Various modifications were tested unsuccessfully and as in the case of <u>Denison</u>, a titanium blade was eventually tried and failed from fatigue failure after only one hour and five minutes of operation.[26] This propeller problem was not limited to the American fully submerged hydrofoil boats. Harbaugh and FitzGerald report that Supramar has experienced years of difficulties with blade erosion.[27]

<u>Power Transmissions</u>. The surface piercing hydrofoil boats used commercially employ an inclined propeller shaft similar to that used on any motor launch. If a boat is to be designed for operation in high sea states, the separation between the hull and propeller must increase.

FIGURE 9

PC (H)-1 Propeller Damage After 10 Hours of Foilborne Operation



In the case of an inclined propeller shaft the large angles that would be required would reduce the propeller efficiency; therefore, the right angle, spiral bevel-gear system, as shown in Figure 8, has been adopted for the oceangoing tyoe hydrofoil vessel. Because of the weight problem, hydrofoil gearing weight is "of the order of one-fifth to one-tenth that of conventional marine gearing".[28] Prior to the Denison transmission design, only slightly over 3000 hp had been transmitted through a single bevel gear mesh. Denison required a total of 20,000 hp and adopted a split arrangement carrying 10,000 hp in each of two gear trains. Highpoint required about 3000 hp per shaft. Experience on these craft indicated that the gears themselves performed in excellent fashion. Difficulties were principally associated with improper installation and assembly and bearing problems.[29] A major design deficiency did become evident with respect to the configuration of the transmission within the foil assembly. Dunne contended that the major problem on Denison and Highpoint was the salt water contamination and remarked:

> Looking back it is hard to imagine how a gear train could have been designed to operate in a highly stressed structure, under water, without a gear case enclosing the gears. Although it mean slightly larger nacelle diameters this lesson has been well learned. AGEH reflects what all nacelle propulsion pods will contain, a sealed gear box with internal oil scavenging of all bearings in the lower part of the system.[30]

Technical Support. The literature reveals other problems but in comparison with those already mentioned they appear relatively minor. One observation that comes into focus is that the problems encountered were not unique to the hydrofoil and their solutions were clearly within the state-of-the-art. This has been substantiated by the exceptional reliability exhibited by the patrol gunboat hydrofoils, although some transmission problems were reported in the early Flagstaff trials.[31] An unfortunate dilemma that resulted from the early technical problems seems to be that they drastically diluted enthusiasm and a sense of urgency for further developmental efforts. The fate of Denison has already been discussed. In the case of Highpoint an extended period of time was allocated to resolve the technical problems. The Puget Sound Naval Shipyard was to provide industrial support with the Boeing Company providing engineering assistance.[32] Developmental work in a naval shipyard, by necessity, received low priority and program schedules and the scope of the work were continually revised as is evidenced in PC(H)-1 weekly activity reports under the Boeing contract NOBS 4838. Similar delays were encountered in the construction of Plainview and this low priority, coupled with substantial problems in design and installation of Plainview's hydraulic system, resulted in the unusually long construction period of over six years. Since testing has commenced, Plainview has been plagued by conventional engineering problems. The hullborne drive units were found to be defective and although the transmissions had a separate casing, salt water erroded the propeller shaft thrust bearings and replacement parts were obtained from Denison.[33] This lack luster performance was obviously one reason that Baron H. Von Schertel remarked:

> The USA tend to apply space technique to hydrofoil vessels. This results not only in a rise of costs that a passenger service becomes economically impossible, it also decreased the reliability of the boat and multiplies maintenance to such an extent that the Navy craft is bound to be found in the harbour most of the time.[34]

CHAPTER VI

TRENDS FOR THE FUTURE

Renewed Emphasis. There is evidence of a rejuvenated interest in the oceangoing hydrofoils. On 24 June 1968, Supramar launched a 165 ton hydrofoil capable of carrying 155 passengers and eight automobiles. This vehicle utilized a hybrid foil arrangement with a surface piercing foil forward and a completely submerged foil aft. Her design speed was 39 knots with a range of 300 nautical miles.[1]

In March of 1969, France announced a design study to investigate the feasibility of constructing a 56 ton, 200 passenger hydrofoil of fully submerged foil design. This craft is ultimately envisioned as powered by two gas turbine engines driving a water-jet propulsion unit.[2]

Reportedly, on 12 December 1970, the Soviet Union lauched a 100 passenger hydrofoil named the "Typhoon". This was the first operational, fully submerged foil craft built by the Soviets.[3]

The Italian Navy also has exhibited interest in oceangoing hydrofoils. A jointly owned company (Boeing-60%, Finmaccanica-30%, and Carlo Rodreguez-10%) was formed in Italy to develop advanced marine systems. This company, Alinavi, S.P.A., has been awarded a contract by the Italian government to build an improved, missile carrying, version of the Tucumcari for use by their navy in the Mediterranean. Delivery is scheduled for 1973.[4]

Lastly, Dr. John S. Foster, Jr., Director of Defense Research and Engineering for the United States, recently made the following statement:

> It is evident that the Soviets have built a navy rather specifically designed to counter our own present naval force and composition. They have responded to our well-established pattern. We must now apply our imagination and our energy to creating new patterns--patterns that decrease the military effectiveness of the force they have built and move in a direction that restores an adequate margin of U.S. technological military superiority. This can only be accomplished by marrying new operational concepts with new operational designs.[5]

A Break with Tradition. In reviewing hydrofoil developments in the United States over the last decade, one cannot help but notice the apparent reluctance on the part of the U.S. Navy and the Maritime Administration to acknowledge innovative change. Knowing the radical differences between hydrofoil craft and conventional ships, it is inconceivable that the first full-scale production hydrofoil vehicles were to be considered operational. What was the rationale for the hurried chartering of Denison to the Grace Lines and why did the Navy go through the expense of installing weapon systems onboard Highpoint and Plainview?

These actions, obviously were an extension of basic procurement philosophies derived from an historical trend of routine and predictable evolutionary changes in surface ship design. Dr. Robert A. Frosh, Assistant Secretary of the Navy for Research and Development, recently noted:

> Ships are never built in R & D. They are never built as prototypes. And, they are never built experimentally. . . Even the prototype submarines are disguised as operating components.[6]

The wisdom of foisting an advanced prototype hydrofoil upon operating personnel, either commercial or military, can certainly be questioned, for difficulties were certain to be legion. The dissatisfaction and eventual aversion these operators develop for systems which do not exhibit their ostensible capabilities can be irreversible and reflect adversely on the potential of the system long into the future. These procedures are allegedly considered unavoidable because the cost to build a prototype ship in terms of time and dollars would be prohibitive. Review of aircraft procurement programs, however, indicates a willingness to accept comparable expense for prototype programs. The U.S. Navy, for example, in its attempt to design a follow-on aircraft for the unsatisfactory TFX, has instituted the F-14 program in which about 600 million dollars will be spent for 12 airplanes that will be "essentially" prototypes.[7] Hence, it is concluded that the constraints imposed upon surface ship development are more traditional than real.

In 1965 the Chief of Naval Operations recognized the need for a more effective system of accomplishing tests and trials on advanced surface craft, and proposed that a specialized plan be instituted whereby the Navy could devise an "in-house" capability of developing such vehicles.[8]

Establishment of a Special Trials Unit. Many of the organizational and traditional constraints were finally broken down in the hydrofoil program in December, 1966, when authorization was received to transfer Highpoint from the operating forces to the "technical control" of the Commanding Officer and Director of the David Taylor Model Basin (name later changed to Naval Ships Research and Development Center).[9] Shortly thereafter, the Director of the Model Basin established a tenant activity designated as the Hydrofoil Special Trials Unit (HYSTU) at the Puget Sound Naval Ship Yard. The Officer in Charge of the newly established unit had the authority to make decisions and to commit funds relative to the following functions:

a. plan and direct all special trials of assigned craft.
b. coordinate logistic support, overhaul, and maintenance.
c. recommend and coordinate re-designs, modifications, and repairs.
d. supervise all contracts for engineering and technical support of the trials program.[10]

Thus, for the first time in almost six years, the constraints of fiscal policies and overhaul schedules peculiar to operating ships was lifted from the project and development could generally continue without the competing demands of operational priorities established by fleet commanders. All navy hydrofoil craft would subsequently be assigned to HYSTU prior to any assignment with fleet commanders.[11]

Builders. Similarity between aircraft and U.S. ocean-going hydrofoil ships has resulted in a natural reliance upon aircraft companies to provide the expertise for hydrofoil design and construction.[12] The total lack of the participation of conventional shipbuilders in the 1966 patrol gunboat hydrofoil program, even in light of an implied multi-ship follow-on procurement package,[13] is considered particularly noteworthy. There were undoubtedly many reasons for this apparent lack of interest by the shipbuilders, known only to the industrial concerns solicited. However, recent remarks by Assistant Secretary of the Navy, Dr. R.A. Frosh, suggest that design of conventional surface ships has been relatively easy and has inhibited innovative undertakings. Dr. Frosh contends:

> If you make a mistake in design of an aircraft, it falls out of the sky and people get killed. If you make a mistake in the design of a submarine, you are taking a great risk of an unrecoverable accident. If you make most of the mistakes that are available in the design of a surface ship, the risks are minimal! The ship stops! No problems are economic--they are problems of design and correction, but they are not catastrophic.[14]

If, in fact, conventional ship designers are reluctant to become involved with the weight-critical hydrofoil whose design features can be more demanding, then the implications are that aerospace industries will continue to dominate activity relating to hydrofoil design and construction.

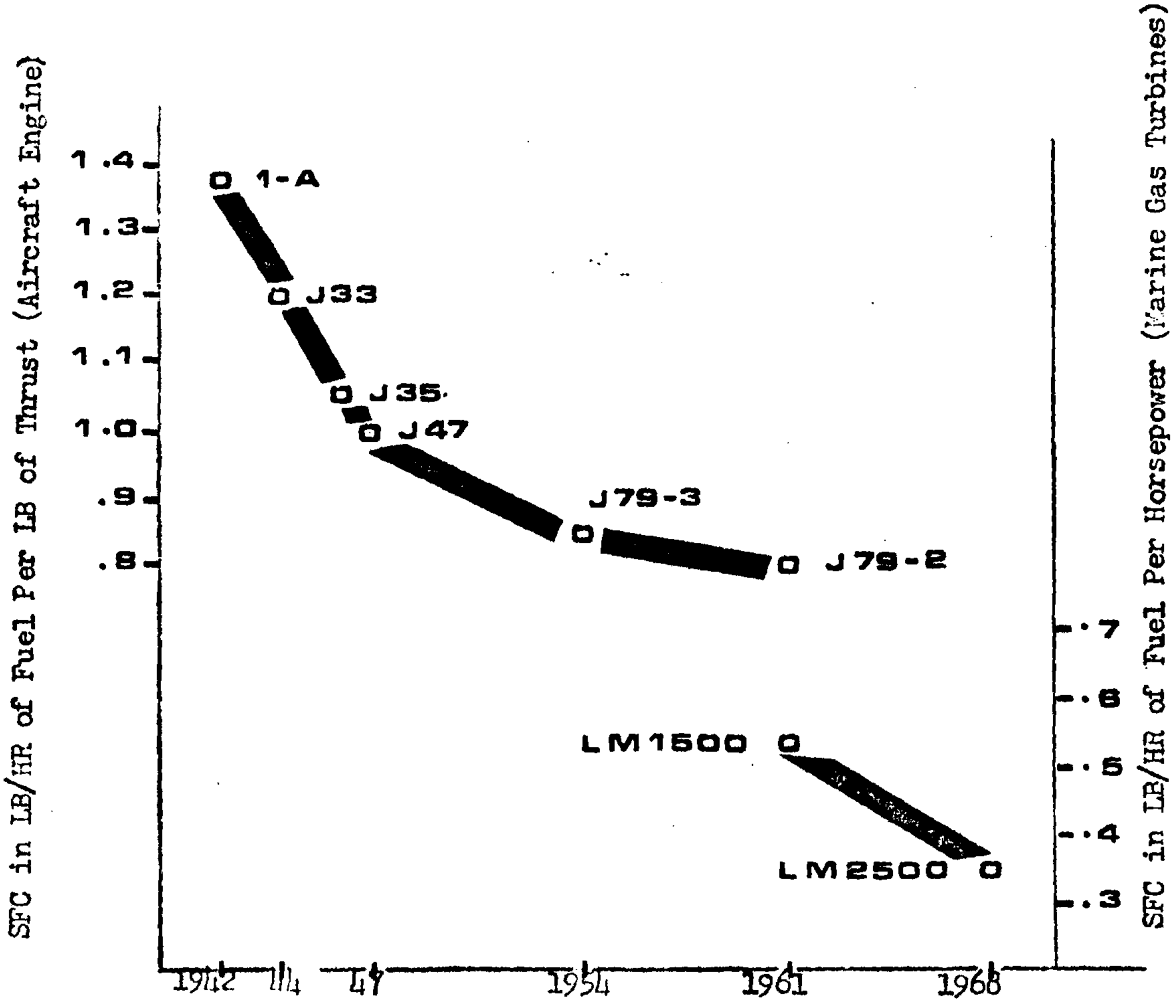
Altered Philosophy. The procurement of the hydrofoil gunboats clearly marked a reversal in the trend toward larger craft as is evidenced by the developmental progression from the 110 ton Highpoint to the 320 ton Plainview, then back to the 57 ton gunboats. The gunboat procurement also differed in that it represented a departure from traditional Navy surface ship procurement practices and amounted to competition between the Boeing and Grumman companies. The contractors were given wide latitude in developing their own designs and customary naval inspection procedures were not followed. The contractors were to demonstrate technical reliability of their craft and an extended period of time for continuous trials at sea under contractor auspices was authorized. The design best fulfilling the Navy's requirement would be ultimately utilized for follow-on multi-ship production. This contrasted widely from the Highpoint contract where only minimal adherence to technical design specifications had to be demonstrated.[15]

Technology. The difficulties U.S. hydrofoils had experienced with propeller cavitation and right-angle power trains aroused an interest in the water-jet as an alternate type of propulsion system, and an intensive series of studies was initiated by the Navy. A comprehensive study conducted by the Lockheed Company concluded, in 1966, that although the propulsive coefficient of the water-jet was about seven percent below that of the propeller, the water-jet could propel even a conventional craft eight percent faster, utilizing the same power because of reduced appendage drag. More important, the report indicated that a potential gain in operational reliability could be expected.[16] Additionally, the Boeing Company had been conducting in-house experiments with water-jet propulsion systems for hydrofoil vessels since 1960 and, as a consequence, they elected to install the water-jet on <u>Tucumcari</u>. The system was a Byron-Jackson two-impeller centrifugal pump, coupled to a gas turbine engine. The pump, if operating at 4900 shaft horsepower, could discharge 110 tons (about 29,000 gallons) of water per minute, and propel the craft at speeds in excess of 40 knots. After 30 months of service the pump was inspected and found to be free of wear or any corrosion or erosion. In addition to the foregoing, water-jet propulsion in general offers the potential for better maneuvering in a following sea and in restricted waterways since the jet thrust can be vectored.[17] The water-jet propulsion system appears to be the major technological accomplishment of the hydrofoil program.

A second trend in technology favoring development of oceangoing hydrofoils is the continued improvement of the marine gas turbine. The performance characteristics of the marine gas turbine have improved to the point that its fuel consumption is now competitive with other propulsion engines of comparable power rating.[18] The trend toward decreased fuel consumption is graphically depicted in Figure 10. Equally as important as fuel economy is that these improved gas turbines operate at higher temperatures and increased pressure ratios, thus producing higher efficiencies and more horsepower per pound of air. Greater reliability, better maintainability, and corrosion protection features are also exhibited, and time between overhauls has increased from about 500 hours in 1959 to about 6000 hours in 1970. Additionally, it is estimated that a 30,000 horsepower shipboard gas turbine can now be replaced in a matter of only a few hours. Recognition of these improvements is exemplified by the fact that horsepower generated by gas turbines in naval ships has tripled since 1965 and there are currently over 1100 gas turbines used for marine propulsion, world wide.[19]

FIGURE 10

SPECIFIC FUEL CONSUMPTION
IMPROVEMENT VS. CALENDAR YEAR



Source: Abstracted from Edwin Pyle and Roy Peterson, "Second Generation Gas Turbine," Naval Engineers Journal, August 1969, p. 39.

CHAPTER VII

CONCLUSIONS

The demonstrated successes of the patrol gunboat hydrofoils of the U.S. Navy vividly dramatize the technical feasibility of the open ocean hydrofoil ship. This achievement was, unfortunately, realized only after years of painfully slow development that ironically appeared to be more often directed toward enhancing reliability than toward advancing the state-of-the-art. Assuredly, the developmental process was impeded by the physical and technical factors identified, but more fundamental organizational and traditional constraints emerged as inherent obstacles to revolutionary change. Since the oceangoing hydrofoil ship represents a major departure from conventional surface ship design, it serves as a precursor for future innovative design efforts. Developmental difficulties similar to those experienced in the hydrofoil program can be expected to inhibit implementation of other innovative concepts of the future.

Lack of a clearly perceived need for open ocean hydrofoil ships also slowed their development. The stage is now set differently, for the sinking of an Israeli destroyer by missiles fired from a Soviet-built, 75 ton vessel, at a range of over 10 miles was a portent for navies of the free world. There can no longer be any question that smaller military vessels can render significant contributions in tomorrow's navies. Oceangoing hydrofoils with their superior performance characteristics are prime candidates for employment in this environment. Conversely, in the commercial sector of operation, no such need exists and the sophistication of such craft will place them well beyond the economic means of most profit-motivated commercial ventures for some time to come. Thus, it is concluded that the military role of the oceangoing hydrofoil ship will predominate for the foreseeable future, and accelerated construction programs for these vehicles will soon become a reality.

Weight considerations will constitute the major limitation confronting this next generation of hydrofoil ships, and a conservative approach will undoubtedly be taken in their design and construction. This investigator estimates that ship size will not increase much beyond that of the *Highpoint* and that subcavitating, fully submerged foils will be utilized, thereby limiting maximum speeds to about 60 knots. The significant success of the water-jet propulsion system suggests that this system will be widely employed to circumvent many of the problems outlined in Chapter V.

Weight considerations will also impose serious constraints upon methods of operating and supporting the hydrofoil ships. The number of personnel assigned to each craft will be fewer and customary onboard repair parts, supplies, and repair facilities will be luxuries that cannot exist. An understanding of the significance and implications posed by such departures from routine practice will be necessary if hydrofoil ships are to be successfully integrated into operational fleet units. To require these vehicles to adhere to traditional operational philosophies developed for the conventional vessel would be prejudicial to the hydrofoils and would not only limit their effectiveness, but would also breed the seeds of disillusionment once again. Realistic operational and logistical support doctrine must be formulated to specifically accommodate these unique vehicles if their full military potential is to be realized.

In summary, the oceangoing hydrofoil ship has come of age. The problems that remain are substantive, but can be resolved.

FOOTNOTES

Chapter I

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APPENDIX I

ILLUSTRATIVE HYDROFOIL LIFT CALCULATIONS

Problem: To determine the total area of a hydrofoil required to support a 1200 pound boat traveling through the water at a speed of 30 knots.

Background: Thanks to the airplane, vast quantities of data on various foil shapes are available and published by the National Advisory Committee for Aeronautics in America (NACA). A foil of the NACA 16 or 63 seris has been found suitable for hydrofoils and exhibits a lift coefficient of about 0.5 if the foil is utilized at a small angle of attack. In this situation the product of this lift coefficient, the square of the speed, the area of the foil, and the density of the fluid in which the foil operates will produce the magnitude of the actual lift.

Governing Equation:

$$L = C_L \frac{\rho}{2} V^2 (S)$$

where

L = lift in pounds
C_L = the dimensionless coefficient of lift, 0.5
ρ = mass density; water under standard conditions has a mass density of 1.99 $\frac{\text{pound.sec}^2}{\text{ft}^4}$
V = velocity
S = total area of the foil

Solving for S:

$$S = \frac{2L}{\rho C_L V^2} = \frac{2(1200\text{ pounds})}{\left(1.99\frac{\text{pound.sec}^2}{\text{ft}^4}\right)(0.5)(30\text{kts})^2}$$

but; one knot equals 1.689 feet per second

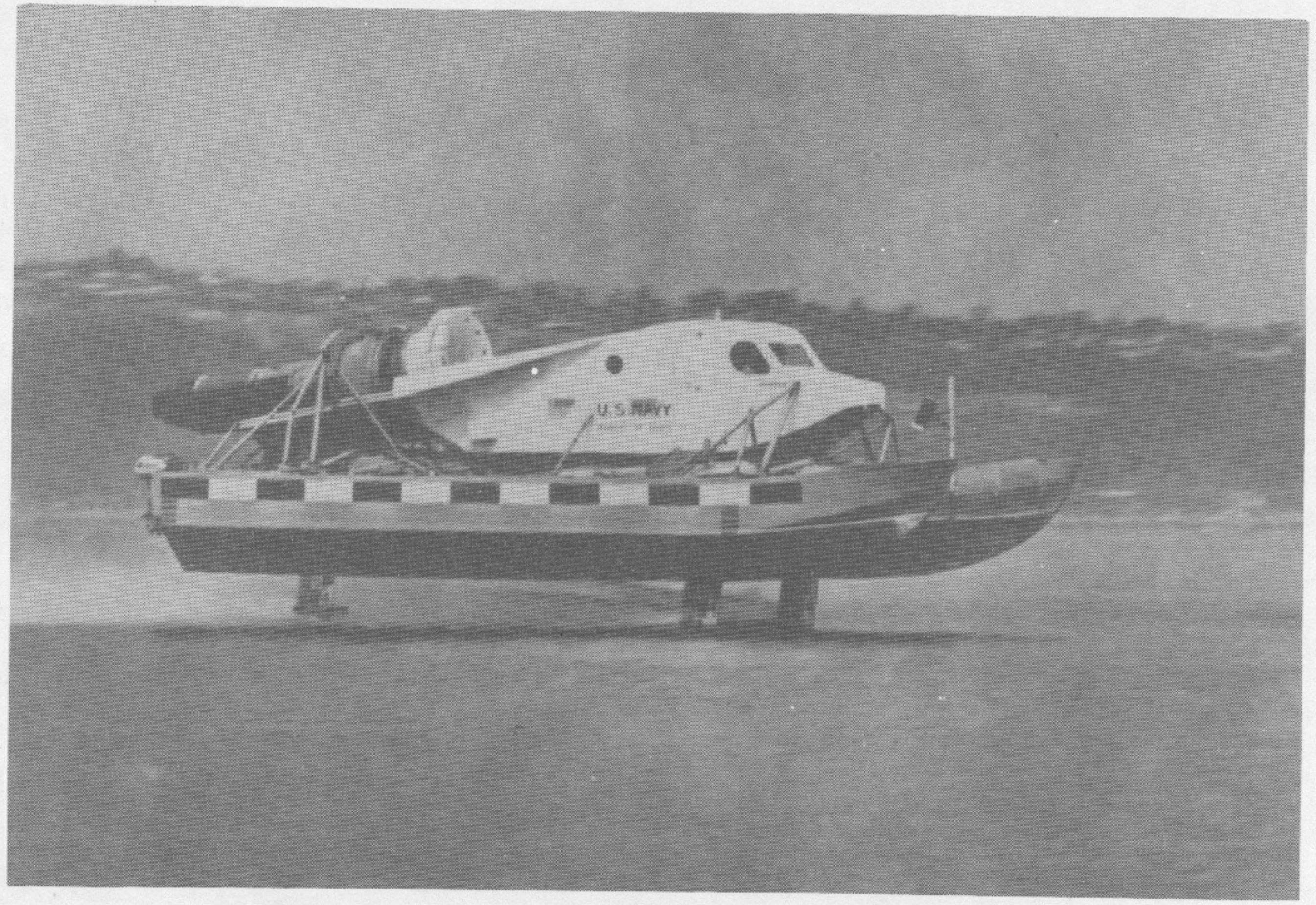
$$S = \frac{2\ (1200)}{1.99\ (0.5)\ (30 \times 1.689)^2} = \underline{0.94\text{ ft}^2}$$

APPENDIX III

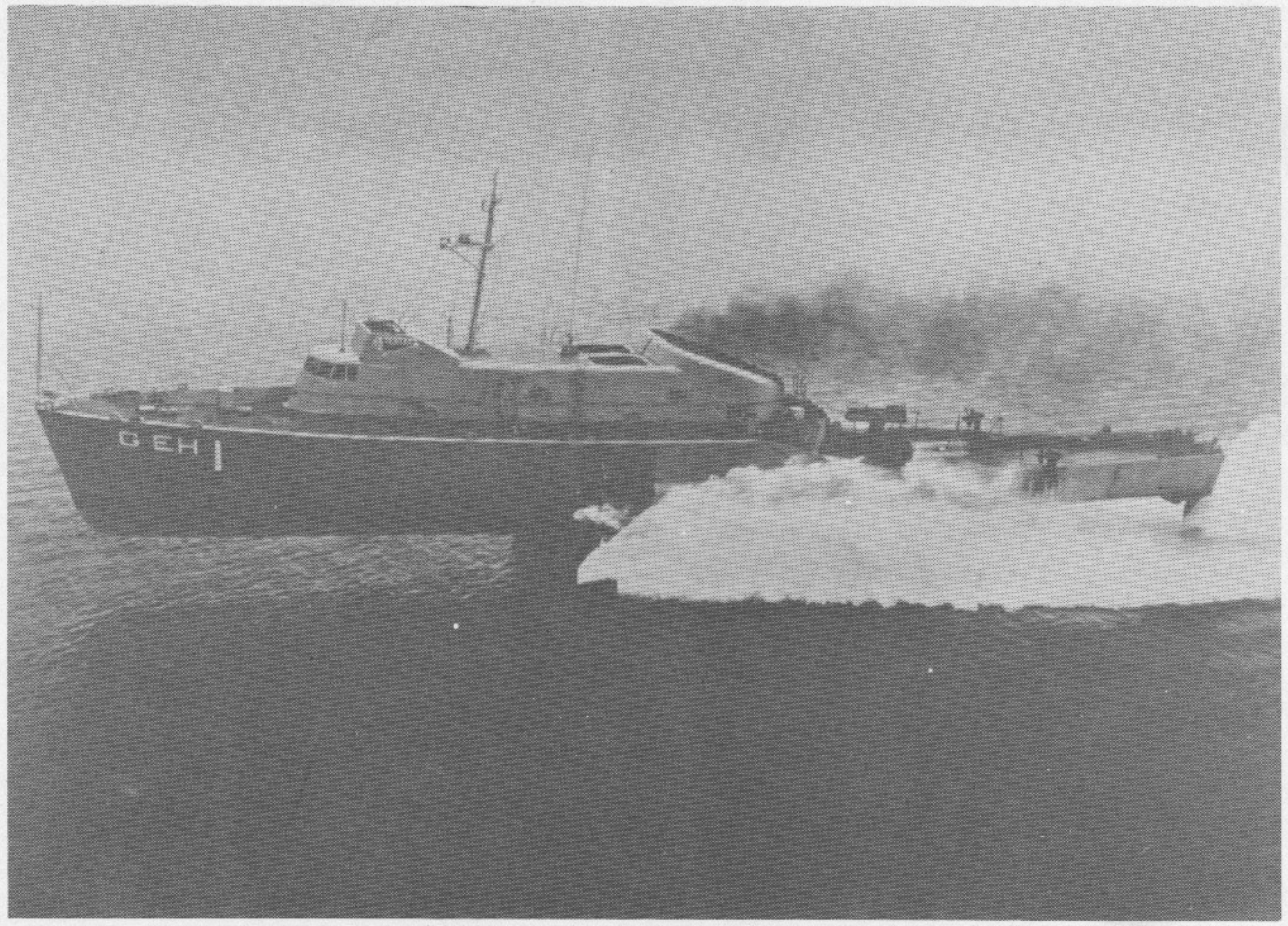
SELECTED PHOTOGRAPHS OF HYDROFOIL SHIPS

(U.S. NAVY PHOTOGRAPHS)

HIGHPOINT (PCH-1) Foilborne

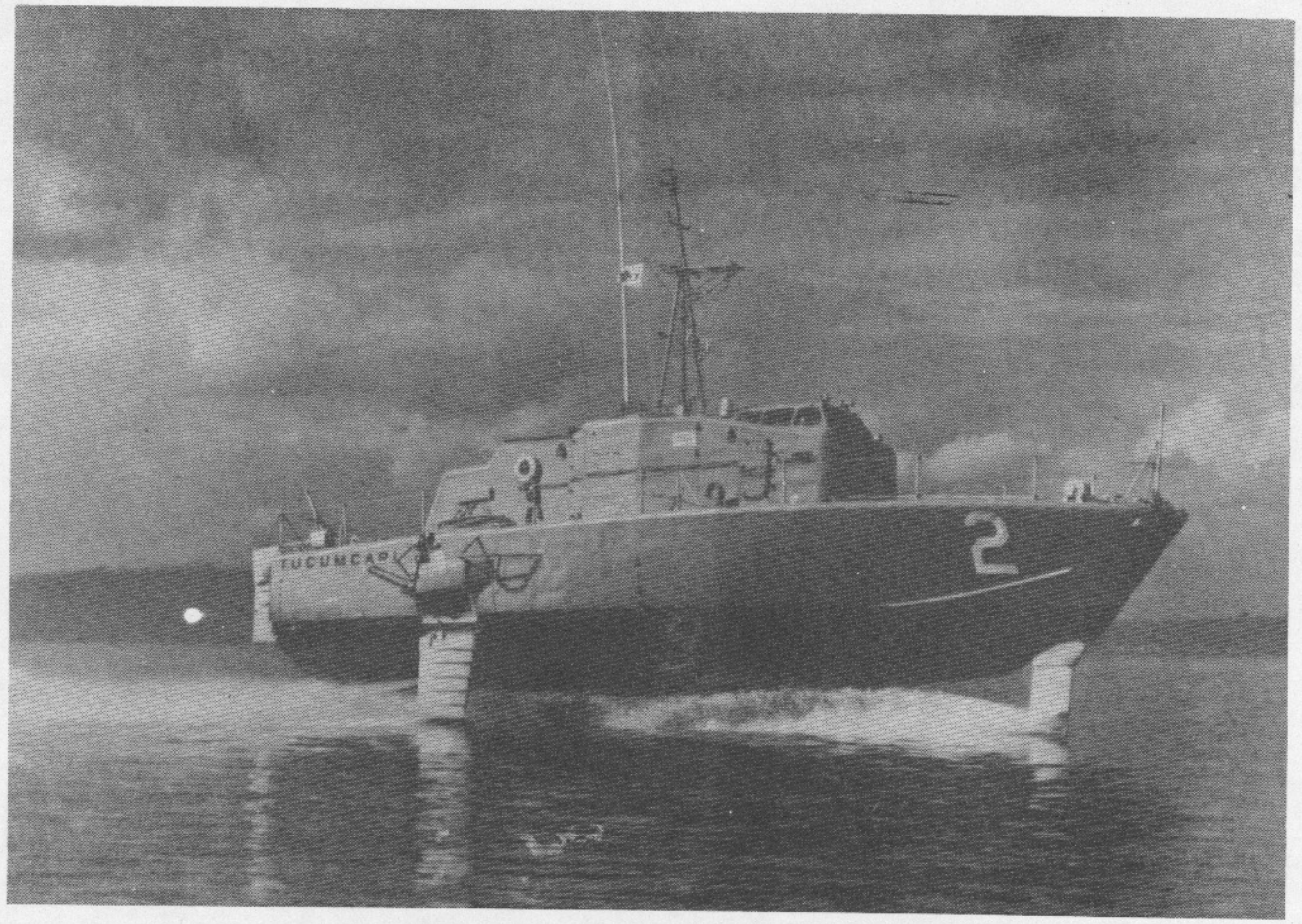


FRESH-1 Foilborne



PLAINVIEW (AGEH-1) Foilborne

FLAGSTAFF (PGH-1) Foilborne



TUCUMCARI (PGH-2) Foilborne

APPENDIX IV

CHARACTERISTICS OF SELECTED HYDROFOIL SHIPS

Characteristics	PCH-1 (Mod-0)	AGEH-1	FRESH-I*	PGH-1	PGH-2
Configuration	Canard	Airplane	Various	Airplane	Canard
Length Overall-Feet	115.7	212	53.1	74.5	71.8
Beam, Extreme, Foils down - Feet	33.3	70.8	22.5	21.5	19.5
Full Load Hullborne Draft - Foils up - Feet	6.5	6.4	----	4.2	4.5
Full Load Hullborne Draft - Foils down - Feet	17	25	10.4	13.5	13.9
Full Load Displacement - Long Tons	120	320	16.7	57	58
Hullborne Propulsion					
Engine	(1) Packard Diesel	(2) GM Diesels		(2) GM Diesels	(1) GM Diesel
Shaft Horsepower	600	1200		320	160
Thrust Producer	(1) 3-bladed Subcav. Prop	(2) 5-bladed Subcav. Props		Waterjet	Waterjet
Foilborne Propulsion					
Engine	(2) Bristol Proteus G. T.	(2) GM LM-1500 G. T.	(1) P&W JT-3D Fan Jet	(1) Rolls-Royce Tyne G. T.	(1) Bristol Proteus G. T.
Shaft Horsepower (continuous)	6200	28,000	**	3150	3100
Thrust Producer	(4) 3-bladed Subcav. Props	(2) 4-bladed Supcav. Props	Turbo Fan	(1) Supcav. Prop	Waterjet
Max. Hullborne Speed, Knots	12	15	4.5	7+	7+
Calm Water Takeoff Speed, Knots	27	33	45		
Max. Foilborne Speed, Knots	40+	45+	80-100	40+	40+
Foil & Strut Material	HY 80 Steel	HY 80/100 Steel	17-4PH	Cast Alum/HY80 4130	17-4 PH
Hull Material	5456 Al	5456 Al	5456/2014Al	5456 Al	5456 Al
Type of Control	Flaps	Incidence	Flaps	Incidence	Flaps

*Demonstration Foil Configuration
**18,000 lbs Static Thrust

Source: William M. Ellsworth, "The U.S. Navy Hydrofoil Developmental Program--a Status Report," (Norfolk, Va.: AIAA/SNAME Advance Marine Vehicles Meeting, Paper No. 67-351, May 1967), p. 23.

APPENDIX II

WIND AND SEA SCALE FOR FULLY ARISEN SEA

SEA-GENERAL				WIND [3]		SEA [3]								
SEA STATE [1]	DESCRIPTION [2]	(BEAUFORT) WIND FORCE	DESCRIPTION	RANGE (KNOTS)	WIND VELOCITY (KNOTS)	WAVE HEIGHT FEET: AVERAGE	WAVE HEIGHT FEET: SIGNIFICANT	WAVE HEIGHT FEET: AVERAGE $\frac{1}{10}$ HIGHEST	SIGNIFICANT RANGE OF PERIODS (SECONDS)	T_{max} (PERIOD OF MAXIMUM ENERGY OF SPECTRUM)	$\bar{T}$ (AVERAGE PERIOD)	$\tilde{L}$ (AVERAGE WAVE LENGTH)	MINIMUM FETCH (NAUTICAL MILES)	MINIMUM DURATION (HOURS)
0	Sea like a mirror.	0	Calm	Less than 1	[a] 0	0	0	0	-	-	-	-	-	-
	Ripples with the appearance of scales are formed, but without foam crests.	1	Light Airs	1 - 3	2	0.05	0.08	0.10	up to 1.2 sec	0.7	0.5	10 in.	5	18 min
1	Small wavelets, still short but more pronounced; crests have a glassy appearance, but do not break.	2	Light Breeze	4 - 6	5	0.18	0.29	0.37	0.4-2.8	2.0	1.4	6.7 ft	8	39 min
	Large wavelets, crests begin to break. Foam of glassy appearance. Perhaps scattered white horses.	3	Gentle Breeze	7 -10	8.5	0.6	1.0	1.2	0.8-5.0	3.4	2.4	20	9.8	1.7 hrs
					10	0.88	1.4	1.8	1.0-6.0	4	2.9	27	10	2.4
2	Small waves, becoming larger; fairly frequent white horses.	4	Moderate Breeze	11-16	12	1.4	2.2	2.8	1.0-7.0	4.8	3.4	40	18	3.8
					13.5	1.8	2.9	3.7	1.4-7.6	5.4	3.9	52	24	4.8
3					14	2.0	3.3	4.2	1.5-7.8	5.6	4.0	59	28	5.2
					16	2.9	4.6	5.8	2.0-8.8	6.5	4.6	71	40	6.6
4	Moderate waves, taking a more pronounced long form; many white horses are formed. (Chance of some spray).	5	Fresh Breeze	17-21	18	3.8	6.1	7.8	2.5-10.0	7.2	5.1	90	55	8.3
					19	4.3	6.9	8.7	2.8-10.6	7.7	5.4	99	65	9.2
					20	5.0	8.0	10	3.0-11.1	8.1	5.7	111	75	10
5	Large waves begin to form; the white foam crests are more extensive everywhere. (Probably some spray).	6	Strong Breeze	22-27	22	6.4	10	13	3.4-12.2	8.9	6.3	134	100	12
					24	7.9	12	16	3.7-13.5	9.7	6.8	160	130	14
					24.5	8.2	13	17	3.8-13.6	9.9	7.0	164	140	15
6					26	9.6	15	20	4.0-14.5	10.5	74	188	180	17
	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind. (Spindrift begins to be seen).	7	Moderate Gale	28-33	28	11	18	23	4.5-15.5	11.3	7.9	212	230	20
					30	14	22	28	4.7-16.7	12.1	8.6	250	280	23
					30.5	14	23	29	4.8-17.0	12.4	8.7	258	290	24
					32	16	26	33	5.0-17.5	12.9	9.1	285	340	27
7	Moderately high waves of greater length; edges of crests break into spindrift. The foam is blown in well marked streaks along the direction of the wind. Spray affects visibility.	8	Fresh Gale	34-40	34	19	30	38	5.5-18.5	13.6	9.7	322	420	30
					36	21	35	44	5.8-19.7	14.5	10.3	363	500	34
					37	23	37	46.7	6-20.5	14.9	10.5	376	530	37
					38	25	40	50	6.2-20.8	15.4	10.7	392	600	38
					40	28	45	58	6.5-21.7	16.1	11.4	444	710	42
8	High waves. Dense streaks of foam along the direction of the wind. Sea begins to roll. Visibility affected.	9	Strong Gale	41-47	42	31	50	64	7-23	17.0	12.0	492	830	47
					44	36	58	73	7-24.2	17.7	12.5	534	960	52
					46	40	64	81	7-25	18.6	13.1	590	1110	57
	Very high waves with long overhanging crests. The resulting foam is in great patches and is blown in dense white streaks along the direction of the wind. On the whole the surface of the sea takes a white appearance. The rolling of the sea becomes heavy and shocklike. Visibility is affected.	10	Whole Gale*	48-55	48	44	71	90	7.5-26	19.4	13.8	650	1250	63
					50	49	78	99	7.5-27	20.2	14.3	700	1420	69
					51.5	52	83	106	8-28.2	20.8	14.7	736	1560	73
9					52	54	87	110	8-28.5	21.0	14.8	750	1610	75
					54	59	95	121	8-29.5	21.8	15.4	810	1800	81
	Exceptionally high waves (Small and medium-sized ships might for a long time be lost to view behind the waves.) The sea is completely covered with long white patches of foam lying along the direction of the wind. Everywhere the edges of the wave crests are blown into froth. Visibility affected.	11	Storm*	56-63	56	64	103	130	8.5-31	22.6	16.3	910	2100	88
					59.5	73	116	148	10-32	24	17.0	985	2500	101
	Air filled with foam and spray. Sea completely white with driving spray; visibility very seriously affected.	12	Hurricane*	64-71	>64	>80[b]	>128[b]	>164[b]	10-(35)	(26)	(18)	~	~	~

*For hurricane winds (and often whole gale and storm winds) required durations and fetches are rarely attained. Seas are therefore not fully arisen.

[a] A heavy box around this value means that the values tabulated are at the center of the Beaufort range.

[b] For such high winds, the seas are confused. The wave crests blow off, and the water and the air mix.

[1] Encyclopedia of Nautical Knowledge, W.A. McEwen and A.H. Lewis, Cornell Maritime Press, Cambridge, Maryland, 1953, p. 483

[2] Manual of Seamansl Volume II, Admiralty, London, H.M. Statione Office, 1952, pp. 717-7

[3] Practical Methods f observing and forecasting Ocean Waves, Pierson, Neumann, James, N.Y. Univ, College of Engin, 1953.

This table compiled by Wilbur Marks,
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Source: The Boeing Company, Advanced Marine Systems Technology Staff, "Special Trials Agenda-Hydrofoil", D2-133000. (Seattle, Wash.:1965), sheet 306.