First International Hydrofoil Society Conference

Ingonish Beach, Nova Scotia, Canada
27-30 July 1982

LIST OF PAPERS
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Author: Johnston, Captain Robert J. USN (Ret)

Title: *History Of U.S. Involvement In Developing The Hydrofoil*

Abstract: This paper on the United States history of hydrofoils has been prepared as one of a tripartite of three papers on the subject of the development of hydrofoils. The other papers cover European and Canadian developments. Emphasis has been placed on the period of the 1950's when hydrofoils went through a decade of experimental models and progress. During this time, hydrofoils moved from skepticism to reality. It is an interesting period that needs to be kept in perspective as today's hydrofoils take on bigger and more ambitious roles. To lead into the 1950 period a review of early progress is presented. The conclusion leads to the fact that a summary of the developments after this period is needed to make the history complete.

Author: Rodriquez, Dott. Ing. Leopoldo and Dott. Ing. Dino Di Blasi (Rodriquez Cantiere Navale, Messina, Italy)

Title: *Current Status And Future Prospects For European Commercial Hydrofoils*

Abstract: European Commercial Hydrofoils (ECH) are briefly reviewed from a technical and commercial point of view. Dimensions, hull, foil systems, propulsion and automatic control system, together with the modifications made in respect of the early design are examined. The results of a worldwide investigation concerning utilization of ECH and current costs are analyzed. Based on the past 25 years of production, trends are given and analyzed for the near future.

Author: von Schertel, Baron Hanns (Supramar AG, Switzerland)

Title: *Current Status And Future Prospects For European Commercial Hydrofoils*

Abstract: The Airplane and Hydrofoil, two means of transportation which are subjected to the same basic physical laws, have nearly the same date of birth. Whereas the Aircraft progressed rapidly, Hydrofoil development advanced slowly and even stagnated fully for nearly 30 years after the successful flights of Alexander Graham Bell. Only during World War II, when a test boat of the Schertel-Sachsenberg system was demonstrated to the German Navy and accepted with several orders, was hydrofoil technology re-awakened. With the construction of five different types of hydrofoil craft in the Sachsenberg shipyard, the age of industrial hydrofoil manufacturing had commenced. We will look at why it took about 50 years to find the first passenger ferries in public service and what caused so many inventors to search for new solutions for the

waterborne vehicles. We find only two predecessors of Forlanini who deserve the honor of having been the first inventors of a practical, usable hydrofoil boat. However, the teachings of Horatio Phillips in 1881 allow us to state that the hydrofoil principle has been known for a hundred years. A chronological review of hydrofoil development in Europe follows, disregarding utopian ideas that did not contribute to technical progress, are disregarded. My own experimental work with its failures and catastrophes, and the first demonstration trip down the Rhine showing feasibility of a Hydrofoil for passenger transportation is delineated. A short technical review giving the life story of the military hydrofoil built during World War II is given. Then follows a description of the development of the public passenger service with hydrofoil ferries. Finally, we discuss the largest hydrofoil development of the world, which is in the Soviet Union, where larger and faster military hydrofoil vessels are built than in the Western Nations. Described is how the Russians accumulated know-how, knowledge and experience from the engineers of the Sachsenberg shipyard who had been involved in the design and construction of our Naval hydrofoil vessels.

Author: Eames, Michael C. (Defence Research Establishment Atlantic, Canada)

Title: *A Review Of Hydrofoil Development In Canada*

Abstract: This paper tells the story of hydrofoil development in Canada from the late 1940s to the present, with emphasis on the concept and design of *HMCS BRAS D'OR*. The early work with *MASSAWIPPI* had very close links with the pioneering efforts of Alexander Graham Bell and F. W. Baldwin. *MASSAWIPPI*'s original foil system is seen to be closely related to that of the Bell-Baldwin HD-4, and the potential of the ladder foil system was further explored in the first *BRAS D'OR* (renamed *BADDECK*) and a smaller experimental craft called the R-X. Shortcomings revealed by *BADDECK* caused a literal turnaround in Canadian thinking about surface-piercing foil systems, and led to the canard configuration first explored in R-X, and now generally associated with *BRAS D'OR*. *BRAS D'OR* was unusual among prototype hydrofoil ships in being designed to a specific operational requirement, and one calling for features significantly different from those of the usual "ferry" type of craft. The development of her design and the reasons for such features as her novel super-ventilated bow foil and very fine hull are explained. While *BRAS D'OR* was being designed and built, R-X and *BADDECK* had strong supporting roles: R-X as the test-bed of a quarter-scale model of *BRAS D'OR*'s foil system; *BADDECK* converted into the world's fastest tug. A major feature of the operational concept was the use of high-speed towed sonar, and the earliest research on towed bodies and faired cables suitable for sprinting at high speed was conducted through half-scale experiments using *BADDECK*. *BRAS D'OR* proved herself to be a technical success, but a political disaster for reasons explained in the paper. Following her decommissioning, DREA has remained active in design method development and conceptual studies of possible future hydrofoil ships, but the last test craft, *PROTEUS*, was used solely for propulsion research and has recently been retired. The story will be illustrated by slides, not all of which will appear in the written text.

Author: Shultz, William M. (Boeing Marine Systems)

Title: *Current Status And Future Prospects United States Commercial Hydrofoils*

Abstract: This paper summarizes U.S. fully submerged foil commercial hydrofoil activities during the past 10 years. The importance of ride quality and productivity are discussed together with technical advancements that have been made to obtain better fuel efficiency and utilization. Operating performance experience is reported on and the future market for advanced marine craft in the U.S. is presented.

Author: Ambs, Albert W. and Kenny Tham (Hong Kong Macao Hydrofoils, Ltd)

Title: *Current Status And Future Prospects For Far East Commercial Hydrofoils*

Abstract: The Far East, including Australia, without a doubt has more high speed surface craft in scheduled operations than any other area. Furthermore, as countries in the area become more developed and industralized (particularly the Philippines and Indonesia) and the need for people to move between destinations increases, there is good potential for new services. With oil exploration activity and subsequent development of proven off-shore reserves just about to get underway, particularly in the South China Sea, there may be significant potential for high speed craft to service rigs and platforms.

Author: Patch, CDR David A. (Office of the Chief of Naval Operations, U.S. Navy)

Title: Operational Utilization Of The Patrol Hydrofoil Missile (PHM)

Abstract: In the early stages of PHM development and acquisition, the hydrofoil concept met with resistance at various levels within the government, as often happens when new, innovative programs are proposed. It can now be said that the PHM is enthusiastically supported within the Department of the Navy. The Navy recognizes that there are many missions which ships of this type can perform more effectively and less expensively than those of conventional design. It is most encouraging to realize that today the Navy's first 6 ships PHM squadron is being formed at Key West, Florida. In addition to PEGASUS, we have 2 ships en route now and plan delivery of the other 3 in time to complete the squadron early in 1983. The PHM is unique and has just begun to show its true operational capabilities as a viable Naval Weapons System able to project significant power at sea in smaller, less expensive, faster reacting, and versatile units than ever before available to the U.S. Navy. Previous papers, presented to the AIAA, SNAME and ASNE, have covered in detail the design, development, acquisition and testing phases of the PHM program. It is my intent to discuss the operational utilization of the PHM. The PHM's role in the various missions of power projection at sea may be generally classed as active and passive. Some tactics have been developed based on testing conducted to date and others remain to be developed. I envision that one major task of PHMRON-2 will be the refinement of current tactics and the development of tactics in support of missions not yet defined in detail for the PHM.

Author: Frauenberger, Howard C. (Grumman Aerospace Corporation)

Title: *SHIMRIT - Mark II Hydrofoil for the Israeli Navy*

Abstract: The M-161 Mark II hydrofoil being developed for the Israeli Navy represents the latest in a series of high performance craft developed over the past two decades by Grumman. It is by far the most sophisticated and best performing hydrofoil of the series and should prove to be a formidable military vehicle. This paper traces the M-161 development from its inception as a successor to the smaller and lighter *PGH-1 FLAGSTAFF* Mark I hydrofoil. Detailed descriptions of the hull and deckhouse construction, struts, foils and major systems are presented along with a discussion of the significant development challenges encountered in the program. A review of the status of the sea trials conducted with the first vessel, commissioned the *SHIMRIT*, is also presented.

Author: James King

Title: *The Evolution of the NIBBIO Class Hydrofoil From TUCUMCARI*

Abstract: The development of the Italian *SPARVIERO* and *NIBBIO* class hydrofoils provides a special lesson. These ships were derived from the U.S. *TUCUMCARI* design. Their evolution offers some insight into the problems of developing a hydrofoil class that is a variant of another, successful class. This paper includes a discussion of the evolution of the *NIBBIO* and its various systems from *TUCUMCARI* via *SPARVIERO*. Lessons which can be applied to other such projects are described.

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The North American Association Int'l. Hydrofoil Society
The Alexander Graham Bell Institute

HISTORY OF U.S. INVOLVEMENT IN DEVELOPING THE HYDROFOIL

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David W. Taylor Naval Ship Research and Development Center, U.S. Department of the Navy

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HISTORY OF U.S. INVOLVEMENT

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ABSTRACT

This paper on the United States history of hydrofoils has been prepared as one of a tripartite of three papers on the subject of the development of hydrofoils. The other papers cover European and Canadian developments.

Emphasis has been placed on the period of the 1950's when hydrofoils went through a decade of experimental models and progress. During this time, hydrofoils moved from skepticism to reality. It is an interesting period that needs to be kept in perspective as today's hydrofoils take on bigger and more ambitious roles.

To lead into the 1950 period a review of early progress is presented. The conclusion leads to the fact that a summary of the developments after this period is needed to make the history complete.

INTRODUCTION

Even though the concept of hydrofoils is older than the concept of airplanes, the transportation needs that can be filled with a hydrofoil are limited, compared to the potential of aircraft. Although the development of airplanes proceeded at a much faster pace, the significant contributions made by some of the very early inventors of hydrofoil principles are worth recognition and comment.

This paper will review the work of some of the individuals who first used hydrofoils, limited to United States efforts, since other papers will cover Canada and Europe. This presentation is divided into two eras: (1) pre-World War II progress and (2) the period of experimental progress which moved hydrofoils out into the open sea. Since the accomplishments of the late 60's and 70's have been the most extensively documented, this paper will concentrate on the experimental models that led to the successes of that period and the functioning hydrofoils of today.

One of the fringe benefits of being in the business long enough to be considered a historian is that you can write the way <u>you</u> believe it happened. So it is understandable that someone may feel neglected or even overlooked when the author of a brief overview of the efforts of many talented people may inadvertently leave out a name here and there. It is also quite likely that others may share different viewpoints as to the significance of certain events. In any case, the author, who participated in several of the events described, offers the following version.

PRE-WORLD WAR II PROGRESS

Like some other writings that start "In the beginning," somebody had an idea. The best record of these old ideas is housed in the U.S. Patent Office and summarized by Leslie Hayward.[1] The following review on how the use of hydrofoils began was compiled with the help of these two sources.

Early Patents

In June of 1888, G. W. Napier who lived in Los Angeles, California, proposed fitting a large adjustable foil to the sides of a ship (Figure 1). What he really was trying to do was reduce the ship's draft by creating dynamic lift with the side foils. We now know

G. W. NAPIER.

FIN FOR VESSELS.

No. 400,592. Patented Apr. 2, 1889.

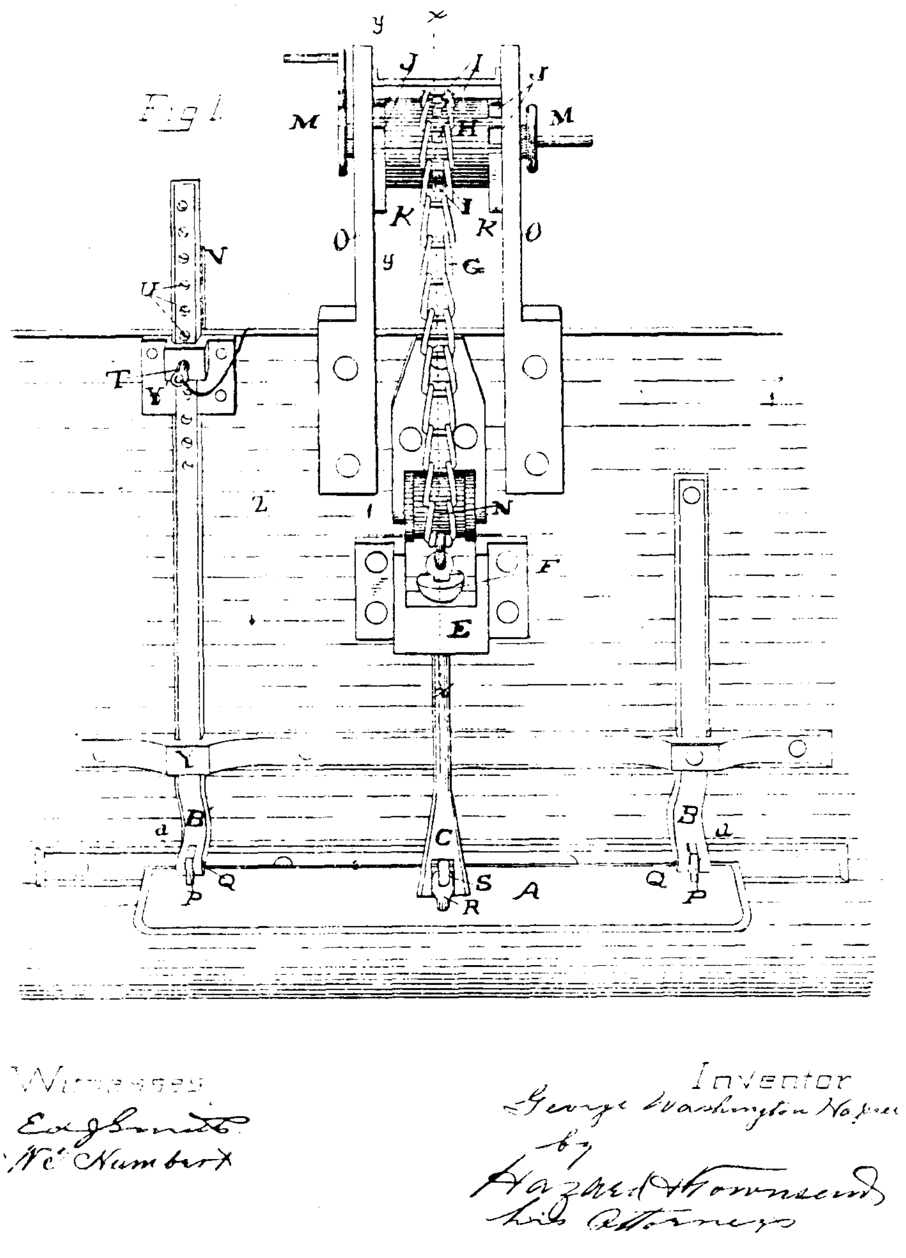


Figure 1. Large Adjustable Foil Fitted to Sides of a Ship

that this is not a very desirable way to prevent groundings. Mr. Napier also pointed out that you could use the same set of foils to increase the draft of a ship. Was he trying to improve sea-keeping? In any event, Napier's concept was certainly an early effort to produce positive and negative lift from a hydrofoil.

In 1890 C. E. Emery of Brooklyn, New York, filed a patent using retractable foils, again applied to the sides of a vessel. These foils were of the ladder type and retracted flush with the surface of the ship. They were retracted or extended to be used as a water brake, or for maneuvering.

The efforts of W. M. Meacham and L. C. Meacham, brothers who lived in Chicago, were first reported in 1894. They recognized the relationship between what they called "aerial navigation" and "water navigation," applying the principle of lifting planes to "water navigation." They also applied the use of lifting planes to support a boat while underway. Their experiments were carried out on a 14 ft. long by 30 inch beam craft (Figure 2). This is the first clear record of a craft in the U.S. attaining flying status through the use of hydrofoils. It is also interesting to note that the foils were submerged and incidence-controlled. A surface feeler was connected to the forward foil to provide some degree of stabilization in waves. By 1906 the Meachams' design had become even more sophisticated with both fore and aft control systems. Each supporting strut had two ladder foils with the upper foil fixed and the lower foil controllable through a system of linkages to the surface feeler.

The Meachams became involved in a patent suit with a Mr. S. A. Reeve. The brothers applied for a patent in 1896 but Reeve had applied for a patent a year earlier on the subject of swinging links adjusting a pivoting foil to a desired position (Figure 3). Mr. Reeve won the judgment in 1904. At least the outcome was quite amicable as Reeve ultimately assigned his patent to the Meacham brothers. The Meachams' interest in hydrofoils continued until at least 1913 when they designed a manual control of the aft foil while retaining the same forward foil control as their 1894 concept (Figure 2). This latter concept of manual control would eventually prove to be an unwise decision as hydrofoils became faster. It is also interesting to note that from 1906 to 1913 they changed from a "conventional" foil system to a "canard," although these definitions would not be used until years later.

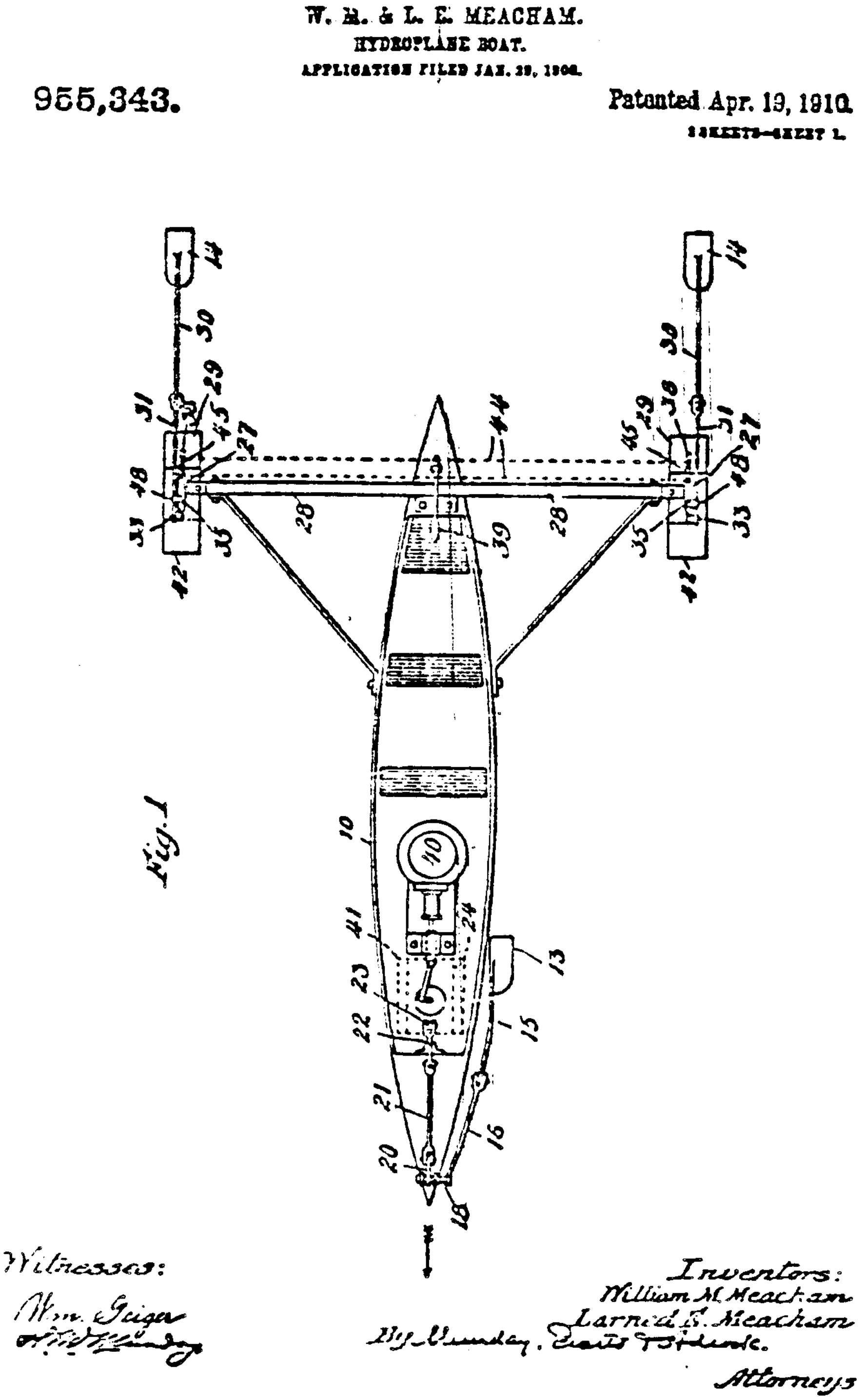


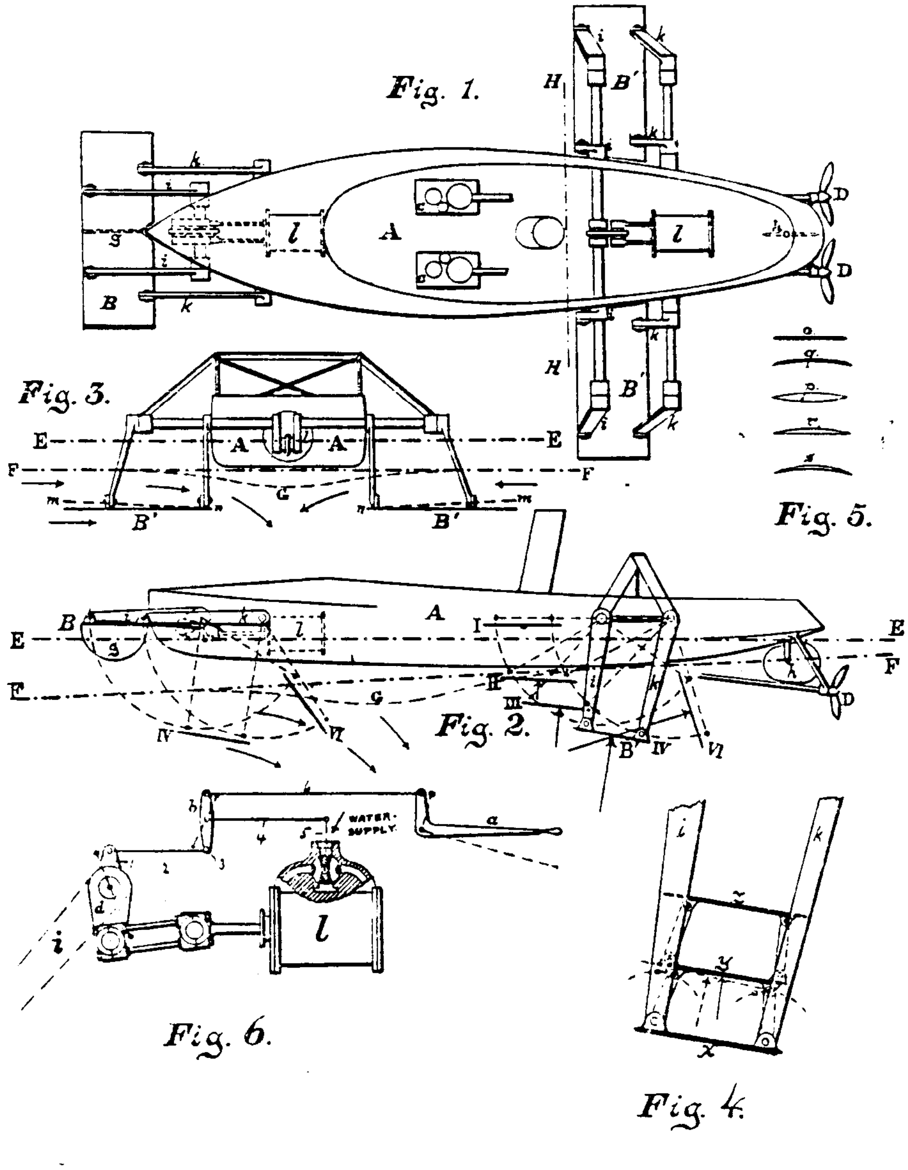
Figure 2. Meachams' Beam Craft

No. 811,743. PATENTED FEB 6, 1906.

S. A. REEVE.

MARINE NAVIGATION.

APPLICATION FILED JULY 31, 1896.



Witnesses:
John F. Marshall.
C. R. Jones.

Inventor:
Sidney A. Reeve

Figure 3. Reeve's Design of Swinging Links Adjusting a Printing Foil

One interesting story which persists from the early years is that the Wright brothers experimented with hydrofoils on one of their Wright fliers in 1906 or 1907. Furthermore, they recognized the similarity of the principle of foils operating in either air or water as a medium for deriving lift; a subject which the Navy would later study in some depth.

Capt. H. C. Richardson, U.S. Navy

The earliest record of U.S. Navy interest in hydrofoils was in 1909 when a young Naval constructor, Holden C. Richardson, fitted a set of submerged foils to a canoe and, under tow, took off and flew at about 6 knots. We remember this officer as Capt. Richardson, USN (RET) who, as an earlier seaplane designer, participated in the design of the NC-4, the first airplane to fly the Atlantic in 1919. He was also a pilot of the NC-3, one of the seaplanes accompanying NC-4 that didn't make it. The author remembers him from a time when he was one of the few naval officers who believed that hydrofoils could be applied to practical seagoing craft. This was during one of those periods when most of the U.S. Navy had written them off. Capt. Richardson's early interest was in part inspired by Enrico Forlanini of Italy who proposed using hydrofoils as landing gear for seaplanes. The Captain's experiments were related to finding a solution to landing planes on the sea.

In these experiments he fitted a dinghy with a set of submerged foils that were manually incidence-controlled. His foil system was conventional in area distribution, had a fixed ladder foil forward and a controllable foil aft. A picture of this dinghy on one of its flights in the Philadelphia River is shown in Figure (4). It is interesting to examine the after foil control arrangement. The incidence angle and the foil tips could be manually controlled. This tip control, much in the fashion of warping the surfaces of an aircraft wing, provided banking in addition to rudder action to improve turning maneuverability. The control of the tips also provided the craft with some roll control authority.

Captain Richardson's efforts in hydrofoil-supported craft continued at least until 1911. In that year he received a patent[2] for a speed boat powered by twin air propellers with controllable fore and aft submerged foils.

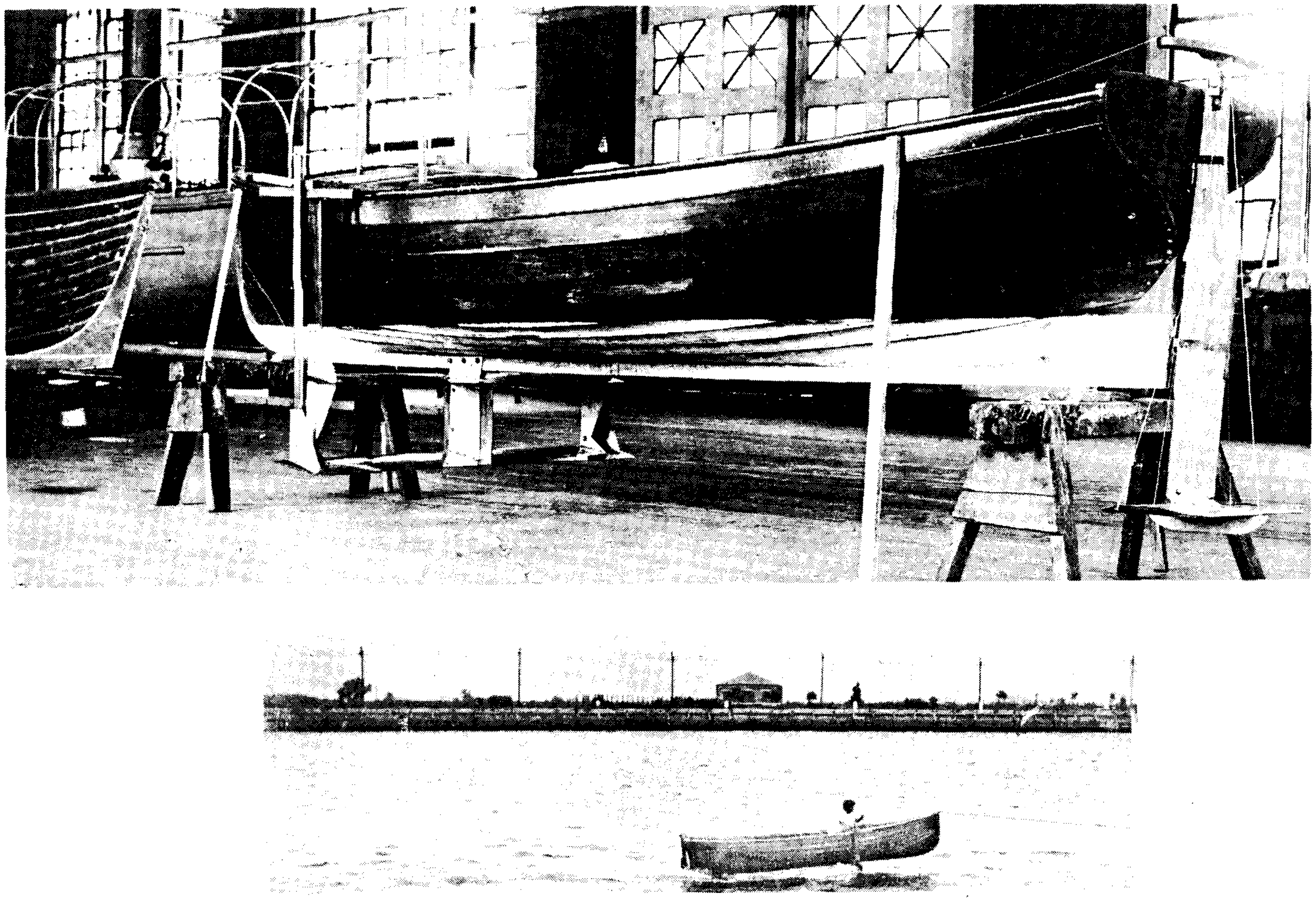


Figure 4. Capt. Richardson's Hydrofoil Dinghy, 1909

United States Interest in the Bell-Baldwin Concept

This paper, as mentioned in the introduction, is a part of a three-way series on the subject of the development history of hydrofoils. Dr. Alexander Graham Bell and Frederick Walter Baldwin, who became legendary in the field of hydrofoils, did their work in Canada. While their story is rightfully a part of Canadian history, the United States did watch their developments and successes with interest, and that little piece of the story needs to be told in this paper.

In 1919, when Bell and Baldwin were setting world speed records, LCDR Jerome C. Hunsaker was sent by the U.S. Navy to investigate their development. (During World War I LCDR Hunsaker USN, a naval constructor, was best known for his efforts in developing the seaplane and in applying its capabilities to the needs of the U.S. Navy. After his Navy career he became an educator in the field of Aeronautical Engineering, ultimately heading MIT's school in that subject.) He reported very favorably on the technical accomplishments of their effort and reviewed the design in some detail. Years later he was questioned by the author as to the Navy's reaction to the Bell/Baldwin concept. According to Dr. Hunsaker, the Navy's dilemma was that, while the concept displayed interesting speeds over the water, the Navy couldn't agree on how this capability could be applied to naval warfare. This dilemma of how best to use the hydrofoil militarily has been discussed periodically for many years.

During the period between the World Wars, Bell and Baldwin tried to interest the U.S. Navy in supporting their efforts. The fact that they had no success in this regard is not surprising since there is no record of any support for hydrofoils by the Navy during this period.

Dr. Tietjens U.S. Experiments

During the 1930's the Westinghouse Corporation brought a group of outstanding European engineers and scientists to the United States. A number of these individuals are known today for having made noteworthy technology contributions in the U.S. as engineers and educators. One of them was Dr. Oscar G. Tietjens from Germany.

Dr. Tietjens investigated a surface-piercing hydrofoil with hoop-shaped foils (Figure 5); the after foil's incidence was controlled manually. He built and tested at least two boats in the U.S. based on this foil design. Like Capt. Richardson he used the Philadelphia River as his test basin. Tietjens' test craft were outboard motor driven and achieved speeds of about 25 miles per hour. Figure (6) is a picture of 1936 vintage, showing one of his boats underway.

In the late 30's Tietjens returned to Germany and in 1940 built the VS-7 for the German war effort using the same foil principle he had tested in Philadelphia. The VS-7 was a 17-ton craft intended for air-sea rescue and cross channel operations and competed with the VS-6, which was built a year earlier using Baron Von Schertel's surface piercing concept. The VS-6 was more successful than Tietjens VS-7, primarily because of lack of roll restoring capability the Tietjens foil system had.

Before leaving the Tietjens story, we should make note of Gordon Baker, a young engineer who was working with Westinghouse during the 1930's. He met and became acquainted with Tietjens and his hydrofoil work. From this spark of interest another "hydrofoiler" was born—but that's another story which we will pick up later.

Grunberg and His NACA Experience

Wsevolode Grunberg was a Russian officer who, after the fall of the Czar, went to live in France. He conceived a submerged foil system which had a single main lifting foil with forward floats or surface riders. These planing floats adjusted the angle of attack of the main foil, controlled foil submergence, and provided roll stability. Models of this craft were tested in the Saint-Cyr model basin. A sketch of the Grunberg configuration is shown in Figure (7).

In the late 1930's Grunberg came to the United States at the invitation of the National Advisory Committee for Aeronautics (NACA) to demonstrate his principle. NACA was interested in a seaplane application. We note repeatedly during the early history of hydrofoils the interest in using them as a means of landing airplanes in rough seas. Mr. Grunberg worked with NACA as a French citizen providing the necessary information so that a model could be built and tested at Langley, Va. As one of the ironies of wartime security classification prevented Grunberg, who was a foreign citizen, from seeing the results of the model tests. Mr. Grunberg left the U.S. and reentered as

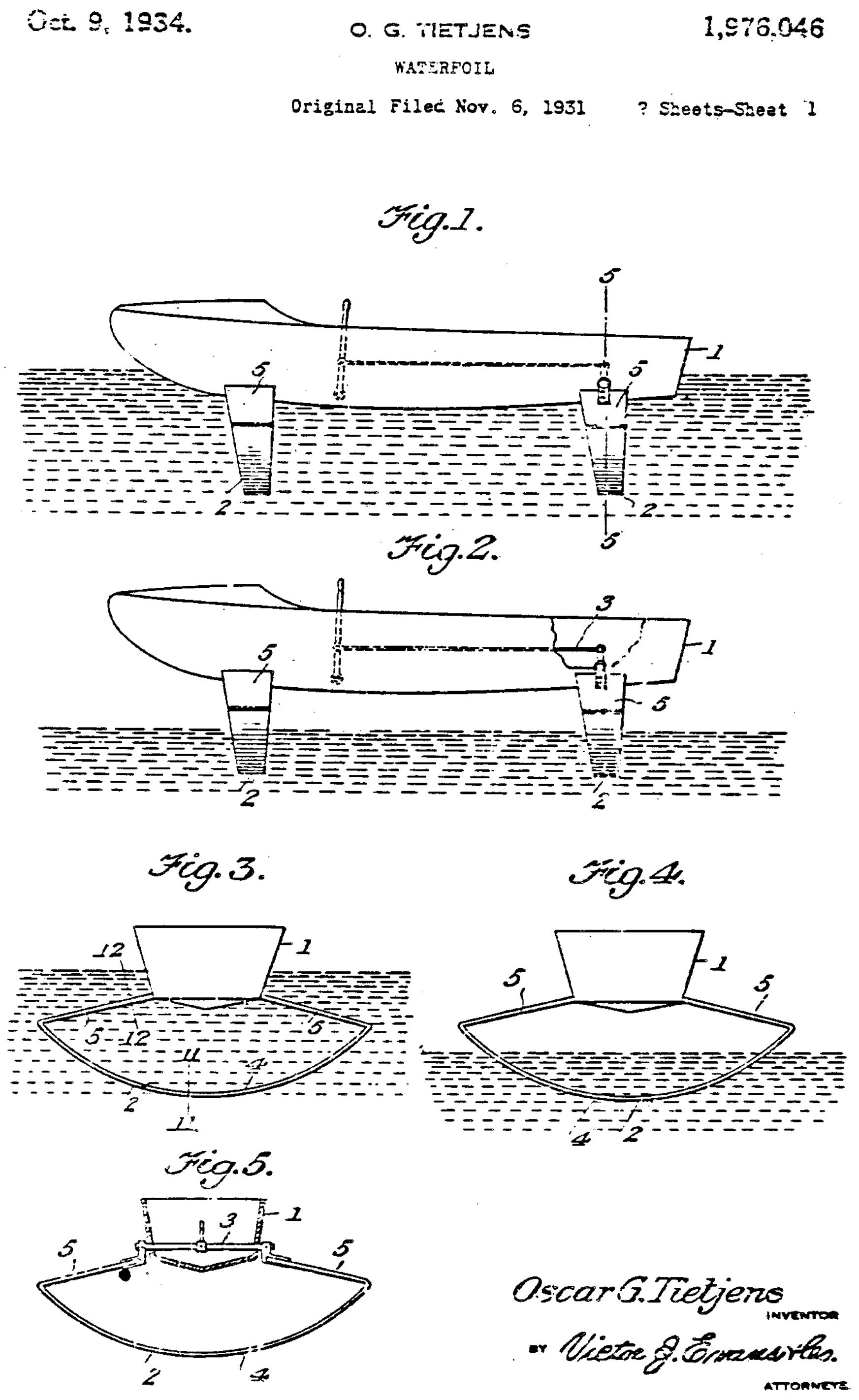
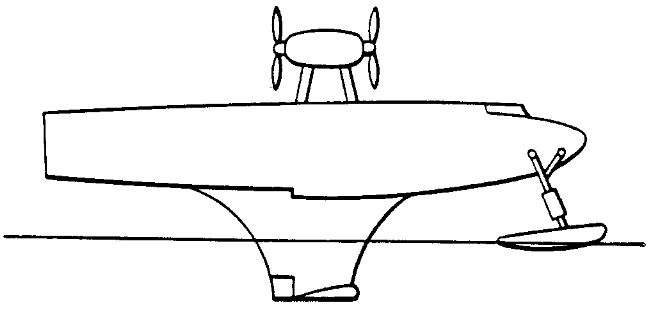
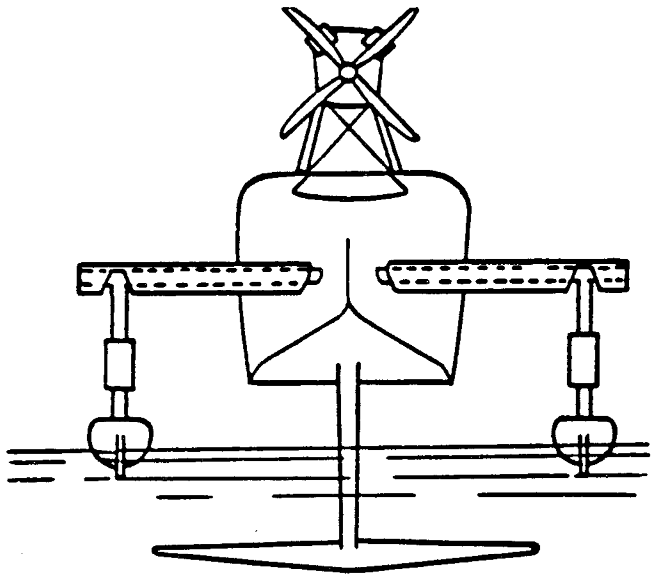


Figure 5. Surface-Piercing Hydrofoil With Hoop-Shaped Foils

Figure 6. Dr. Tietjens' Test Craft



Grunberg arrangement of foils



W. GRUNBERG. 1934.

Figure 7. Sketch of Grunberg's Craft

an immigrant, changed his name, and became a U.S. citizen. We honor him today as Waldemar A. Graig, a life member of the International Hydrofoil Society and our North American Association. It wasn't until years after the war when all interest in hydrofoil landing gear for seaplanes had ceased that Graig found out how really successful the NACA model tests had been.

One of the individuals working on these model tests at Langley was Robert Gilruth. While best known for his role in the manned space program, his name will also appear again in our hydrofoil development story. The Grunberg system was proposed by Gibbs and Cox during the 1953-1954 competition for a landing craft. Gibbs and Cox configured their test craft and ran a series of tests on this system,[3] but their design was not selected by the competition. While the Grunberg configuration is reviewed from time to time, it has not been used on any other craft.

THE 1950's - A DECADE OF EXPERIMENTAL PROGRESS

Although there is no record of any U.S. Navy interest in hydrofoils during the second World War. Philip Rhoades, a U.S. Navy architect, did undertake some effort with Canada during this period and private interests continued to pursue the challenge of the hydrofoil. Bob Gilruth engaged in such experimental work primarily as a hobby. He developed a pendulum which carried a foil and when released from a given height, swung through a body of water at a known speed measuring lift and drag forces. He also created a rotating basin in which a foil section could be suspended in a rotating water stream to measure forces. Both of these devices were later developed into full scale test facilities by Dynamic Developments and Grumman. Based on data obtained from these self-developed test devices, Gilruth built a 13-foot-2 inch long sail-powered hydrofoil catamaran. This boat was later turned over to the Hydrofoil Corporation of America and a 5 HP motor was added.[4] Figure (8) shows this self-propelled hydrofoil underway. Gilruth's early work resulted in a patent for a submerged foil system.[5]

The Carl XCH-4

During the war period, William P. Carl was stationed at NACA as an Air Corps liaison officer. Bill Carl, a sailing enthusiast, was intrigued with Bob Gilruth's experiments with sailing hydrofoils, and there began a long association and friendship. In the early postwar period, Dr. Kenneth Davidson of Stevens Institute of Technology,

Figure 8. Gilruth Boat in Flight Under Manual Control

founder and director of what is now called Davidson Laboratory, supported the efforts of Carl and Gilruth. This combined effort led to a proposal in 1947 to the Office of Naval Research for the development of a high speed hydrofoil configuration. As a result, a contract was awarded to John H. Carl & Sons, a corporation owned by Bill Carl's family. This marked the true beginning of what was to be the U.S. Navy's continued interest in hydrofoils.

Test work was undertaken at Stevens Institute and several models were built, including one 12-foot unmanned model which was ram jet propelled. The length of each test run was controlled by the amount of fuel carried. On one particular demonstration in Great South Bay off Long Island, the model, which in some respects was torpedo-shaped, was headed on a collision course for a steaming yacht. The observers were all convinced that they were about to witness the first sinking by a hydrofoil. Much to everyone's relief the fuel ran out at the last moment so that the model glided to a halt a few feet from the traveling yacht. In spite of this near sinking, the success of these tests led to a contract for the construction and test of a high speed, half-scale test vehicle, designated XCH-4 (Experimental Carl Hydrofoil No. 4).

XCH-4 had a design speed of 65 mph at a design weight of 15,000 pounds. The craft, shaped like a seaplane, was 53'-7¼" long with a hull beam of 6'-11".[6] The foil system was conventional with two sets of main supporting foils. Each set consisted of three foils cantilevered from a central strut and configured in a reefing arrangement, which made a smooth area transition as higher speeds were attained. Initially, the after-foil assembly also consisted of three reefing foils; during the tests to correct some longitudinal instability, the tail was modified and a single flat trail foil with a 45 sweep angle was installed for most tests.

The XCH-4 was powered by two Pratt & Whitney R-985 Wasp Jr. air-cooled engines of 450 HP each. These engines each drove a two-bladed, controllable pitch, 8'-4" diameter steel propeller. During the trials the design speed was repeatedly exceeded with 65 mph achieved in three to four foot waves. Figure (9) is a picture of the XCH-4 underway at 65 mph. The maximum speed attained over a measured course was 74.4 mph which, in 1954, was the speed record for hydrofoils, exceeding Bell's 1919 record. The good performance and stability of XCH-4 encouraged the Navy to continue the development of hydrofoils.

From the experience with XCH-4, Bill Carl left John H. Carl & Sons and formed his own company — Dynamics Developments, Inc., — with Bob Gilruth as a partner. Dynamics Developments initially developed and produced a kit boat as a sport hydrofoil runabout (Figure 10). As hydrofoil interest expanded, Grumman Aircraft Engineering Corporation purchased interest in, and ultimately acquired, all of Dynamic Developments. This combination formed the team for construction of the H.S. DENISON, a 60-knot, open ocean hydrofoil for the Maritime Administration.

Gordon Baker's Contributions

The name J. Gordon Baker was previously mentioned in connection with his observations of Tietjens' experiments. By the early 1950's he had left Westinghouse and had returned as President of his family's business, the Baker Manufacturing Company. Baker Manufacturing was, and still is, well known throughout the mid-west as a producer of windmills and farm water systems. In order to make life more technically interesting, Gordon Baker added hydrofoils to the company's product line. His early experiments

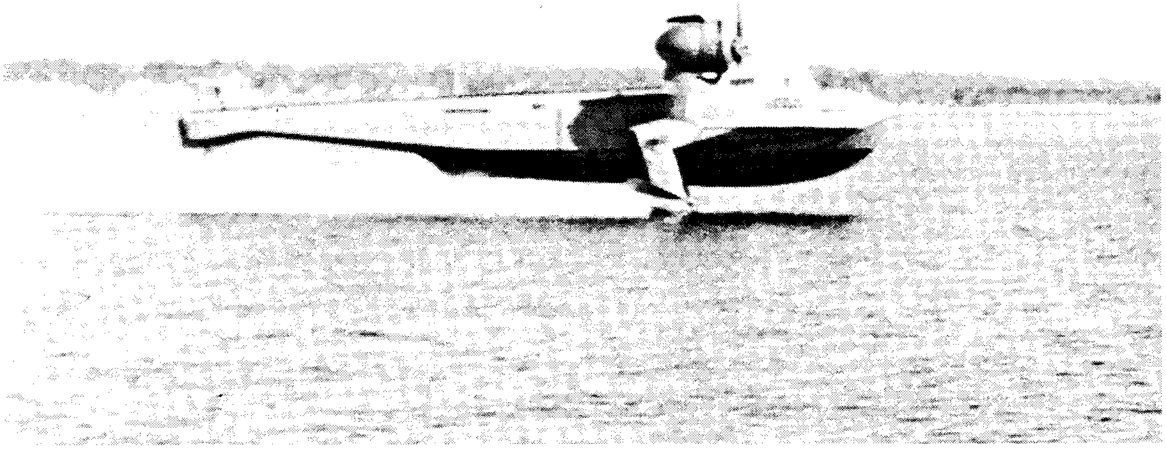


Figure 9. The XCH-4 Underway, 1954

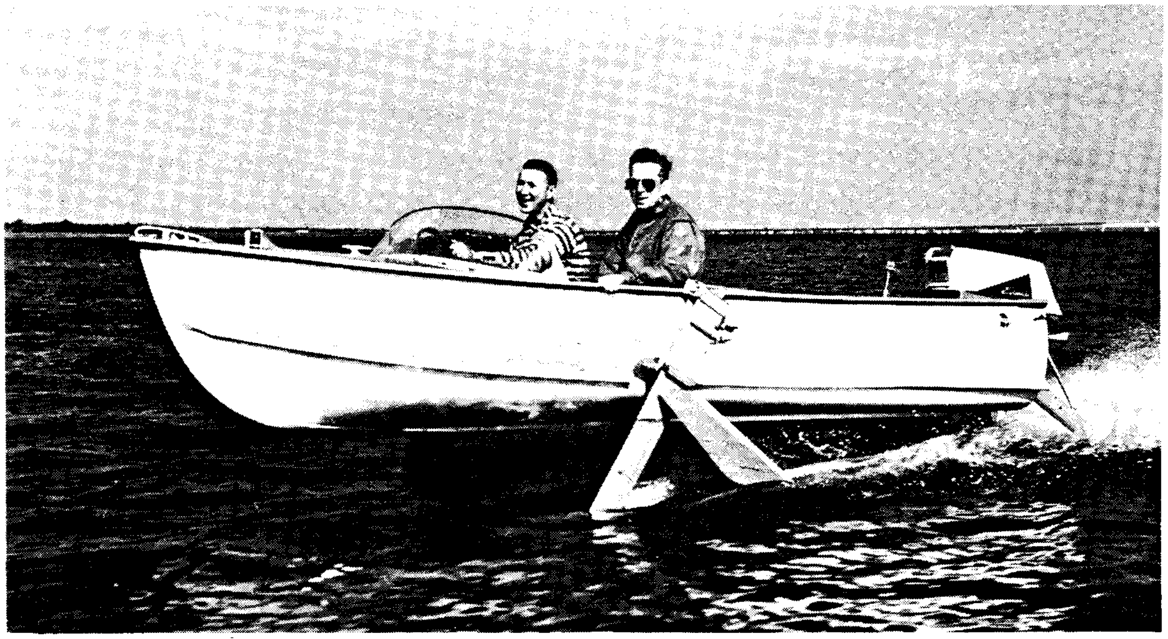


Figure 10. Early Model of the Dynamic Developments Kit Boat

were related to V-foils systems which led to the marketing of a small runabout (Figure 11). When he learned of the Navy's expanded interest in hydrofoils, he proposed undertaking an experimental study comparing surface-piercing hydrofoils with submerged hydrofoils. The Navy constrained his submerged foil efforts to evaluating only mechanical-hydraulic controls. The results were used for comparison with other studies of electro-hydraulic control systems.

In 1951 the Office of Naval Research contracted with the Baker Manufacturing Company for the construction of two 24-foot hydrofoils.[7] The first of these was HIGH POCKETS, a surface piercing configuration (Figure 12). This hydrofoil had four retractable V-foils which could be steered and rotated to provide inboard bank while turning. HIGH POCKETS was demonstrated extensively by the Navy to show the capability of hydrofoils including the first hydrofoil trip for a Chief of Naval Operations, Admiral Carney, in the summer of 1953.

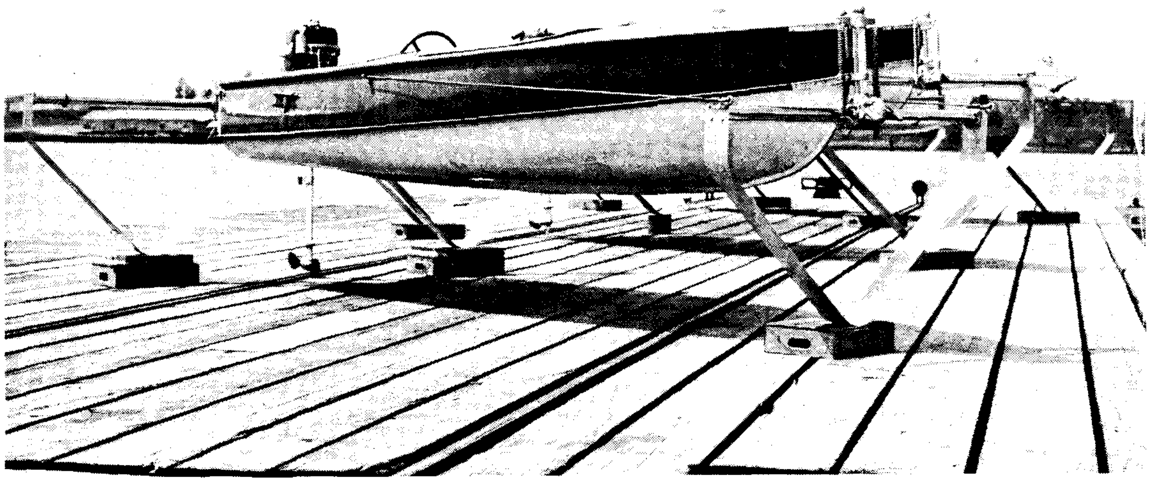


Figure 11. V-Foil Runabout, Baker Manufacturing Company

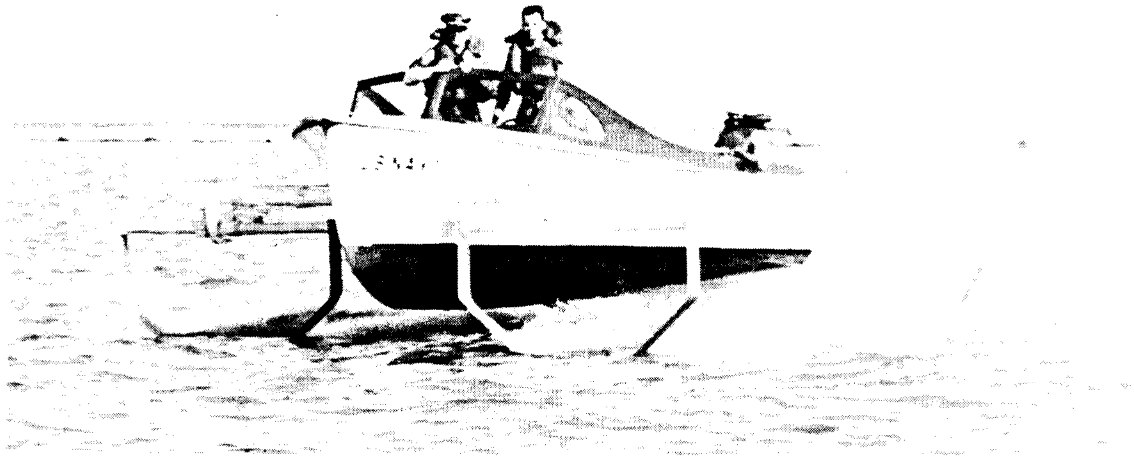


Figure 12. HIGH POCKETS

The second Baker hydrofoil, known as HIGH TAIL, (Figure 13) was a controlled, fully submerged hydrofoil system. HIGH TAIL had a three foil system, one forward and two aft. Three mechanical sensors, one touching the water ahead of each hydrofoil, provided the input for controlling the foils. The forward hydrofoil was mounted on a vertical axis which provided foilborne steering. The automatic control system was mechanical as specified by the Navy. Three output signals from the mechanical computer commanded three hydraulic servos which introduced smoothing effects and actuated the angular control movement of the hydrofoils. For an excellent report on HIGH TAIL see Reference 7.

Upon viewing HIGH TAIL for the first time several observers commented that the sensors consisted of one "anticipator" and two "regrettors." Actually this observation was in error as the two trailing feelers were in fact controlling the after two foils with some spatial anticipation. Table 1 is a comparison of HIGH POCKETS and HIGH TAIL.

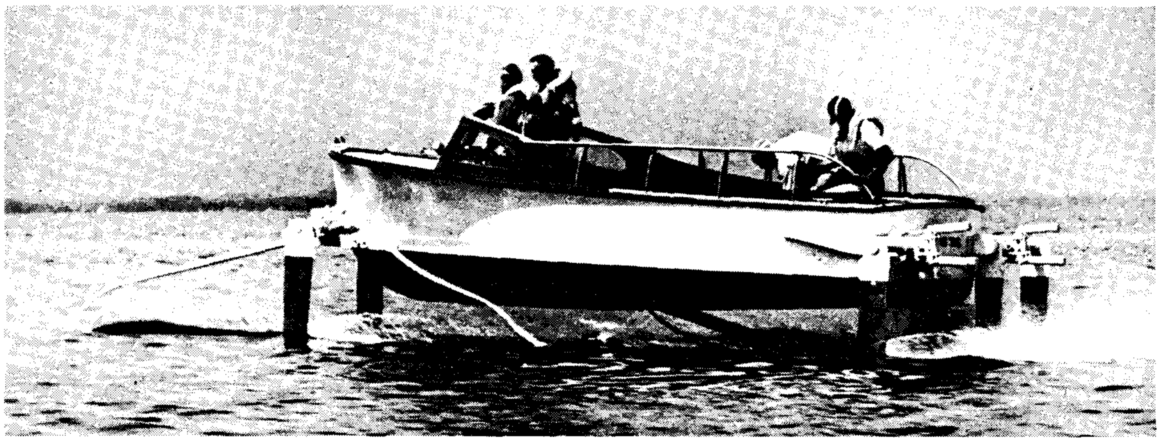


Figure 13. HIGH TAIL

During the late 1950's the Navy evaluated the use of hydrofoils to provide more speed for landing craft. The LCVP was the selected craft used for this evaluation. This subject will be discussed more extensively later in this paper. It should be noted here that the Navy contracted with the Baker Manufacturing Company to build the HIGH LANDER, a V-foil supported LCVP. The selection was made on the basis of the highly successful HIGH POCKETS. In fact, the HIGH LANDER, (Figure 14), was essentially a scaled-up version of HIGH POCKETS.

All of Gordon Baker's mechanical genius was not expended on military applications. He was also quite interested in using hydrofoils for sailing purposes. He initially built a three V-foil, cat boat (two foils forward and one aft) which produced remarkable speeds while beating into the wind. However, it had a tendency to "pitch pole" when running before the wind and would go into "irons" when coming about. These features led Baker to develop the MONITOR, a sloop with two ladder foils forward and a submerged foil aft (Figure 15). The forces of all the stays were fed into a mechanical computer. Based on these inputs the computer determined and then set the appropriate angle of attack on the aft foil for the wind in which the boat was sailing. This solved the problem of pitch-polling and made it possible to come about and stay on the foils. Speeds of 35 knots were reported during trials of the MONITOR.

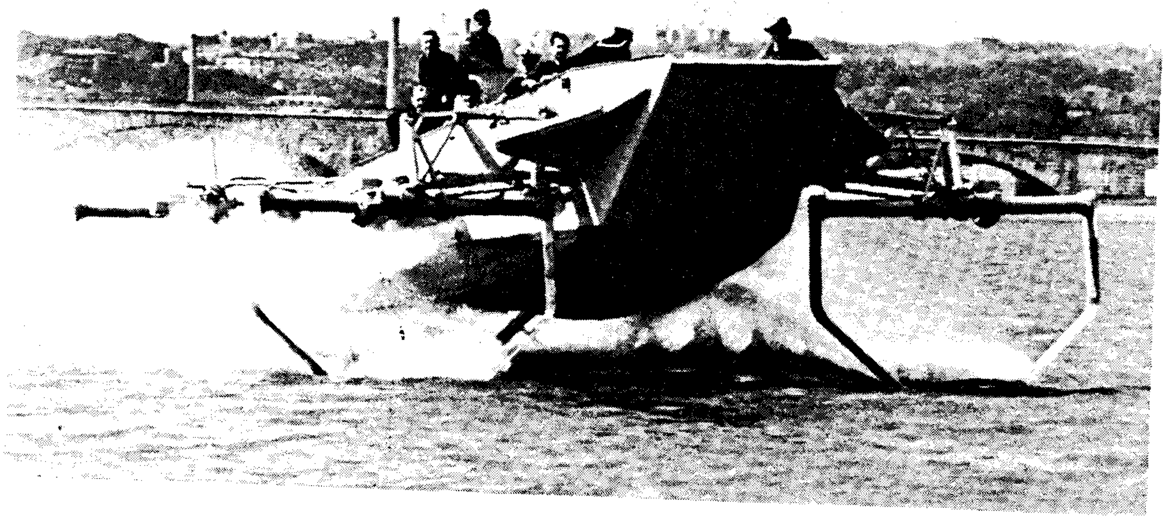


Figure 14. HIGH LANDER

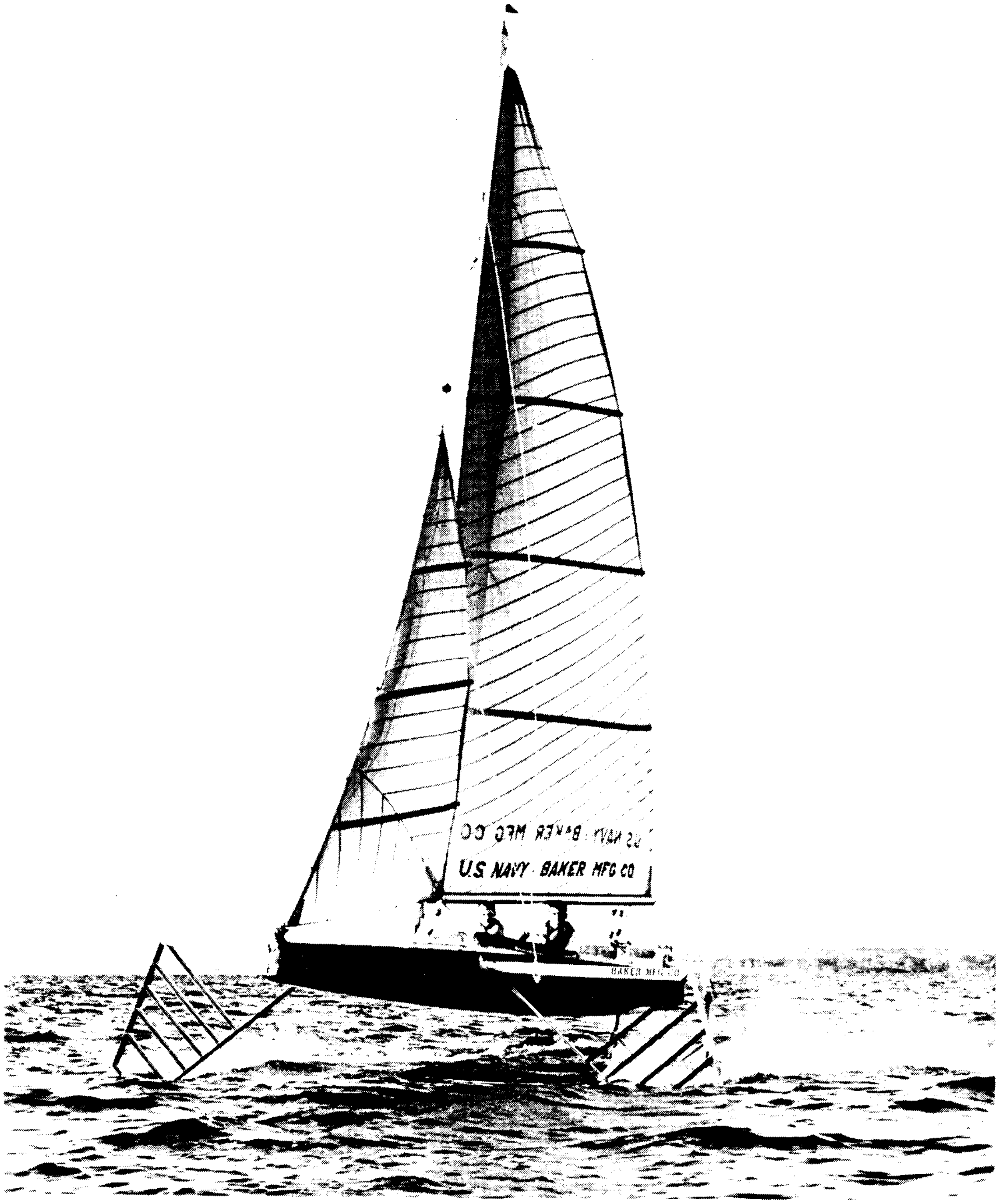


Figure 15. MONITOR

As a result of these trials, the Navy moved more in the direction of developing submerged foil systems. Even though Baker's mechanical genius led to a very workable mechanical-hydraulic autopilot, the conclusion was that future autopilots should be electro-hydraulic. Gordon Baker's contributions during this experimental stage of hydrofoil development was significant and helpful for future design decisions.

Table 1. - A Comparison of HIGH TAIL and HIGH POCKETS

	HIGH TAIL	HIGH POCKETS
Length (Hull)	24'	24'
Beam (Hull)	7' - 6"	7' - 6"
Draft (Foils down)	3' - 5"	3' - 5"
Cruise Speed, Kts	22	30
Max Speed, Kts	30	35
Horsepower	115	115
Displacement, lbs.	6000	6000
Pay Load, lbs.	915	950
Turning Circle Diameter, Ft.	230 @ 22 kts	360 @ 32 kts

Dr. Vannevar Bush and the Hydrofoil Corporation

One of the interesting and stimulating events of the 1950's was the investigation of a trans-ocean, hydrofoil cargo carrier. Dr. Vannevar Bush, who was president of Carnegie Institution and scientific advisor to the President of the United States, had become concerned over the extensive shipping damage inflicted during World War II by a few submarines. He directed a study seeking a solution to sustain transocean operations in the event of hostilities involving a considerable number of enemy submarines. One of the potential solutions envisioned was a hydrofoil cargo-carrier. The hydrofoil, with its speed and small submerged area, was considered virtually impervious to torpedo attack.

From 1951 to 1954, funding was budgeted to build a 3500-ton hydrofoil cargo-carrier with a destroyer type hull. An organization was actually formed to design and build the ship. The Office of Naval Research (ONR) was given the program management responsibility for the U.S. Navy supported by the Bureau of Ships, the Bureau of

Aeronautics, and the David Taylor Model Basin. The basic research was undertaken by the Hydrofoil Corporation of America, a non-profit organization formed by Dr. Bush. Gibbs and Cox was given a contract to undertake experiments leading to the design of the hydrofoil. Bath Iron Works was selected as the construction yard. Other interested parties such as William Carl of John H. Carl & Sons, Robert Gilruth, and Gordon Baker contributed to the technology development. LCDR Patrick Leahy, who would retire from the Navy as a Captain, was the designated Hydrofoil Project Officer in the Office of Naval Research . It has always been the author's opinion that BUSHI"S agreed to this because they didn't want to be accused of sponsoring such a concept. CDR James Stillwell, who would eventually retire as an Admiral, of the Bureau of Ships, and Fred Locke of the Bureau of Aeronautics, were assigned to make up the basic Navy management team. LCDR Leahy was replaced as Project Manager by the author (then a CDR in ONR). The author can well remember the periodic personal reporting sessions to Dr. Bush on the progress of the program. As time went on, the program became more and more overwhelming and impractical based on the inadequate state of hydrofoil knowledge. In 1954 it was concluded that to develop a propulsion system for a workable 3500-ton hydrofoil would tax the total capability of the United States industry. On this note the project ended.

Although the hydrofoil cargo-carrier was put aside, a number of hydrofoil initiatives did result from the project. Gibbs and Cox entered the hydrofoil design field and made major contributions to stimulating hydrofoil development. We will detail their effort later in this paper. The Hydrofoil Corporation of America assembled a technical group that derived basic hydrodynamic theories for submerged foil systems. One of the concepts that they investigated was the so-called Constant Lift Control System (CLCS). Intitially conceived[8] to attain depth control, a submerged pilot foil would control the forward main foil's angle of attack. A tandem foil system was proposed. The pilot foil, operating near the water surface, was directly connected through a linkage arrangement to the main foil. Increases in depth of the pilot foil resulted in increased lift and drag forces which increased the angle of attack of the main foil; likewise, decreases in running depth of the pilot foil resulted in decreased angle of attack. The objective was to have the foils adjust automatically to the changes of angle of incidence due to orbital motions. This concept led to a test craft named LANTERN, which was built to evaluate CLSC.

LANTERN (Figure 16) was built by the Hydrofoil Corporation of America and first flew in 1953. LANTERN had tandem submerged foils, displaced about 10 tons, and was 35 feet long with a beam of 22 feet. The craft was powered by a 200-H^r Chrysler marine engine. The foils, hull, and struts were all the same section, a symmetrical 24 percent thick NACA section. The craft became foilborne at about 14 knots and had a maximum speed of about 18 knots. The Constant Lift System, initially conceived using a pilot foil, was never evaluated. Instead, the main foils were pivoted about transverse axles ahead of their center of lift and loaded by a spring to effect a constant load (Figure 17). The height sensor was a hydrostatic probe that provided a signal, along with a gyro output, to a modified Sperry A-12 aircraft autopilot. This gyropilot controlled the craft in roll, pitch, and yaw. This is believed to be the first application of an aircraft-type autopilot to stabilize a hydrofoil. The foils were tandem in arrangement with about equal load fore and aft. Each foil was split in the middle and could be separately controlled, port or starboard, to provide roll control. For a time there was interest in LANTERN for use as a photographic platform to assess changes in harbor bottoms, but that interest waned and the program ended. Constant lift devices, as such, were not used on any other design. The end of the LANTERN program rendered the Hydrofoil Corporation inactive, although the influence of Dr. Bush on the Navy's hydrofoil program continued for some time.

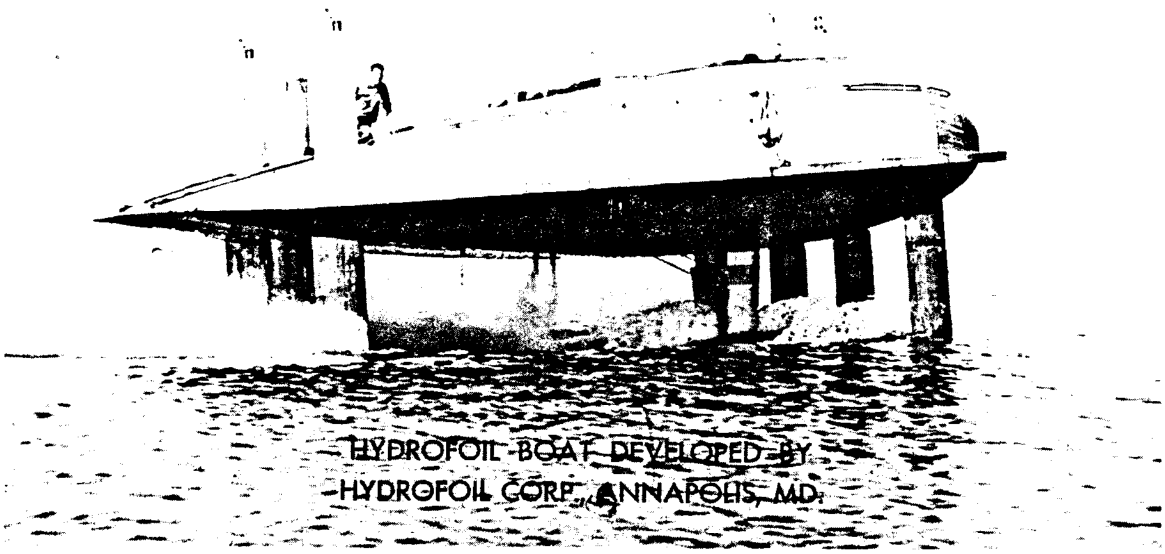


Figure 16. LANTERN, Hydrofoil Corporation of America

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HYDROFOIL CRAFT

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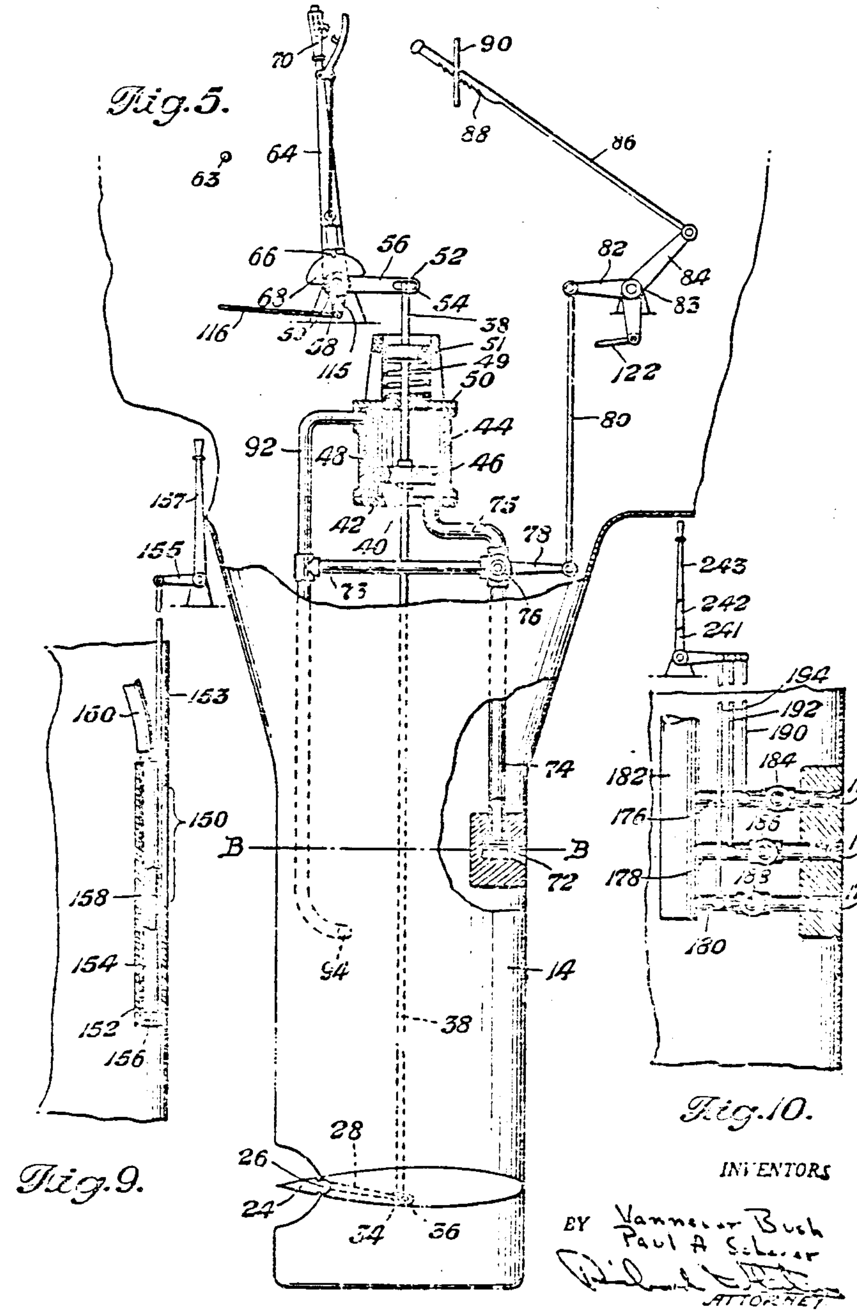

Figure 17. Bush's Design for LANTERN

Miami Shipbuilding Corporation and the LCVP

During the early 1950's as the various experimental craft were being demonstrated, a common remark was "This is a lot of fun but what would the Navy ever do with hydrofoils?" This viewpoint seems to permeate the entire history of early U.S. Navy hydrofoil development. Although there was interest created by Bush and the cargo-carrier program, what really accelerated the interest in hydrofoils was the Marine Corps and their complaint that the speed of approaching the beach (during the Korean amphibious landings) had not changed since William the Conqueror headed for a beach in 1066. Hydrofoils represented a possible answer to that complaint. As a result, a program was initiated in 1954 to evaluate a hydrofoil-supported landing craft, designated the LCVP.

During this same time an enthusiastic British inventor was touring the United States demonstrating a submerged foil boat. His name was Christopher Hook. Mr. Hook was a designer and builder of pipe organs prior to World War II. He was captured in Vichy, France during World War II during which time he studied naval architecture and aerodynamics. He escaped to Lisbon and eventually to Kenya where he started to experiment with hydrofoils. By salvaging scrapped aircraft and engine parts and using his own mechanical genius, he put together his first hydrofoil, GENESIS, in Mombasa in 1943. In November of the previous year he had applied for his first hydrofoil patents both in Great Britain and the United States. In these patents he revealed his concept of controlling the incidence of a hydrofoil by a control float that skimmed along the surface of the water in advance of the lifting foils. The float had a leaf spring-like trailing edge which dampened the effect of small waves. A dash pot at the upper end of the feeler arm was effective in regulating the rate of incidence change and was adjusted to suit varying sea conditions. It was Hook's ability to properly adjust the dash pot that made so many of his demonstrations look good. Anyway, this was the hydrofoil principle that Hook named his "Hydrofin."

Lack of interest and support from the British during the post war period propelled Hook to exploit his invention in the U.S. In January 1951 he exhibited a one-person craft (RED BUG) in the New York Boat Show. Following the show he carried out demonstrations in Long Island Sound, NY; Washington, D.C.; Annapolis, MD; and finally Miami, FL where he had a partner, C. P. Holt.

When the Request For Proposals (RFP) for an LCVP hydrofoil was released by the Navy, Hook teamed up with Miami Shipbuilding Corporation to respond. Much to the surprise of the Navy, the corporation won the competition even though it had not been involved in the Navy's earlier experimental and development programs. Miami Shipbuilding was well known to the Navy as the builders of PT-1 and the designers and builders of the 63-foot air/sea rescue boats widely used during the second World War. During the RFP evaluation phase the Navy team traveled to Miami to evaluate Hook's concept. Figure (18) is a picture of Hook's hydrofoil named the ICARUS. The Navy took ICARUS to sea off Miami Beach; in spite of waves of a height equal to the length of the boat, it continually remained foilborne and could not be capsized. The Navy arrived skeptical and left impressed with Icarus's stability. As a result, in 1954, Miami Shipbuilding Corporation was selected to build a hydrofoil supported LCVP using the Hook concept.

Before building the full-scale LCVP the Navy ordered a half-scale model from Miami Shipbuilding to further evaluate the Hook principle. This half-scale model was named $\partial\alpha/\partial t$ (Figure 19), and was built to confirm the calculations made in the preliminary design of the full-scale vehicle. Based on the availability of a 50 hp outboard motor, a Froude scale factor of 0.46 was selected for $\partial\alpha/\partial t$.[9] An excellent description of this craft is contained in Reference 9.

Following are a list of performance characteristics demonstrated during trial of $\partial\alpha/\partial t$.

Maximum weight flown	3242 pounds
Minimum weight flown	1857 pounds
Payload Capability	42.7% of full load
Maximum Speed	25 knots
Minimum Speed	14 knots
Minimum Turning Radius	70 ft. @ 19 knots

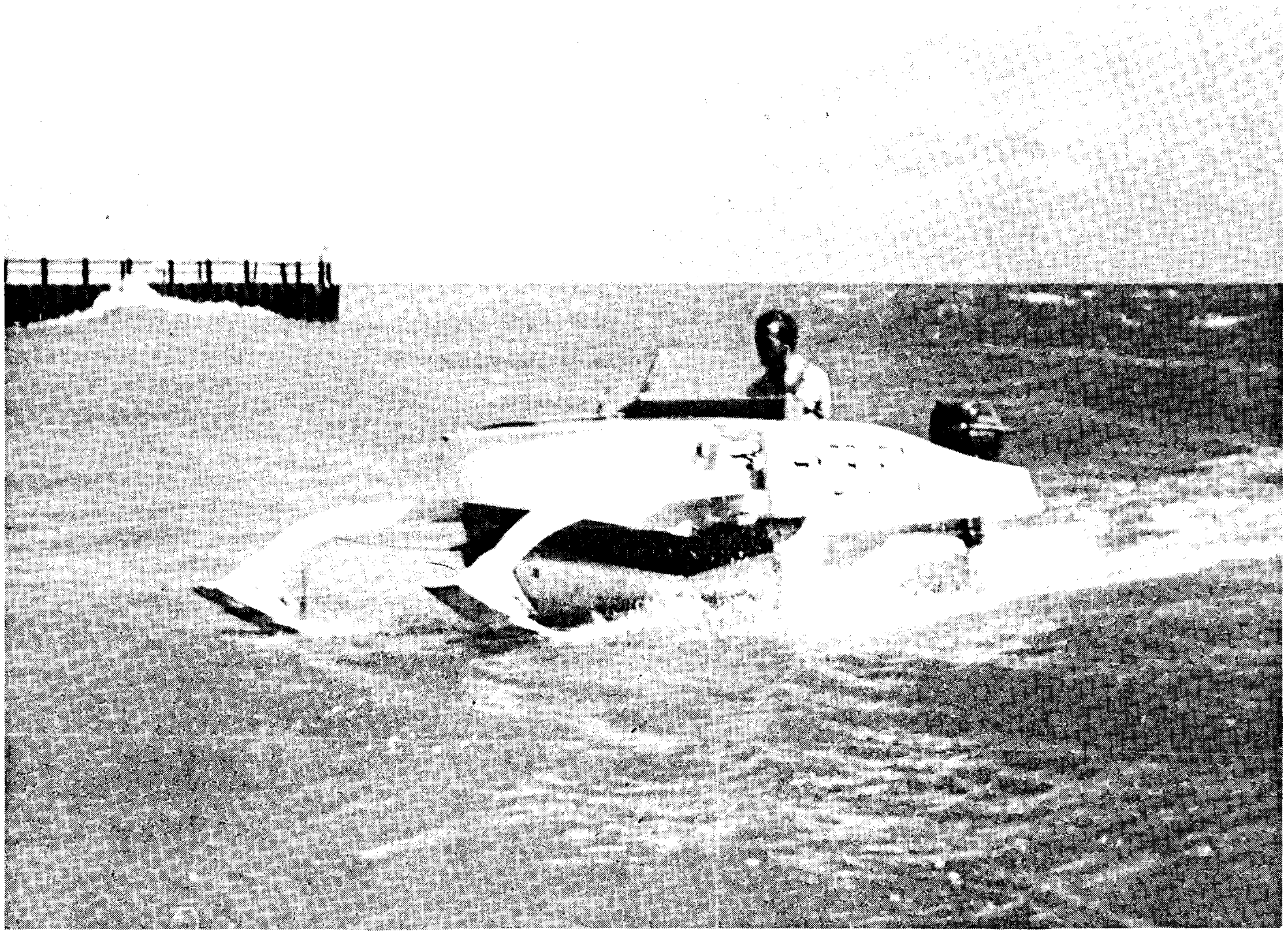

Figure 18. ICARUS

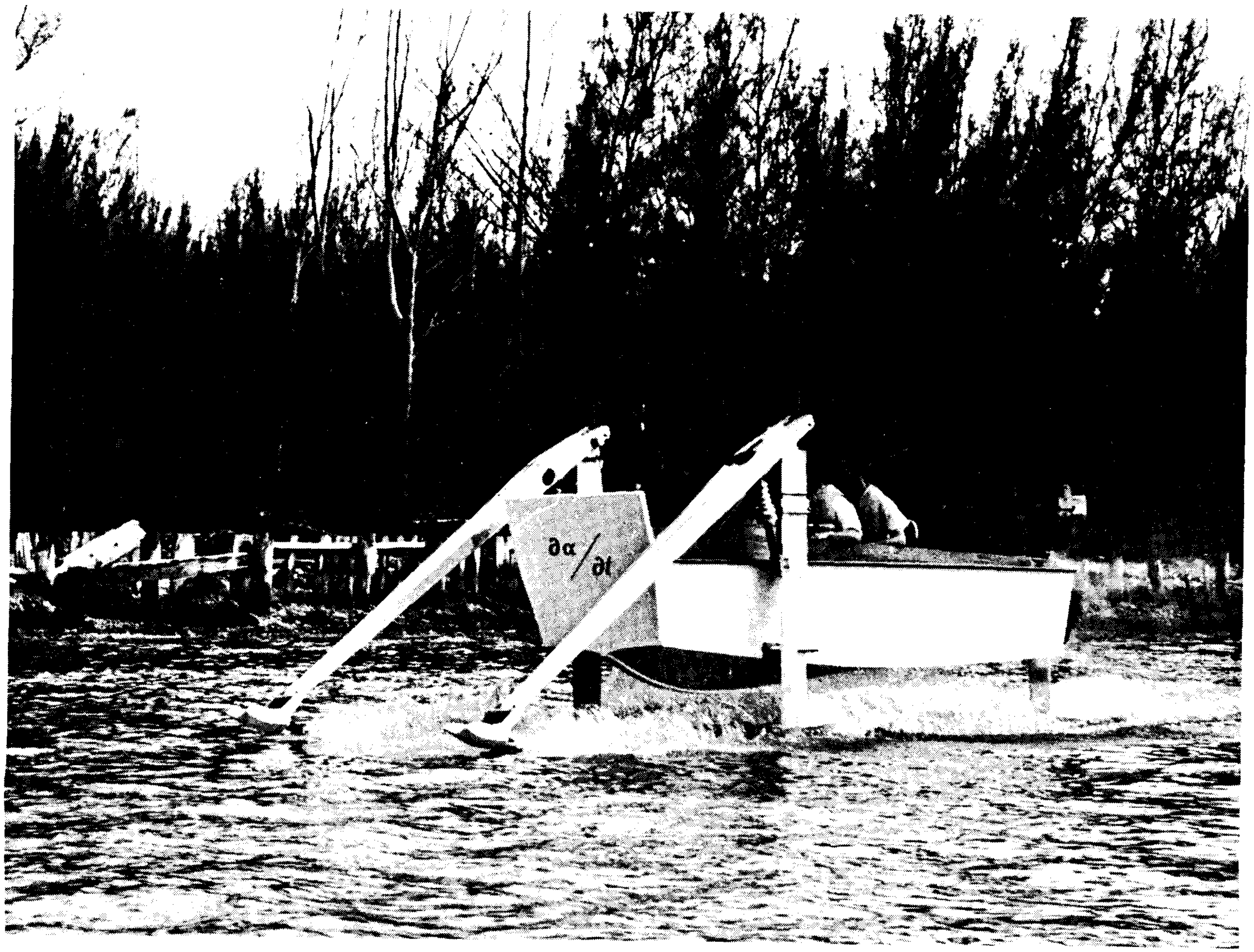

Figure 19. Half-Scale Model of the LCVP, " $\partial\alpha/\partial t$ "

Other characteristics of d /dt were:

Length overall	16' - 3½"
Beam	5' - 5"
Foil section	NACA (64,-A412)
Forward Foil Area	2.00 sq. ft.
Aft Foil Area	2.51 sq. ft.

$\partial\alpha/\partial t$ taught us a couple of lessons. It was assumed that because of the loss of lift, a submerged foil could not be flown out of the water as it approached the free surface. This premise was tested on one of the first flights. The forward foils were deliberately brought to the surface to see if hydrofoils could fly out of the water. As we all know now, there is no real difficulty in doing this. So, of course, out came the front foils with a resultant hard landing. As one engineer said - "back to the drawing board."

$\partial\alpha/\partial t$ also taught us the consequence of load reversal on the control mechanism. When the hydrodynamic center of lift crosses the center of foil pivot, the control forces change from tension to compression. All the mechanical slop in the control system is taken up and sharp changes in the angle of incidence occur. One failed mechanical control box with a resultant hard landing and some bruised bodies produced a "not-to-be-forgotten" design consideration: Avoid control load reversals.

The results of $\partial\alpha/\partial t$ tests provided the basic engineering data to permit proceeding with the full scale LCVP. The final report,[10] which was mainly the work of Chief Naval Architect Jean E. Buhler and consultant John Gill, provides an interesting insight into the mechanics of a feeler arm control system. Their effort moved the Hook Hydrofin from a clever mechanic's mechanism to an analytical design. $\partial\alpha/\partial t$'s configuration suggested that there had to be a less cumbersome control system than a long feeler arm.

With that background, Miami Shipbuilding Corporation began to construct the full scale LCVP using a feeler arm sensing system[10] to provide inputs to a mechanical control system. The LCVP was christened HALOBATES, a name suggested by the Marine Laboratory of the University of Miami. (HALOBATES is a sea-going insect which has forward extending feelers.)

HALOBATES was built essentially as a modified LCVP (Figure 20). A transverse bulkhead was installed amidship making it a two compartment craft. The engine room was covered and the pilothouse enclosed. The beam was increased over the standard LCVP for stability considerations. The principle dimensions were as follows:

Length overall	35' - 6"
Beam	11' - 8"
Hull Depth	6' - 1"
Full Load Weight	31,000 pounds

One of the requirements of the design was that the craft be capable of essentially flying up or down, that is, as the craft approached the beach for a landing the foils could be retracted while flying with diminishing maximum foil depth making a continuous transition from foilborne to hullborne as the water shoaled. To accomplish this all foils and the propulsion system were supported by retracting parallelograms making this transition possible. The retraction action was driven by ball screws. As has been the case in several designs, the utilization of the hydrofoil principle was complicated by the need for complex retraction mechanisms.

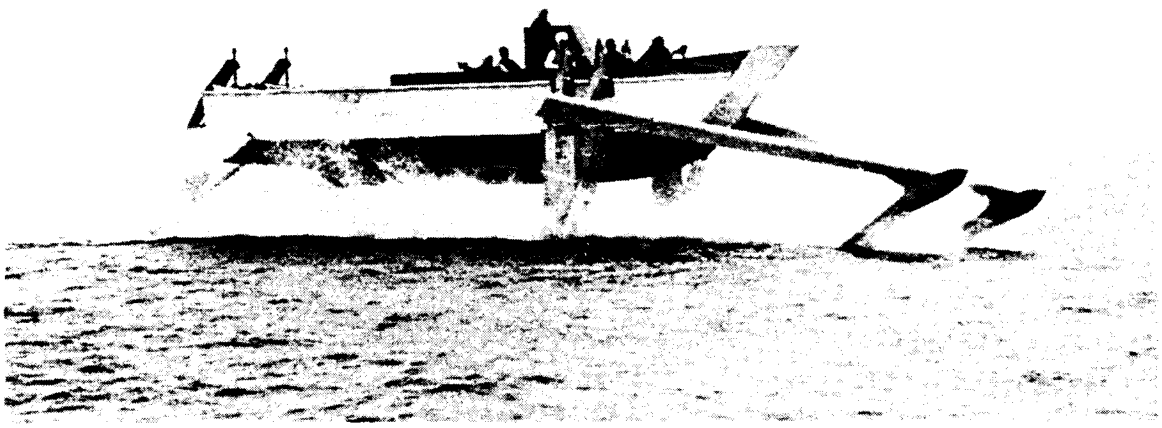

Figure 20. HALOBATES, Miami Shipbuilding Corporation

The propulsion system was powered by a 630 hp Hall Scott gasoline engine driving a speed-increasing gear system of 1.63 to 1. The gear train was designed and built by Cabi-Cattaneo of Milan, Italy. Cabi-Cattaneo was selected as they had considerable experience as builders of right angle gear trains for speed boats. Since the propulsion system had to retract on a parallelogram principle, the retraction axes were on the center lines of omnikinetic universal joints (Figure 21). The steering axis was located at about the center line of the upper bevel gear box. Cabi-Cattaneo, in the initial design, used a four-bevel gear box to balance the gear loads in this upper gear box. While this was useful for the power train design, the gear box was locked as far as steering was concerned. This error was not discovered until the unit was built and on the test stand. The Miami engineer, Ted Buhler, who was at the Milan plant at the time, witnessed a complete company shutdown to mourn the mistake of their senior engineer. Although this gear problem was corrected, the result was that the bearings had an inadequate useful life, something which plagued HALOBATES throughout the test program.

During the flight test program speeds of up to 34 knots were achieved in five-foot waves. The craft was demonstrated over a weight variance of 23,690 pounds to 31,165 pounds, and turns of 400 feet diameter were made. The operational Navy strongly disagreed with the use of large feeler arms and considered them quite impractical. At one point the entire program was in jeopardy of being scratched when an amphibious admiral said to "forget the whole idea" if HALOBATES with feeler arms represented operational hydrofoils.

The development of HALOBATES was the Navy's first attempt to meet an operational requirement by utilizing hydrofoils. From the outset it was recognized that once the mechanical control of hydrofoil systems was understood, an analogue, electro-hydraulic system could be built to accomplish the same functions. (Reference 11 has a good description of the transition from mechanical to electronic autopilot.) Different height sensors were being evaluated to provide the same height inputs as the feeler arm. Several companies were working this problem including Miami Shipbulding Corporation which had assembled a team consisting of Ray Wright, Walter Keller, Rod Rose and the author to pursue this effort. So fortunately, at about the same time as the Navy became discouraged with feeler arms, the autopilot was ready to go. A step resistance, on the leading edge of the forward struts provided the height signal. During the same period, the Navy became interested in the installation of a gas turbine in a marine vehicle and the hydrofoil represented a direct pay-off for the use of these lightweight engines. So

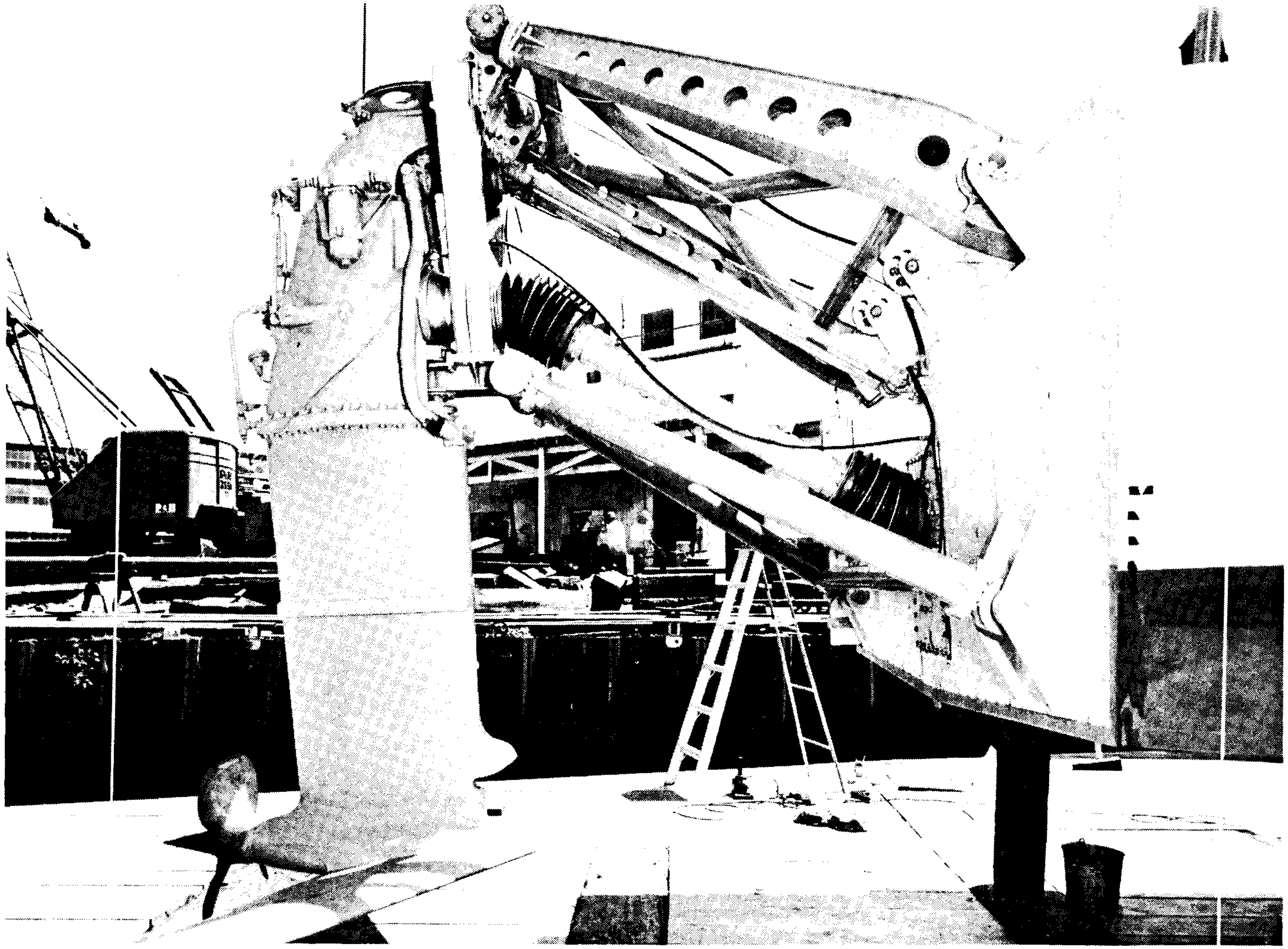

Figure 21. HALOBATES Retractable, Steerable Propulsion System

when HALOBATES was changed to an electronic autopilot control, the craft was also modified for the installation of an AVCO T-53 gas turbine. Figure (22) shows HALOBATES underway with the new configuration. The smokestack, not a steam boiler, is the exhaust duct for the gas turbine. HALOBATES completed the trial program with the autopilot and the Navy's first gas turbine installation. This configuration received more popular acceptance from the Navy decision makers.

As the Navy was proceeding with the amphibious LCVP program, the Army became interested in increasing the water speed of their amphibious DUKW. This vehicle was a World War II workhorse whose water speed was only a few knots. Miami Shipbuilding, working with the Lycoming Division of AVCO, was given the responsibility of demonstrating a FLYING DUKW. The same HALOBATES autopilot and AVCO gas turbine were utilized and the DUKW went flying (Figure 23). There were several traffic jams when this wheeled monstrosity lifted out of the water during trials along Mac Arthur Causeway in Miami. As a result of the hydrofoil application, the DUKW's water speed increased from 6 to 35 mph.

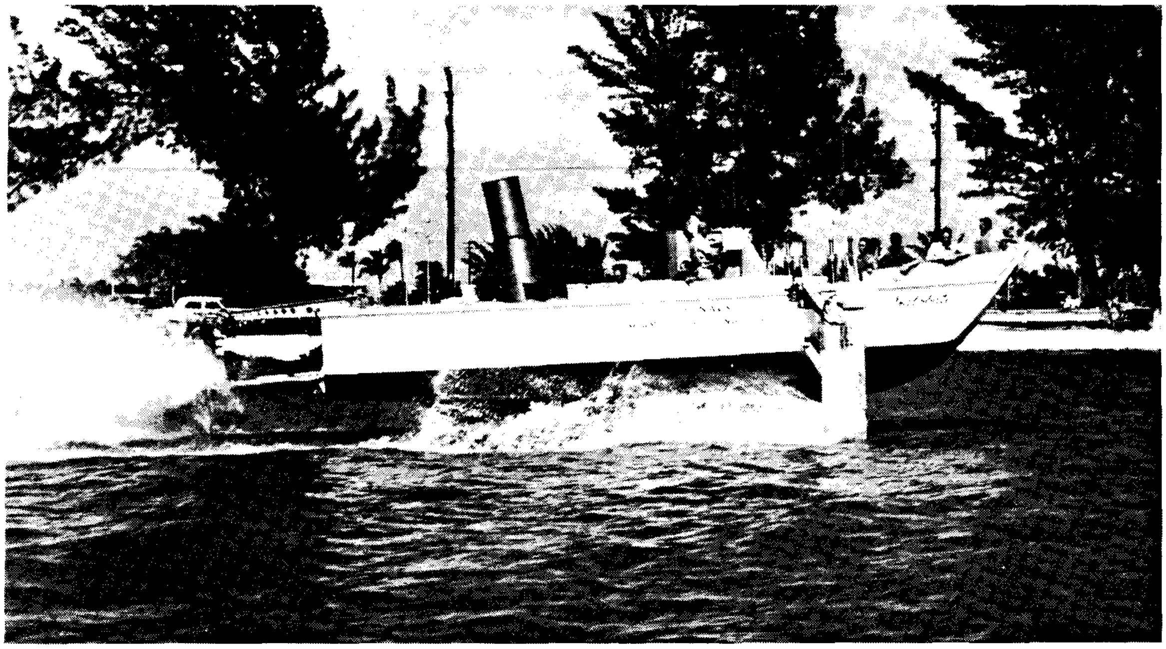

Figure 22. HALOBATES With ACS

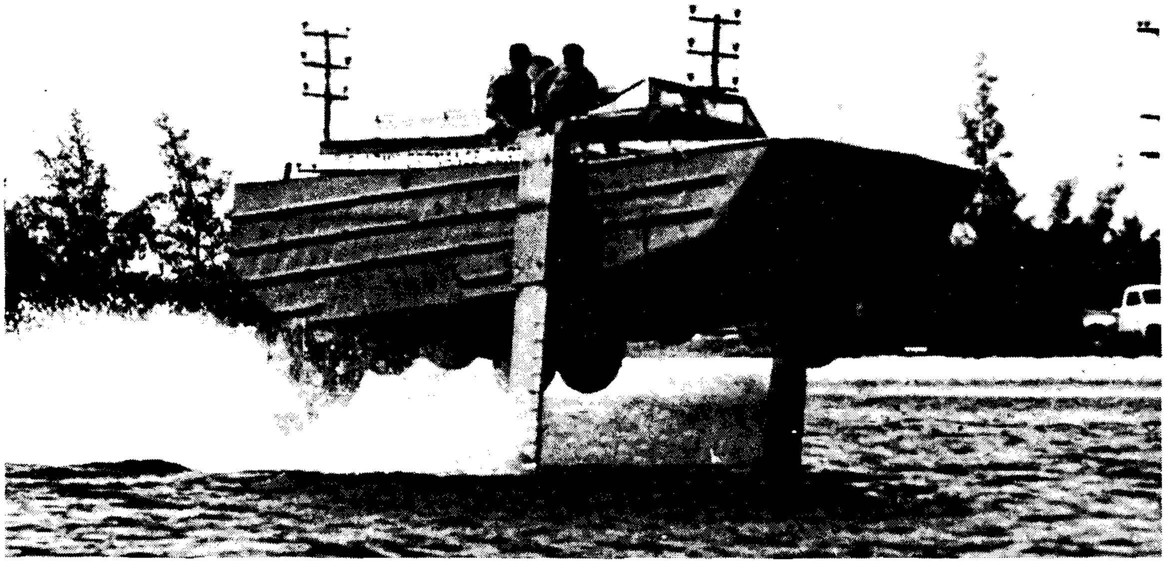

Figure 23. FLYING DUKW

After the DUKW demonstrations were completed, the Army extended the program into a more advanced application of the use of hydrofoils in a wheeled amphibious vehicle. Contracts were let for the design and construction of two LVHX's of identical size with aluminum hulls 38 feet long, a 5-ton payload and a speed of 35 knots. LVHX-1, built by the Lycoming Division of AVCO, had a submerged foil system with electronic automatic control and was powered by a T-53 gas turbine (Figure 24). LVHX-2, built by FMC, used a surface-piercing system forward and a submerged rear foil and was powered by a solar gas turbine (Figure 25). The objective was to trade the two systems off before making a production decision. Here again, the complexities of retraction and dual propulsion systems overwhelmed the use of hydrofoil. In the meantime, air cushion vehicles were showing great promise for amphibious applications. The end result of the LVHX's was the conclusion that for amphibious application, this was not the way to go.

Figure 24. LVHX-1

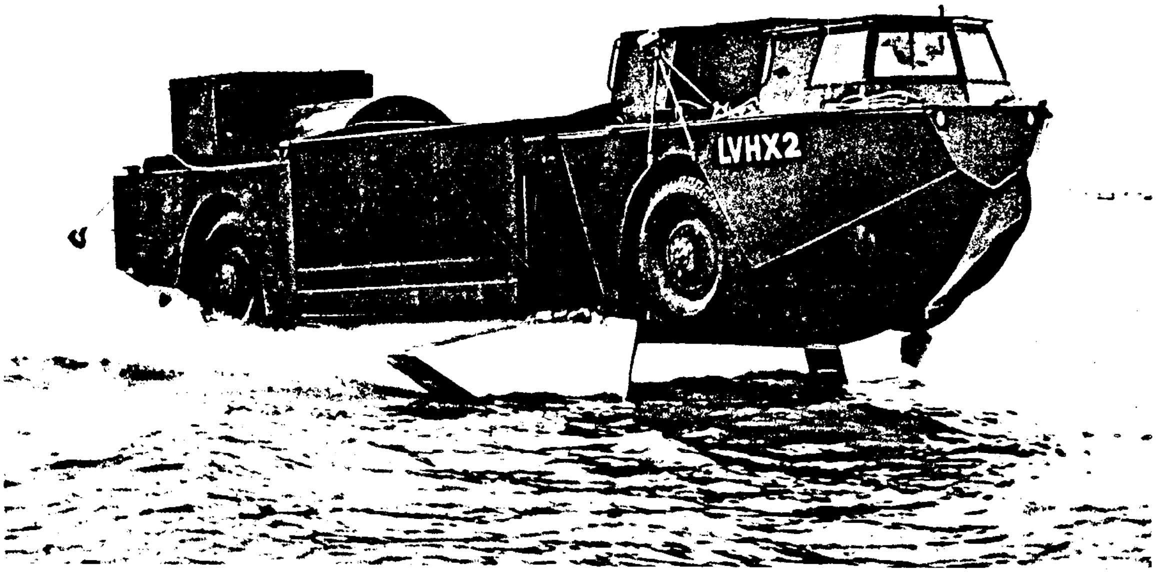

Figure 25. LVHX-2

Gibbs and Cox and SEA LEGS

Now we step back again a few years to the early 1950's. We have already mentioned the role Gibbs and Cox played in the study of Dr. Bush's cargo-carrier and the Grunberg design submitted in the LCVP competition. During this early 1950 period, Gibbs and Cox built a versatile test craft which carried the name BIW (Figure 26). As previously mentioned, Bath Iron Works was the designated builder of the cargo-carrier, and since the test craft was to be used for experimental purposes for that design, it was designated BIW. This craft did yeoman work in exploring different foil arrangements; different control schemes including manual, mechanical and electronic; and different height sensors. Several conclusions were drawn from these experiments but among the most important was the potential for an electro-hydraulic autopilot.

Gibbs and Cox had assembled a hydrofoil team headed by Tom Buerman which included Dr. John Breslin, their hydrodynamicist, Dr. S. F. Hoerner, who wrote the book on dynamic drag,[12] and L. E. Sutton and Richard Browne, who worked on stabilization systems. In 1954 Sutton and Browne were assigned to supervise the contruction of an autopilot-stabilized test craft that was to become SEA LEGS (Figure 27).

Starting with a Chris-Craft hull, the original design conditions were as follows:

Length overall	28.5 feet
Beam	9.0 feet
Design Weight	8000 pounds
Design Horsepower	200

As the design developed, the fulload weight grew to 10,550 pounds.[13] The engine selected was a Chrysler marine gasoline engine with a maximum horsepower of 235. The engine drove through a V-drive with reduction gear of 2.09 - 1 through an inclined shaft to a propeller.

The foils were made of aluminum with a German section and were arranged in a canard configuration. The forward foil had an area of 4.6 sq. ft. with the main foil having an area of 11.7 sq. ft. Flaps were actuated for the control authority by hydraulic actuators. As we look at submerged foil configurations of today, we can see their beginnings in SEA LEGS. That one fact alone makes SEA LEGS important.

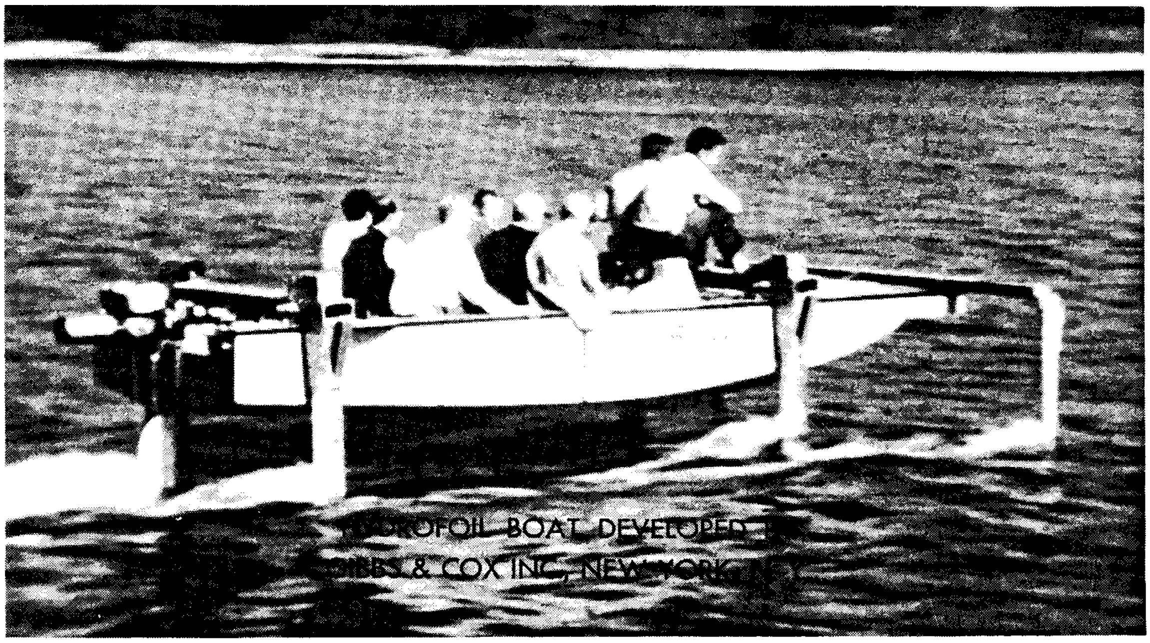

Figure 26. BIW

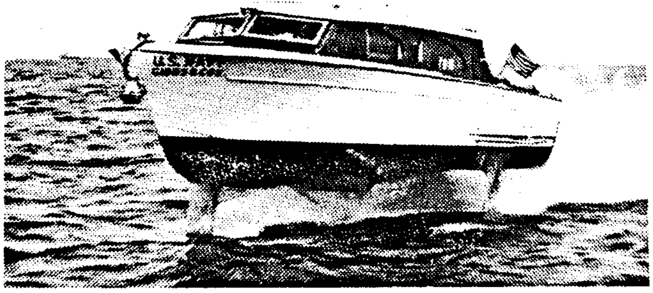

Figure 27. SEA LEGS

The early work on the automatic control system for BIW had been done by the Draper Laboratory of the Massachusetts Institute of Technology. For the SEA LEGS design Richard Browne started with the basic technology developed by Draper and assembled a practical working autopilot. For the height signal input he utilized a sonic height sensor which was to be the standard for many years to come. It is interesting now to look back and realize that this autopilot had 160 vacuum tube elements. In spite of all this, SEA LEGS' first flight in 1957 was impressive indeed. The autopilot stabilized the craft in rough seas and it achieved speeds of 27 knots.

After interested navy personnel witnessed successful demonstrations in the New York area during 1957 and 1958, SEA LEGS was transported to Washington to give wider exposure to the capability of hydrofoils. The trip was made in the open ocean accompanied by the U.S. Navy's PT-812. On July 16, 1958 the two craft left New York, rendezvoused and then proceeded from Scotland Lightship to Cape May, New Jersey. After stopping overnight and refueling, SEA LEGS proceeded from Cape May through the Delaware Canal into the Chesapeake Bay and on to Annapolis. When SEA LEGS averaged 23 knots through 4 to 5-foot waves in the open sea, participants agreed that the craft had demonstrated seakeeping and performance absolutely impossible for a conventional boat of the same size. Those on board reported a dry, comfortable ride while conditions on PT-812 were quite different indeed.

This particular adventure, headed up by three Navy Commanders, William Nicholson, Randy King and Ken Wilson, did more to interest the Navy in the hydrofoil potential than any other one event. From Annapolis, SEA LEGS flew to Washington, D.C. and embarked a number of interested senior military and government personnel. Among them was the Chief of Naval Operations, Admiral Arleigh Burke. This was recorded as the second U.S. Navy CNO to ride a U.S. Navy hydrofoil.

An excellent, detailed description of this entire trip can be found in reference [14] which was dictated by Richard Browne from his notes and the log of SEA LEGS. The log describes the ingenuity of the crew and dedication that has characterized so many hydrofoilers.

SEA LEGS, in 1962 and 1963 underwent a more detailed evaluation by the David Taylor Model Basin.[15] For these trials, the craft was extensively instrumented to provide at-sea data for future designs. The nature and purpose of Navy trials were beginning to change from proving concepts to obtaining design data. After the trials SEA LEGS was retired with honors and refurbished for display in the Smithsonian.

The Boeing Company, FRESH-I and LITTLE SQUIRT

By the early 1960's small developmental models were becoming a thing of the past, and large scale test craft were being built to identify and solve major problems. Dynamic Developments, Inc. built a scale model of their proposed H. S. DENISON and extensively tested it during the design phase. This craft, so appropriately named GREAT EXPECTATIONS, is shown underway in Figure 28. When the Navy made the decision to proceed with HIGH POINT (PCH-1), there was much discussion of the pros and cons of building and testing a scale model before proceeding with the full-scale program. Those for a manned model argued that any new design has some surprises and that rectifying those surprises could be accomplished more readily and less expensively on a small vehicle. Opponents disagreed, citing increased cost and time, and the fact that the autopilot would not scale. The decision was made to proceed with the full-scale design without building a test model. In retrospect one wonders, if in fact a manned model wouldn't have saved time and money in making PCH-1 fully operational. In any event, manned models have not been seriously considered since PCH-1 except for the Foil Research Hydrofoil test craft otherwise known as FRESH-I.

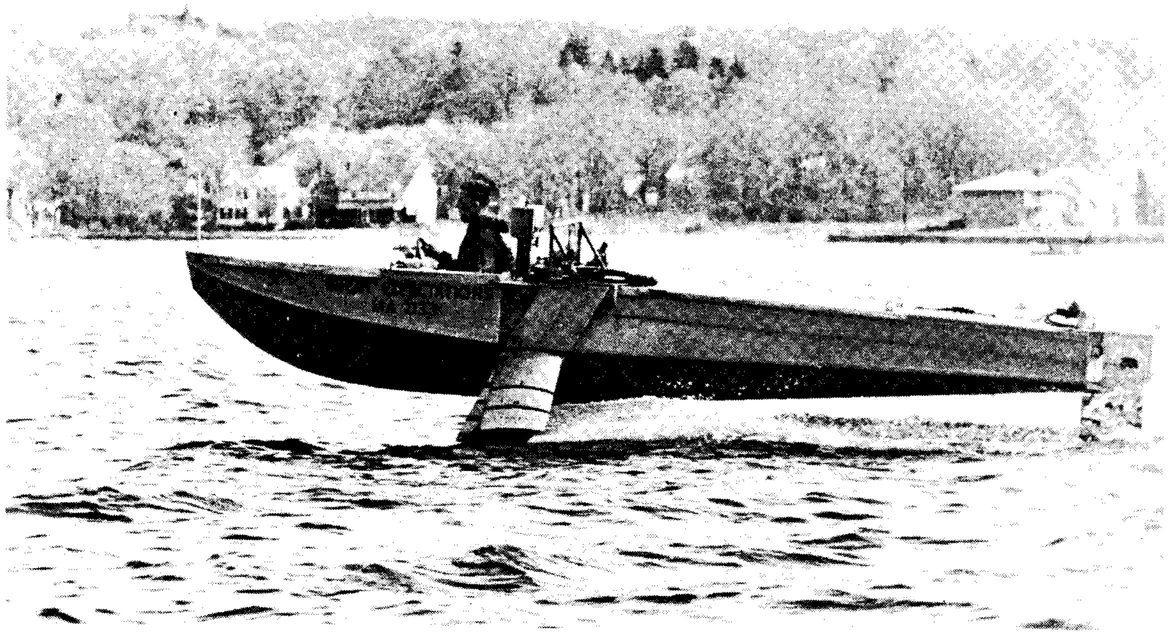

Figure 28. GREAT EXPECTATIONS

In the early 1960's the interest in very high speeds in hydrofoils was quite keen. The H. S. DENISON was initially conceived as an 80-knot ship. With a reduction in available funds, the design speed was reduced to 60 knots, although a design was completed for the Navy for an 80-knot configuration of DENISON. The PLAINVIEW (AGEH-1) was designed as a 340-ton, 50-knot ship with the ability to be converted to an 80-knot configuration.

In 1961 the Navy's Bureau of Ships sponsored the Hydrofoil Accelerated Research Program (HARPY). This program was directed toward the development of bigger, better and faster hydrofoil ships. The program was initially directed by James Schuler, who is still active in the Naval Ship System Command research and development hydrofoil program. He was assisted by Owen Oakley and Ralph Lacey of BUSHIPS, who were key players in the development of hydrofoils. In 1964 William Ellsworth, still a key Navy hydrofoiler, became a major factor in the HARPY program. HARPY recognized the need for a fast research hydrofoil to evaluate high speed type hydrofoils such as supercavitating and ventilating. In 1961 the Bureau of Ships held a competition for the development of a hydrofoil test craft which could be highly instrumented, be propelled at speeds up to 100 knots, and be capable of evaluating different types and arrangements of foil systems. In June 1961 the Boeing Company was awarded a contract for the design and construction of FRESH-I. The "I" stood for the first configuration. Reference [16] by Don Stevens, another Bureau of Ships hydrofoil designer, is an excellent description of the program and is the source of most of the information on FRESH-I contained in this paper.

The principal characteristics of FRESH-I, shown foilborne in Figure (29), were as follows:

Length	53' - 1"
Beam	22' - 6"
Draft (Hullborne)	10' - 5"
Draft (Foilborne)	3' - 8"
Speed, Takeoff	45 knots
Speed, Foilborne	80 knots
Design Speed Max	100 knots
Endurance	1 hour

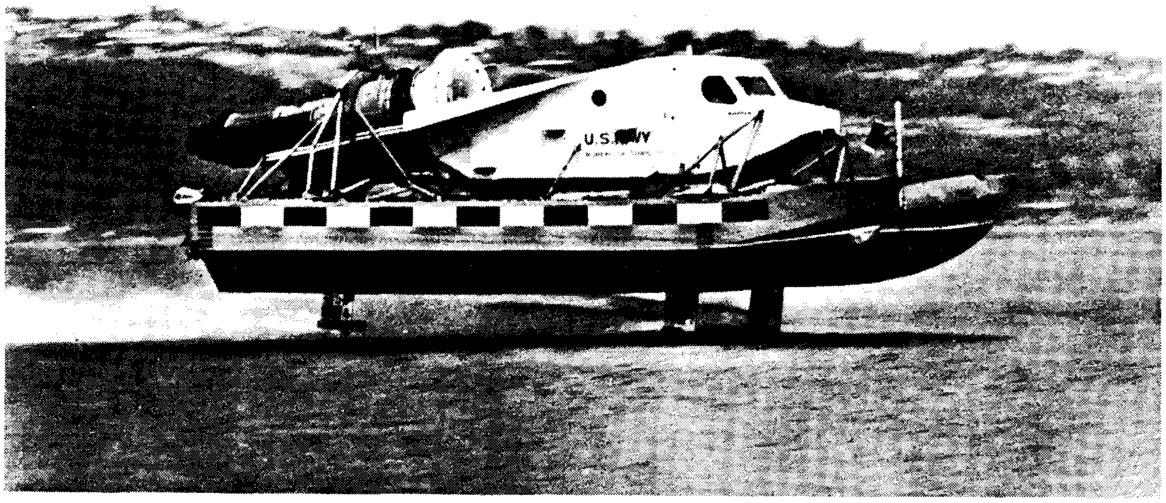

Figure 29. FRESH-I

The craft was powered with a Pratt and Whitney JT3D-3 engine which could develop 18,000 pounds of static thrust. Two outboard engines provided hullborne propulsion at about 4 knots.

The required flexibility of foil locations was attainable since the supporting struts could be placed at various longitudinal and transverse locations. The design made it possible to evaluate conventional, canard or tandem foil systems.

For the initial demonstrations FRESH-I had three cambered parabolic, base-vented foils, each carrying equal load. All foils were flap-controlled by an electro-hydraulic, automatic control system. A sonic height sensor was used, backed up by a strut-mounted electrical depth sensor.

On February 8, 1963 when FRESH-I was launched, debugging trials started immediately. On May 3, 1963 the craft attained a speed of 80 knots, exceeding the record set by Bill Carl's XCH-4 in 1954 of 63 knots. FRESH-I's 80 knots still stands as the top speed achieved by a hydrofoil.

Builder's trials were completed by July 1963 and on July 10, 1963 FRESH-I was demonstrated to the Navy Trial Board in a conventional configuration. The days operations were quite successful and included maneuvering and speeds to 80 knots. The configuration was changed to a canard and on July 18, 1963, a second series of demonstrations were made for the Navy Trial Board. Demonstration runs were made at speeds up to 80 knots. During maneuvers, a foil broaching occurred and FRESH-I capsized. FRESH-I was refurbished and reengined with a YTF-33 turbofan, and successfully operated about another year. During this period, the FRESH-I completed the acceptance trials and demonstrated the ability to test other foil systems. A second set of hydrofoils had been built by Grumman for FRESH-II trials. This second set of foils was to investigate a concept called "Transit Foil".[17] Transit foils were designed to operate both subcavitating and supercavitating while making a smooth operational transition between these two speed regimes. Unfortunately, funding was never provided and the transit concept has never been fully evaluated.

At about this time the Navy essentially changed its requirement for high speed platforms. Admiral William Brockett, Chief of the Bureau of Ships, expressed it best when he stated that the Navy had better develop weapon systems for the 40- to 50-knot speed range before attempting to develop 80-knot platforms. With that decision the 80-knot DENISON design was put aside, along with the plans to convert PLAINVIEW to an 80-knot configuration, and FRESH-I was laid up.

The Boeing Company, as explained by Gene Myers,[18] recognized early in its hydrofoil experience the need for a hydrodynamic test facility. Boeing first employed the Hydrodynamic Test System (HTS) as the test vehicle. HTS was a 16,000 pound 38-foot hydroplane operated on Lake Washington at speeds to about 80 knots (Figure 30). It was instrumented and equipped to support a hydrofoil of about 0.5 sq. ft.

While HTS provided Boeing with considerable data, they recognized the need for a hydrofoil supported test craft. This need led to the decision to build LITTLE SQUIRT (Figure 31). LITTLE SQUIRT had a three foil tandem configuration, equal area fore and aft, with incidence-controlled foils which had flaps that could be extended during take-off. The craft employed an automatic control system and was used in the development of the Boeing acoustic height sensor.

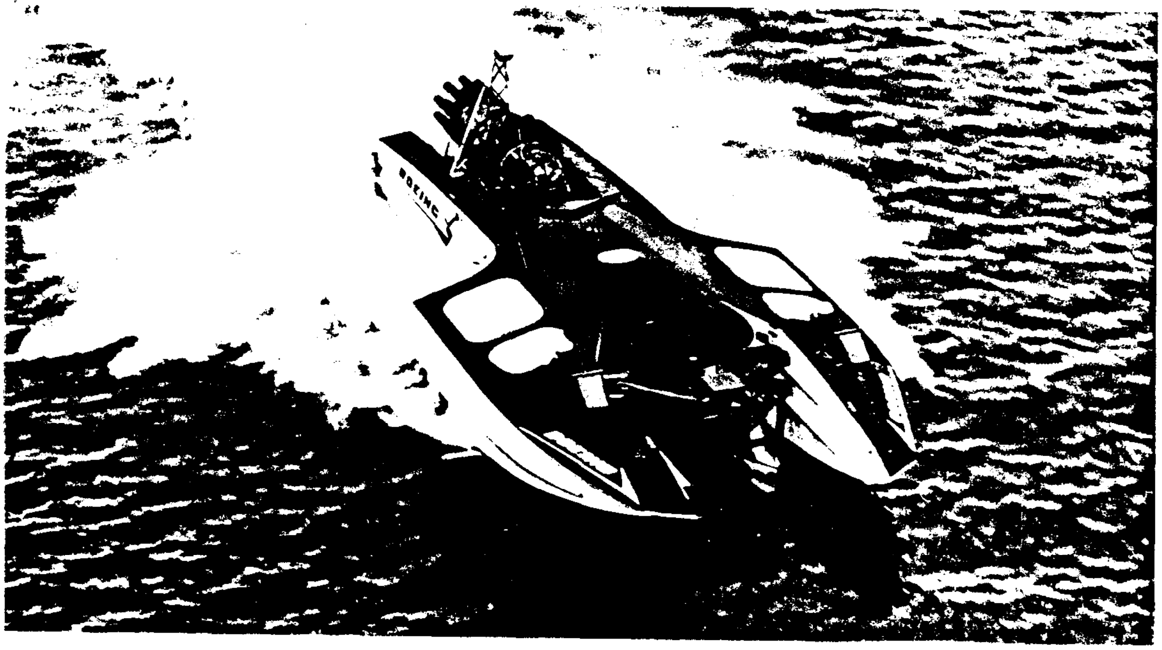

Figure 30. HTS

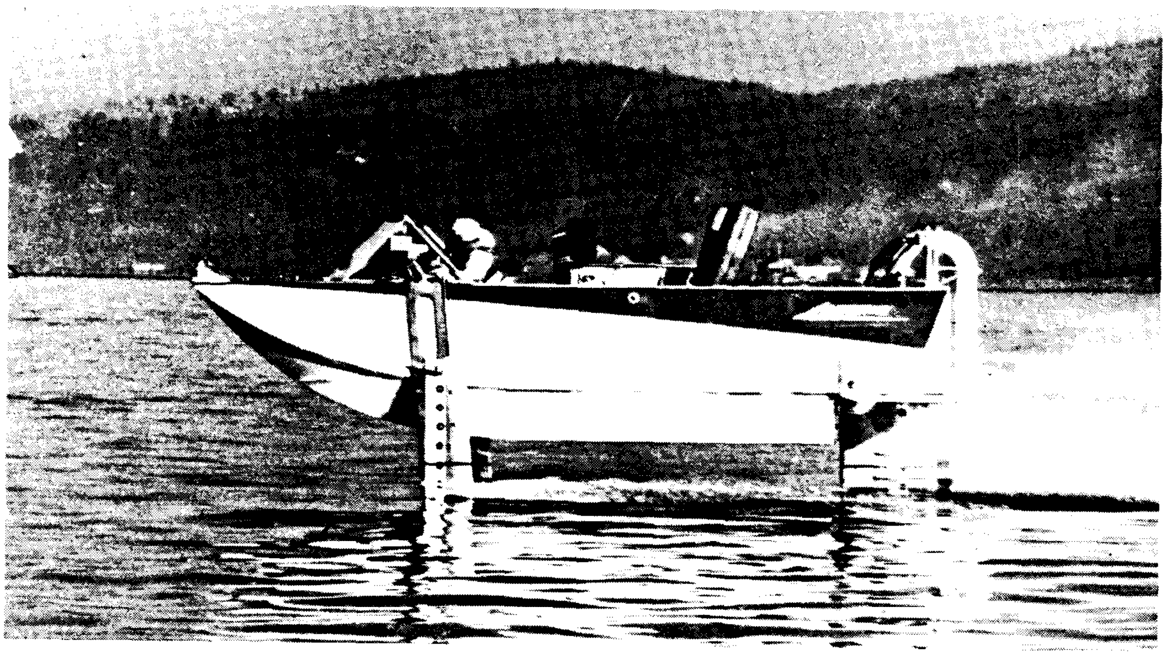

Figure 31. LITTLE SQUIRT

LITTLE SQUIRT was essentially employed by Boeing as a general hydrofoil research vehicle, but it is best remembered for its evaluation of the waterjet principle. In the early 1960's there was interest in exploring alternatives to geared propeller drives. LITTLE SQUIRT gets it's name from the first-time waterjet installation on a hydrofoil. The jet stream was produced by a Pacific Pump Company double-suction, centrifugal pump producing a flow of 3600 gpm at a 400-foot pressure head. The pump was powered through a reduction gear by a 425 HP Boeing gas turbine.

The following table describes the principal characteristics of LITTLE SQUIRT.

Length overall	20' - 0"
Beam	8' - 0"
Foil Span	
2 forward	3' - 1"
1 aft	4' - 6"
Strut length	2' - 9"
Displacement	
Light ship	2.2 long tons
Full load	2.6 long tons

LITTLE SQUIRT measured propulsive performance up to 45 knots and established the basis for proceeding to the water-jet propulsion design of TUCUMCARI (PGH-2). TUCUMCARI then became the base for the current propulsion systems for the PHM class and the Boeing commercial Jetfoil. From little acorns mighty oaks are grown, and with LITTLE SQUIRT the era of small experimental models came to an end.

CONCLUSION

There are other chapters to be written on the development of hydrofoils. After the experimental models talked about in this paper, the 1960's saw hydrofoils move out into the open sea both commercially and militarily. These ships include:

H. S. DENISON
HIGH POINT (PCH-1)
PLAINVIEW (AGEH-1)
VICTORIA

ENDEAVOR
FLAGSTAFF (PCH-1)
TUCUMCARI (PCH-2)
DOLPHIN
JET FOIL

and the first United States Navy Squadron:

USS PEGASUS	(PHM-1)
USS HERCULES	(PHM-2)
USS TAURUS	(PHM-3)
USS AQUILA	(PHM-4)
USS ARIES	(PHM-5)
USS GEMINI	(PHM-6)

Each one of these has a development story as interesting or more so than the small models, but that's another chapter and must await another day.

This paper is written at a time when spirits in the U.S. hydrofoil community are not high. The programs mentioned followed about the same pattern of enthusiasm with many ups and downs. Figure (32) is a barometric chart of programs ups and downs as a function of program events. You can fill in your own time scale for any program selected. But look at the trends. The peaks get higher and the valleys get lower as time goes on. As more people become involved, more effort goes into solving the problems and the problems do get solved. If there is a lesson to be learned from history, it is that hydrofoils continue to fill a need and the industry continues to grow. This trend will continue and will lead to the next development of these relatively small, fast, open ocean vehicles. Only the time scale is unknown. So don't get discouraged! Hang in there!

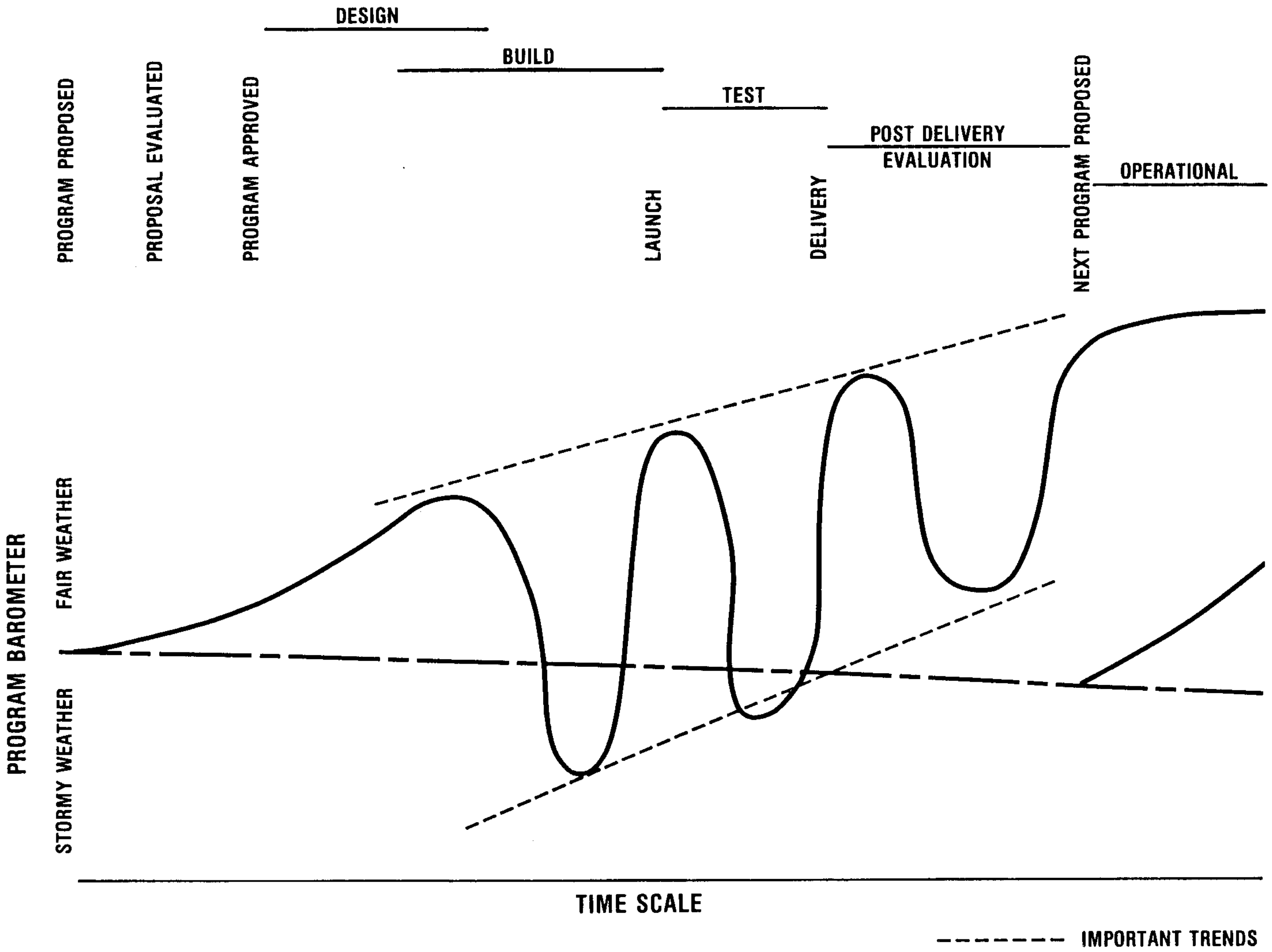

Figure 32. The Enthusiasm Barometer

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CURRENT STATUS AND FUTURE PROSPECTS FOR EUROPEAN COMMERCIAL HYDROFOILS

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FIRST INTERNATIONAL
HYDROFOIL SOCIETY
CONFERENCE

Ingonish Beach, Nova Scotia, Canada - July 27-30 1982

CURRENT STATUS AND FUTURE PROSPECTS FOR EUROPEAN COMMERCIAL HYDROFOILS

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SUMMARY

European Commercial Hydrofoils (ECH) are briefly reviewed from a technical and commercial point of view. Dimensions, hull, foil systems, propulsion and automatic control system, together with the modifications made in respect of the early design are examined. The results of a worldwide investigation concerning utilization of ECH and current costs are analyzed. Based on the past 25 years of production, trends are given and analyzed for the near future.

INTRODUCTION

It is well-known that the hydrofoil concept was born in Europe during the last century, but a lot of study, research and efforts were necessary before the first commercial hydrofoil craft intended for service on the River Rhine was ordered in 1936 by a German owner to the Schertel-Sachsenberg Speed Boat Syndicate.

Another 20 years were necessary before the first commercial hydrofoil intended for operation in open sea entered service on the Strait of Messina in 1956.

Since then, a lot of water has passed under the .... foils of hydrofoil ships and, today, there is no doubt that this new means of transportation has modified the world communication system on short distances where a waterway is involved.

As the history of European Commercial Hydrofoils (ECH) will be dealt with in a separate paper, no mention of it will be made here.

Several European shipyards have produced hydrofoil ships for the commercial market: Gustoverft of Netherlands; Westermoen of Norway; Vosper Thornycroft of Great Britain; Rodriquez of Italy, and others but, all of their production has been based upon General Crocco's principles and Baron Von Schertel's studies, with or without modification.

As the aim of this paper is to point out the current status and the prospects for European-built hydrofoils for commercial utilization, the subject will be considered under its technical and commercial aspects.

The evolution of ECH from a technical point of view has been continuous, not only as a result of studies and research but also as a result of modifications and requirements generated by the daily utilization of hydrofoil ships on commercial service during the last 25 years.

This has generated improvements in many areas from the size to the structure, from performance to comfort. Let's analyze the most important ones.

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DIMENSIONS

Due to the continuous growth in the utilization of hydrofoils and to the operation in open, and sometimes rough waters, the ability to carry more passengers and to operate even in adverse sea conditions became an absolute need. As a consequence, the dimensions of hydrofoils had to be increased, see Fig. 1.

From the first italian PT 20 hydrofoil, launched in 1956, with its 20 meters length, 32 tonn displacement and a capacity of 72 passengers, today, we have a full range of craft for different services going from the above-mentioned PT 20 to the 37.5 meters of the PT 150 built in Norway.

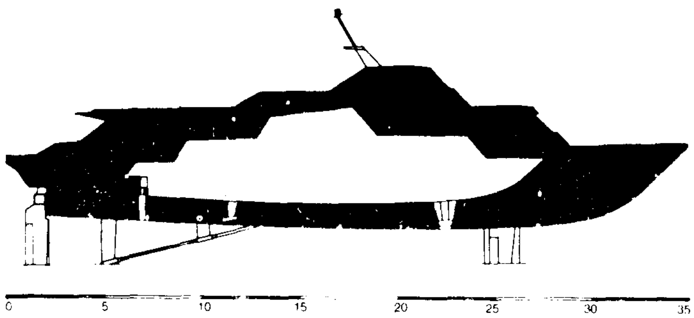

Fig. 1 Profiles

The capacity of transport spans from the earlier 72 to the 330 passengers of the newest RHS 200 in its commuter version, Fig. 2.

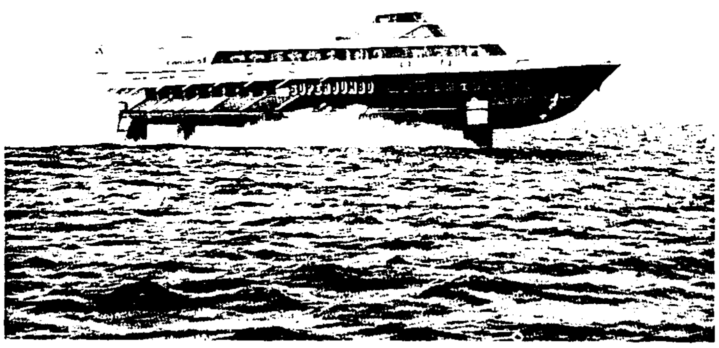

Fig. 2 RHS 200

Relevant data concerning main dimensions of today's ECH is given in Appendix A.

The modified requirements connected with the increased length of the routes, which place passenger comfort as one of the first aims to be fulfilled, have changed some significant dimension parameters.

For instance, the cabin volume per passenger has increased from 1.29 to 1.78 cubic meters while the correspondent cabin surface per passenger has increased from 0.65 to 0.80 square meter per passenger.

Other parameters have remained in the same range. For example, displacement per passenger has remained between 0.47 and 0.51 tonn. This has been possible, even though there has been an increase in weight due to the addition of equipment to improve comfort, performance, and safety, by the reduction in weight structure as a result of improved technology.

H U L L

Construction

ECH builders have preferred to maintain simplicity of construction, operation and maintenance as basic characteristics of their production, keeping in mind the influence these have during the entire life of the craft. As a consequence, the construction system, in principle, has basically remained unchanged in respect of the early period.

The main changes consist in the replacement of the original all riveted construction with a combination of Argon welded and riveted parts, while the structures, originally of the transversal type, Fig. 3, are now fully longitudinal, Fig. 4.

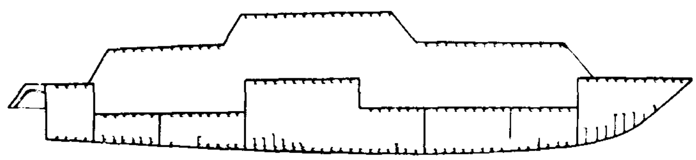

Fig. 3 Transversal Structure

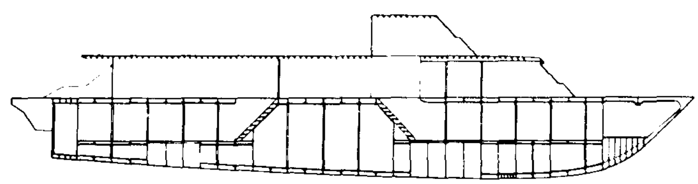

Fig. 4 Longitudinal Structure

Today, the frames are mostly welded while the hull plates are still riveted. With the above innovation, it has been possible to fully utilize the benefit of the elasticity of the riveted joints with the soundness of the welded parts.

With the increased dimensions the hull

weight to length ratio, which was around 0.25 for the PT 20, has gradually increased and is now 0.60 tonn/meter for the RHS 200.

Material

The hull material has remained alluminum-magnesium alloy which during the years of service has confirmed good resistance to both corrosion and daily service stress.

The characteristics of this alloy are given in Tab. 1.

Composition %		Mechanical Properties	
Mg	4.40	Specific Weight	2.66 Kg/dm^3
Mn	0.50	Tensile Strength	30 Kg/mm^2
Cu max	0.05	Yeld Strength	22 Kg/mm^2
Fe max	0.40	Elongation	12 %
Si max	0.30	Young's Modulus	7000 Kg/mm^2
Zn max	0.10	Hardness (Brinell)	80 Kg/mm^2
Ti max	0.10		
Ni max	0.01		
Al remainder			

Tab. 1 - Al Mg 4.4 Alloy

Even if the above materials have basically remained unchanged, the ratio hull weight/displacement has been slightly reduced from 0.19 to 0.16, as a result of the technogical improvement in the structure and in the construction.

F O I L S

The foil system is one of the key features of the ECH success. In this area, advantage has been taken of a remarkable consistency of development through these years.

The principle governing the design based on tandem surface piercing foils has remained basically unchanged from the early days up to now. As it is known, fixed surface piercing foils are not only inherently stable but in respect of the fully-submerged type, they benefit of wider speed range, of lower take-off speed, of higher margin of safety in case of failure, and of greater potential for remaining foilborne in high to extreme sea states.

Some of these features are more valuable for military utilization than for commercial, but lower take-off speed, and therefore lower required power, and higher margin of safety are also of primary interest to the commercial owner.

Some attempts to adopt fully submerged foils have been made with good technical results. Though they have proved technically valid, nevertheless, for a commercial service, today they are economically unacceptable.

As was the case with the aeronautic pool which produced the Concorde, technically valid but commercially a disaster, similarly, it is expected that the fully submerged hydrofoils can be utilized only for special Navy programmes or for very particular commercial services which can afford the luxury of placing at the bottom of their list, the economics of operation.

ECH builders have preferred to maintain in the various parts of their product simplicity, reliability and economy as guiding principles.

As a consequence, they have preferred to keep for their hydrofoils a surface-piercing system.

Let us briefly review now the variations to the original characteristics of the European foil system.

Front Foil

The original dihedral V-shaped foil has generally been changed in the last decade designs, in favour of the W-shaped foil, Fig. 5.

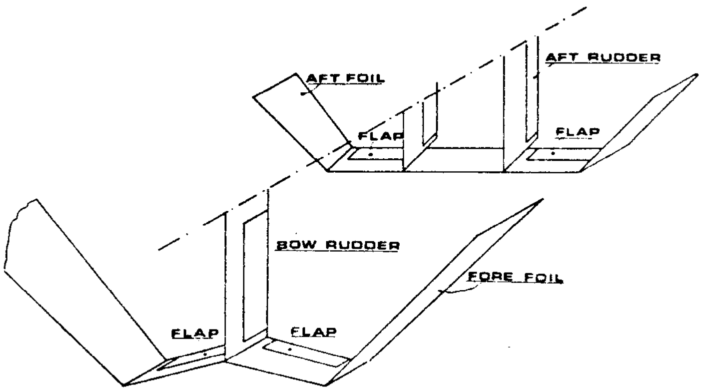

Fig. 5 W-shaped foil

The modification allowed :

- reducing the draught though maintaining high virtual immersion and consequently low sensitivity to heave;
- increasing the aspect ratio and therefore the lift to drag ratio;
- providing the foil with a central strut. This enables easier actuation of the flaps and the installation of a forward rudder which dramatically improves the turning ability of the craft. Furthermore the structural strength is improved;
- obtaining optimum efficiency of the flaps which can be placed in the inner part of the W. In this position, the flaps are then less sensitive to immersion variations and provide a longer lever arm for transversal stability. As a consequence, a greater righting moment for roll control can be generated by smaller hydrodynamic forces with reduced drag and less hydraulic power.

Rear Foil

The rear foils have practically remained unchanged as far as shape even if the new designs have flaps for a better control of pitch and heave.

Materials - Structure

In the early years, many sections of the foil structure were made of casted steel and the remaining parts were in high quality antiaging steel.

Today, the casted parts have been almost completely substituted in favour of a more extended hollow construction as a result of improvements in design, structural calculation, and welding techniques. Furthermore, a new type of steel with higher mechanical characteristics has been introduced. The use of the latter, together with the mentioned improvements in design and manufacturing, has resulted in improved foils and consequently craft performance.

Composition %		Machanical Properties	
C	0.06	Specific Weight	7.86 Kg/dm^3
Ni	0.70-1.00	Tensile Strength	75 Kg/mm^2
Cu	1.00-1.30	Yeld Strength	65 Kg/mm^2
Cb	0.02 min	Elongation	25 %
Mn	0.40-0.65	Young's Modulus	20700 Kg/mm^2
Si	0.20-0.35	Hardness (Vickers)	230 HV

Tab. 2 - NiCuAge Characteristics

Even if today the form, dimensions and the material used for foils are different with respect to the first generation hydrofoils, the ratio foil weight to fully loaded dispacement has remained practically unchanged, the value being around 0.16. The ratio relative to the foil load has also been constant; in fact, it has been maintained at about 5.8 to 6 tonn/m^2 for the bow foil and 5.5 to 5.9 for the aft foil. The above values have proved their full validity during the many years of successful service.

P R O P U L S I O N

ECH are propelled by a system which, in principle, is made up of :

diesel engine → reverse reduction gearbox → inclined shaft → fixed pitch prop.

It is remarkable that this type of system has always been employed on all European Hydrofoil, from the very first 'Freccia del Sole' up to the latest RHS 200, with only minor departures concerning some components.

The only known exception to this rule was the British Sea Ranger which embodied a hydrostatic transmission. The minor departures referred to have been up to now the use of the torque converter and the introduction of CPPs. The first has not involved particular problems, but it introduced a weight penalty affecting performance and/or payload, whilst CPPs on the RHS 200 have proved most satisfactory inasmuch as they allow very good control of the engine load and therefore of fuel consumption. Furthermore, in the RHS 200, the propeller life has been dramatically prolonged due to use of super cavitating blade design.

Now, one may wonder why such a conservative behavior on behalf of European builders when dealing with a craft of the so called advanced type. The answer is quite simple.

The reason behind the success of the ECH is to be found in the consistent fulfilment of a few basic requirements:

(i) economy in running;
(ii) easy to operate;
(iii) low initial costs;
(iv) reliability.

The requirement (i) means basically high propulsive efficiency obtained through the product of the efficiencies of the components. Therefore, to meet this requirement, we are to use:

- the most efficient prime mover. Diesel engines, as compared with gas turbines, still today offer the most attractive figures of specific fuel consumption, so meeting requirement (i), they are easier to operate - requirement (ii) -, have lower initial costs requirement (iii) -, and are reliable - requirement (iv) -.

- the best combination of power transmission and propulsive device. In this area it is pointless discussing the superiority of both mechanical transmission and marine propeller, the latter in the range of speed covered by current commercial hydrofoils. It may be argued that even higher efficiencies could be obtained through the use of Z-drive rather than inclined shafts. Unfortunately, at the moment we do not know of a Z-drive capable of meeting requirement (iv).

In summary, the propulsion system adopted has fulfilled in the best way the above-mentioned requirements. Furthermore, the constant use of the same system has made possible to refine the relative technology up to the highest grade.

Today's ratio of power/displacement is in the range of 27 kW/tonn while the power ratio to passenger knots is in the range of 0.38 kW/pass.

The above considerations and figures may give an explanation as to why the propulsion system can be considered as another reason for the success of the ECH.

AUTOMATIC CONTROL SYSTEM

As previously mentioned, the ECH have always had a surface-piercing foil system which is inherently stable. In order to improve passenger comfort in rough sea, an automatic control system has been developed. This has the only task of counteracting the wave generated motions.

For this reason, the proper terminology for the automatic control system is Seakeeping Augmentation System (SAS) which means that if the system is not operated, the comfort of the flying craft will only be impaired, while the operation in foilborne mode need not be discontinued.

Today, SAS's are simply made of:

- sensors, i.e. gyro, accelerometer, and position transducers, to feel craft trim and motions;
- computer for making decisions about the actions to undertake;
- actuators, i. e. trailing edge flaps on both foils.

Very little hydraulic power is needed to generate flaps movements.

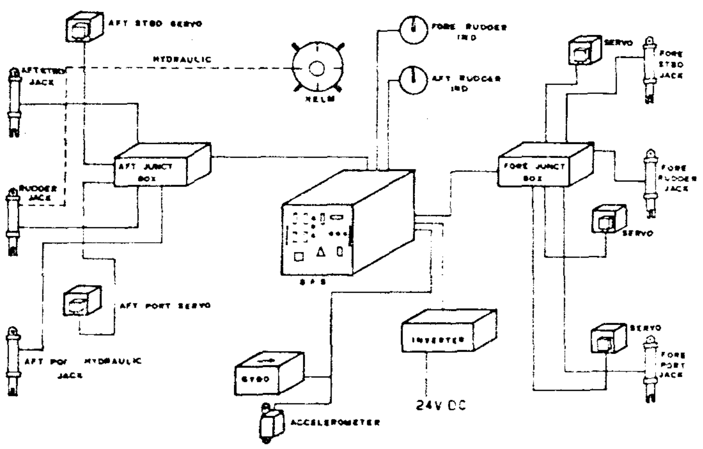

Fig. 6 SAS scheme

Fig. 6 shows today's SAS system which is used in the large Rodriquez built hydrofoils where it has given excellent results.

Fig. 7 shows roll and pitch motions in sea state low 6 at 33 knots, vs. significant angle of encounter to sea, as recorded during British Ministry of Defence sea trials on an RHS 160 hydrofoil, controlled by SAS.

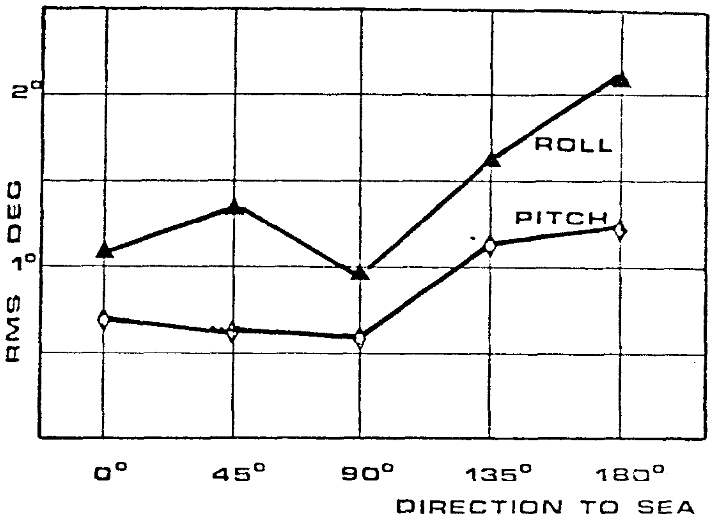

Fig. 7 Foilborne roll and pitch

Fig. 8 gives the improvement obtained by means of SAS in respect to the uncontrolled mode - i.e. with controls fixed -

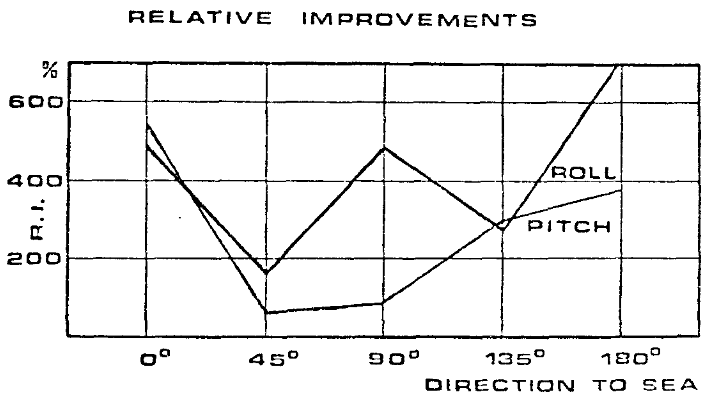

Fig. 8 Relative improvement

The sea trials were carried out on the Channel Islands-France route. In this very rough area, the SAS system has accumulated more than 5 years continuous hard service.

The above mentioned results and the experience gained over the years with this SAS system on several hydrofoils have confirmed that it is both effective and reliable.

COMMERCIAL ASPECTS

General considerations

The development and the success of a product or service is dependent upon many factors. It must fulfill the customer needs, must be reliable and up to specifications, must have an adequate support from advertising to product service and, last but not least, must be economically acceptable from the various cost aspects.

If we look at the rapid growth of the ECH, we can deduct that it has been and is a product supplying a service and both product and service have and are obtaining a great success.

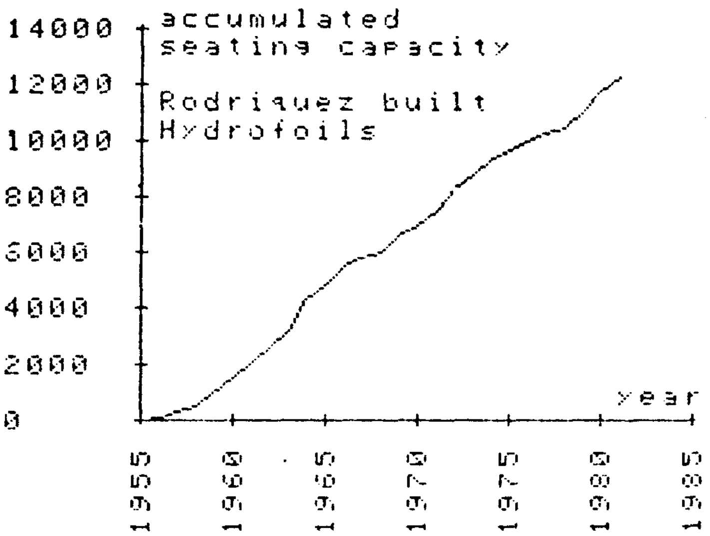

Fig. 9 Accumulated seating capacity, Rodriquez built hydrofoils

An indication of such growth is given by the Fig. 9 where the accumulated seating capacity of the Rodriquez shipyard hydrofoil production is shown.

From 1956, when the first hydrofoil entered service across the Strait of Messina up to the end of 1981, the hydrofoil fleet has spread over the waters of 5 continents where today 150 of these craft are running their useful service.

Types of service: quality and speed

During the years, in general, ECH have proved to represent the cheapest fast means of passenger transportation wherever water has been used as a connecting link between populated areas.

Several types of service are rendered in the various countries. In fact, they vary from "commuter service" which utilize waterways to shortcut long distances or avoid traffic jams (as in Sydney Bay; Rio de Janiero; etc..) to "rapid passenger service" where with speed and comfort, hydrofoils connect places by waterway (as Hong Kong - Macao, Buenos Aires - Colonia, Guernsey - St. Malò, etc..).

The distances covered by various routes are different depending upon the area where the operation is performed and the type of service rendered. They vary from the very short connection like Rio de Janiero - Niteroi in Brasil, covering 2.8 sea miles to the longest route, up to now, between Palermo and Naples with its 180 sea miles.

For the Rio Niteroi service there is a continuous chain moving passengers, with a few moments interval for embarking and disembarking on the 7 minute crossing. While the Palermo - Naples service offers passengers a daily trip to Naples in about 5 hours in a luxurious environment, against a 13 hour train trip or a full night sailing by ship.

From the above examples, it may be seen that hydrofoil services are very competitive with sea and ground transportation but on many routes, they are even successfully competing with air transportation. This is the case, for instance, between Copenhagen-Malmoe, Guernsey-Jersey, etc., where the hydrofoil service has the advantage of connecting with city centers rather than out of town terminals and of offering a reduced price in respect of air transport.

ECH builders have always held in due consideration the Gabrielli-Von Karmann question: "What price Speed?"

The relevance of this question has been proven many times during the past years. In fact, it is with great concern that we note that about 90% of the advanced commercial hydrofoils built in the U.S.A. according to a design which has not taken into due consideration the above mentioned question, have been compelled to stop their service in many countries around the world due to their high cost of operation and resultant severe economic losses suffered by the owners. Of course, this can very well have a negative effect on the future market for all of the hydrofoil industry in general.

It is to avoid the above that the service speed of the ECH has been maintained within the 35 knots which is quite acceptable for sea transportation on short/medium distances, and rappresents the economic answer for fast water transportation, especially today when the cost of fuel is so high.

Public acceptance

But what has been and is the public's acceptance of the ECH? In order to answer this question with up-dated information, a worldwide investigation has been carried out during the last few months in order to determine some basic elements of the services performed by the hydrofoils of european construction.

Out of a total of 150 commercial hydrofoils built in Europe, the data which was received in time for the completion of this paper concerned 80 hydrofoils representing 53% of the total. As a consequence, the figures concerning the total hydrofoil fleet will be given as an extrapolation.

To quantify the public's acceptance, a rough idea may be obtained by the total number of passengers carried around the world during the 25 years of service.

If we extrapolate the 150,347,054 passengers carried in the 25 years ending 1981 by the 80 hydrofoils under consideration, we obtain that the total number of passengers transported should be more than 260 million, and, similarly, extrapolating the 31,135,782 sea miles logged, the total distance sailed should exceed 60 million sea miles.

Of the recorded 80 hydrofoils, it has been ascertained that 46 are running a daily service for the full year while the remaining have performed seasonal services.

During 1981, they have transported 9,810,681 passengers for a distance of 2,474,960 sea miles. This is equivalent to having carried half the population of the United States to the moon!

The above figures by their magnitude confirm that ECH have become an integral part of the daily life wherever a service has been established.

Reliability and Costs

Reliability analysis of the recorded services in respect of unforeseen stops due to weather conditions, for the year 1981 service shows a world average of:

99.78%

Time and cost for maintenance and cost for running are among the very many important points to be considered.

The results show that the average time required for yearly maintenance is:

4.43% of the operated hours.

Therefore, in considering a daily 10 hour run, a 16 minute stop should be allowed for maintenance.

Taking into consideration the different types of service, nation where the service is operated, different fiscal regulations, as well as different company accounting systems, the results of the investigation concerning data for the year 1981 give the following.

(a) Maintenance cost:
23 to 35 US$ per running hour,
according to the dimension of the craft and the type and duration of the service. This includes ordinary and extraordinary maintenance.

(b) Overall cost of transport:
0.08 and 0.12 US$ per passenger mile,
this figure includes amortization, capital interests, insurance, running expenses, maintenance, crew and shore personnel, agency and harbour fees.

According to a recent study on points to be taken into account in purchasing a product, price is the last item to be considered in respect of other factors such as reliability, performance, meeting of specifications and after-sale service.

For this reason initial cost has been left as the last item to be dealt with. Of course, the price reflects the type of ECH, the service that the hydrofoil is scheduled to perform and many other factors. In general, it is possible to say that today it ranges from US dollars 25,000 - 30,000 per passenger seat which is quite reasonable if compared with recently published figures of similar US-built fast means of water transportation.

With regards to amortization - this is very favourable due to the long life of the craft. In fact, ECHs have logged more than one quarter of century of continuous service.

For this reason and for all of the above considerations, it is easy to understand why operation of the ECH represents a sound economic enterprise.

FUTURE PROSPECTS

Analyzing the production of the Rodriquez Shipyard which accounts for more than 85% of the ECH, we can see that there has been a constant increase in dimension and consequently seating capacity due to the increased market request.

This is shown in Figures 10 and 11.

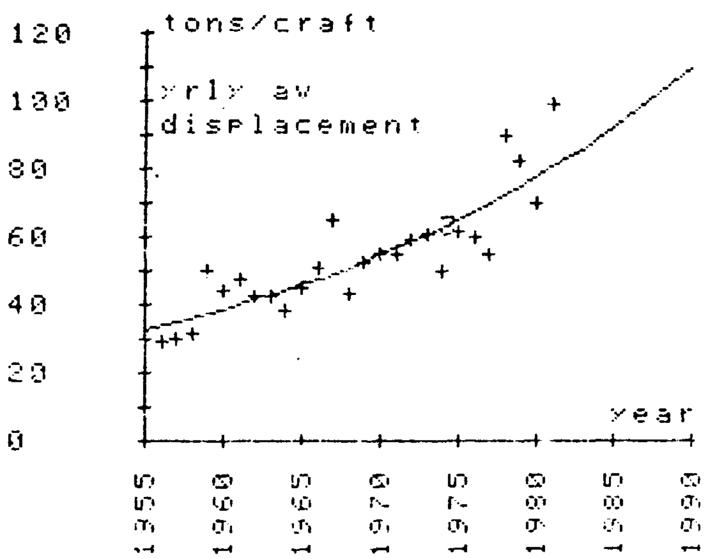

Fig. 10 Trend of average dispacement

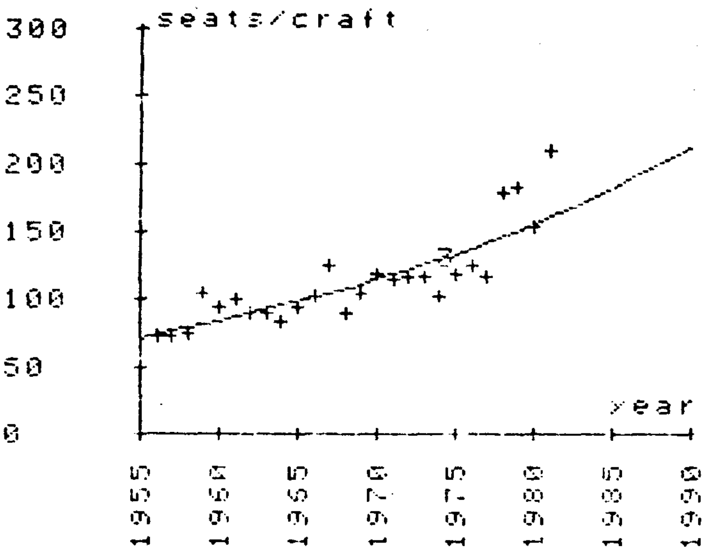

Fig. 11 Trend of seating capacity

Fig. 10 shows the yearly average displacement. The growth is extrapolated up to 1990, giving the trend for the next decade, while in Fig. 11 the seating capacity is shown.

As can be ascertained from the above mentioned graphs, both average displacement and seating capacity have increased following an exponential law.

According to the results of this analysis, the ECH maximum seating capacity in 1990 should be 336 for the touristic service and 421 for the commuter service. Therefore, we should expect to see hydrofoils of about 200 tons displacement.

This growth may be expected in both types of service, i. e. passenger/touristic and commuter traffic.

In fact, a large hydrofoil would be more attractive for the first type of service because of the increased comfort on long routes; for the second type of service because of the increased passenger capacity for commuters in the metropolis areas.

But, while for the traditional service, i.e. passenger/touristic, a limit to the dimension would come from the volume of traffic itself, for the hydrofoil destined for the commuter service, the limit would come from the time necessary for the embarking/disembarking of the passengers. In fact, on short routes, as this service is generally, this element is a major part of the overall time for the trip itself and, consequently, passengers would surely prefer more frequent departures in respect of a larger craft.

Nevertheless, in general, a potential growth in dimensions is to be foreseen.

From a commercial point of view, the choice would be determined by the public's requirements which means traffic demand and by the economics of the service involved.

From the technical point of view,large craft mean longer strut length according to an approximately cubic law and this in turn would affect the pay-load fraction.

Furthermore, the power per single prime mover should be increased and this is problematic because the currently available fast diesel engine in the range of presumably requested power, are already very close to their limit of economic convenience. On the other hand, gas turbines are still too demanding in terms of fuel.

Generally speaking, we should seek lighter structures. A possibility is the application of advance composities to hull structures and maybe foils. The latter could alternatively benefit, together with shafting, of the use of titanium.But, with all of these, due attention should be paid to the cost of such innovations.

As far as comfort is concerned,we can expect a new SAS which will be of the self-adapting type based on digital microcomputers. This means a SAS which provides the best response to the type of sea encountered, granting a further improvement in the craft's perfomance in rough sea, thus offering maximum comfort to the passenger.

CONCLUSION

In this paper we have briefly reviewed the development and growth of the ECH and we have noted that, while establishing itself as a valid means of transportation all over the world, it has grown in size, quality and market.

ECH builders have always been cost conscious when introducing innovations, since economy of operation and construction have been their guideline. Generally, there has been a process of progressive refinement rather than substantial changes, the use of active control of the surface piercing foils being the most remarkable and effective departure from the early design. The validity of this attitude has been confirmed by the commercial results achieved.

Taking into account that the fuel crisis is and will continue to strangle the world's economy, it is the authors' opinion that we cannot expect to see hydrofoils of very large dimensions and with very high speed without running into serious economic problems.

For this reason, we are sure that hydrofoils with surface-piercing foils, diesel engines, cruising speed around 35/40 knots, and SAS, built in Europe or elsewhere in the world, will continue to supply during the future years a suitable and very useful communication means.

As far as future trends are concerned, we can expect to see continuous technical improvements which will bring higher efficiency and better performance and above all, we will see the ECH revolutionize the means of commuter mass transportation around the world.

ACKNOWLEDGEMENTS

Most sincere thanks go to all the managers and directors of the following companies, who have kindly supplied the requested information.

- Alimar - S.A.N.C.I.y F. - Buenos Aires, Argentina
- Alimar S.p.A. - Palermo, Italy
- Aliscafi SNAV S.p.A. - Messina, Italy
- Belt S.A. - Montevideo, Uruguay
- Condor Ltd. - Guernsey, C.I. Great Britain
- A/S Dampskibsgeselskabet Oresund -Copenhagen Denmark
- Fast East Hydrofoil Co. - Hong Kong
- Han Ryeo Development Co. Ltd. - Seoul, Korea
- Hong Kong Macao Hydrofoil Co. - Hong Kong
- Ministero dei Trasporti- Gestione Nav.Laghi- Italy
- Red Funnel Group - Southampton - Great Britain
- Società di Navigazione Adriatica - Venezia, Italy
- Transtur Aerobarcos do Brasil - Niteroi, Brasil
- Urban Transit authority of NSW - Sydney, Australia

All seakeeping data has been taken from the results of trials performed by the British Ministry of Defence on the Rodriquez built RHS 160 'Condor 5'.

APPENDIX A

Main characteristics of current production of European Commercial Hydrofoils.

Type		RHS 70	RHS 150	RHS 160	RHS 200
Lenght o.a.	m	22.2	28.7	30.95	35.5
Moulded breadth	m	4.8	5.85	6.2	7.0
Foils span	m	7.8	11.0	12.6	14.4
Displacement f.l.	t	33	72	90	135
Engine power	kW	1050	2x1050	2x1380	2x1860
Cruising speed	kts	35	34	35	35
Provided with SAS		no	yes	yes	yes
Passengers: touristic/commuter		72	151/190	180/210	254/330

NOTES:

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The North American Association Int'l. Hydrofoil Society
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EUROPEAN DEVELOPMENT OF HYDROFOIL CRAFT TECHNOLOGY

Baron Hanns Von Schertel

Supramar AG, Switzerland

FIRST INTERNATIONAL HYDROFOIL SOCIETY CONFERENCE

Ingonish Beach, Nova Scotia, Canada - July 27-30 1982

EUROPEAN DEVELOPMENT
OF
HYDROFOIL CRAFT TECHNOLOGY

by

HANNS FREIHERR VON SCHERTEL

ABSTRACT

The Airplane and Hydrofoil, two means of transportation which are subjected to the same basic physical laws, have nearly the same date of birth. Whereas the Aircraft progressed rapidly, Hydrofoil development advanced very slowly and even stagnated fully for nearly 30 years after the successful flights of Alexander Graham Bell. Only during World War II, when a test boat of the Schertel-Sachsenberg system was demonstrated to the German Navy and accepted by the giving of several orders, was hydrofoil technology awakened again. With the construction of five different types of hydrofoil craft in the Sachsenberg shipyard, the age of industrial manufacturing had commenced.

We will look at the question of why it took about 50 years until we find the first passenger ferries in public service and what caused so many inventors to search for new solutions for the waterborne vehicles.

We find only two predecessors of Forlanini who deserve the honor of having been the first inventors of a practical, usable hydrofoil boat. However, the teachings of Horatio Phillips in 1881 allow us to state that the hydrofoil principle has been known for a hundred years.

A chronological review of hydrofoil development in Europe follows whereby utopian ideas, which cannot be considered as a contribution to technical progress, are disregarded. My own experimental work with its failures and catastrophes, and the first demonstration trip down the Rhine showing feasibility of a Hydrofoil for passenger transportation is delineated.

A short technical review giving the life story of the military hydrofoil built during World War II is given. Then follows a description of the development of the public passenger service with hydrofoil ferries.

Finally, we discuss the largest hydrofoil development of the world, which is in the Soviet Union, where larger and faster military hydrofoil vessels are built than in the Western Nations. Described is how the Russians accumulated know-how, knowledge and experience from the engineers of the Sachsenberg shipyard who had been involved in the design and construction of our Naval hydrofoil vessels.

EUROPEAN DEVELOPMENT OF HYDROFOIL CRAFT TECHNOLOGY

The date of birth of the hydrofoil and the airplane nearly coincide, if we regard 1905 as the beginning of hydrofoil development when the hull of the Forlanini's boat left the water for the first time, and 1903 as the start of aviation, when the Wright brothers made their first hops. However, the priority which is given everywhere to the Wrights is historically not correct. It was the German inventor Gustav Weisskopf who succeeded in making the doubtlessly proven and witnessed first motor-driven flight in history. This was in Bridgeport, Connecticut, in 1902 nearly two years before the accomplishments of the Wright brothers. This ingenious pioneer, who also designed and constructed aircraft engines with variable pitch propellers, died poor and forgotten.

These two new means of transportation, which are subjected to the same basic physical laws, developed very differently. Aircraft progressed rapidly, borne by the enthusiasm of the public who saw the old dream "to fly like a bird" come true.

Large amounts of public and private monies poured into the aviation field. In constrast, the Hydrofoil craft had to fight against the conservatism of shipowners who watched the new development with preconceived notions and skepticism. The tendency to stick to the traditional types of ships, derived from random development over thousands of years and without governmental support in Europe, was difficult to overcome. The importance of the hydrofoil for fast short-haul passenger transportation or other specific missions had not yet been foreseen.

After the impressive flights of Alexander Graham Bell in 1911 with his air screw drive craft in Canada, hydrofoil development stagnated for nearly 30 years at a time when air service had already been consolidated in all major countries. After eight years of independent experiments, I successfully demonstrated a 3-ton hydrofoil boat to the Germany Navy. Hydrofoil technology was awakened from its 30-year sleep. This boat was designed with the assistance of engineers of the Sachsenberg shipyard and built in my own workshop. Believing that a hydrofoil craft would not be sturdy enough for military purposes, German officers came with the intention of rejecting the boat. However, a happy little accident helped change their minds.

During the landing maneuver, the motor suddenly stopped and the boat ran into a post with the fin part of the foil, without the slightest damage. Because the Navy demanded a further demonstration in sea waves, we sailed down the river Elbe to the Baltic Sea. Anxious to experience the behavior of the boat in sea waves, we drove straight to the open sea without waiting for instructions and in our ignorance successfully passed through a mine barrier, proving involuntarily that pressure mines do not respond to hydrofoil craft when foilborne.

After the craft had met the requirements and Navy officials were satisfied with its seaworthiness, the licensed Sachsenberg Shipyards in Dessan-Rosslau and Hamburg received orders for different types of hydrofoil craft, due to the indefatigable initiative of Gotthard Sachsenberg. In a joint work with a very competent team of the licensed shipyard headed by Prof. Weinblum and Prof. Schuster, intensive research and development work commenced. All problems were theoretical and, with the aid of model tests, were seriously approached. After completion of the design work, production was set up under the energetic management of Gotthard Sachsenberg. The age of industrial hydrofoil craft manufacturing had started.

Why did it take nearly 40 years to reach this stage, while the aircraft industry had arrived at this point 20 years earlier? Besides the aforementioned reasons, there were also an abundance of physical and technical difficulties to be solved for the performance in a seaway, which are not unlike the intricate phenomenon appearing at supersonic flight. The most obstinate difficulty proved to be avoiding lift impeding ventilation of the foils when operating in the interface of two media of highly different density. With increased speed, the problems are aggravated by the onset of the cavitation phenomenon. The stability question about the three axes--mainly the longitudinal stability, particularly in a following sea--require by far more studying and attention than for the conventional case. When the craft is running in following waves the boat is subjected to the adverse influence of the orbital motion of the water particles due to the unfavorable phase shift between the vertical motion of these particles and the contour of the waves. The foil is lifted at the wave's front slope and dives deeply in the afterpart of the wave, losing lift and speed. To combat his detrimental phenomenon poses problems no less difficult than avoiding foil-ventilation. Moreover, the propulsion systems from the elevated hull down into the water demand unusual engineering efforts which grow tremendously with increasing speed. Neither Forlanini nor Crocco or Bell could solve all these problems, and thus failed to develop their craft into a seaworthy boat serviceable for public transportation or military missions. Obviously discouraged by persistent foil ventilation in waves, all three gave up their attempts after a comparatively short trial period. This resignation was another reason hydrofoil development was retarded. Many examples show that after discontinuation of unsuccessful trials, a long time passes before other engineers risk a new attempt.

No doubt Enrico Forlanini, being the first to put his idea successfully into practice in 1904, deserves the honor of being the first inventor of a hydrofoil which could fly with stability under its own propulsion power and also carry a crew.

To help decide at what point the hydrofoil principle actually became known before Forlanini's time, we need to define a hydrofoil boat: It is a craft, the hull of which is elevated clearly above the water surface in a stable state by aid of submerged foil portions, which produce lift forces by suction on the upper side and overpressure on the lower side when the foil sections are moving through the water.

Using this definition, we find that Forlanini had only two predecessors. One, Horatio Phillips in 1881, who only towed his models. His teachings and the results of his experiments lead us to believe that the hydrofoil principle has been known for 100 years. The second forerunner was really two people, the Meacham brothers who, in 1894, used fully-submerged, automatic depth-controlled foils by a similar system that Christopher Hook applied later. Like Phillips' craft, the small-manned boat was also towed.

Count Lambert, a Russian citizen who demonstrated his craft on the Seine in 1891, is erroneously regarded as Forlanini's predecessor. This opinion is strongly supported by the Russians, who put forward the claim for accomplishing the first ride on foils in history. Given the above definition, Lambert's craft was not a hydrofoil but a planing boat where only the lifting effect on the lower side of inclined plates was utilized. A plurality of arched plates had been arranged sidewards one after the other, skimming the water surface without lifting the hull clear of the water. In his own words: "The boat is maintained well on the surface of the water." Another indication that Lambert's boat performed as a planing craft is the absence of a disclosure of the maintenance of stability, which needs no particular consideration in the case of a surface-skimming boat.

Before describing the different attempts and the trial craft which have materialized in Europe, the question arises as to what caused inventors, engineers and scientists of several nations to leave the 5000-year old displacement ship, already developed to the highest perfection, and endeavor to find other solutions for the waterborne craft. It probably was the depressingly low speed on water, along with competition from the continuously accelerated means of transportation on road, rail and air, which intrigued the pioneers. The well-known large drag increase of a hull with growing Froude number disqualifies smaller displacement boats from attaining high speeds. On the other hand, the surface-skimming craft did not solve the problem under economically acceptable conditions and comfortable sea behavior. So finally the idea broke through to lift the hull with its elevated drag at high Froude numbers completely out of the water.

Now I shall give a chronological review of the hydrofoil developments which took place in Europe. Hereby all utopian ideas, visions and wishful thinking are disregarded since they had no practical application and therefore cannot be considered as a contribution to technical progress. To an invention belongs the successful materialization of the idea or a clear-cut disclosure of ways and means for attaining the objective.

The Italian Enrico Forlanini was the first who made practical trials with a manned, motor-driven craft. He carried out his test runs in 1905 on the Lago Maggiore in Italy with a 1.6-ton boat. For propulsion he used an air propeller with which he attained the remarkable speed of 37 knots. This was the state-of-the-art of those days, and the actually applied, doubtlessly partially cavitating foil sections were a great success, even though the speed fell far short of the 100 knots which Forlanini expected, unaware as he was of the cavitation phenomenon. Certainly such a speed will remain a wishful-fulfillment with subcavitating foils.

Our main interest is, of course, directed to the applied foil system. Forlanini is the inventor of the ladder system, at which a plurality of smaller foils are arranged one above the other and fitted horizontally. (He took his first patent in 1898.) A deviation of the equilibrium causes stepwise immergence or emergence of a rung of the ladder thus changing the wetted lift-producing foil area. While gaining speed, one foil after the other emerges reducing effective foil area to a minimum with near-optimum lift coefficient and without losing the craft's stability. This explains the high speeds which have been recorded. On the other hand, a drawback of the system is its relatively high drag at medium speed due to the interference between foil and struts in the large number of intersections, causing flow disturbance and advancing ventilation. Finally, the ladder foil easily catches debris which is normally pushed away by V-foils. These disadvantages proved to be so serious that the application of the ladder system has been abandoned.

The ladder foil was used in 1955 by Carl in a much-improved configuration with only one central strut, as first used by the Samuel White Company at Cowes. Dihedral angles are provided for the rungs and their vertical spacing is such that the lower end of one rung leaves the water surface, as the top end of the next pierces the same in order to attain smooth variation of lift. With this configuration and screw propulsion, Carl conquered the world speed record for hydrofoils by going 78 knots. This is probably the speed limit for foils with conventional foil profiles. The last craft built with a ladder foil configuration was the Bras d'Or in Canada where dihedral rungs had been provided as well.

In 1906 Forlanini was followed by the Italian airship builder General Arturo Crocco and his collaborator Ricaldoni. His boat had a displacement of 1.5 tons and the same speed as the craft of Forlanini. The boat was powered by an 80-HP engine which drove the two airscrews. The important difference constituted the foil system. Crocco was the first to apply at the bow and stern a surface-piercing dihedral foil configuration. This system was a forerunner of today's, which is applied by Supramar and which I developed more than 20 years later named "Schertel-Sachsenberg." (I had syndicated with Gotthard Sachsenberg in recognition of his outstanding merits for the materialization and introduction of the new ideas.) The progress over Crocco's design is a configuration by which ventilation is suppressed, longitudinal stability ensured, and operation in a seaway enabled.

I was happy that I had the opportunity to talk with old General Crocco when I visited him in Rome before his death. I was very eager to hear about the problems he had faced, the failures which occurred and the reason that caused him to discontinue his work after a short trial period. However, I was very disappointed because he spoke only about his successful achievements, which are fully recognized. His words gave me the feeling that there were no shortcomings at all. He was not interested in improvements which had been made in the meantime and he did not accept my invitation to have a ride on our boats. He always came back to his own technical accomplishment. As to why he had stopped further development of this well-performing craft he answered only that the objective of the venture was to test propellers for his airships and that this was terminated. To the most interesting question about the behavior of the craft in waves, he replied that he had never tried it. However, a pamphlet which he wrote in 1907 ends with the conclusion that a hydrofoil could be applied for sport on rivers and calm lakes. This seems to indicate that he faced a serious problem in maintaining his boat flying in rough seas and that this discouraged him to continue his efforts in spite of the high speed which manifested his success.

Crocco was acquainted with Forlanini but he was surely not his friend. He accused him of not having been courageous enough to drive his own boat, fearing that it would undercut and dash into the depths.

The third Italian who had been involved in hydrofoil technology was Guidoni, making Italy fully the birthplace of the hydrofoil. Guidoni took over the Forlanini foil system to use it as a take-off aid for seaplanes. It had been applied successfully on many planes until the planes lost their usefulness with higher take-off speeds and had to contend with the onset of cavitation.

In 1927, 26 years after the impressive demonstration of Alexander Graham Bell and Baldwin with ladder foils in which period hydrofoil technology was completely forgotten, I started my own experimental work without collaborators, fully obsessed with finding a solution for the problems of the flying boat. This happened a year after I had begun studies at the Technical University in Berlin-Charlottenburg. In the course of eight years I tested all foil configurations which appeared promissing--fully-submerged and surface-piercing--and for which seven experimental boats had been built. It was a hard time during which failures kept following each other, and periods of disappointment and discouragement had to be overcome. But I never lost hope and believed that development work meant finding the right concept among a series of errors. First, I had to decide what principle would be more advantageous: the surface-piercing or the fully-submerged foil. I gave preference to the fully-submerged system to get as far away as possible from the disturbing influence of water surface in waves. I hoped that surface effect would be strong enough to stabilize the foil at a certain immersion depth.

The first trial runs at the Berlin lake "Wannsee" with a boat powered by a very obsolete air-cooled aircraft engine and propelled by an air screw, finished catastrophically. The old engine did not give enough power for taking off. When I noticed that the steering control was nearly ineffective I cut off the ignition, but the motor was already so much overheated that it went on running perfectly by self-ignition. The boat approached more and more the numerous, frantically escaping boats which had gathered around me and I had to count myself very lucky that I did not hit one of the fleeing boats with the propeller. The adventure finished with me crashing into an island on the lake.

This experience taught me to abandon the traffic-endangering airscrew and to use a water propeller for the next experiments. Several traffic crashes with the second craft due to ventilation made it clear that the surface effect stability would not be feasible for seagoing hydrofoils. We know that the Russians succeeded later in making use of the surface effect for stabilizing the immersion of foils with a small lift coefficient operating in calm inland waters. They accepted the jerks that occasionally occurred when the foils came too near to the water surface in the wake of passing ships.

For the following two boats I applied a mechanically-operated depth sensor which activated the angle of attack or the deflection of flaps. The foils had been arranged in canard configuration. With this appliance the experimental boat could fly in good weather, but it had already failed in a slight seaway.

With an improved sixth test boat in which a device was provided to compensaate the occurring lift changes, I had my first success. The boat operated very nicely and attained a speed of 36 knots with less than 30 hp. This was eight years after I started my experimental work. However, it did not yet come up to my expectations under heavier sea conditions and there was no doubt for me that the development of a satisfactory working depth sensing device would require a still longer time. Therefore, it is understandable that I became impatient and wished to find a quick solution. I abandoned the fully-submerged foil system for the seventh test boat built in 1935, in which all acquired experiences had been incorporated. The craft was provided with a V-shaped front and aft-foil with trapezoid outer portions. She performed fully satisfactorily under all weather conditions on the Rhine River. With only 50 hp she carried seven persons at a speed of nearly 30 knots. This craft proved for the first time that a hydrofoil is a fast and economical means of transportation and that its seaworthiness could no longer be doubted. This attracted representatives of the German Navy, Air Force, Ministry of Transportation and Finance and finally brought about the partnership of Gotthard Sachsenberg, with his shipbuilding organization.

Again we direct our attention to the applied foil system and to the progress attained over the old Crocco foil configuration. The Schertel-Sachsenberg system, applied by the former and present licensees of the Supramar Company, is a tandem foil system consisting of a dihedral surface-piercing front and rear foil. The foils are of varying section according to their position in relation to the water surface and in view of ventilation. As the most important feature, front and rear foils are shaped differently in relation to each other such that the two foils perform differently. Lift of the front foil changes at a higher rate with variation of submergence than lift at the rear foil. Consequently, it is more strongly tied to the water surface than is the rear foil, whose lift changes at a higher rate with the angle of attack than does the front foil. This means that the rear foil has greater damping than the front foil. The form of the rear foil and its distance from the front foil are such that the rear foil recovers the wave drag generated by the front foil which results in a substantial increase of lift/drag ratio.

The dynamic attitude of the craft can be easily understood. If the craft is depressed or the load increased, it will trim bow up increasing the angle of attack and foils. Lift is augmented, counteracting the disturbing force and vice versa. The response to speed changes work in the same correcting sense. Take-off is facilitated, and longitudinal stability and seakeeping capability is largely increased. When the craft is entering the face of a large wave the stiff bow foil with its lower lift slope responds strongly to the increasing immersion and climbs the wave crest, whereas the rear foil, with its strong reaction to changes of angles, tends to follow the heaving motion of the front foil thus avoiding excessive trim angles. When speed is reduced in front of a high approaching wave, the bow rises, preventing the boat from dipping into the wave crest.

A demonstration trip from Mainz to Cologne and back covering 370 kilometers convinced the Koln. Dusseldorfer Shipline, which had watched and subsidized my work, of the future of this new means of transportation and its feasibility for passenger service. They placed an order with the Sachsenberg Shipyard for delivery of a passenger hydrofoil. This was the first order ever given for a foilborne craft for commercial use. However, Mr. Sachsenberg and I had founded a syndicate for a joint development and decided to build a larger test boat to be on the safe side. It was completed at the outbreak of World War II and later, as described, demonstrated to the Navy. The war prevented the materialization of the given order.

During my test work in 1932 the German Professor O. Tietjens came to a success with a small boat of 240 kg weight. With a motor of only 5 hp he recorded a speed of 22 knots. The foil system departed from the previous configurations by the application of a single foil following the example of the aircraft. The foil seen in front-view was arched and emerged partly in transit. At the stern a tail fin was provided which generated a slight negative lift. The system had an amazingly high lift/drag ratio and good lateral stability, but longitudinal stability was insufficient. On request of the armed forces the licensed Vertens Shipyard of Tietjens, which had already built several smaller boats, constructed a larger 17-ton craft as a competitor to our VS 6 (described later). With exactly the same displacement and power this craft attained the outstanding speed of 50 knots. In order to find out which boat had the best performance, a demonstration day was arranged between the two competitors. Tietjens came off as winner of the speed record. We reached only 47 knots. However, his turning circles were poor in comparison with our boat and he had difficulty with the take-off, which could only be achieved when a person moved all the way aft. A short time later, due to the low longitudinal stability, his craft dashed deeply into a wave and smashed the foreship. This was the end of the Tietjens development.

With our orders for five different types of hydrofoil vessels, the development of technology progressed rapidly during World War II. Besides the structural experience we gained by building the craft, we learned much through the hydrodynamic investigations conducted during trial runs. We also made tank tests in our own flow canal to bring to light unknown phenomena. I also developed a new method for testing models. A specifically-designed boat pushed the hydrofoil model, which was connected by rods to the craft at a sufficient distance. Drag was measured by a balance fitted to a platform on the test vehicle. This method proved to be very expedient and the results reliable. We could measure 10 test points in 20 minutes.

Since the specifications of different types of craft that were built during the war have been published repeatedly, here is only a short technical review with the life story.

The 17-ton mine layer, VS 6, propelled by two Hispano Suiza Gasoline engines of 1560 hp at 47 knots speed, was the craft most used for performance studies carried out until the end of the war, when the Navy decided to commission it as an ambulance transporter. However, the end came too early and the boat was finally shipped to England. The six surveillance craft, TS 1-6 of 6.3 tons were built (the last of which had a double bevel gear drive). Before we could test the boat, it fell into the hands of the Russian occupation army. Although the entire deck was filled with curious soldiers, the boat took off. It was then sent to the Soviet Union.

The 80-ton VS 8, launched in 1943, was designed for the provisioning of the Rommel Army in Africa, and was, at that time, the largest hydrofoil vessel ever built. Twenty years elapsed before the American Navy built a vessel which exceeded our craft in size. In the aft body an opening was provided for accommodating a tank. The ship was designed for a speed of 45 knots. However, the Navy did not release the called-for supercharged Mercedes Diesel. At the end, with some weight increase, the specific engine power went down to 60% of the projected rate. Nevertheless the heavily underpowered boat could run against waves of 6 feet at 37 knots. In September 1944 the ship became the victim of sabotage. With one engine broken down the captain left the harbor of Goteburg on a stormy day against strict orders without the escort vessel provided. On the second day a gale blew up to such a force that water penetrated the engine room and the second engine failed. The craft drifted against the coast, the radio for distress calling did not function and the anchor chain broke. The craft became stranded. All attempts to rescue the vessel failed. When it was planned to cut away the foils, the oxygen bottles were delivered empty. A new gale came up and broke the hull in two.

The worst disaster happened to our 46-ton vessel, VS 10, which was designed for 60 knots. With great impatience we awaited the trial runs for confirmation of the theoretical speed forecast. We could never get that confirmation because the vessel was destroyed during an air attack shortly before it was launched.

Our last constructions were two small, single-seater torpedo boats, designed to approach the enemy as closely as possible, then turn back sharply, launch a torpedo over the stern and make the escape at 50 knots. The tests were interrupted by the termination of the war. Finally, we built a 5-ton hydrofoil-catamaran with retractable foils for the pioneers. The vehicle was sent to Berlin, but it never arrived.

No hydrofoil vessel could be equipped in time for warfare and be commissioned before the termination of the war and after the occupation of Germany, none of the military craft was left in our hands. What had been left was the know-how, the experience in building, testing and operating hydrofoil vessels, the results of tank tests, the scientific dissertations and last but not least, the construction plans. With this enormous quantity of software we were in position to design and construct commercial hydrofoils for peaceful application.

In 1934, W. Grunberg had filed a patent in which a fully-immersed main foil was provided closely behind the center of gravity. The foil was controlled by aid of a stabilizer at the bow tied to the water surface in the form of a float for a surface skimmer. Variations of submergence depth of the main foil were associated with a turn about the stabilizer, whereby a change of angle of attack of the foil was brought about in a restoring sense. By 1950 the basic principle of this invention was improved by the two Swedish engineers, Almquist and Elkstrom, using a surface-piercing foil for lateral stability. Several smaller and one large boat were built that could cope with astonishingly high waves. The ride was buffeted with strong spray-development. The craft were never commissioned for scheduled passenger service and production stopped after a few years.

In July 1953 Supramar inaugurated the first public passenger service in the world with a 30-seat hydrofoil craft on the Lago Maggiore, the same lake where Forlanini had made his first flight 50 years before. The boat ran from Ascona to Arona connecting the Swiss part of the lake with the Italian. The hydrofoil had an enthusiastic reception, mainly from the Italian public. It eventually proved that a waterborne hydrofoil could successfully compete with land vehicles when the craft and a motor car began a race from Arona to Ascona. Although the motor car travelled at the highest possible speed on the road, the hydrofoil arrived long before the car even appeared. In most cases the hydrofoil has the advantage of taking a straight course whereas the land vehicle usually has to follow the coastline. A good example is the distance between Messina-Palermo which is covered by water in 5 hours and 40 minutes, against 8 hours 30 minutes by railroad.

The lake service was the origin of the development of a worldwide hydrofoil passenger service with the well-known vessels PT 20 and PT 50 built in Japan, Sicily, Norway, Holland and Hong Kong.

The PT 20, built in 1956, was the first foilborne boat constructed in accordance with all safety regulations and the first hydrofoil ever to be classed for near-coast operation. Thus she marked the beginning of passenger transportation at sea. The PT 20 can maintain full speed in waves up to 1.5m and cope with waves up to 2.10m with reduced speed, but still in flying condition with the front foil and gliding on the hull's aft part. Seaworthiness is nearly unlimited if speed is adjusted to sea condition. For example, the PT 20 could ride out in the Caribbean Sea long waves of 4m height in the tail of a hurricane. Profitable operation with the PT 20 stirred up sufficient interest for construction of the larger PT 50 vessel in 1959, which received classification for off-coast routes. This vessel can maintain full speed in waves up to 1.8m and 2.5m with reduced speed. The development turned now to still larger vessels. Three units of the world's largest sea-going passenger hydrofoil craft, PTS 150, were built in Norway. The first vessel was launched in 1968. Displacement was 170 tons which, five years later, was caught up to by the Jetfoil of Boeing. This vessel is air-stabilized after the Schertel-Supramar system which works as follows.

The low pressure regions at the foil suck in air from the free atmosphere via ducts and air-exit apertures on the foil surface. As a result, lift is reduced, varying with the air-quantity admitted which in turn is controlled by a valve. The mechanical work necessary for actuating the valve involves only a small fraction of that required for foil flaps and is brought up by the low pressure at the foil as propulsive power between sensors and valve. Cavitation is suppressed by air-feeding. It is noticeable that the control remains effective in the transition from steady, non-cavitating flow to super-cavitation where a flapped foil is no longer lift-controllable. The system is of convincing simplicity and does away with all movable foil parts and their hydraulic actuators. However, the accomplishment of the feeding system and the proper foil section requires intensive investigations and tank tests.

In 1966 under a U.S. Navy contract, we built a gas turbine driven 4-ton experimental boat with fully submerged air-controlled foils. The boat, which attained a speed of 54 knots, was first tested with good results on Lake Lucerne and the Mediterranean coast.

We conducted tank tests at Wageningen for the American Navy with airfed foils at an actual model speed of 60 knots. For this purpose the carriage was shot off by water pressure.

The next step was to design and build the vessel PTS 75 with advanced stabilization for reducing roll, pitch and heave motions. The first hydrofoil for transport to oilrigs was built in 1959.

The Soviet Union has by far the largest development of foilborne craft in the world. The number of operating hydrofoils is estimated to be on the order of 1,000 units. The Soviet Uniont has ideal conditions for transportation with hydrofoil craft. Inland waterways are spread over the whole territory in a net of rivers and canals, and roads are very bad. This was fully recognized by the party leaders. The very active design office for hydrofoil vessels in Gorki employs approximately 1,000 people. As far as we know, more than 20 different craft have been developed and designed here with a variety of foil configurations and hull designs. At least five military types of up to 440 tons and with speeds of 55 knots have been built. The largest passenger vessel has a displacement of 140 tons with 250 seats, and the fastest commercial boat attains a speed of 50 knots. It is claimed that the speed range of the experimental boat "Chaika" with super ventilated foils exceeds 50-80 knots with an engine of 1200 hp. This means that the Soviet-developed naval hydrofoils exceed the Western vessels in size and speed.

However, just as in all technical branches, the fundamental knowledge came from western countries, in this case from Germany. Immediately after the war Russians established a design office in the Sachsenberg Shipyard, Dessau-Rosslau, where our military boats had been built. They engaged the still available engineers and scientists who had been involved in hydrofoil technology, in addition to engineers from the former Junkers Aircraft Company--100 people altogether--for accumulating know-how. First, a hydrodynamic theory for hydrofoils was elaborated on and reported to Russia. The already-mentioned surface effect for controlling foil submergence came to the knowledge of the Soviet engineers by the experimental work of the person who first used it--Wankel. The next step for the office was to design and construct a 57-ton Torpedo hydrofoil vessel projected for 55 knots and powered by two Mercedes Diesel engines of 1000 hp each. After completing a short, successful trial, the vessel was shipped to the Soviet Union. Among several experimental boats, a catamaran projected for 80 knots with supercavitating foils, was noted and when the boat showed that it could take off, it disappeared right away into Russia.

The production of hydrofoil craft started in the Soviet Union in 1957 at a time when our boats had already been offering scheduled passenger service. Their boats are now powered both by diesel engines and gas turbines. The Russian diesels are mostly overloaded and very susceptible to troubles. In recognition of this weakness, an arrangement was made with MTU in Germany for delivering Diesel engines. The following types are built in Russia according to a modified Schertel-Sachsenberg system: "Strela", "Pchela", "Nevka", "Turya" and "Babochka". It is interesting how, in the seagoing boats like "Meteor", parts of the foils of the Russian system are always placed deeper under the water-surface, approaching the V-foil.

In 1962 we received an invitation from the Ministry of Shipping to visit the Soviet Union in order to get acquainted with their hyrdofoils and to discuss technology in meetings. Our way led from Leningrad to the Black Sea.

The performance of the surface effect controlled "Raketa" on inland seas has already been described. The Meteor at that time did not have the sea performance it has today. The poorest performance showed by the 6-seater run-about "Volga" (probably now substituted by "Nevka") that the foils aerated permanently and the craft dropped to the next higher placed foil, came up again. The boat could only be turned in a hullborne mode. When two engineers visited us, they simply could not understand that our little sport boat could take sharp turns at full speed.

In our present development work supported by tank tests, we hope to maintain the advantages of the inherently stable, simple, reliable and economic surface-piercing foil configuration and largely eliminate the most serious drawback of the surface-piercing foil: vertical and lateral acceleration to which the craft is subjected in a seaway. A further objective is to enable adjustment for "contouring" and "platforming" with a low cost system which can be handled by normally trained sailors. Such a craft--uniting the merits of both systems--will offer to passengers comfortable sea performance, and to the military vessel better qualifications than the inherent stable systems of today can furnish.

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A REVIEW OF HYDROFOIL DEVELOPMENT IN CANADA

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Defence Research Establishment Atlantic, Canada

FIRST INTERNATIONAL HYDROFOIL SOCIETY CONFERENCE

Ingonish Beach, Nova Scotia, Canada - July 27-30 1982

IHS CONFERENCE, JULY 1982

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ABSTRACT

This paper tells the story of hydrofoil development in Canada from the late 1940s to the present, with emphasis on the concept and design of HMCS BRAS D'OR.

The early work with MASSAWIPPI had very close links with the pioneering efforts of Alexander Graham Bell and F. W. Baldwin. MASSAWIPPI's original foil system is seen to be closely related to that of the Bell-Baldwin HD-4, and the potential of the ladder foil system was further explored in the first BRAS D'OR (renamed BADDECK) and a smaller experimental craft called the R-X.

Shortcomings revealed by BADDECK caused a literal turnaround in Canadian thinking about surface-piercing foil systems, and led to the canard configuration first explored in R-X, and now generally associated with BRAS D'OR.

BRAS D'OR was unusual among prototype hydrofoil ships in being designed to a specific operational requirement, and one calling for features significantly different from those of the usual "ferry" type of craft. The development of her design and the reasons for such features as her novel super-ventilated bow foil and very fine hull are explained.

While BRAS D'OR was being designed and built, R-X and BADDECK had strong supporting roles: R-X as the test-bed of a quarter-scale model of BRAS D'OR's foil system; BADDECK converted into the world's fastest tug. A major feature of the operational concept was the use of high-speed towed sonar, and the earliest research on towed bodies and faired cables suitable for sprinting at high speed was conducted through half-scale experiments using BADDECK.

BRAS D'OR proved herself to be a technical success, but a political disaster for reasons explained in the paper. Following her decommissioning, DREA has remained active in design method development and conceptual studies of possible future hydrofoil ships, but the last test craft, PROTEUS, was used solely for propulsion research and has recently been retired.

The story will be illustrated by slides, not all of which will appear in the written text.

A REVIEW OF HYDROFOIL DEVELOPMENT IN CANADA

M. C. EAMES*

The hydrofoil program of the Canadian Forces had its origins in the pioneering work of Bell and Baldwin (Fig. 1). Assuming that presentations at the Bell Museum will cover the full scope of Baldwin's efforts, this paper begins where Baldwin finished. Full details of the earlier work will be found in the excellent book by J. H. Parkin[1].

PART 1 - DEVELOPMENT OF THE BELL-BALDWIN LADDER HYDROFOIL SYSTEM

It seems incredible today, but Canada emerged from World War II possessing the world's third largest navy, and anti-submarine warfare was the sole function of that navy. The development of nuclear propulsion posed a severe threat to ASW, with its promise of underwater endurance and speed exceeding that of surface warships. It sparked major efforts in naval research; the RCN was the first navy to operate anti-submarine helicopters from its destroyers, and the first to develop variable-depth sonar. Our most ambitious, and longer-term objective, however, was to regain the advantage of sea speed for the surface ship, through application of the hydrofoil principle.

Originally, our aim was to assess and develop the potential of the Bell-Baldwin ladder system for naval applications. This concentration on one particular system was based partly on historical grounds, and partly on the fact that other promising systems appeared to be well covered by research effort in the United States. Ours was thus a complementary effort.

R-100 - MASSAWIPPI

When this program began at the Naval Research Establishment (now DREA) in 1951, a test craft was already available. In 1948, Duncan Hodgson, an ex-RCN(R) officer, had commissioned Philip Rhodes, the New York naval architect associated with Baldwin's later work, to design a hydrofoil boat for an attempt on the world's water-speed record. However, a friend of Hodgson's, E. L. Davies, then the Vice Chairman of Canada's Defence Research Board, convinced him that this was unlikely to succeed, and that a more worthy endeavour would be to design a craft to demonstrate the naval potential of the hydrofoil principle.

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The 45 ft, 5 ton craft shown in Fig. 2 was the result. Originally, named "KCB" (after Casey Baldwin), she was built at Lake Massawippi in Quebec, and clearly shows her heritage, with configuration and foil ladders based on Baldwin's later designs. Hodgson rejoined the Navy as a Commander, Special Branch, and ran the boat from the Halifax Dockyard, in a series of rough-water demonstration trials.

Naively, it was thought that demonstrating the seakeeping ability of a hydrofoil boat would be enough to convince the Admirals to order a fleet of anti-submarine hydrofoil ships.

The Admirals were unmoved, but the Defence Research Board saw the potential and, in May 1951, Hodgson's project was transferred to the Naval Research Establishment. The craft was instrumented for quantitative trials to collect data for the design of larger, operationally capable craft.

She was now officially known as the R-100 (after the number of the DRB project file), but an original unofficial name - MASSAWIPPI - is the name that prevailed throughout her life.

The original foils were much too lightly loaded to represent a feasible scaled-up craft. However, a 20% increase in loading was enough to cause violent porpoising at speeds between 40 and 50 knots, and the 1952-53 trials were devoted to this problem. A combination of cavitation and ventilation was the primary cause(2). Anti-ventilation fences were developed as a quick fix to enable trials to proceed, but it was clear that a complete re-design of the foil system was needed, to move from the empirical Bell-Baldwin to the 1950's state of knowledge of aerofoil design.

The modified MASSAWIPPI was virtually a different boat (Fig.3). The foil system was designed for a 50% increase of displacement, to 7 1/2 tons, and the main foils were moved forward to equalize the loading on all three ladder units. The craft was now a realistic scale model of a possible ship in the 50-100 ton range, with an increased hull clearance for rough water operation. Trials in 1956 showed that the porpoising problem had been solved, and the boat performed well at 45 knots in 6 ft seas, a significant achievement for a 45 ft craft with surface-piercing foils.

These trials also demonstrated that the foils were very effective in damping motions at slow hullborne speeds, a fact that was to prove most important for our later concepts.

An interesting example of U.S.-Canadian cooperation took place during these trials. The theory of supercavitating propellers had just been developed at DTMB (now DTNSRDC) by Tulin, following ideas of Lerbs, and MASSAWIPPI appeared to be the ideal test bed for such a propeller. The need for practical testing was demonstrated when the blades of the first supercavitating propeller crumpled on our initial take-off. However, nothing daunted, the DTMB project officer, Dr. Morgan, arrived with a second and much strengthened propeller, and all went well.

Fig. 4 shows this second propeller, with its characteristic thick trailing edges, concave faces and sharp leading edges.

R-103 - BADDECK

While work with MASSAWIPPI was proceeding at NRE, Saunders-Roe Ltd., under contract to DRB and the British Admiralty, were studying problems involved in the design of larger craft. Canadian interest centered in a 100 ton ASW design-study, known as R-102. However, in 1953, these studies concluded that practical craft would be limited to about 50 tons, mainly because of power plant limitations.(3)

Fig. 5 shows Saunders-Roe's recommended 50 ton design, R-101, which we had to conclude would be too limited in payload and range for Canadian anti-submarine applications. The project all but ended at this point.

However, the RN were interested in this concept as a fast patrol boat, and the Admiralty encouraged DRB to proceed. The step from MASSAWIPPI to this 50 tonner was judged too ambitious, and Canada agreed to fund an intermediate sized prototype, known as R-103. The RN would then finance the full-scale R-101.

R-103 was a 17 ton craft, chosen to be the smallest size that could introduce the structural and mechanical engineering features required in the R-101 (Fig. 6). For example, an aluminum hull, as opposed to MASSAWIPPI's plywood construction, built-up rather than solid foils and struts, and right-angle bevel-gear transmission instead of a long inclined shaft.

She was powered by two Rolls Royce GRIFFON engines, facing each other, and driving through a separate propulsion appendage (necessarily out of scale), to propellers at both ends of the nacelle.

R-103 was originally christened BRAS D'OR, a name that later had to be changed to BADDECK, in favour of her much larger successor. She was delivered to NRE late in 1957, and trials began in earnest in 1958 (Fig. 7).

Although BADDECK met her intended purpose of proving structural and mechanical features for the design of larger craft, and eventually proved invaluable for an associated project to be discussed later, her original behaviour proved disappointing.

In contrast to the promise shown by MASSAWIPPI's second foil system, BADDECK's foil system was capable of maintaining stability over only a narrow range of angles of attack - a range too narrow for satisfactory rough-water operation. The problem was eventually traced to errors in foil nose shape, leading to premature cavitation and encouraging ventilation too extensive to be controlled by fences. Moreover, too low a rate of change of lift with draft prevented her recovery from sudden local losses of lift. This was an expensive lesson in the importance of scale effects, since her model tests had promised exemplary behaviour.

THE R-X CRAFT

During the construction of BADDECK in the U.K., conscious of our lack of high-speed model-test facilities in Canada, NRE had been building a versatile "floating Meccano set", known as the R-X, a 3-ton craft.

This was a simple plywood box, from which could be hung, via dynamometers, any configuration of foil system. Fig. 8 shows her modelling the BADDECK foil system, with the steerable stern foil mounted on a tube projecting from her transom stern. However, the cross beam carrying the main foils could be positioned anywhere along the length of the hull, and a false triangular bow section could be removed to allow a steerable bow foil to be mounted on a tube projecting from her forward transom.

Although the first experiments with R-X, in 1958, were concerned with investigating BADDECK's shortcomings, it was about this time that our theoretical work was suggesting that we had things the wrong way round, quite literally. It was almost a sacrilegious thought, but Bell and Baldwin had been wrong.

The principles of what is now known as the Canadian foil system have been well documented[4],[9]. In brief, very different characteristics are required of surface-piercing foils forward and aft. The forward foil has to be responsive to changes of immersion, but be insensitive to angle of attack. It acts like a feeler, setting the ship to the trim required and allowing the stern foil to anticipate the oncoming wave. It is inherently an inefficient foil and consequently should be kept small. Conversely, the after foil requires a high lift-curve slope, but only needs to respond to immersion changes at its ends, for lateral stability. It is inherently efficient, and its behaviour is enhanced by large span. (Fig. 9)

Thus, a tail-first, or canard, configuration is essential to achieving good seakeeping ability with reasonable efficiency in a surface-piercing system.

PART 2 - DEVELOPMENT OF HMCS BRAS D'OR

Late in 1958 we faced a serious dilemma. We had a partly successful 17-ton model of a 50-ton FPB. We thought we knew how to redesign the foils to make it satisfactory for rough water operation, but were equally convinced that the best foil configuration was one that would be totally incompatible with the Saunders-Roe R-101 design concept.

Moreover, the RN had recently "mothballed" Coastal Forces, and Admiralty's interest in a 50-ton FPB had consequently faded. This size of craft was of no interest to the RCN. At the same time, however, emergence of the marinized gas turbine was changing the criteria that had led to the prudent limit of 50 tons established in 1953.

In essence, we wiped the slate clean, and began to study the feasibility of meeting Canadian requirements for ASW, with the hydrofoil knowledge we had accumulated.

The major problem of ASW was initial detection, reliable sonar ranges being very small compared with the vast area of ocean to be covered. A promising alternative to the direct approach of improving sonar range was to devise means of providing a significantly larger number of sonars economically - the so-called "small and many" concept.

The basic requirements of ASW demand an extremely versatile vehicle. Initial detection calls for long endurance at slow search speeds; interception and attack require short bursts at speeds exceeding those of conventional ships. These needs have forced the development of vehicle combinations which possess the combined characteristics of ships and aircraft, such as destroyers carrying helicopters. In this respect, the "small and many" hydrofoil ship promises unique advantages. Apart from its potential speed, the degree of stabilization offered by the hydrofoil principle, hullborne as well as foilborne, makes the hydrofoil by far the smallest surface ship capable of sustained operation in the open ocean.

There is an important difference in the concept of an ASW hydrofoil ship, as compared with passenger ferries or other craft intended to operate continuously at high speed from one harbour to another. Since the ASW craft can be expected to spend most of its operating hours on search duties, hullborne operation at slow speed is at least as important as foilborne operation. Hullborne seakeeping, endurance and habitability are of vital concern. Moreover, because of the short duration of foilborne operations, behaviour and reliability in severe weather are more important than the attainment of extreme efficiency. Even in the foilborne mode the design priorities differ from those of the ferry type of craft.

The R-200 CONCEPT

Fig. 10 shows the first sketch of a 200-ton design of ASW hydrofoil ship that resulted from our studies, known as R-200. The surface-piercing system was retained for its fundamental simplicity, and for the large foil area immersed at slow speed to provide the massive damping needed to achieve the hullborne seakeeping ability of a destroyer.

Quite apart from the foilborne advantages of the tail-first arrangement, the need for a hull shape optimizing hullborne endurance and seakeeping, and the requirements imposed by sonar towing, clearly dictated an extreme canard configuration for this ASW ship. There are many secondary advantages; the fine bow enables wave crests to be cut at high speed without pounding; heavy components such as machinery can be mounted close to the main point of support, in a position encountering the lowest accelerations, this leading to more efficient structural design, and generally the internal layout of the hull can be more satisfactorily arranged.

Another important design consideration in an open-ocean craft is to avoid having the bow overhanging the forward foil significantly, to prevent the bow dipping deep into the face of a wave. More dangerous than the actual impact is the abrupt forward shift of the centre of lateral area, which can lead to directional instability, the craft tripping sideways on its nose.

In January 1960, the R-200 concept was studied, both operationally and technically, by a group of experts from the U.S., the U.K. and Canada. The meeting concluded that the concept promised a significant improvement in ASW capability and that the proposal was technically sound. It also suggested that its development in Canada would "complement in a very essential way the U.S. program now underway on the PCH craft", which involved fully-submerged, actively controlled foil systems. This set the basis for U.S.-Canadian cooperation in hydrofoil development, which we have enjoyed continuously since 1960.

DE HAVILLAND DESIGN STUDIES

Late in that year a contract was placed with De Havilland Aircraft of Canada, Ltd. to conduct the detailed engineering studies necessary to confirm technical feasibility. The study confirmed that, at a hullborne speed of 12 knots, the ship's endurance and seakeeping ability should compare with those of a conventional frigate. Foilborne speeds up to 60 knots in calm water and 50 knots in rough water, with a range of several hundred miles, would be feasible.

These studies included a comprehensive series of model tests conducted at the National Physical Laboratory in England, and at Stevens Institute of Technology in the U.S. Fig. 11 shows an investigation of take-off, which occurs at a low speed of 20 knots. Consequently, the hull does not need to contribute planing lift, and a high deadrise and rounded bilge can be maintained throughout its length. De Havilland recommended an even finer hull than envisaged in the NRE proposal.

Fig. 11 well illustrates the role that the small bow foil plays in trimming the whole craft, and hence controlling the angle of attack of the main foils.

The De Havilland study culminated in October, 1962, with a preliminary design report. Fig. 12 shows the configuration that emerged from the results of the model testing and computer simulations of dynamic behaviour, which was perhaps the major contribution to the hydrofoil design process made by De Havilland(5).

A novel feature introduced at this stage was the use of superventilated sections in the bow foil to obtain the optimum combination of hydrodynamic stiffness and damping.

RCN interest had now grown to the extent that the Naval Board recommended proceeding with design and construction of a 200 ton ship, now known as FHE-400 (Fast Hydrofoil Escort). Control of the program was transferred from DRB to the RCN in March 1963, when a Hydrofoil Project Group was formed under the Chief of Naval Technical Services.[6]

NRE CONTRIBUTIONS

NRE remained in the picture, however, as advisers to De Havilland, and particularly to develop details of the foil system design by way of a quarter-scale model on the R-X craft[7]. Fig. 13 shows a comparison of the model and full-scale configurations. The only major differences were the reversed flare of the main struts necessary to clear the hull of R-X, and additional outboard supports needed to connect the foil rigidly to the crossbeam. Also, of course, R-X had independent propulsion appendages.

The original purpose of the R-X foil system model was to provide data from operation in random seas for comparison with computer predictions. In practice, R-X was invaluable in exploring a number of hydrodynamic effects not revealed by theory or controlled model tests. A major concern was design of the superventilated sections for the bow foil, with the objective of inhibiting and controlling intermittent flow re-attachment on the upper surfaces.

Fig. 14 shows the final design of FHE-400, with her fighting equipment, primarily a special variable-depth sonar and twelve anti-submarine torpedoes.

The aim of the program was an integrated ASW weapons system, and development of the fighting equipment and the ship proceeded in parallel. There were to be two phases of trials, first as a vehicle, with the ship ballasted to her full load displacement, second as a weapons system with the fighting equipment installed.. Unfortunately, as we shall see, the program was placed in abeyance after the first phase, despite the promising results, and the fighting equipment was never installed.

However, the novelty of the variable-depth sonar warrants a brief digression on the development of high-speed towed systems at NRE.[8]

In 1963, NRE began an experimental program to develop a variable-depth sonar system that would remain depressed when towed at foilborne speed. Fundamentally, this requires a towed body fitted with inverted hydrofoils so that the dynamic down-force increases with speed at the same rate as the system's drag. Fig. 15 shows a model winged body (MOBY III) being tested in the wind tunnel at NAE, Ottawa.

BADDECK was converted into a high-speed towing facility capable of handling half-scale models of possible sonar systems for FHE-400 up to dynamically scaled speed. This involved modified main foils to improve lateral stability and the installation of winch and towing boom over the stern. The towing boom was capable of being oscillated vertically over a range of frequencies to simulate the movement of the tow point in a regular seaway in a controlled manner. (Fig. 16)

One of the problems of relying on dynamic down-force rather than weight to depress a body is that the system can all too easily lose its sense of the vertical direction. Very minor assymmetries in a faired tow-cable can generate large lateral forces, and the system can find equilibrium at alarming kiting angles. Indeed, during these trials, we had one or two spectacular incidents of bodies leaping sideways from the water. It appears that some form of active control, referenced to a vertical gyroscope, will be advisable to tell the body which way is down.

For FHE-400, a two-stage development was envisaged. The ship would first be fitted with a ballasted wing-less body. Such a system would tow at the required depth at hullborne speeds, but would come shallow and stream aft on take-off. Such a system would be compatible with the early sonar, which was not expected to have a significant acoustic capability against the high noise of foilborne operation. Sprint and drift tactics would be required, but no time would have to be lost in streaming and recovering the body.

NRE were to pursue the development of wings and controls for this body for a later sonar, hopefully with a look-while-fly capability.

Another approach we investigated was a ballasted body designed to minimize flow noise - MOBY I (Fig. 17). Although this would run at a comparatively shallow depth at high speed, it was hoped that some look-while-fly capability might be attained. From NRE's point of view, however, this body was intended for a more academic study of flow noise.

FEATURES OF HMCS BRAS D'OR

Let us now return to FHE-400 and take a closer look at some of her features [9].

Hull construction commenced at Marine Industries Ltd., Sorel, in 1964 and was completed late in 1965. The hull was erected upside down to allow maximum use of downhand aluminum welding, and large sections of the shell were welded as sub-assemblies.

In the final stages of outfitting, in November 1966, a major fire occurred in the engine room during tests of the auxiliary gas-turbine. The centre of the ship virtually had to be rebuilt, and it was not until July 1968 that the ship was transferred to Halifax on the slave dock that served as her maintenance base. This involved a passage under tow of some 1200 miles. Fig. 18 shows her arriving in Halifax.

The main foil unit used delayed-cavitation sections with fences to control ventilation. A central, fully-submerged, horizontal foil carries over half the weight and makes this a heavily damped and efficient unit. Outboard of the transmission carrying struts are intersecting dihedral and anhedral foil elements that provide lateral stability.

The anhedral tips are incidence-controlled in the manner of conventional ship stabilizing fins. This departure from the original all-fixed foil concept was caused by a requirement, introduced late in the design process, for extended cruising at slow foilborne speeds of 25-30 knots, towing sonar. It was difficult to achieve satisfactory lateral characteristics over the full range from take-off at 20 knots to 60 knots with fixed geometry. If the top speed had been 50 knots, or the minimum required flying speed 30 knots, this complication could have been avoided. The tips are normally gyro controlled, but can be manually controlled to allow coordinated turns to be made.

The bow foil is steerable and acts as the rudder for both foilborne and hullborne operation. It can also be adjusted in rake, enabling the best angle-of-attack to be selected for foilborne or hullborne operation under the prevailing load and sea conditions.

It supports 10% of the ship's weight on its novel superventilated foils. Once ventilation has been established, the spoilers on the upper surface prevent rewetting and make the bow foil comparatively insensitive to angular variations in the oncoming flow. This provides excellent behaviour in a following sea, which was a shortcoming of many early surface-piercing hydrofoil concepts.

The very different speed and power levels involved in hullborne and foilborne operation dictate separate propulsion systems, as shown in Fig. 19. For the low power, long endurance hullborne system, fuel weight is the critical factor and a high-speed diesel engine is the logical choice. The hullborne engine is a Paxman 16 YJCM diesel with a continuous rating of 2000 SHP, driving two 3-bladed propellers on pods mounted on the main anhedral foils. A central inboard gearbox drives bevel gears in the pods, through shafts mounted within the foils, to the 7 ft diameter, fully-reversible controllable-pitch propellers. These propellers are feathered, and come clear of the water for foilborne operation. Their 30 ft lateral spacing provides exceptional manoeuvrability at slow speed through differential pitch control.

The high power required at maximum speed demands a gas turbine, specific engine weight being more critical than fuel consumption for the short periods of use. The foilborne engine is a Pratt and Whitney FT4A-2 gas turbine, continuously rated at 22,000 SHP. It drives two fixed pitch, 3-bladed supercavitating propellers, 4 ft in diameter, through dual downshafts in the main struts. These propellers were designed jointly by De Havilland and the National Physical Laboratory [10].

A common fuel is used by both engines, providing complete flexibility of operations. JP-5 turbine fuel is normally used, but high-distillate marine diesel oil is also satisfactory.

Internal arrangements are shown in Fig. 20. They are based on a normal crew of 20 officers and men working in two watches under cruising conditions, and all accommodation is well insulated and roomy by small warship standards. Abaft the narrow bow compartments containing bow-foil steering and rake-adjustment mechanisms, is the living accommmodation for 4 petty officers and 12 seamen. A small electronics bay separates the sleeping quarters from the galley and common dining-recreation area.

The galley is designed to provide pre-packaged meals for a 14-day period, being equipped with a large freezer and two microwave ovens, as well as conventional cooking facilities. Abaft the galley is the officers' accommodation comprising two single-berth and one double-berth cabins, plus a wardroom with spare berth-settees.

The main machinery space houses the hullborne diesel engine and its gearboxes, auxiliary and emergency gas turbines, foilborne transmission casings and fluid systems components. An electronics bay and workshop area is located abaft the main space, with VDS well and towing-winch machinery at the stern.

The forward superstructure comprises the bridge and operations room, containing the fighting equipment, radio communications and engineer's control consoles. The bridge resembles an aircraft cockpit, with dual controls for the captain and coxswain, and a navigator's position aft. Engine and propeller controls are provided both at the engineer's console and on the bridge.

Abaft the bridge superstructure are the air intake and nacelle for the foilborne gas turbine. This upper deck location facilitates complete removal for maintenance, simplifies air and exhaust ducting and minimizes transfer of noise and heat to the accommodation areas. However, it is undeniably a vulnerable location for the main engine, and would probably not be acceptable today.

SEA TRIALS

From September 1968, until July 1971, when trials terminated, the ship logged 648 hours of sea time, 552 hullborne and 96 foilborne. The most operationally representative trial was a 2500 mile trip to Hamilton, Bermuda, and Norfolk, Virginia, in June 1971.

The biggest disappointment from the scientific point of view was that the amount of significant rough-water data was regrettably small. At no time were limiting rough-water conditions experienced, either foilborne or hullborne. A detailed account of these trials has been published (11).

Hullborne seakeeping was exceptionally good, and is perhaps best described by a signal received from HMCS FRASER, a 3000-ton frigate sailing in company during a rough water trial.

"Weather conditions were considered most unpleasant, heavy seas and 15-20 ft swell, wind gusting to 60 knots, ship spraying overall with upper deck out of bounds most of the time. BRAS D'OR appeared to possess enviable seakeeping qualities. She was remarkably stable with a noticeable absence of roll and pitch and apparently no lack of manoeuvrability. The almost complete absence of spray over the focsle and bridge was very impressive."

Foilborne, BRAS D'OR exceeded her calm-water design speed, achieving 63 knots at full load in 3-4 ft waves (Fig. 21). She takes-off and lands smoothly, exhibits good stability and control at all speeds, and does not require foil-tip control above 30 knots.

At about 40 knots in sea state 5, RMS vertical accelerations of 0.22 g at the bow and 0.15 g at the CG were recorded in the worst direction to the sea. Corresponding lateral accelerations in beam seas were 0.08 g and 0.05 g in the operations room and at the CG. In general, accelerations at 40 knots were only twice those measured hullborne at 12.5 knots in the same sea, which is quite a remarkable result for a surface-piercing hydrofoil ship. The RMS roll angle at 40 knots in beam sea state 5 was 2.1°, while pitch angle increased to 1.5° RMS as the ship approached the following sea direction.

Again the overall impression of seakeeping ability is best summarized by a signal from a frigate being overtaken:

"Performance your ship foilborne in seas of 3 ft on swell of 10 ft was impressive. You looked more comfortable at 40 knots than SAGUENAY at 18. Maximum sensible speed of a DDH in these conditions without straining the ship would have been about 22 knots. Your motion appeared smooth, both in pitch and roll. Ship seemed to be borne entirely by foils, although forward foil did come clear of water on occasion."

ENGINEERING PROBLEMS

A variety of teething problems interfered with the progress of trials. These involved the hullborne transmission system, the bow foil pivot bearing, the foil-tip and steering actuators, the electrical system and the hydraulic pumps. None was basic, and steady progress was made in overcoming them.

However, in July 1969, the ship was docked to repair persistent foil-system leaks, and a large crack was discovered in the lower surface of the centre main foil. When the neoprene coating was removed, an extensive network of cracks was found, some at least entering into the spar and rib members of the sub-structure.

A replacement foil element was constructed, but in July 1971, this too developed severe cracking, and it became evident that more extensive foil-system replacement would be required. Subsequent investigation has shown that the maraging steel chosen for the foil system becomes highly susceptible to stress corrosion after prolonged immersion in seawater. Ironically, it was thought that the propagation of the cracks from residually stressed welds was accelerated by the presence of a zinc coating which had been used as an internal sacrifical anode.

PROJECT CURTAILMENT

Contrary to much popular opinion, it was not the problem of foil cracking that caused the October 1971 decision to lay-up the ship. Success of the trials was recognized, and it was appreciated that a production class would not have to employ maraging steel for foil construction.

The real reason was a change in defence policy announced in the White Paper on Defence issued in August 1971, which assigned priority, not to ASW, but to the protection of sovereignty and the surveillance of Canadian territory and coastlines. The implementation of this policy would place a specialized ASW hydrofoil behind at least three major procurement programs for Maritime Command:

- (a) Replacement of the ARGUS long-range patrol aircraft.
- (b) Replacement of some frigates with ships capable of operating in heavy ice conditions.
- (c) Replacement of other frigates with ships having multi-purpose capability.

The Minister of National Defence announced in the House of Commons on 2 November 1971 that: "A decision has been made by the Department to lay-up the hydrofoil BRAS D'OR for a five-year period because a re-assessment of Maritime Command's requirements has scaled down its priority. However, I would like to emphasize that research into hydrofoils will be continued by the Defence Research Board, and that the BRAS D'OR could be reactivated at any time should circumstances alter."

We can, of course, speculate that if the disastrous engine-room fire had not occurred, and if the foil had not cracked, so that funds remained in the program for installation of the fighting equipment, then the second phase of BRAS D'OR's trials might have been allowed to go forward. But the end result would have been the same, and circumstances have not altered sufficiently since 1971 to justify the reactivation of the ship.

PART 3 - CONTINUING RESEARCH AND DEVELOPMENT

The value of the R-X craft in developing BRAS D'OR's foil system had suggested the need for a more sophisticated open-water test facility at DREA. Of particular interest was research into high-speed propulsion, for which conventional laboratory facilities left much to be desired.

The replacement "Meccano" set was named PROTEUS, derived from her objectives of Propulsion Research and Open-Water Testing of Experimental Underwater Systems[12]. The original intent was to propel her with both water propeller and airscrew, as shown in Fig. 22, so that propellers could be tested over a range of thrust and advance coefficients.

She could operate at high speeds as a hydrofoil, or at modest speeds as a planing craft. In the latter condition, the bow foil would be replaced by a dynamometer system and strut, enabling her to test models such as sonar bodies in the undisturbed water ahead of her hull.

PROTEUS was employed from 1973 to 1980 in propulsion research concerned with the structural strength, vibration and noise of high-speed propellers. Unfortunately, the comparatively low priority of this project did not enable us to complete the facility as originally planned. She still lacks the separate airscrew propulsion unit, and her usefulness has been limited by this. PROTEUS has recently been retired.

Towards the end of the BRAS D'OR project, we pursued the design of a smaller, simpler craft of 150 tons in response to a NATO requirement for a missile-armed strike craft. Indeed, FH Type 1, shown in Fig. 23, is what the PHM class would look like, if the results of the competition had been different.

In fact, Canada had no interest in a single-purposed missile boat. Fig. 24 shows our FH Type 2 design, which represented an attempt to combine the NATO requirements with our own (pre-1971) requirements for ASW. This was a 250 ton design which might have been the production version of BRAS D'OR, had we stayed in the game.

Since the change of policy, we have been active in developing design methods for hydrofoil ships, and have contracted small research programs with universities on foil-section design and on the fundamental mechanisms of ventilation. We have pursued several later design studies of multi-purpose hydrofoil ships, and perhaps it is an encouraging sign that we are not able to show you these in an unclassified paper.

An underlying theme of our latest concepts has been simplification, to what we call the "intermediate" hydrofoil. We see European commercial hydrofoils successfully employing diesel engines driving inclined shafts, simply constructed non-retractable foils, and hulls built in a shipyard. Then we see USN designs with gas turbines driving through complex transmissions, sophisticated retractable foils, and hulls built to airframe standards of engineering. The resulting difference in cost per ton is striking and may not be worth the gain in performance; we suspect that some of the reasons behind these differences are traditional, rather than being the result of careful trade-off studies.

Our own studies are leading to a concept intermediate between these extreme design philosophies. We need gas turbines, and we transmit power through bevel gears, but our transmissions and our foils are simplified by lower design speeds and lack of retraction. We attempt to judge the cost-effectiveness of each design feature.

Finally, it may come as a surprise to learn that our latest designs employ fully-submerged flap-controlled foils. This is because of the larger size and lower speed regimes now of interest, and other factors that cannot be discussed here. It should not be implied that the choice of surface-piercing foils for BRAS D'OR was wrong. On the contrary, with the design studies and dynamic simulations we have conducted over a wide range of sizes, speeds and other requirements, we believe that we now have a good understanding of how to select the best design features for any given requirement.

Our latest design concept does not look much like the HD-4, but we think that Bell and Baldwin would approve.

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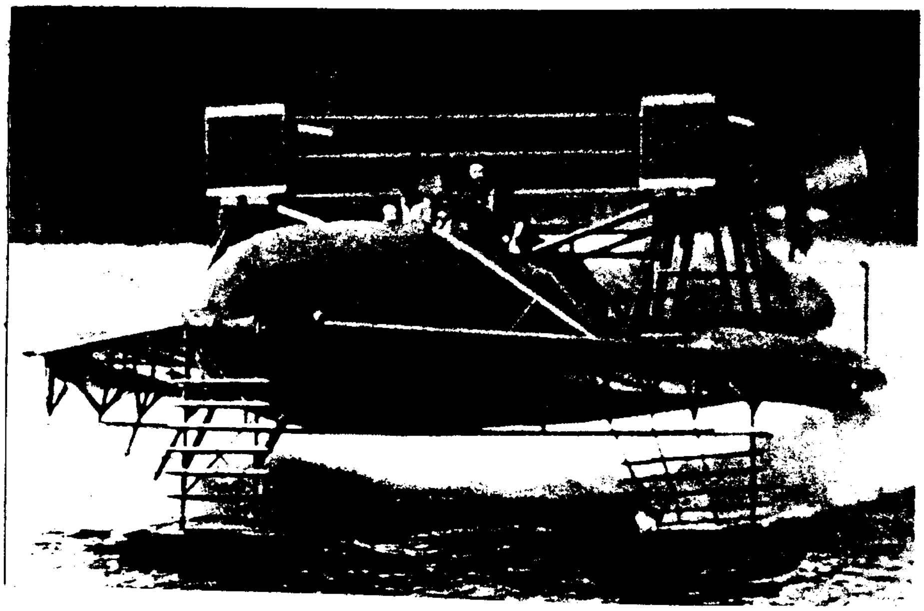
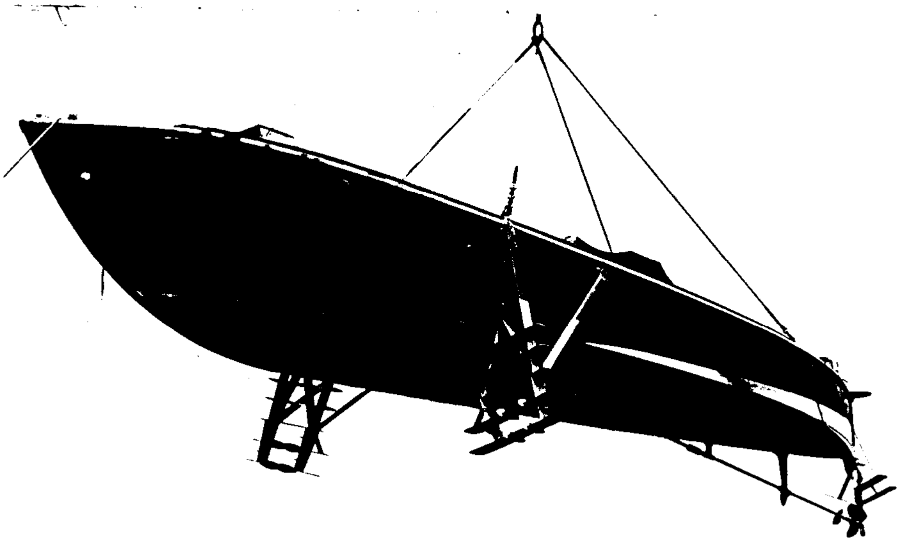


FIG. 1

FIG. 2



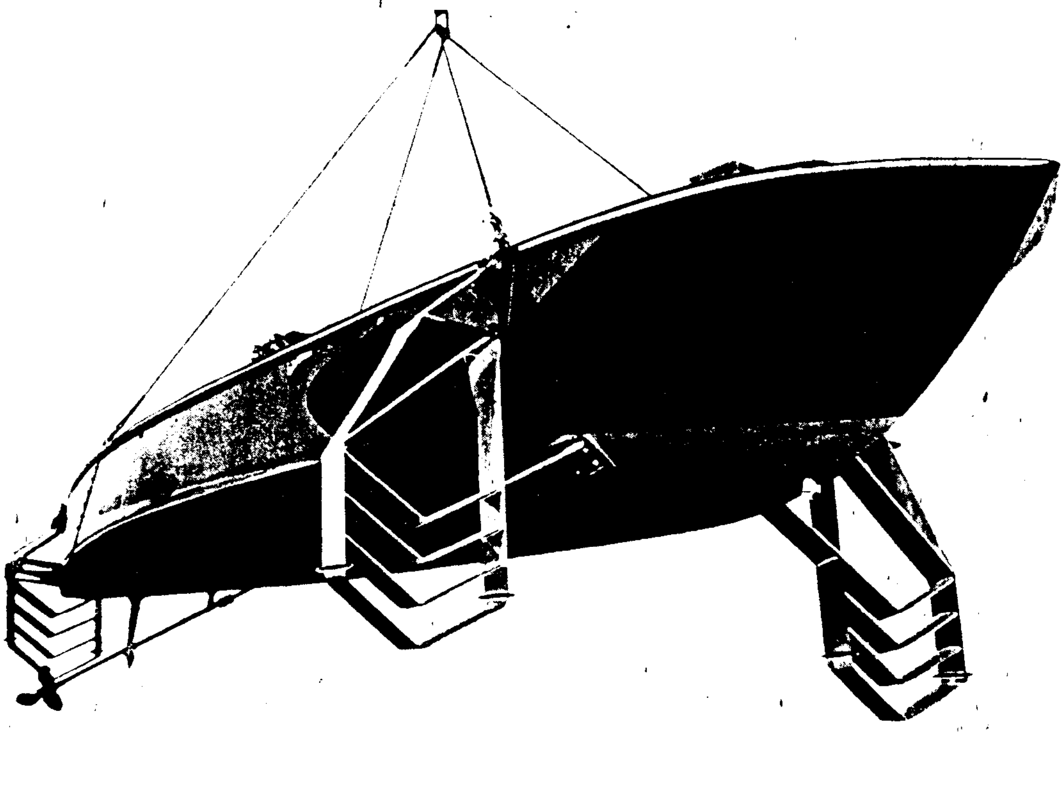


FIG. 3

FIG. 4

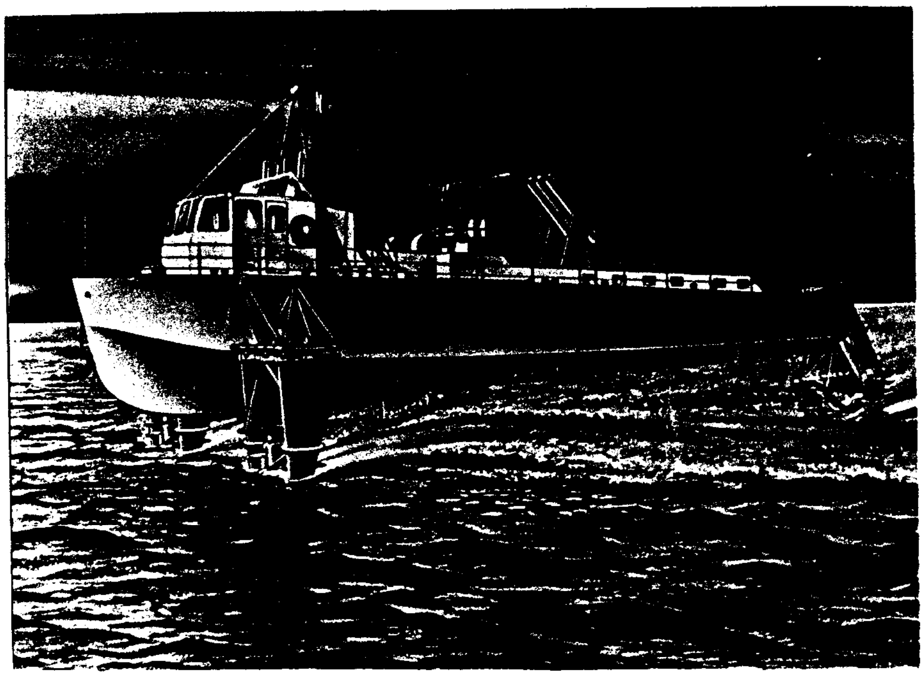


FIG. 5

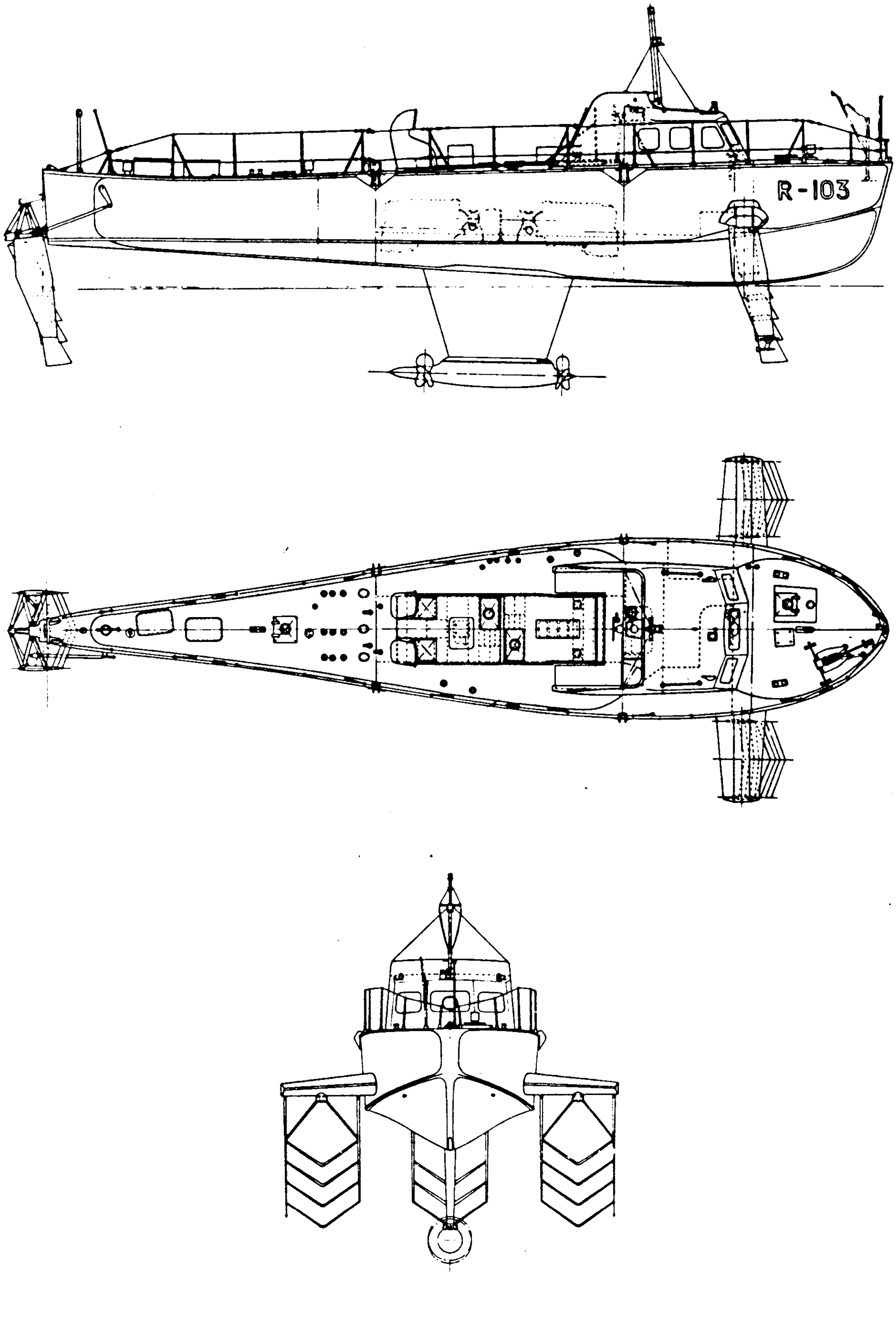


FIG. 6.

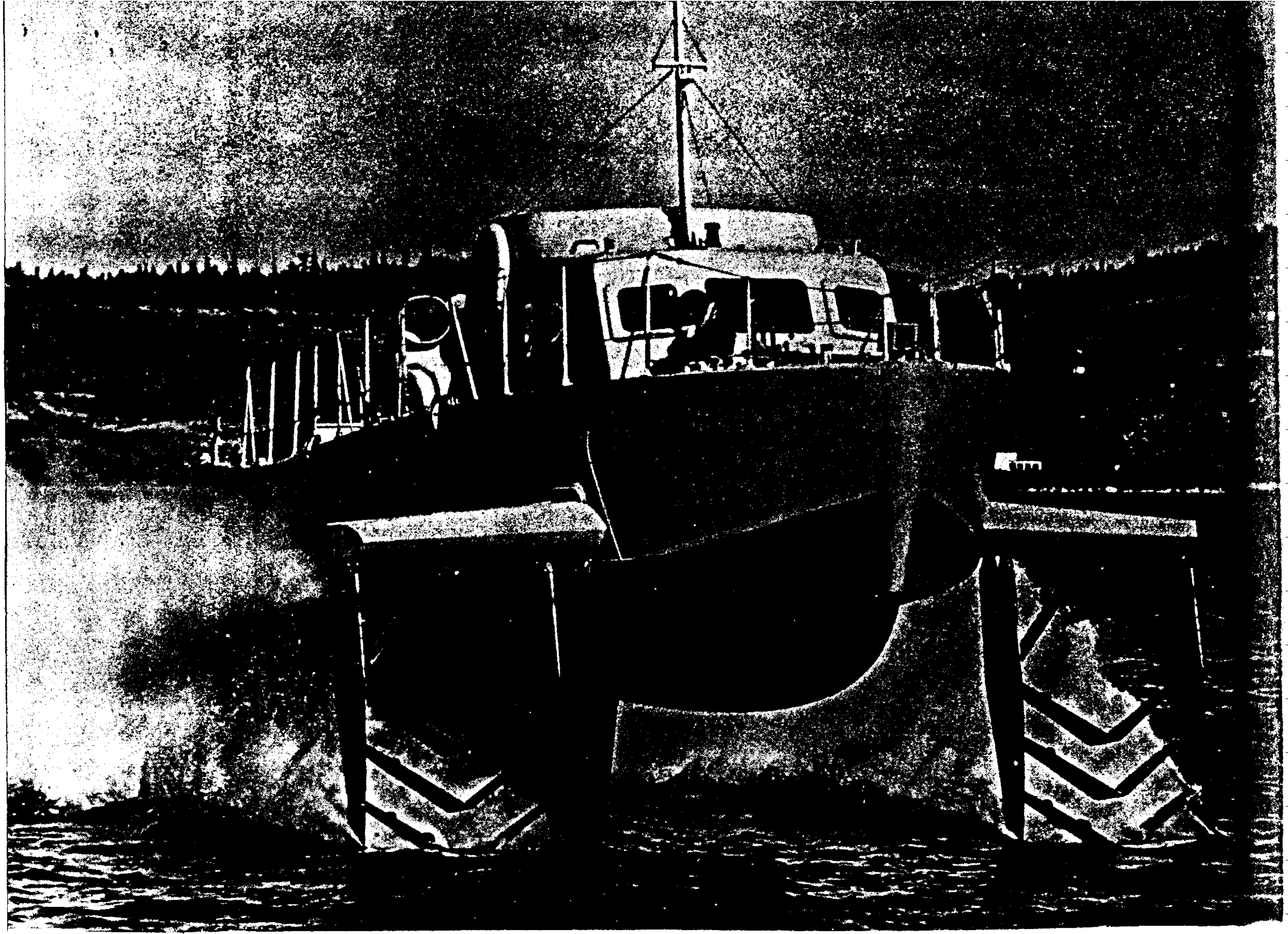


FIG. 7

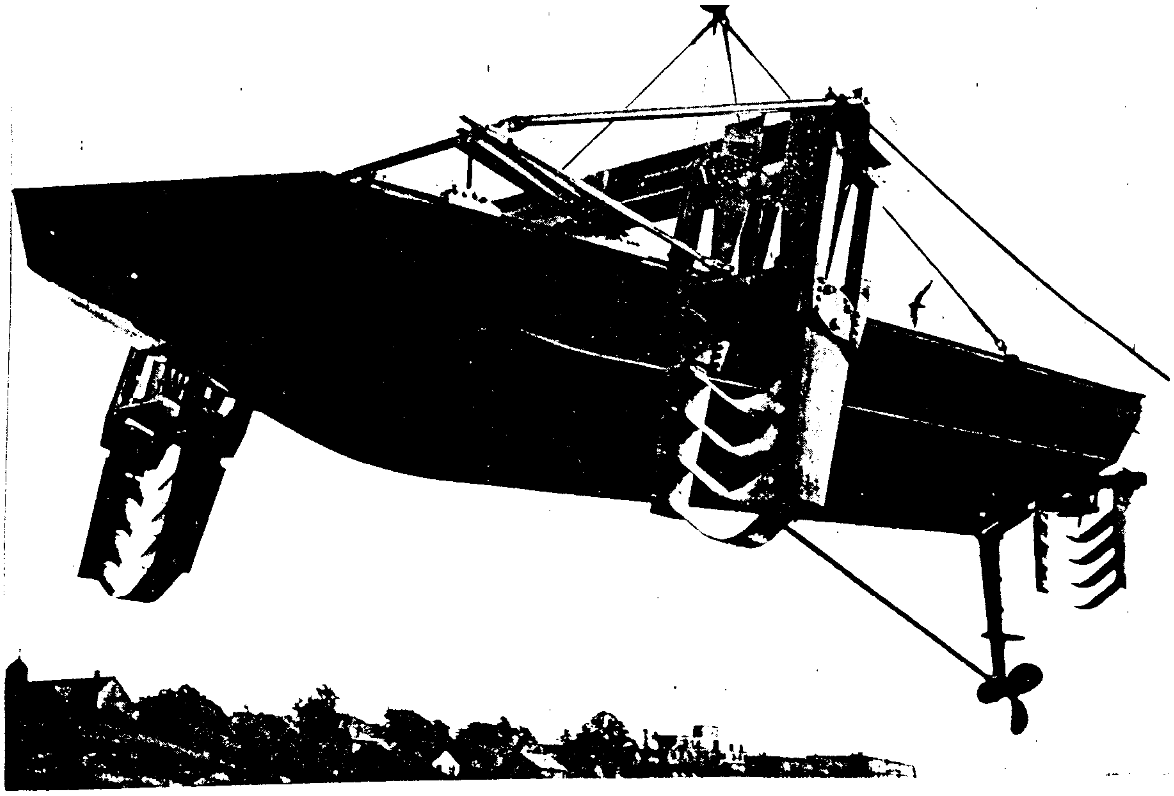


FIG. 8

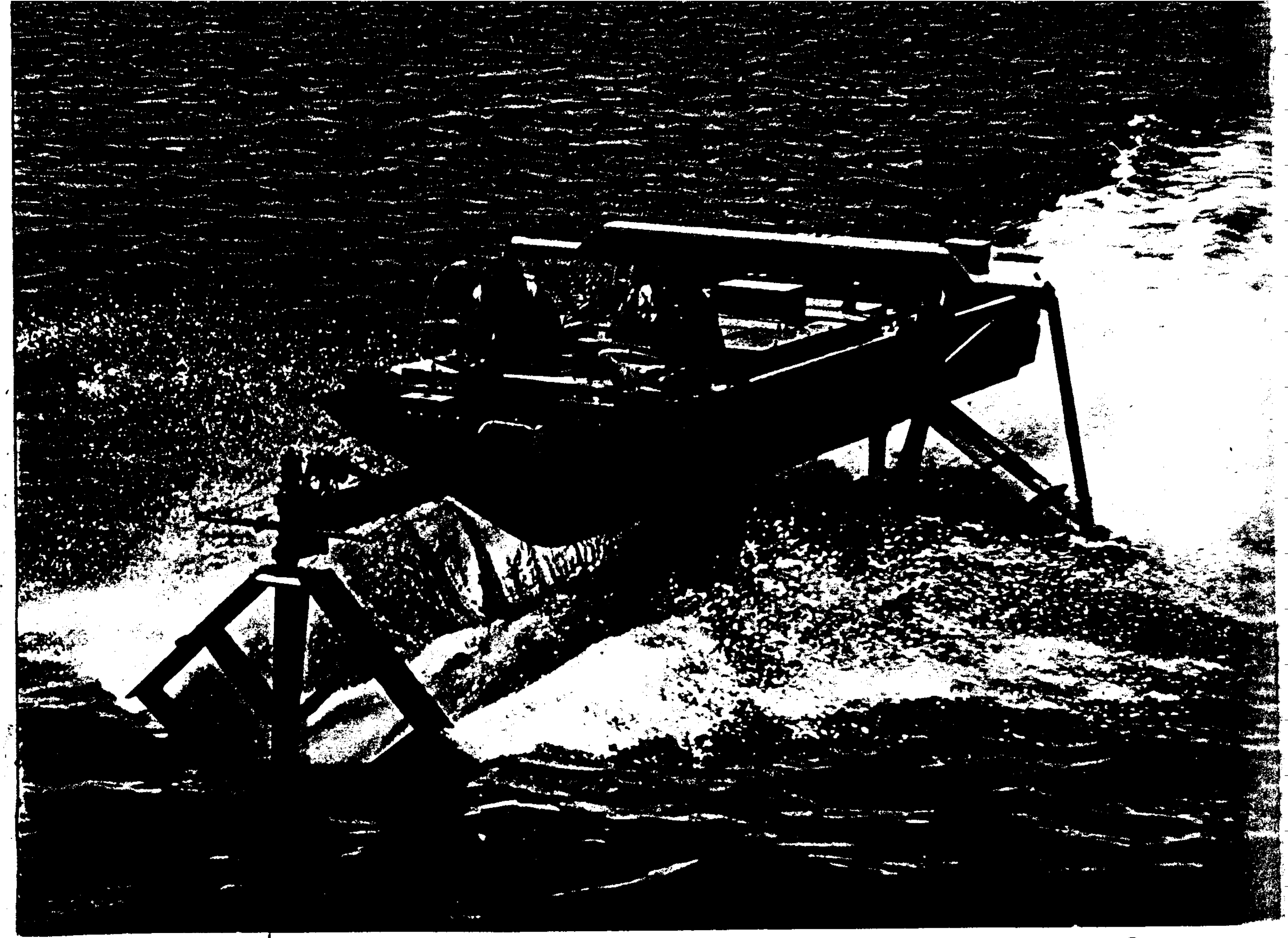


FIG. 9

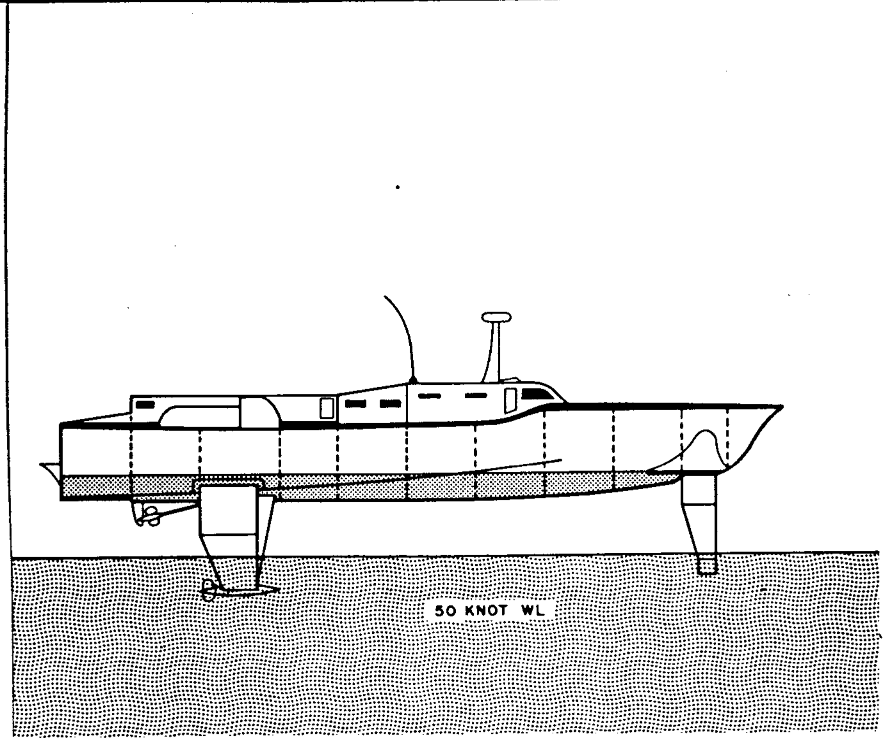


FIG. 10

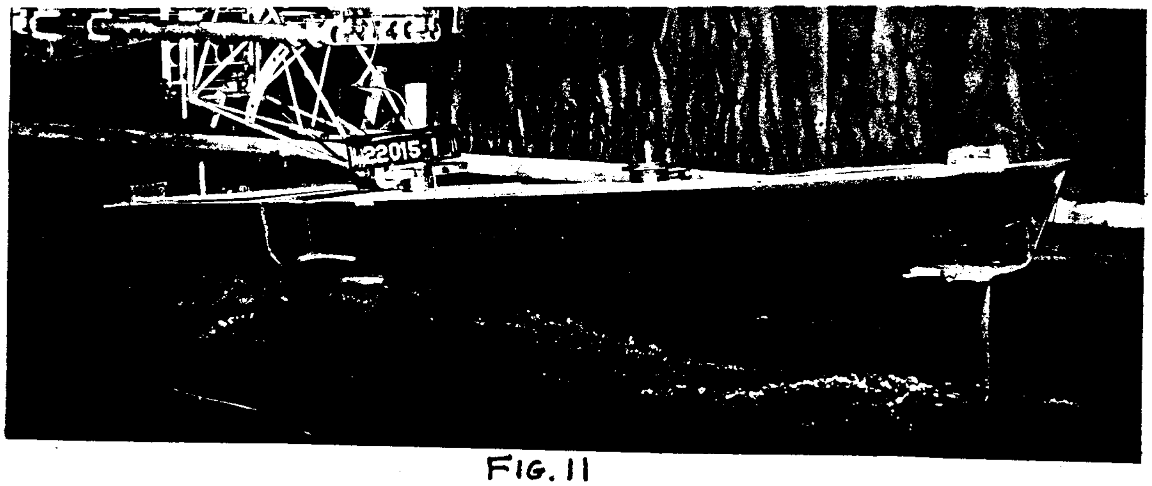


FIG. 11

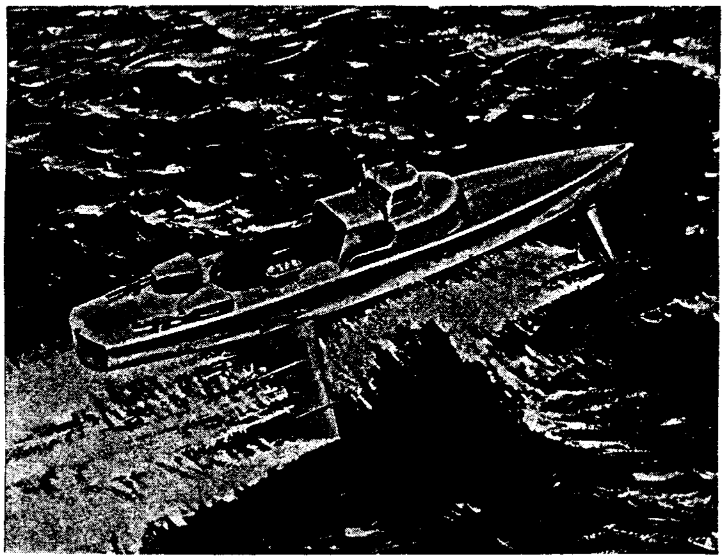
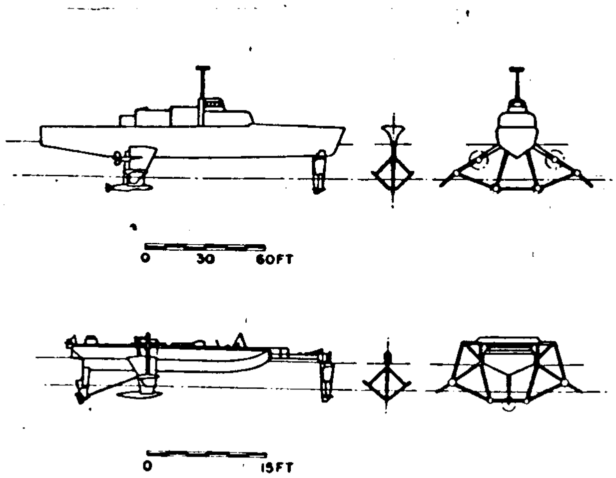


FIG. 12



Comparison of FHE-400 and 'Rx' craft

FIG. 13

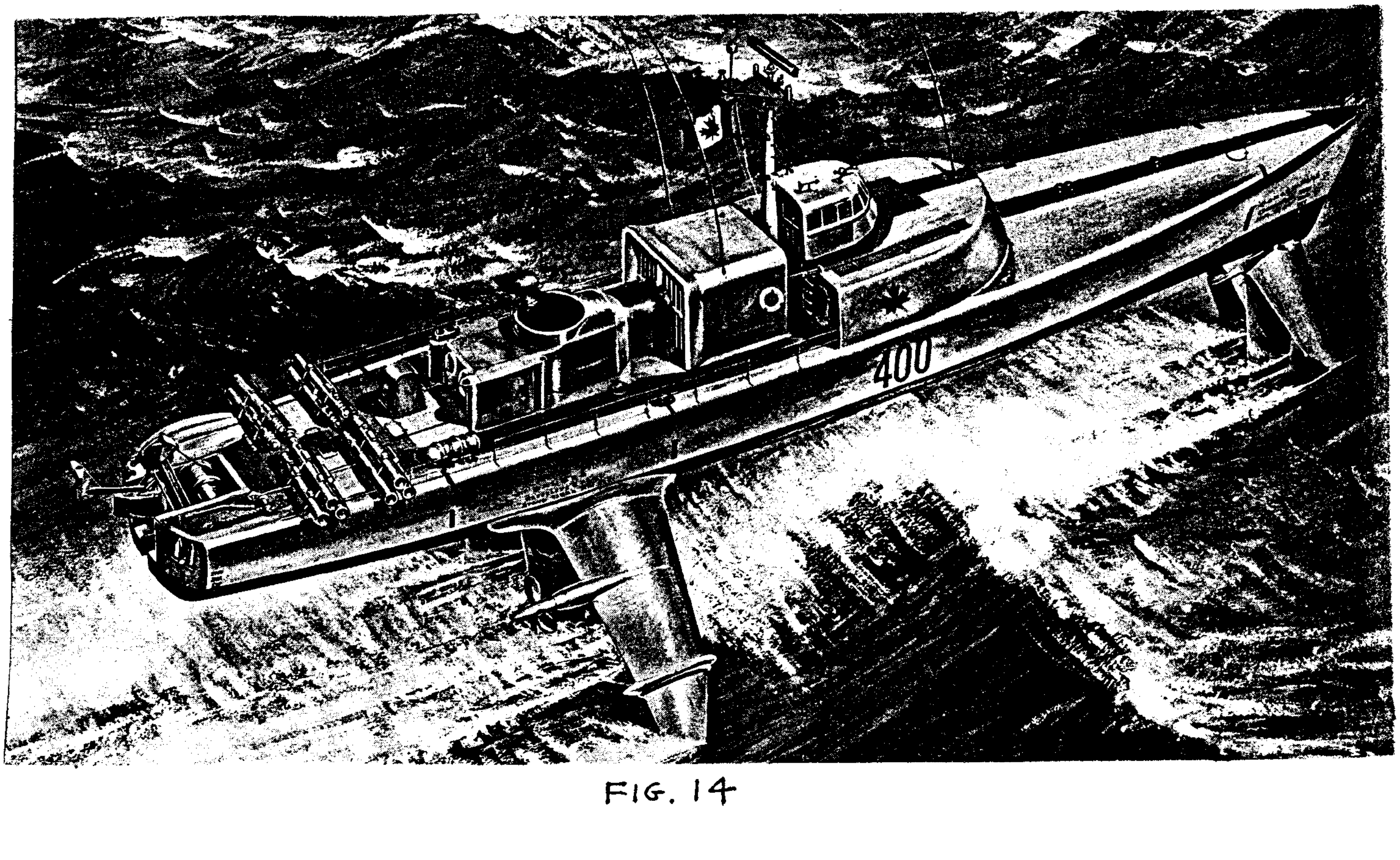


FIG. 14

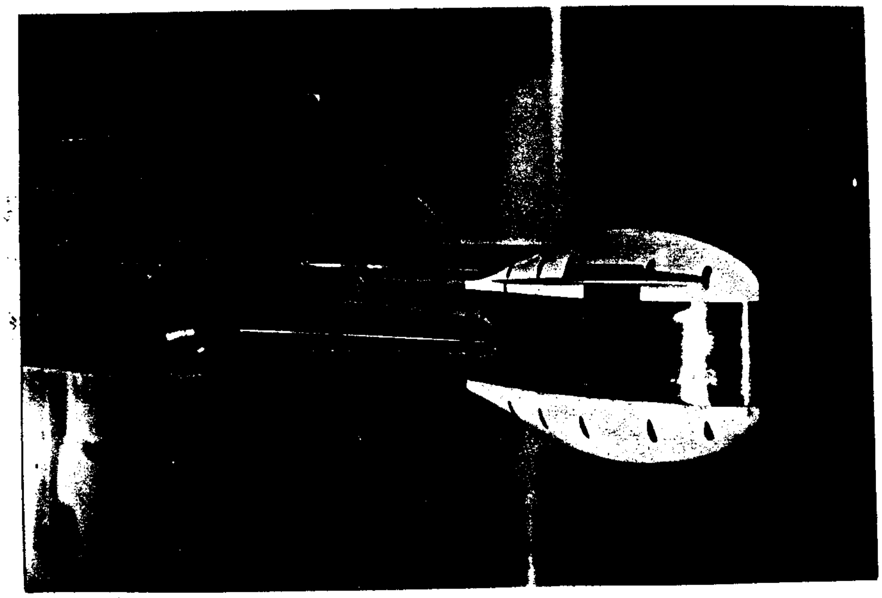
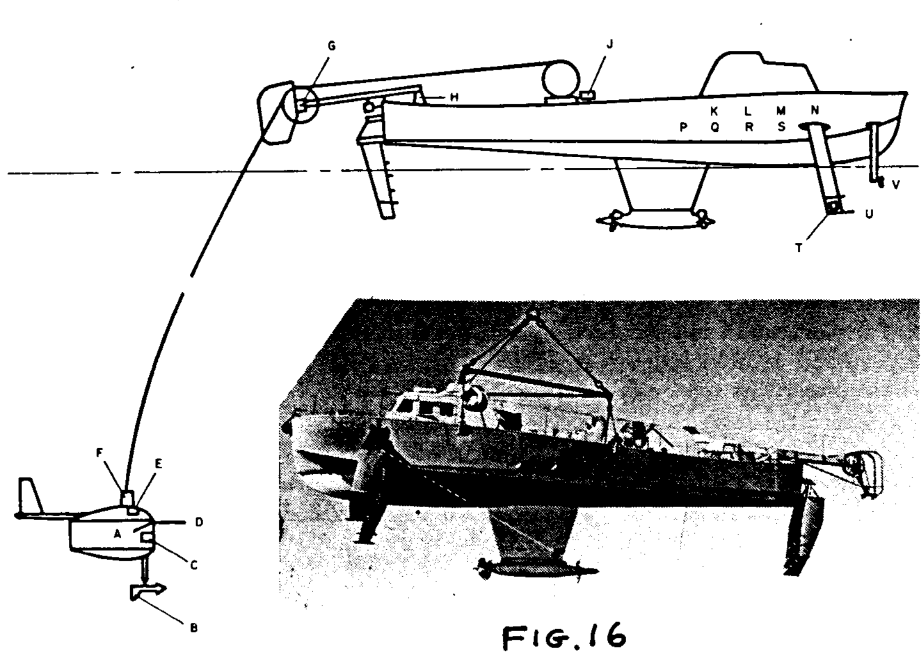


FIG. 15



Instrument locations on body and Baddeck

A Instrument package
B Sideslip vane
C Sideslip transducer
D Static pressure tube
E Tow staff angle transducer
F Cable tension transducer
G Boom accelerometer
H Boom position indicator
J Winch tension transducer
K Power supply for body instruments
L Discriminator
M Oscillograph recorder
N Tape recorder
P Boom function generator
Q Heading gyroscope
R Vertical gyroscope
S Yaw rate gyroscope
T Speed transducers (4)
U Pitot static tubes
V Bow speed impeller

FIG. 16

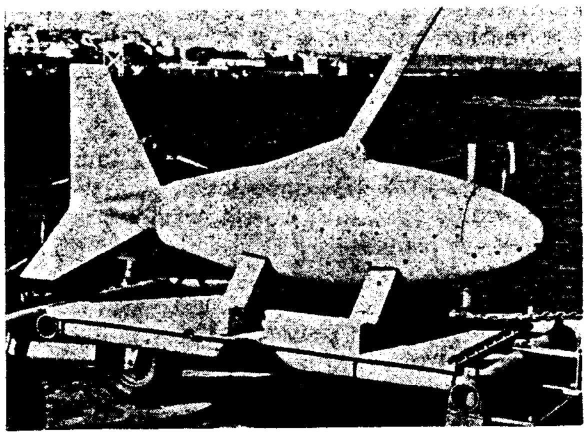


FIG. 17

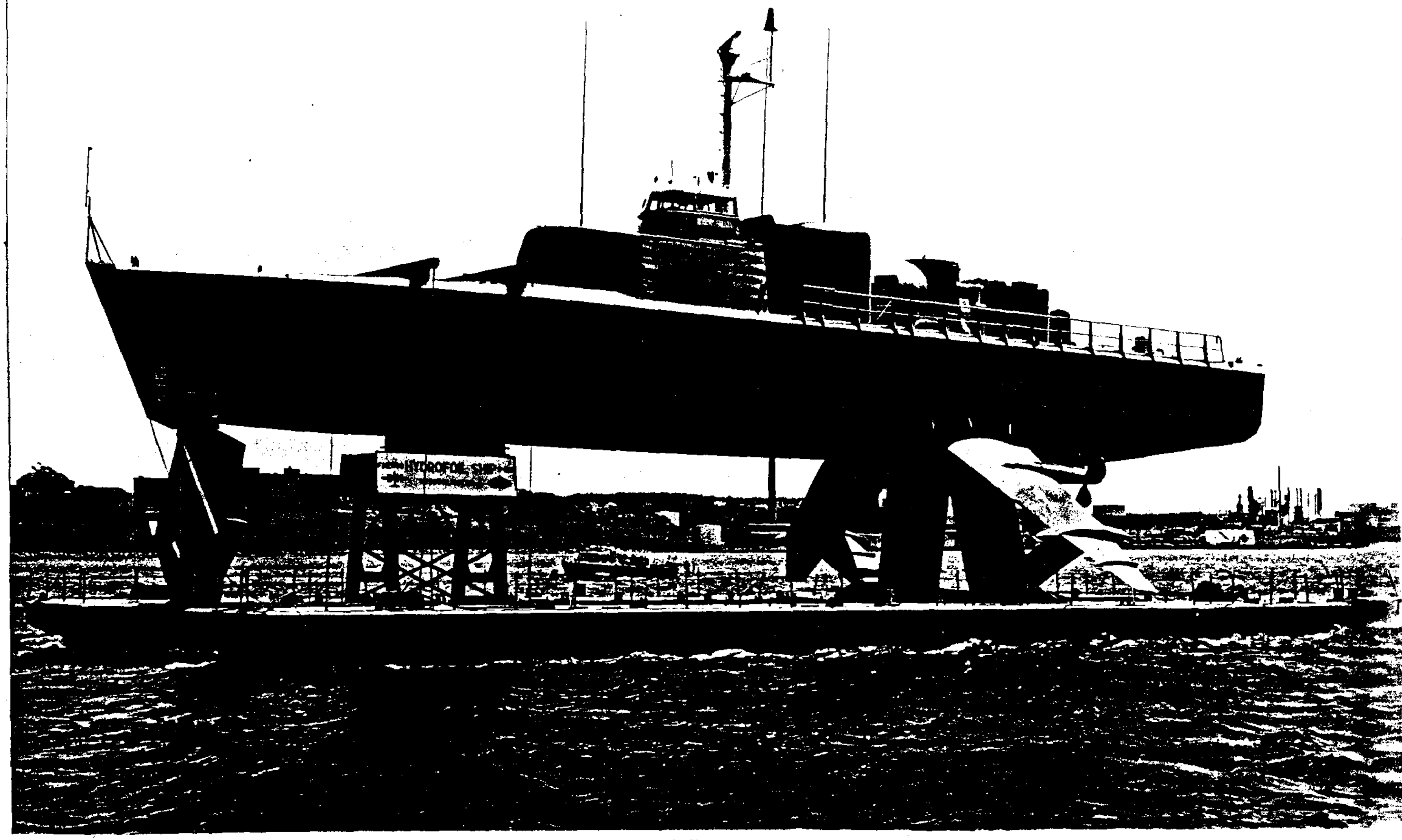


FIG. 18

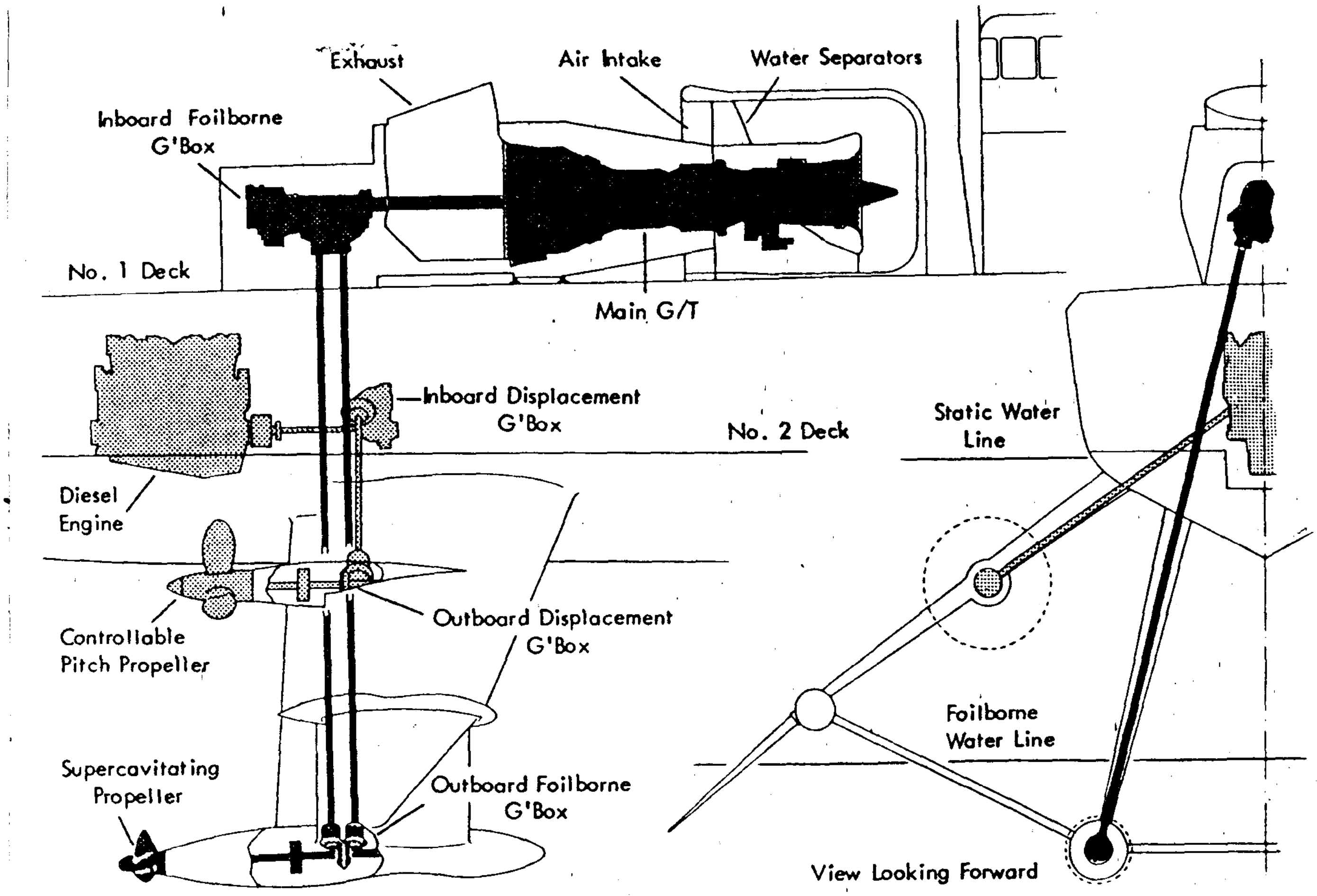


Fig. 19. Propulsion systems arrangement (DeHavilland Drawing)

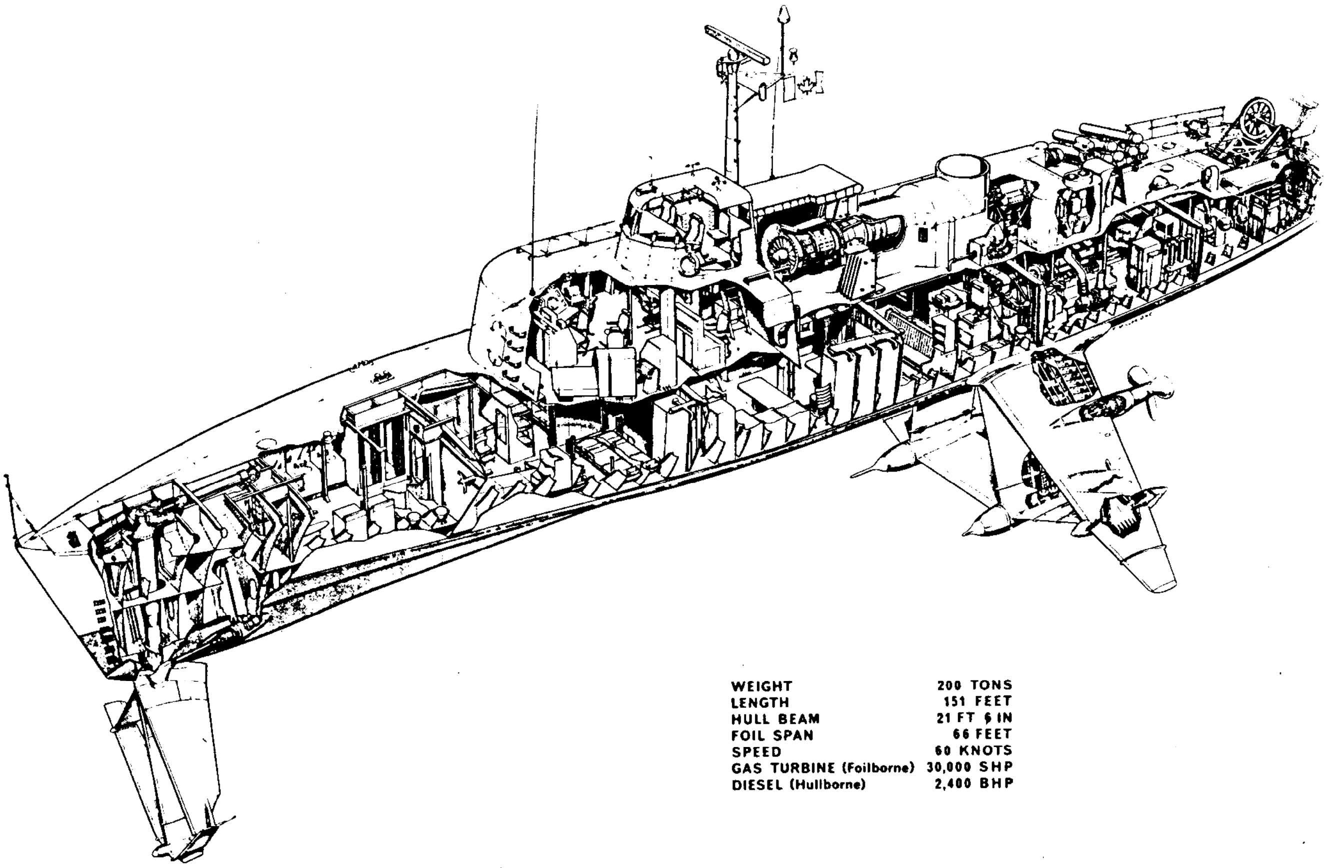


Fig.20 HMCS *Bras d'Or*, leading particulars.

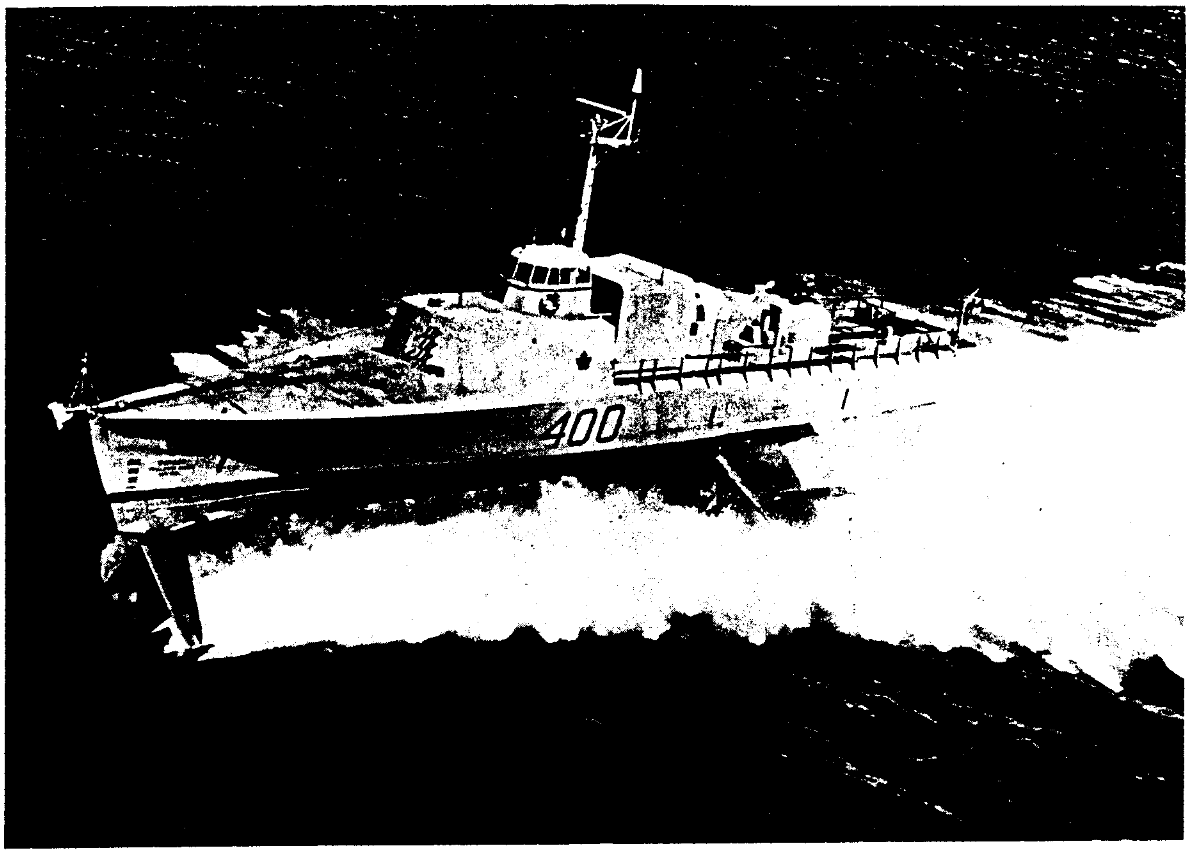


Fig.21 BRAS D'OR at 62 knots

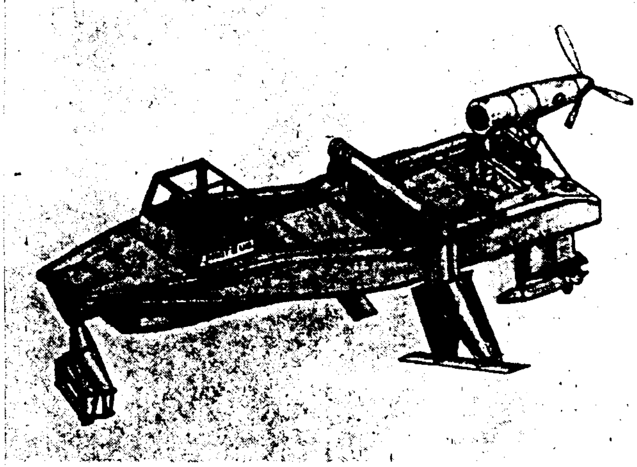


FIG.22 PROTEUS.

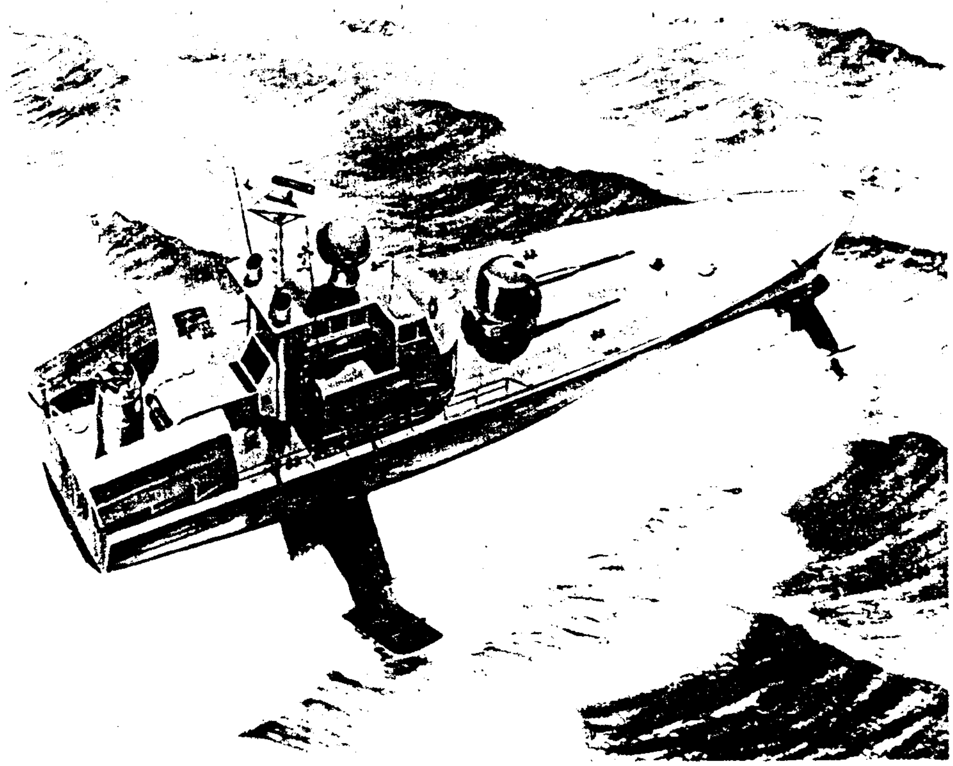


FIG.23 FH Type 1 DESIGN

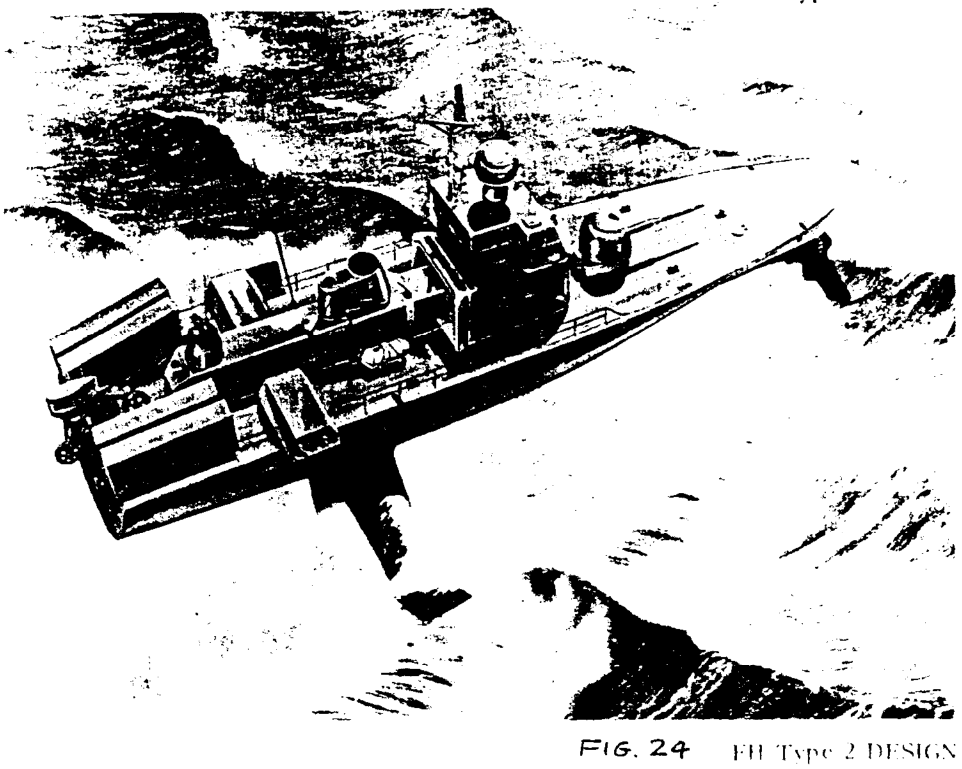


FIG. 24 FH Type 2 DESIGN

SPONSORED BY

THE NORTH AMERICAN ASSOCIATION INTERNATIONAL HYDROFOIL SOCIETY

THE ALEXANDER GRAHAM BELL INSTITUTE

CURRENT STATUS AND FUTURE PROSPECTS

UNITED STATES COMMERCIAL HYDROFOILS

WILLIAM M. SHULTZ

BOEING MARINE SYSTEMS

FIRST INTERNATIONAL

HYDROFOIL SOCIETY

CONFERENCE

INGONISH BEACH, NOVA SCOTIA, CANADA   JULY 27 - 30, 1982

CURRENT STATUS AND FUTURE PROSPECTS FOR U.S. COMMERCIAL HYDROFOILS

W. M. SHULTZ*
NAA-IHS DIRECTOR

SUMMARY

This paper summarizes U.S. fully submerged foil commercial hydrofoil activities during the past 10 years. The importance of ride quality and productivity are discussed together with technical advancements that have been made to obtain better fuel efficiency and utilization. Operating performance experience is reported on and the future market for advanced marine craft in the U.S. is presented.

INTRODUCTION

At the outset it is essential to establish that in this paper "commercial" is taken to mean vehicles and services whose intent is other than recreation or amusement. Having done so the United States activity can be summed very quickly. There are no commercial passenger hydrofoil services. There is only one commercial hydrofoil in current production - The Boeing Jetfoil. (1) One might appropriately ask, "Why should there even be a paper on this subject at this conference?" I am sure that it was because your organizers recognized that no report to the International Hydrofoil Society would be complete that failed to include an update on this program. Besides there are areas in the United States which do offer future opportunities for hydrofoil services.

Since 1972, 22 Jetfoils have been built and sold, 20 of which were purchased for scheduled commercial passenger services and 2 for evaluation for other applications. These craft have carried out a variety of services throughout the world, including the U.S. The program has had its share of challenges and there have been problems - both technical and non-technical. For the most part, it has been possible to develop solutions and from a technical point of view the original objectives for the design were met or exceeded. From an economic standpoint, the program has not yet produced the results hoped for, by some of the operators or by the builder.

* Director of Sales, Boeing Marine Systems

The Jetfoil program has had a major influence on the high speed marine vehicle field. If nothing else, it focused attention on the importance and value of ride quality at high speed and in rough seas. In the 1976-1977 issue of "Janes Surface Skimmers", a number of eminent pioneers in the advanced marine vehicle field gave their views as to what the next decade might hold in store for us. Baron von Schertel, the IHS first President, and a gentlemen to whom hydrofoilers owe a considerable amount, said:

> "Speed and comfort are primary targets in the development of vehicles that operate on road, rail, water and in the air. The hydrofoil designer cannot ignore these objectives if his craft are to remain competitive. Most shipowners, however, are of the opinion that the speed of hydrofoils in current use is sufficient for some time to come. This view is based on the assumption that the direct competitor, the displacement passenger ferry, is incapable of increasing its speed to any great extent, without impairing its economy. Moreover, preference is given to safety and reliability of operation over comfort, and there is a general unwillingness to accept costly and unreliable systems which could raise maintenance costs.
>
> The outstanding success of Jetfoil, the speed and comfort of which has considerable praise from the travelling public, will encourage a revision of this philosphy, although the new concept does not match the profitability of hydrofoils currently in service. In consequence we can anticipate that during the next decade the trend will be towards second generation craft with greater structural simplicity, and an avoidance of sophisticated components in order to increase reliability and productivity. They will, be the product of shipyards rather than of the aircraft industry.
>
> The surface-piercing foil system is about to be provided with important improvements in respect of seaworthiness and comfort, thus strengthening its viability. For the coming decade, at least, this type will be favoured for use in areas with moderate sea states, as long as it ensures better dependability and a higher return on investments than its fully-submerged-foil competitor."

Others at this conference will report on what has been done to improve the surface piercing hydrofoils comfort, performance and productivity. This paper will summarize what has been done in these areas in the US fully submerged foil commercial hydrofoil program.

COMFORT

The main technical goal of U.S. development has been to provide the highest possible level of vehicle stability (ride quality) at high speed in the sea conditions that existed on the worlds major open water routes. The initial thrust for this development was for military uses and the potential that could be attained for commercial use became evident in the PGH-2 "TUCUMCARI". It was from this technology base that the Jetfoil was derived. In specific terms the design objective was to achieve a ride quality that would be acceptable to 95% of the passengers 95% of the time. To get the ride quality to meet this objective, it was necessary to attain a vehicle pitch stability that would be 4 times better than the "TUCUMCARI" which was already 2 times better than any other vehicle in operation.

There were many who believed that that quality of ride wasn't needed and some who said that it couldn't even be done. In the 10 years that have elapsed since the Jetfoil was originally designed passenger reaction to its speed and comfort has confirmed that people want a smooth comfortable ride and that given the choice they will take the more comfortable vehicle even at a premium fare. As an example in Hong Kong conventional ferries are operating side by side with conventional hydrofoils and Jetfoils. The hydrofoils and Jetfoils are carrying 79 percent of the total traffic at fares which range from 1 1/2 to 3 times those of the ferries. The Jetfoil fares range from 1 1/4 to 2 times those of the hydrofils but in spite of that they carry 68 percent of the high speed market. While there are other factors which influence people to travel on one or the other of the competing modes, it is generally accepted that it is the comfort of the Jetfoils that has been the key to their immense popularity.

PRODUCTIVITY

o Fuel Efficiency

In 1973, Diesel No. 2 was selling for 13 cents a gallon and engines cost about $50 per horsepower. To design and build the lightest weight structure and minimum drag strut/foil system would have been very expensive. The best compromise appeared to be to provide an excess of power rather than an excess of design sophistication. In addition, excess power would provide growth capability in future years.

Unfortunately that decision did not anticipate the coming fuel crisis and the 8 to 10 times increase in fuel costs. When the crisis did occur, an extensive technical program was initiated to increase load carrying capacity and decrease fuel burn. The foil/strut system was redesigned. The Model-100 forward foil had a rectangular planform and straight-sided pod. (FIG. 1) The redesign for the Model-115 used a tapered planform and contoured pod. (FIG. 1) [(2), (3)] The two craft are shown in FIG. 2.

To increase the load carrying capability the foil area was increased and a higher aspect ratio was selected. The planform and taper ratio were selected to achieve increased fatigue and flaw growth life. The pod was shaped to maintain the foil upper surface chordwise pressure distribution and the strut pressure distribution at the undisturbed level, reducing mutual interference effects. The pod was lengthened and enlarged laterally and placed so the lower surface of pod and foil were coincident. The forward strut was lengthened in chord, the spanwise thickness distribution changed, and the section shape modified. Changes to the aft foil system were less extensive. Foil thickness was increased near the center pod where bending loads are the greatest. The chord length and thickness ratio were increased and the shape was slightly modified to increase camber and change the thickness distribution.

The hull structure was modified to reduce weight. The air conditioning, sea water, fuel, fire protection, hydraulic and control air systems were redesigned and in some cases relocated to reduce weight, improve accessibility and increase reliability.

As a result, the average full load take-off dynamic lift was increased to 115 long tons from 112 long tons and the useful load was increased from 31.6 long tons to 37 long tons.

Hydrodynamic drag was also reduced and cavitation inception speed increased. The relocation of the forward foil tip vortices outboard had a salutary effect on the hydrodynamic behavior of the aft foil.

Take-off thrust margin was increased by 85 % even at the higher dynamic lift. For the same gross weight and cruise speed fuel consumption was reduced by 6 percent.

Defining productivity as fuel efficiency (seat miles per gallon of fuel) the first Model-115s delivered in 1979 had 20 percent better productivity than the Model-100s delivered four years earlier. By the end of 1980, additional improvements in waterjet pump performance resulted in an additional 5 percent increase in fuel efficiency.

Work has continued on this very important aspect of commercial economics and product viability. In 1980, a spectrum of potential improvements that would further increase fuel efficiency were identified (FIG.3) with an expected time scale for their development. These included: 8 propulsion sytstem modifications with a total average fuel reduction of 31 percent; 3 hydrodynamic modifications with a total average fuel reduction of 12 percent; and 4 useful load improvements with an equivalent total average fuel reduction of 20 percent. If all of these benefits were to be realized, the fuel efficiency would be between 41 and 57 percent better than the Jetfoils delivered in 1980. (FIG. 4)

In April of this year, Boeing offered the Model-117 for sale. The -117 would be 23 percent more fuel efficient than the -115 and 55 percent more fuel efficient than the original Model-100.

o Utilization

Advanced marine vehicles are higher capital cost items than conventional ships of comparable size. As a result, operators must get a high utilization out of the craft in order to make money. Hours on service times speed times passenger capacity is another measure of Productivity of a transport system. There are two aspects of utilization which require attention: craft availability, which is a function of reliability; craft operability, the capability to operate under the conditions that exist in the local operating area, i.e. weather, sea conditions, traffic, regulatory requirements, etc.

In several areas of the world, there are restrictions to running high speed marine services at night. One such area is Hong Kong. The Jetfoil operator in Hong Kong believed that high speed night service would have great passenger appeal. However, the requirements laid down for such service by the Hong Kong Marine Department required the development of special electronic equipment for crew vision enhancement. The general opinion was that with proper vision augmentation, the Jetfoil could be approved because of its inherent stability, high maneuverability and stopping capability, and the fact that its fully automatic control permitted the master to devote the majority of his attention to collision avoidance and navigation. Therefore, at the request of the operator, Boeing undertook responsibility to develop a suitable system to meet the HKMD requirements.

The result was the development of the VAS (Visual Augmentation System) which is a low light level television system that provides a real-time display of a wide field-of-view to the crew. To meet the detection requirements of the HKMD it was necessary to develop an "active" system. An air-cooled shaped-beam infra-red illuminator was developed. The camera employs an isocon tube and is capable of resolving very small obstacles at ranges sufficient to permit normal avoidance maneuvers at normal cruise speed. The VAS installation is shown in FIG. 5.

In February 1980, the Jetfoil/VAS was approved for night service by HKMD. To date, more than 1 million passengers have availed themselves of the high speed night service in spite of the fact that the fare is triple that charged on the coventional ferries, the only other available night service. Some additional statistics are indicative of the appeal for the passengers and the benefit for the operator. In 1981:

- o operating only 9 percent as many trips as all of the conventional hydrofoil day service

- o night Jetfoils carried 23 percent as many passengers

- o night Jetfoils generated 40 percent as much revenue

The results so far in 1982 have been even more spectacular.

Since the start of service in 1975 through the end of 1981, Jetfoils have carried over 14 million passengers about 600 million passenger miles. The fleet has accumulated more than 114,000 underway hours with the high time vessel of 13,000 hours. Trip completion reliability due to mechanical reasons has been 94.2 percent average (97.5 percent average over the past 4 years). Trip completion reliability due to weather has averaged 98.4 percent since 1975 (97.8 percent average over the past 4 years). During 1981, 3,851,692 passengers were carried 155,565,000 passenger miles. For the first 5 months of 1982, Jetfoils carried nearly 2 1/4 million passengers.

OPERATING PERFORMANCE

There is only one area in which the same operator has run both surface piercing and fully submerged foil hydrofoils over the same route in sufficient numbers on a daily basis to provide a meaningful comparison, Far East Hydrofoil Co. Ltd of Hong Kong. They have been kind enough to furnish information for this paper which summarizes their cost/revenue experience for the six years that the two types have been operating there. It must be pointed out that both their hydrofoil and Jetfoil fleets should be considered as first generation craft although they have recently incorporated some waterjet pump improvements in some of their Model-100 Jetfoils.

- Total Operating Costs

Total operating costs includes: depreciation, capital interests, insurance, fuel, oil, consumables, maintenance, crew, government fees and other indirect operating expenses.

The Jetfoils total operating costs per passenger carried have varied from 17 percent higher to 20 percent lower than the hydrofoils total operating costs per passenger carried.

- Maintenance Costs

Maintenance costs include spare parts consumed, repair charges, labor costs and overhead.

From the start of service, the Jetfoils maintenance costs per passenger carried have been consistently lower than the Hyrdofoils - from 6 percent lower to 53 percent lower.

o Fuel Costs

Fuel costs per passenger carried have ranged from 70 percent higher for the Jetfoils to 35 percent higher, the relative reduction being partly due to the reduction in fuel burn experienced last year resulting from the incorporation of waterjet pump improvements in part of their Jetfoil fleet.

o Revenue

The Jetfoils have, over the entire time span, on average generated about 50 percent more income per passenger carried than the Hydrofoils.

For these reasons and due to their immense popularity, Far East Hyrdrofoil has decided to lay up all Hydrofoils and solely operate Jetfoils.

The story in other operating areas has been both good and bad. Of the 20 boats originally sold for passenger services, 16 are presently in operation and it is expected that the other 4 will be back in operation by year-end. Existing services are:

o	Hong-Kong - Macao	10 Boats
o	Niigata - Sado Island	2 Boats
o	Dover - Ostende	2 Boats
o	Canary Islands	2 Boats

Services which were attempted but which have since been discontinued were:

- o Hawaiian Islands — 3 Boats
- o Puerto la Cruz - Porlamar — 2 Boats
- o Brighton - Dieppe — 1 Boat
- o London - Ostende — 2 Boats
- o Dublin-Liverpool — 1 Boat
- o Buenos Aires - Montevideo — 1 Boat

Three of these services introduced marine craft where no sea service existed. Two were on routes served by conventional ferries. Four of the routes had very competative air services.

All but one fell victim to economics, for a variety of reasons. In some cases operating costs were higher than planned for. In some cases passenger loads did not come up to expectation. Weather restrictions placed on the operator by the regulatory agency caused higher than anticipated cancellations on a few routes. Not the least of the problem was the general state of the economy in several areas where the craft were being operated, particularly in 1981. 7 of the 10 Jetfoils have been re-sold.

Several of the operators have stated that they would like to start up Jetfoil service again when the state of the economy improves and a new service is currently being negotiated for one of the areas.

OFFSHORE CREW VARIANT

The offshore crew variant (OCV) JETFOIL, [4], [5] designated Model 929-202, is illustrated by FIG. 6. Several significant modifications from the standard JETFOIL include:

- Removal of the aft portion of the upper deckhouse to provide a working deck for a personnel transfer system and light priority cargo.

- Larger capacity fuel tanks for the long operating times.

- Addition of a stern directed hullborne auxiliary control station for vessel positioning and transfer system control during station keeping and transfer operations.

- Integrated hullborne "joystick" control to automatically coordinate operation of a new bow thruster, and an improved main thrusting control.

Extensive effort has also been carried out to develop a suitable ship-to-platform-to-ship personnel transfer system. These efforts and the system resulting are also described in Reference (4) & (5).

FUTURE PROSPECTS

At the beginning of this paper, it was stated that, "there are areas in the United States which do offer future opportunities for hydrofoil services". During 1981 an extensive market research program was carried out to characterize the present marine transport market and what it might be expected to look like in the future. Specific routes were examined and the market characteristics defined. A summary of the basic characteristics are presented in Figure 7. Other characteristics considered were those unique for a specific route such as water depth, sea states, weather, existing services, local restrictions, etc. Traffic growth was also projected.

Three types of marine craft were then evaluated to determine which would be the most suitable type of new vehicle to acquire for the specific characteristics of each route. No consideration was given to factors of laws which might restrict a particular vehicle or the potential bias against "pioneering" into advanced marine vehicles where none operate today.

In all, there were 28 areas in the United States that were evaluated: 25 passenger routes and 3 offshore oil markets. The results were: 10 best suited to hydrofoils; 8 best suited to SES; 2 best suited to ferries; 7 suited to more than one type of vehicle and for 1 route no marine craft was considered as appropriate.

Extending the area to include Canada, Mexico and the Caribbean area the results were: 46 areas evaluated; 21 best for hydrofoils; 8 best for SES; 4 best for ferries; 12 suited to more than one type and 1 as not recommended for marine. This represents a 20 year potential new vehicle market of 300 vessels.

CONCLUSIONS

The U.S. fully submerged foil commercial hydrofoil is a relative newcomer to the commercial hydrofoil marketplace. But the results have forged new standards of passenger comfort and appeal for high speed marine vehicles. Standards which cannot be ignored. Market opportunities exist in the United States for modern high speed marine craft, and specifically submerged foil hydrofoils.

Highly capital intensive, these craft must acheive high productivity to provide a satisfactory return for the operator. The situation is not unlike that which existed in the commercial air transport marketplace when the Jetliners were first introduced. There must be a continuing program to maintain high reliability and utilization and to improve fuel efficiency while keeping cost as low as possible. Even so modern transportation systems will continue to be highly susceptible to the fluctuations of world economics.

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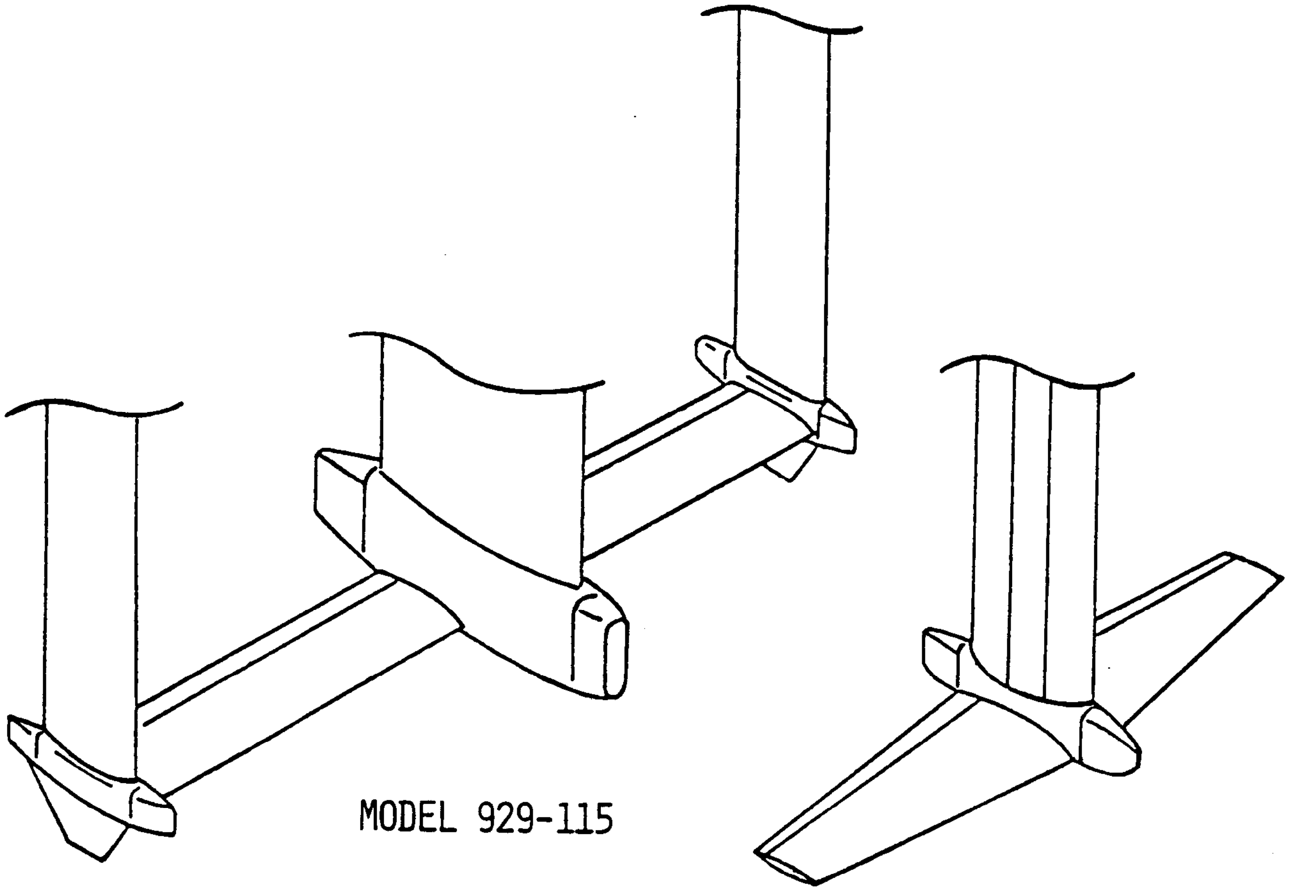
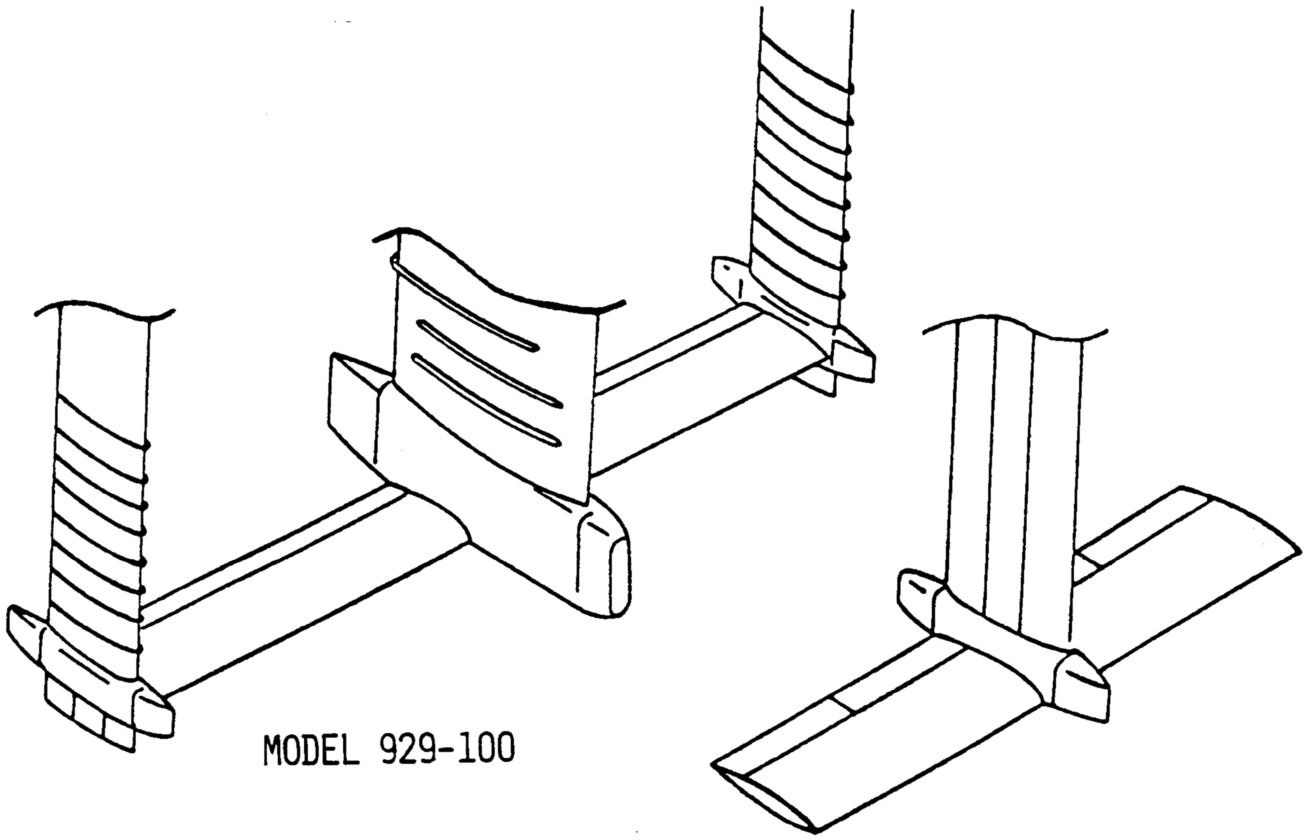
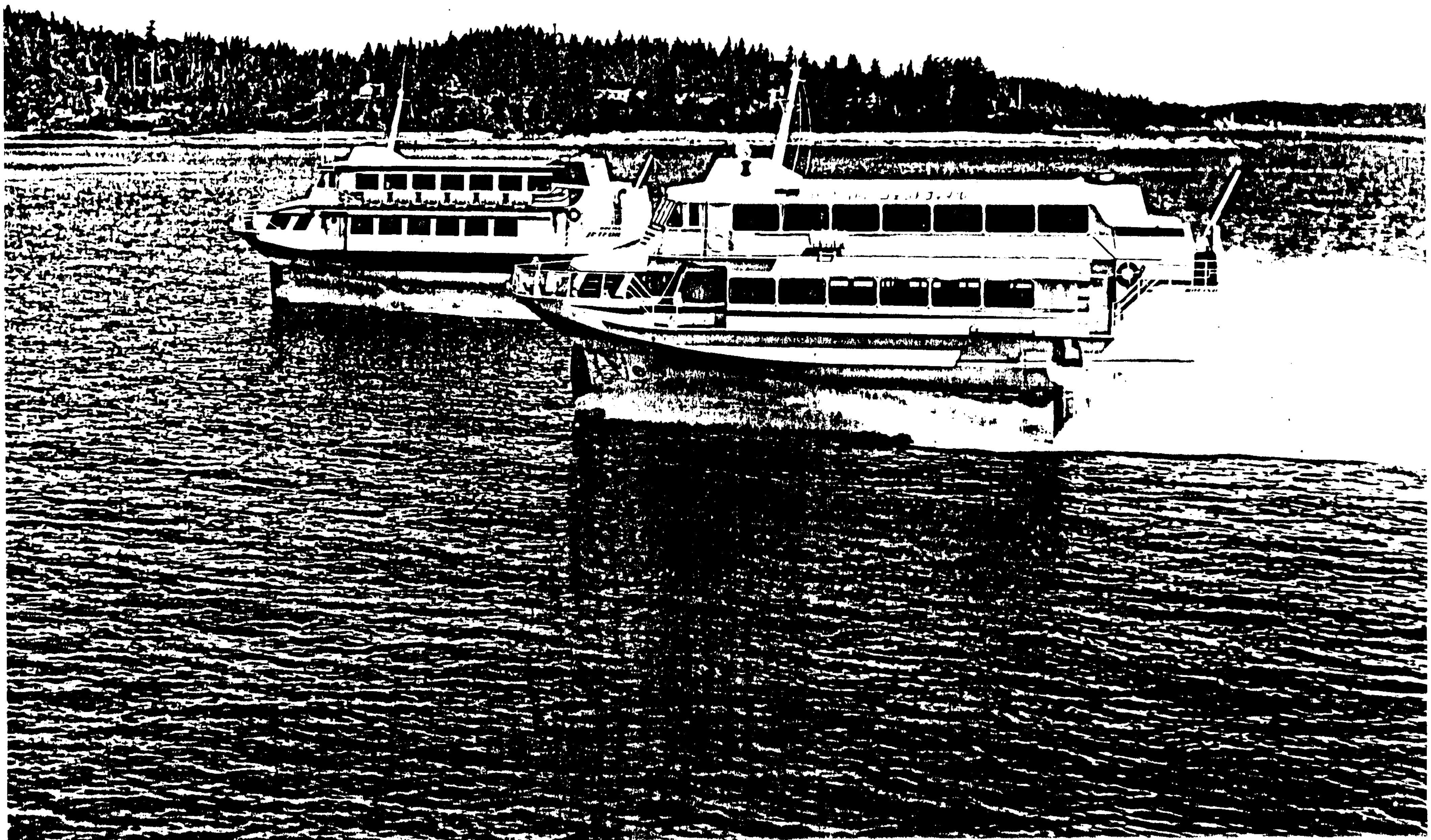


MODEL 929-115



MODEL 929-100

FIGURE 1



POTENTIAL FUEL CONSUMPTION REDUCTIONS

ESTIMATED AVERAGE VALUES

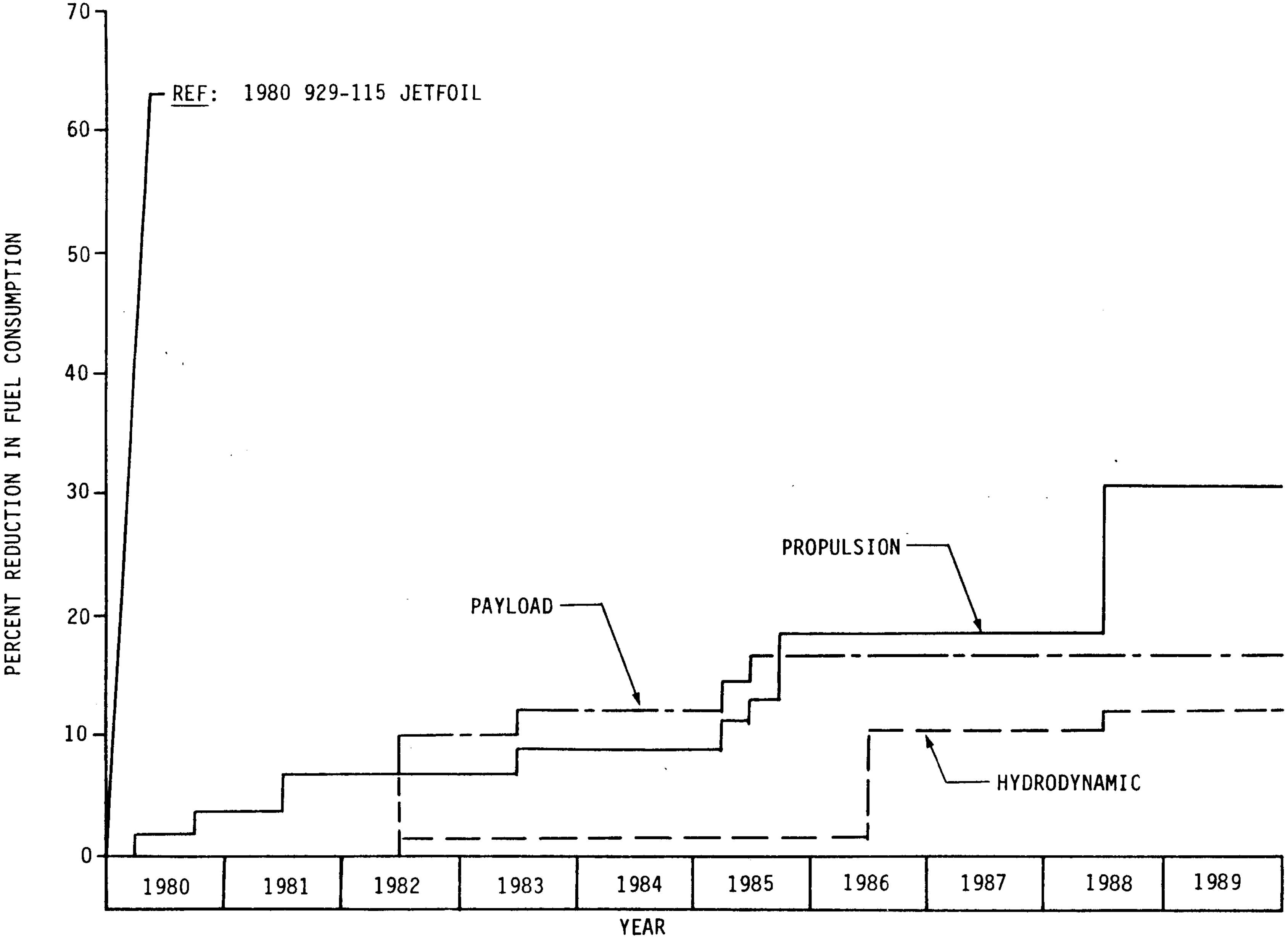


FIGURE 3

POTENTIAL FUEL EFFICIENCY IMPROVEMENT

COMBINED PROPULSION, HYDRODYNAMIC AND PAYLOAD

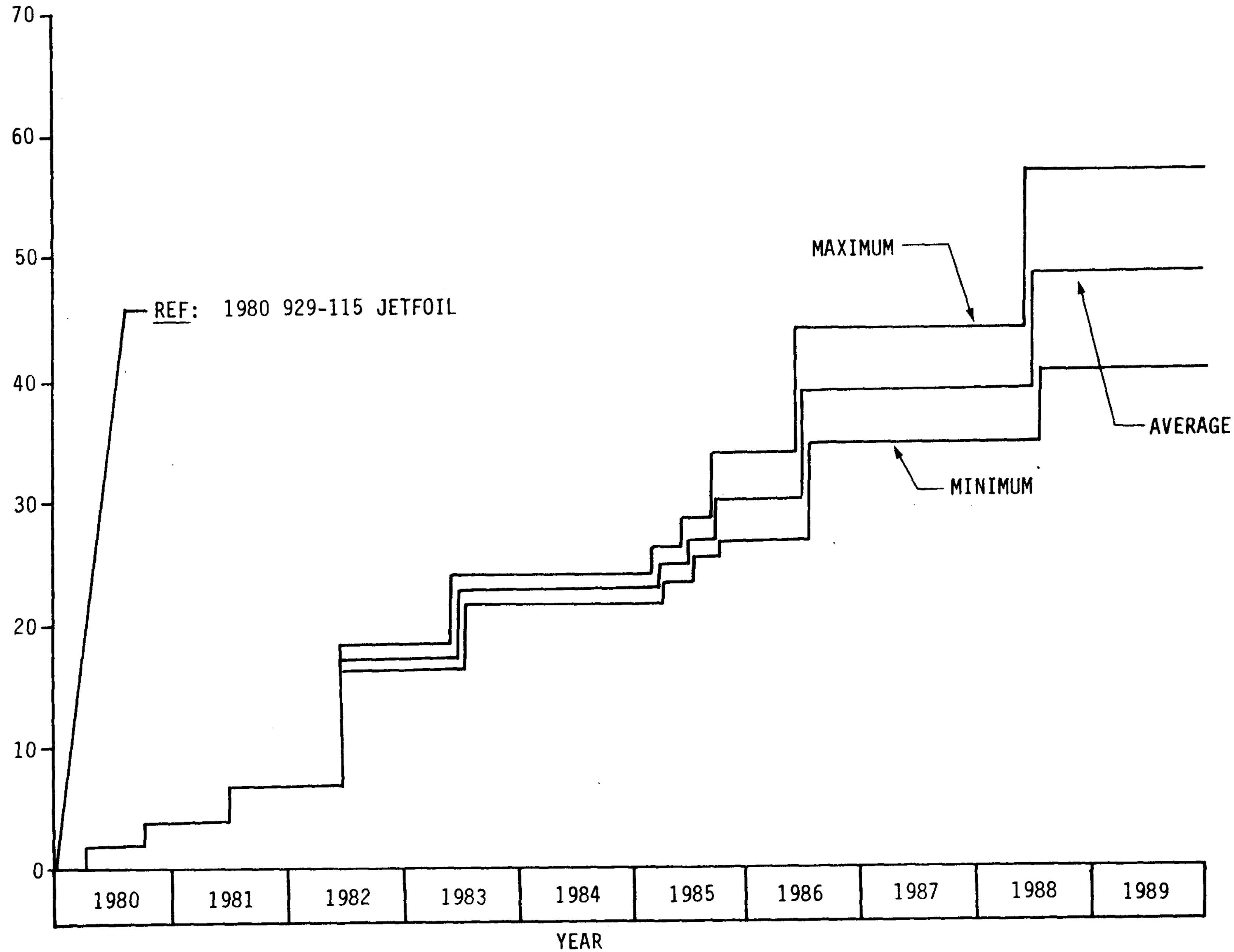
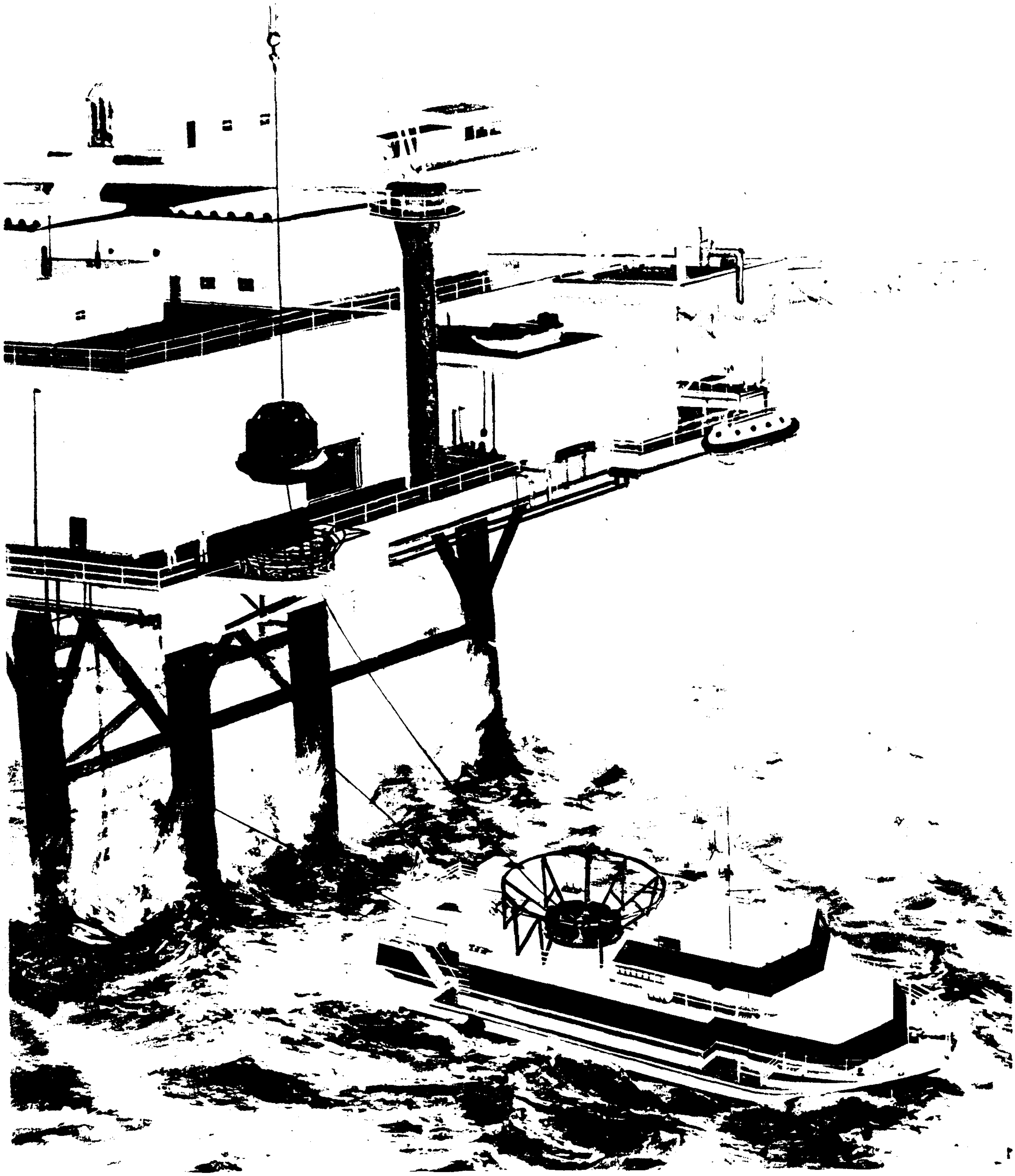


FIGURE 4

The VAS sensors on a Jetfoil with camera inset top left and illuminator bottom right

FIGURE 5



MARKET CHARACTERISTICS

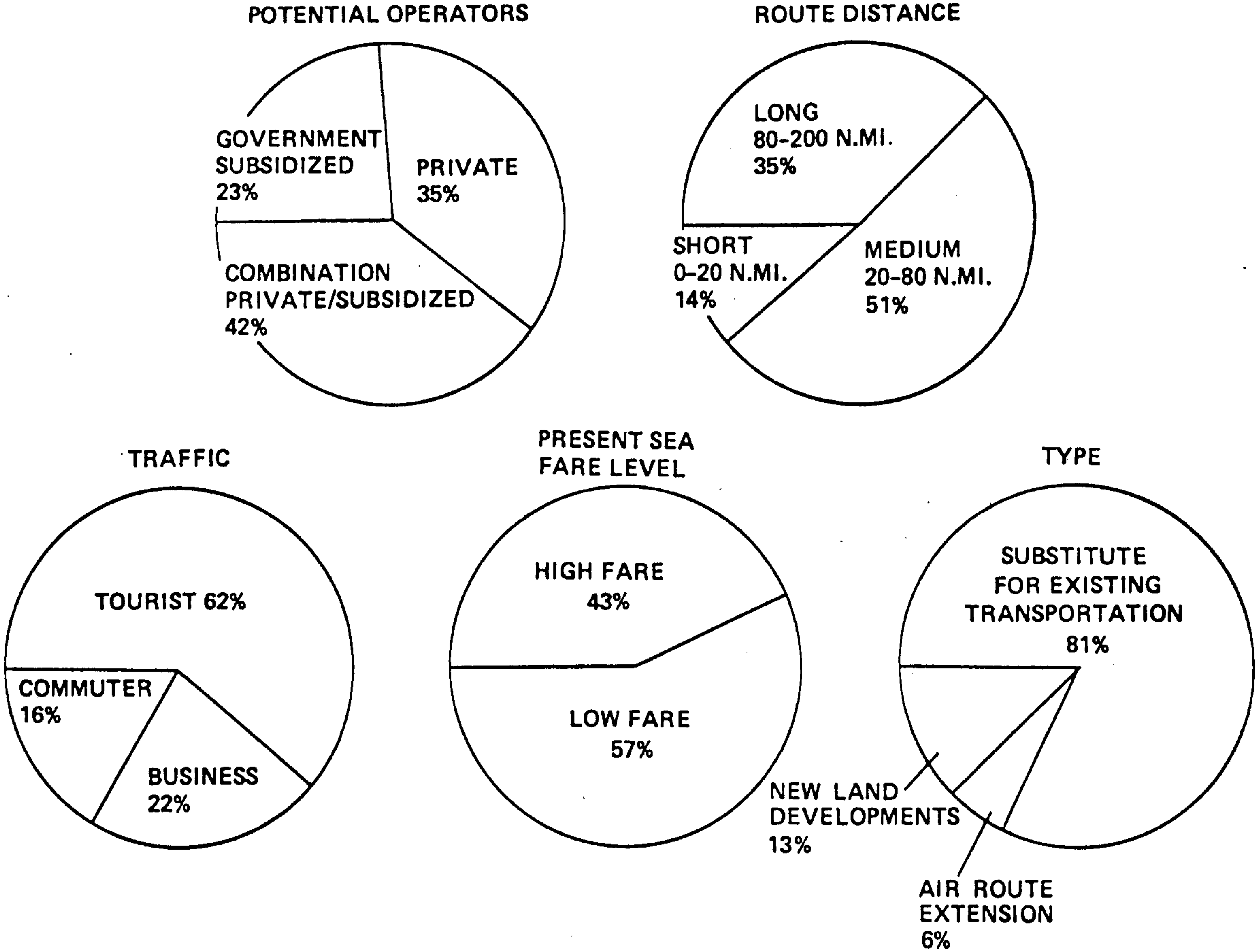


FIGURE 7

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CURRENT STATUS AND FUTURE PROSPECTS FOR FAR EAST COMMERCIAL HYDROFOILS

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Kenny Tham

Hong Kong Macao Hydrofoils, Ltd.

FIRST INTERNATIONAL
HYDROFOIL SOCIETY
CONFERENCE

Ingonish Beach, Nova Scotia, Canada - July 27-30 1982

CURRENT STATUS AND FUTURE PROSPECTS
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CURRENT STATUS AND FUTURE PROSPECTS FOR FAR EAST COMMERCIAL HYDROFOILS

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Hongkong Macao Hydrofoil Company Limited

The commercial hydrofoil picture in the Far East is like a movie film: constant action and changing scenes. A "still" picture at any given moment very quickly becomes history rather than depicting a continuing scene.

These changes involve new services, discontinued services; new equipment, obsolete equipment removed from service; new operators, others disappearing. It is almost impossible to keep track of what is happening throughout the area. A service may be inaugurated with great fanfare only to be discontinued quietly when not supported by traffic volume.

Part of this changing scene involves the proliferation of non-hydrofoil, high speed craft throughout the area. These new craft can be broadly described as propeller-driven hoverferries, propeller-driven catamarans, and water-jet propelled catamarans. There are several reasons for this: initial capital cost; operating cost efficiency; maintenance cost efficiency; sea or river depth, both on routes and in ports; and, last but not least, passenger comfort.

Other than Hong Kong, which is a unique market, there are several high speed passenger services in the area. In Australia (which is 'down under' rather than 'Far East), the Government of New South Wales is operating a service between Sydney and Manley using PT50's and one RHS160, all built in the late sixties. The service, subsidized by the state, is designed to relieve uncontrollable traffic congestion and reduce the travelling time for thousands of commuters between the two points. In Queensland a new service has just begun with the launching of a 20 metre aluminium catamaran with a top speed of 30 knots. This service operates between Cairns and Fitzroy Island (a new tourist haven 30 kilometres away) as well as cruising the Barrier Reef, 40 kilometres off the Island. This is one of few boats qualified for public transportation to the area. This is an Australian built boat produced by a yard in Hobart at a cost of approximately US$650,000. It is designed to carry both passengers and cargo. The boat is powered by twin engines, propelled by conventional propellers. It is not known if this is a subsidized service or purely commercial venture.

In Japan there is very limited hydrofoil service, not much publicized. It is believed that there is one Boeing Jetfoil still in service there. High speed surface passenger craft are not a significant factor in Japan at this moment.

There is limited hydrofoil activity in both Taiwan and Korea, but again the potential demand for high speed water passenger transport is not significant. Indonesia seems a logical area for such service, particularly as industrial development accelerates and people mobility becomes more of a requirement. The Philippines, with its many islands, also would seem to have potential as these areas develop. There is little forseeable potential in Singapore, Malaysia or Thailand.

As mentioned earlier, Hong Kong is a unique market. With a population of six million compressed in an area of approximately 400 square miles, comprising Hong Kong Island, the Kowloon and New Territories peninsula and some sparsely populated out-islands, plus over two and one half million visitors a year, water transportation is vital to the economy. Over three million people a week travel between destinations on some form of public water transport.

While most of these travellers use low speed, high density ferry boats, there is a significant volume using high speed craft. On the Hong Kong - Macau route alone, over 100,000 people per week are carried. There are other international services to various destinations in Mainland China, some using high speed craft, others the legendary "slow boat to China". Because of the hundreds of vessels - freighters, tankers, tugs, barges, junks, sampans, passenger ships, ferries and pleasures boats - constantly plying the harbour, high speed craft are impractical for cross-harbour, nearby destination services.

There are several different types of craft currently in high speed service in Hong Kong with another to come before year-end. Following are some specifics:

1) <u>Hong Kong - Macau Route</u>

There are currently two operators on this route. Hongkong Macao Hydrofoil and Far East Hydrofoil. HMH operates nine hydrofoils, 4 PT50's and 5 RHS140's (the specifications of which are very familiar to you) and two water-jet propelled catamarans built in Sweden. These catamarans are a new design vessel powered by twin MTU diesel engines, propelled by KaMeWa water-jets, travelling at a speed of 33 knots. They have a passenger capacity of 215. On a seat-trip basis, fuel consumption is about 8-10% more efficient than the other craft in the fleet. During more than six months of scheduled operation this new design vessel has completed more than 95% of its scheduled runs - a highly satisfactory performance. Another of these catamarans will be placed in this service within the next nine months.

FEH is operating 10 Boeing Jet Foils with four PT50 hydrofoils on a back-up basis. From published financial reports of the operator, the Jet Foil operation is only possible in this market with casino subsidies of $15-20 H.K. per passenger. For a non-casino affiliated operator such as HMH, the Jet Foil, with operating costs two to three times greater than other high speed craft, is not commercially viable. Jet Foils without a doubt have great passenger appeal, evidenced by the fact that people readily pay 25-30% more to travel on them. For the past year some of these Jet Foils have been equipped with night scope equipment at a cost of about US$1,000,000 per vessel, thus increasing the daily utilization of these craft. This night service, even with a substantial premium fare, has proven very popular with the public.

At year-end, a third operator - Sea Link - will inaugurate service to Macau using Vosper Hovermarine built hoverferries. While not yet delivered and in service, these craft will have a capacity of 180 to 200 passengers with speeds of 30 to 35 knots. They are powered by twin MTU diesel engines. The delivered price is around US$6,000,000.

2) China Service

Currently there are two routes operated by different companies, both using shallow draft, high speed craft.

Hong Kong To Canton - HYF is the operator using Vosper Hovermarine built hoverferries. These vessels have a capacity of 67 passengers, with maximum speed of 28 knots. Identified as Model HM2, they are powered by twin General Motors diesel engines, and propeller driven.

Hong Kong To Kong Moon - China Merchant is the operator. The craft are Hong Kong built catamarans, constructed under license from an Australian designer. They have a capacity of 150 passengers and a cruising speed of 25 knots. These are powered by Isotta Frachini engines, with conventional propulsion. Delivered cost is in the range of US$1,000,000.

Later this year a third operator, an HMH affiliated company, will start service to Zhuhai from Hong Kong using a Swedish built catamaran - a sister ship of the catamarans in the Macau service.

3) Intra - Hong Kong Service

HYF operates a fleet of twenty odd hoverferries to out-lying areas of Hong Kong. Craft in these services vary in size with passenger capacity ranging from 67 to 98 and maximum speeds of 25 knots.

Over the years the most successful high speed craft in the Far East area have been the Rodriquez built hydrofoils and Boeing jetfoils. Hoverferries and catamarans are relatively new to the area and are opening new routes to shallow water destinations on which foil craft cannot operate. Japanese built hydrofoils have been in limited service. US and Russian built hydrofoils have been examined but have not been selected either because of capital cost, reliability, or operating capability for the service.

North Queensland Engineers and Agents Pty Ltd. in Australia is very actively designing and developing catamarans. Yards in both Hong Kong and Australia have been licensed to build craft using their designs. In June, their latest design completed the first sea trials in Australia. It is a 22 metre craft, with a possible pay load of 230 passengers. Cost - not advertised as yet.

In summary, the Far East, including Australia, without a doubt has more high speed surface craft in scheduled operations than any other area. Furthermore, as countries in the area become more developed and industralized (particularly the Philippines and Indonesia) and the need for people to move between destinations increases, there is good potential for new services. With oil exploration activity and subsequent development of proven off-shore reserves just about to get underway, particularly in the South China Sea, there may be significant potential for high speed craft to service rigs and platforms.

1st June 1982

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OPERATIONAL UTILIZATION OF THE PATROL HYDROFOIL MISSILE (PHM)

Commander David A. Patch

Office of the Chief of Naval Operations, U.S. Department of the Navy

FIRST INTERNATIONAL HYDROFOIL SOCIETY CONFERENCE

Ingonish Beach, Nova Scotia, Canada - July 27-30 1982

OPERATIONAL UTILIZATION OF
THE
PATROL HYDROFOIL MISSILE
(PHM)

by

COMMANDER DAVID A. PATCH

PHM Program Coordinator (OP373D)
Advanced Naval Vehicles Division
Chief of Naval Operations
U.S. Department of the Navy

INTRODUCTION

In the early stages of PHM development and acquisition, the hydrofoil concept met with resistance at various levels within the government, as often happens when new, innovative programs are proposed. It can now be said that the PHM is enthusiastically supported within the Department of the Navy. The Navy recognizes that there are many missions which ships of this type can perform more effectively and less expensively than those of conventional design. It is most encouraging to realize that today the Navy's first 6 ships PHM squadron is being formed at Key West, Florida. In addition to PEGASUS, we have 2 ships en route now and plan delivery of the other 3 in time to complete the squadron early in Calendar Year 1983. The commissioning of the first squadron will be a major milestone, the first of many in what may be expected to be a long and successful career for this class ship.

Many of you here today have played important roles in hydrofoil development and testing which has paved the way for the PHM and you can be proud of your efforts. The PHM is unique and has just begun to show its true operational capabilities as a viable Naval Weapons System able to project significant power at sea in smaller, less expensive, faster reacting, and versatile units than ever before available to the U.S. Navy.

Previous papers, presented to the AIAA, SNAME and ASNE, have covered in detail the design, development, acquisition and testing phases of the PHM program. It is my intent to discuss the operational utilization of the PHM. The PHM's role in the various missions of power projection at sea may be generally classed as active and passive. Some tactics have been developed based on testing conducted to date and others remain to be developed. I envision that one major task of PHMRON-2 will be the refinement of current tactics and the development of tactics in support of missions not yet defined in detail for the PHM.

CONCEPT

The basic concept of the PHM is to operate offensively against major surface combatants and other surface craft to conduct surveillance, screening, and special operations. Essentially the rationale for the ship is based on three elements. What can it do that other ships cannot do? What can it do that aircraft cannot do? And what can it do as a substitute for other ships or aircraft? Measured against other ships, the PHM offers greater speed than that of any other operational ship type. Further, the PHM can use its top speed and employ its weapons in heavy seas which would severely limit the effectiveness of any of the larger conventional ships. Because the PHM is small, which renders it difficult to detect, it has the potential for stealth. Compared to aircraft, the PHM offers high, unrefueled endurance (days vs hours) depending on the speed required. Also, as a small surface ship it presents an ambiguous target for an enemy, as opposed to an aircraft which is, to a large degree, self-identifying. The PHM is less weather limited than an aircraft and more able in low visibility conditions to carry out duties which require positive identification and contact. As a substitute for other ships or aircraft, the PHM can perform several selective roles such as the operation of patrol and surveillance functions. It can also intercept, identify, and provide a platform from which to board and inspect other ships. As a surface-to-surface missile launching platform, it can shadow potentially hostile ships and if necessary conduct attacks against them. The PHM thus becomes a candidate for a variety of mission applications. Let us now investigate some of these mission applications.

MISSION APPLICATIONS

Close Surveillance and Tattletailing

Pre-hostility crisis management provides a role for the PHM for which it is well suited. Here the PHM may be employed in close surveillance and trailing of either large or small surface ships. The PHM can maintain close station on these combatants for continuous day and night visual inspection and thus be in a position to report on perceived hostile intentions or actual commencement of hostile action. Further, the PHM can maintain an optimum station for counter-attack regardless of enemy attempts to evade at high speed to obtain open range. Thus the coordination and timing of a pre-emptive initial attack becomes significantly more difficult for the opposition when the PHMs are assigned to the close-in trailing stations. In the event of actual hostile action, the PHM would respond with rapid salvo counter-attacks at first report of an enemy initial strike on any U.S. ship or an attack on the PHM itself. This mission tactic has been evaluated and it has been found that the PHM could effect a significant number of mission kills on opposition combatants if these combatants launch surface-to-surface missiles using simultaneous arrival doctrine; i.e., their launches are staggered with the objective of achieving maximum missile saturation effect. Conversely, if the opposition were to attempt simultaneous launch doctrine, the arrival density is less; therefore, engagements can better handle the threat. Thus, area point defense, anti-ship missile defense systems, and the carrier strike force would become significantly more effective. Of the alternative surface combatants we have that might be used on trailing missions, only the PHM was capable of maintaining the desired close-in station on all classes of opposition main surface combatants. This capability is significant in view of the possible use by the opposition of high speed evasion tactics prior to the launch of a pre-emptive strike. Using the PHM to maintain continuous close-in surveillance on opposition ships also provides the U.S. with the added options for deterrence by the threat of a U.S. pre-emptive strike.

Analyses have been conducted on the PHM logistics support, reliability requirements, and ship on station and rotation schedules during long duration missions, conducted at various mission radii from the home base. These studies show that when operating at mission radii from base stations, one PHM can be maintained continuously on a close-in station at a ratio of slightly more than one PHM to one enemy combatant. An alternative to a return to base for refueling procedures when on an extended station trailing/surveillance mission is to deploy a fleet oiler or other ship capable of transferring fuel to support the PHMs. PHMs will normally be operated on a working week mission cycle. The crew accomplishes only corrective maintenance because they are standing a minimum of 12 hours on watch a day. Maintenance is expected to be performed by a 127 man mobile logistic support force located at their home base during the 2-day in port period between mission cycles. An extended station operation would require a modified maintenance plan and it would have to extend its limited stores by highlining critical items from the support ship. Back up PHMs are required to ensure ship availability and reliability. This would comprise a ratio of one additional PHM per PHM six ship squadron. With only a six ship squadron currently available, contingency plans would have to be incorporated into the operational planning in the event of PHM down time. Figure 1 illustrates the strengths and limitations of the PHM and air platforms.

Surveillance and Patrol of Choke Points

In a cold war scenario, surveillance and patrol of choke point areas is a very viable mission for the PHM. As currently planned, the mobile support group for the PHM squadron will be based ashore at an appropriate operating base. The PHM squadron may be the sole surveillance and patrol force or can operate in conjunction with aircraft.

(PHM)

STRENGTHS

- GOOD VISUAL SURVEILLANCE
- RESPONSIVE FIRE POWER
- SURFACE PRESENCE
- LOW ASSET EXPOSURE

LIMITATIONS

- SSM VULNERABILITY
- POSSIBLE SPEED MISMATCH

(AIR)

STRENGTHS

- LOWEST ASSET EXPOSURE

LIMITATIONS

- CV ASSET DRAWDOWN
- LOW EXTENDED-MISSION AVAILABILITY
- LIMITED FIRE POWER RESPONSIVENESS
- SAM VULNERABILITY
- POOR CLOSE VISUAL SURVEILLANCE

Figure 1. CLOSE SURVEILLANCE AND TATTLETALE

Aircraft can readily conduct wide area search but are limited in the ability to conduct close-in inspection tasks and, of course, cannot provide a platform for boarding parties.

Surface missile combatants however, are best suited for the follow up inspection and attack role based on aircraft conducted surveillance and unknown surface combatant recognition. The PHMs can rapidly inspect targets and attack from beyond the horizon. They are difficult to identify, analyze, and classify because of the higher speed and small radar target size. The advantage of physical size, surprise and low detectability as an approaching target from beyond the horizon is clearly in favor of the PHM. These advantages, coupled with the capability of third party targeting relayed from the aircraft, make the PHM well suited for choke point missions. Figure 2 illustrates the strengths and limitations of the PHM and air platforms.

Stationkeeping (Blockade, Quarantine, etc. Operations)

Another mode of operation is the station keeping mode. This involves transiting from a base, keeping a continuous station either in a geographical area or on an assigned surface force and returning to base. Several ships are required in this cycle to maintain a single ship on station. The number required increases as the distance to station from base of support increases. Included in this mission scenario is a blockade or quarantine operation. This mission is similar to the surveillance mission described above but with the distance from base increased. Should either of the above two missions just discussed disclose hostile action the real world applicability of the PHMs speed comes into play. A foilborne sortie can be implemented.

While operating in this mode range endurance is reduced; however, the PHM can strike at an enemy force in a relatively short time. With very powerful offensive firepower of up to eight HARPOON missiles together with adequate communications, command and control facilities, with sufficient range to cover restricted sea patches and coastal areas, the PHM provides a formidable weapon system for surface warfare applications. Its high speed, superior sea keeping ability and ambiguity as a surface target make the PHM a unique surface raider.

(PHM)

STRENGTHS

- MOBILITY
- FIRE POWER
- DIFFICULT TO TARGET

LIMITATIONS

- LINE OF SIGHT SURVEILLANCE
- ANCHORAGE FOR SUPPORT SHIP
- VULNERABLE TO SSMS

(AIR)

STRENGTHS

- LONG RANGE RADAR SURVEILLANCE

LIMITATIONS

- VULNERABLE TO AIR THREAT
- POSSIBLE BASING PROBLEMS
- LIMITED FIRE POWER
- VULNERABLE TO SAMS
- WEATHER/VISIBLITY RESTRICTIONS

Figure 2. SURVEILLANCE AND PATROL OF CHOKE POINT

Battle Group Operations

The PHMs should not be thought of as strictly a coastal ship. As screening ships transiting open waters, PHMs can be used to best advantage by investigating suspicious contacts from a station ahead of the high value surface combatants under advisory control of a designated surface combatant or patrol aircraft. They can be utilized to investigate surface contacts before the protected forces come within their radar range.

Normal employment envisions about one working week underway followed by two days in port for maintenance and crew rest. Thus the PHM is most effective in closed ocean areas conducting concentrated anti-shipping attacks. Crew endurance, fuel capacity, weapon reload requirements, manning levels, and communications equipment limitations militate against the PHM completely fulfilling the traditional battle group escort role. However, the PHM unique sea keeping capability and long range weapon systems permit operations with a battle group and can increase the battle group surface attack and sensor posture. Effective PHM command and control requires an appreciation of ship capabilities and limitations within the battle group.

A PHM support ship is essential to successful PHM operations in a battle group. The support ship provides communications and tactical support to the PHM. The support ship maintains the PHM broadcast guard and provides the PHM with a battle group threat picture tailored to PHM requirements. The PHM maintains a loiter condition within UHF or visual range until its weapons capabilities are required. During the loiter period, the PHM maintains only skeletal watches and operates at maximum fuel economy consistent with maintaining plan of intended movement. As necessary, the support ship alters the PHM to increase readiness condition, and to pass essential contact position information and detailed mission requirements. The support ship controls the PHM during the assigned mission or passes PHM tactical control to a control platform (ship or aircraft). The support ship maintains PHM communications support duties when tactical control is passed to a control platform. The PHM control platform takes tactical control of the PHM to accomplish a specific mission. The PHM support ship normally maintains tactical control of the assigned PHM and is the primary PHM control platform. Situations will develop which require passing tactical control of a PHM from the support ship to another battle group platform. The PHM control platform may be any ship or aircraft with sufficient command control communications capability. Potential control platforms are surface combatants, or E2C, P3C, and S3 aircraft.

It would be a mistake not to consider the PHM in a Battle Group (BG) support role. Tactics can be tailored from existing over-the-horizon targeting attack tactics to the PHM and its control platform. This command and control (C^2) concept combines PHM over-the-horizon attack capabilities with BG search and classification capabilities to improve anti-surface warfare (ASUW)/over-the-horizon targeting (OTH) strike effectiveness. The control platform may direct all aspects of the OTH engagement or pass targeting and missile launch timing control to the PHM.

Use of PHMs to defend a task force against a surface attack can free other ships to concentrate their efforts on anti-submarine and anti-air warfare, enabling carrier aircraft to carry out offensive operations instead of being required to defend their home plate. Figure 3 illustrates the strengths and limitations of the PHM and air platforms.

Other missions include unconventional warfare, search, rescue operations, and "presence" missions.

Unconventional Warfare Mission

Because of their small size, their capability to store and launch small craft (rubber boats), and the compatible weapons and communications suite, missile ships/boats are suited for clandestine or advanced force operation missions close to the shore. Operating from their support ships provides the capability of deploying an entire inshore warfare task group for extensive periods. Debarkation and achieving the objective can be accomplished without light or sound. The ship can then proceed to a position from which it can provide an emergency fire support or conduct a suitable diversion.

Search and Rescue

Due to their low freeboard, excellent maneuverability, and flexible speed capability, missile boats are well suited for search and rescue. Their ability to conduct pilot rescue operations is feasible even in unfavorable sea states. Hydrofoils with foils down, even when hullborne, are extremely stable in more unfavorable sea states. Use of destroyer slide back positioning techniques reduces fuel consumption and improves crew fatigue. Deployment of a PHM squadron in company with carrier task forces can provide both search and rescue and surface defense, and again free more capable but more costly

(PHM)

STRENGTHS

- HIGH FIRE POWER CONCENTRATION (LONG-RANGE MISSILE/MOBILITY)
- LOW ASSET EXPOSURE

LIMITATIONS

- LINE OF SIGHT SURVEILLANCE
- AIR SURVEILLANCE AUGMENTATION DESIRABLE
- REMOTE TARGETING DESIRABLE

(AIR)

STRENGTHS

- HIGH FIRE POWER CONCENTRATION POSSIBLE
- LOWEST ASSET EXPOSURE
- EXTENDED RADAR COVERAGE

LIMITATIONS

- CV ASSET DRAW DOWN
- LIMITED EXTENDED MISSION AVAILABILITY
- SIMULTANEOUS READY DLA AND ASSAULT SUPPORT OPS.
- WEATHER RESTRICTIONS

Figure 3. SURFACE SCREENING/POUNCER

units from this task. Figure 4 illustrates the strengths and limitations of the PHM and air/Helo platforms.

"Presence" Mission

In conducting show of the flag visits, small modern missile ships can impart a decided impression of determination and friendliness to an entire area. Small sensitive ports with smaller fishing villages respond to ship visits enthusiastically and have found the crews to be professional and well disciplined. In towns of 4,000 to 6,000 people over one half of the population has visited a single missile ship in a two or three day stay. For employment of liberal visiting hours and high speed demonstration cruises for civic leaders, a friendly response is virtually assured. PHM capabilities in this area are much the same as missile gun boats.

During a two year period in the Mediterranean, one patrol gun boat visited 19 significant ports and over 20 villages and towns. Not only can several ships/boats visit more ports than a single larger unit but, for whatever the reasons, these boats provoke greater feeling of U.S. Navy presence in the people of small neutral nations than do larger conventional ships.

LESSONS LEARNED FROM FLEET EXERCISES

Lessons learned from various Fleet exercises have been invaluable to the overall development of the PHM program. The PEGASUS was used in a variety of roles which enabled improvements to be made on her and be included in the follow on production ships.

Communication

The most important lessons learned are that communication is vital and that a communications link capability is essential. Another lesson was the need to continually have an accurate location for the third party targeting platform. The platform which is carrying the HARPOON missile must know the exact location of the targeting ship in order to provide the requisite targeting information into the fire control system.

Referencing System

A common reference system must be identified and employed by all units to minimize the effects of navigation and plotting errors. The reference system utilization must be based on simplicity, and should be employed consistently throughout an operation. Operating with a squadron of PHMs with a limited communications package onboard necessitates a minimal amount of two-way exchange once an operation is underway. The limited personnel capability and watchstanders under battle conditions means that the procedures used should be kept as simple as possible. A common reference system will simplify and minimize communications between units.

Deceptiveness

The PHM, using high speed, often confused the adversary. At low speed, with her small size, she was often mistaken as a fishing vessel.

Maneuverability

The PHM maneuverability made her a difficult, sometimes impossible, target to enable the adversary to develop a fire control solution.

Speed

Fast attack, hit and run procedures made the PHM an incredibly deadly threat and extremely difficult to counter.

COMMENTS FROM OTHERS

The commander of the cruiser, destroyer group in the Pacific Fleet during the time in which PEGASUS was assigned to the Pacific Fleet made this comment concerning the PEGASUS and her time spent in this group. "The tactical advantages of speed and low detectability make this an exciting platform, and it is obviously applicable in all warfare areas. Looking into the future we should keep an open mind on this platform and continue to assess her capabilities and limitations. Although constrained in general to a coastal area of operations during Fleet EXs in 1978, I was most impressed with tactical utility of this platform throughout all phases."

The following comment was extracted from a Chief of Naval Material Combat Systems Advisory Group report. "...the U.S. Navy must regain the initiative in surface warfare. Substantial surface strike capability provided by small high speed missile combatants is the opportunity we have been waiting for."

The Commanding Officers of two Australian ships involved in an exercise with the PEGASUS made these comments: "PEGASUS was able to position rapidly for missile launch, to rearm, refuel expeditiously, and move quickly to a new location." "There is the possibility that the CVA might try to run away from other surface units (tattletails and shooters); PEGASUS was an important ace in the hole."

The Commander in Chief Atlantic said of the PHM ships, "These ships have an important role in today's fleet..."

The Deputy Chief of Naval Operations (Surface Warfare) stated, "The Navy continues to believe that the PHM will make important contributions to U.S. sea power."

CONCLUSION

The following comment applies strictly to PHM capabilities. Construction of the NATO missile patrol hydrofoil, or PHM, will give the U.S. Navy a quantum jump in missile combat capability. Not only will the computer controlled hydrofoils provide a stable weapons platform in high seas, but a maximum speed of over 40 knots will increase their operational radius and enable more rapid positioning for attack and provide a greater chance of evading enemy guns and missiles. The greater increased range and larger warhead of the eight installed HARPOON surface-to-surface missiles gives the PHM more surface firepower per pound than any other U.S. surface combatant. This offensive capability, enhanced by the 76mm OTO-MELARA rapid fire gun, provides significant AAW protection as well. The foils themselves may dictate operational limitations; however, PHMs with foils extended will be significantly more stable, even when hullborne. Greater capability for the PHM will undoubtedly be the results of innovative tactical developments. Large benefits can be realized by insuring PHMs are integrated on a real-time basis with other units of the task force for command and control and over-the-horizon surveillance and targeting.

Strategically, there are other thoughts concerning the use of small missile ships in various parts of the world; however, they are classified and can not be included in this paper. I will say, however, that the ability to deploy the PHM squadron as it is currently envisioned is being studied. The location of the deployment has yet to be determined, and many areas are being considered. Each area has problems relative to the deployment that need to be resolved. It is anticipated that within the next year, the exact location will be identified and the work will begin to enable the six ship squadron and the mobile logistics support group to deploy.

ACKNOWLEDGEMENTS

Mr. John Monk	Wheeler Industries
Mr. Ray Hoop	Wheeler Industries
Mr. Doug LaPierre	Wheeler Industries
Mr. Ron Adler	Adler Corporation

1st International Hydrofoil Society Conference

SHIMRIT
Mark II Hydrofoil for the Israeli Navy

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JULY 27-30, 1982
INGONISH BEACH, NOVA SCOTIA, CANADA

SHIMRIT

MARK II HYDROFOIL FOR THE ISRAELI NAVY

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Abstract

The M-161 Mark II hydrofoil being developed for the Israeli Navy represents the latest in a series of high performance craft developed over the past two decades by Grumman. It is by far the most sophisticated and best performing hydrofoil of the series and should prove to be a formidable military vehicle.

This paper traces the M-161 development from its inception as a successor to the smaller and lighter PGH-1 FLAGSTAFF Mark I hydrofoil. Detailed descriptions of the hull and deckhouse construction, struts, foils and major systems are presented along with a discussion of the significant development challenges encountered in the program. A review of the status of the sea trials conducted with the first vessel, commissioned the SHIMRIT, is also presented.

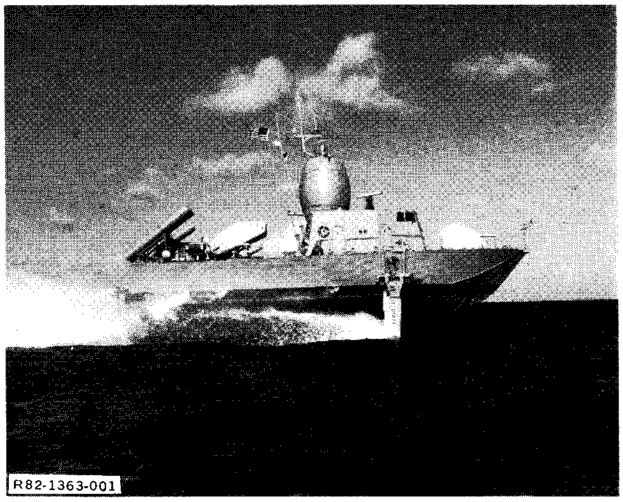

Fig. 1 SHIMRIT Foilborne During Sea Trials Evaluation

Introduction

In December of 1977, Grumman entered into an agreement with the Government of Israel (GOI) for the development, production, and test of high performance military hydrofoil patrol boats. This contractual agreement culminated many months of negotiation during which a comprehensive specification defining the craft's performance and, in some cases, basic design philosophy and system configuration was developed. In the four-and-a-half years since contract signing, a dedicated team working in some difficult circumstances, against stringent contractual and specification requirements, has brought the Program to the point where the first vessel has received conditional acceptance by the customer and the second vessel is nearing a launch in Israel.

With approximately 550 operational hours on Vessel Number 1 all indications are that the M-161 Mark II hydrofoil is one of, if not the most, sophisticated and best performing military hydrofoils in the world today. Unfortunately, the classified and sensitive nature of most of the significant performance parameters precludes their discussion in the context of this paper. We will however present an overview of the first vessel, commissioned the SHIMRIT (Guardian), and summarize some of the significant development problems and experiences of the extensive sea trials program.

FLAGSTAFF Background

The Mark II SHIMRIT shown in Figure 1 evolved as an advanced, improved reliability version of the Mark I PGH-1 FLAGSTAFF developed for the U.S. Navy in the mid 1960's. Following its delivery in September 1968, FLAGSTAFF underwent a year-long operational evaluation in San Diego and Viet Nam. It returned from Viet Nam in late 1969 and re-commenced operations in San Diego in January 1970. These operations continued until October, when the fourth failure of a transmission bearing resulted in a failure investigation and subsequent modification of the strut shaft of the main transmission. Foilborne operations resumed in April 1970 with successful test firings of a large (152 mm) gun mounted on the fore deck. Through an inter-service agreement the vessel was transferred to the U.S. Coast Guard where, following recommissioning and repainting, it was utilized in various Coast Guard missions operating out of San Diego and later Boston and Woods Hole, Massachusetts. Two Coast Guard evaluations were conducted during the periods of August 1974 to February 1975 and from September 1976 to September 1978, when the vessel was laid up due to severe economic constraints and increasing downtime due to shortages of one-of-a-kind spare parts. U.S. Navy operations were conducted between the two Coast Guard evaluations. In all, over 1000 foilborne hours had been accumulated on FLAGSTAFF. The experience and knowledge gained in these evaluations weighed heavily in the design and development of the Mark II SHIMRIT.

Schedule and Milestones

The GOI-Grumman contract signed in December 1977 provided for the transfer of the knowledge and technology required to fabricate subsequent vessels through the early construction of a vessel in Israel. Accordingly, the first vessel was constructed in the US (Lantana, Florida), and a second vessel is under construction in Israel by Israeli Shipyards

Limited (ISL) with proprietary equipment and subsystems supplied by Grumman.

Subsequent to contract signing, dual program offices with supporting personnel were established in Florida and Israel. An extensive team of subcontractors was established as shown in Figure 2 to design, develop and test major components, equipment and systems. Within two months of contract

SUBCONTRACTOR	RESPONSIBILITY
LANTANA BOATYARD	FABRICATION VESSEL NO. 1
ISRAELI SHIPYARDS LTD.	FABRICATION VESSEL NO. 2
DETROIT DIESEL ALLISON	MAIN ENGINE
WESTERN GEAR CORPORATION	FOILBORNE TRANSMISSION
PROPULSION SYSTEMS INC/BIRD JOHNSON CO.	CONTROLLABLE PITCH PROPELLER
PRATT & WHITNEY CANADA	AUXILIARY POWER UNITS
MARITIME INDUSTRIES LTD.	HULLBORNE STERNDRIVES
AIRSCREW HOWDEN (U.K.)	AIR CONDITIONING
HAMILTON STANDARD	AUTO FLIGHT CONTROL SYSTEM, DEMISTERS
BRUNSWICK CORP.	RADOME
NELSON	SWITCHBOARD
SPECTRONIX (ISRAEL)	FIRE DETECTION/SUPPRESSION

Fig. 2 Program Major Subcontractors

signing the first engineering drawings were released with many detail design specifications for major equipment released shortly thereafter.

As can be anticipated with any development program of this magnitude, problems arose which adversely impacted the initial schedule. The problems were primarily in the timely delivery of major systems and components by suppliers. The Grumman team worked extremely hard to minimize the impact of slippages on the program. The achieved milestones for Vessel No. 1 are defined in Figure 3. Vessel No. 2 is currently in an advanced state of construction at ISL. It lags Vessel No. 1 by approximately 18 months. It is currently scheduled for launch this year and will undergo a

CONTRACT SIGNING: DEC. 77

FIRST DRAWING RELEASED: FEB '78

MILESTONE	APPROX. DATE
KEEL LAID	28 SEPT '78
HULL JOINING COMPLETED	27 NOV '79
DECKHOUSE FABRICATION COMPLETION	13 MAR '80
BOAT MOVED TO HIGH STAND	OCT/NOV '80
FWD STRUTS MATED	17 NOV '80
AFT STRUT MATED	NOV '80
INITIAL ENGINE RUN (HIGH STAND)	11 APRIL '81
LAUNCH	27 MAY '81
FIRST VOYAGE	11 JUNE '81
FIRST FOILBORNE FLIGHT	13 JULY '81
SEA TRIALS COMPLETED	22 JUNE '82

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Fig. 3 Program Milestones - Vessel No. 1

similar sea trials evaluation program as that conducted with SHIMRIT.

Description

The SHIMRIT is slightly larger and considerably heavier than the FLAGSTAFF, as evidenced by the data of Figure 4. This increased size provides deck space for mounting missile launchers aft of the forward deckhouse and on either side of the aft deckhouse. It also provides additional space on the foredeck for the gun, an enlarged forward deckhouse with provisions for mounting a large radome and accommodations for a 13 man contingent in the Combat Information Center (CIC) and a small crew's quarters below deck.

	MARK I (PGH-1)	MARK II (M-161)
LENGTH OVERALL - HULL	73 FT	84 FT
BEAM - HULL ONLY	21½ FT	24 FT
DRAFT - FOILS RETRACTED	4 FT 4 IN	5 FT
- FOILS EXTENDED STATIC		15 FT 7 IN
WEIGHT - FULL LOAD DISPLACEMENT	68 LT	103.5 LT
- MAXIMUM FUEL CAPACITY	11.8 LT	
POWER - ENGINE TYPE	(1) RR TYNE 621/10	(1) ALLISON 501-KF
- Hp	3550	5400
FOILS - SPAN	13 FT 10 IN	17 FT 2 IN
- AREA	35 SQ FT	53.5 SQ FT
- ASPECT RATIO	5.5	5.5
- ALLOY	6061-T652	6061-T652
FOILBORNE PROPELLER	3-BLADED, C.P. SUPERCAVITATING	4-BLADED, C.P. TRANSCAVITATED
HULLBORNE PROPULSION - TYPE	(2) GMC6V-53 DIESELS	(2) HYDRAULIC
- Hp EACH	193	80

R82-1363-004

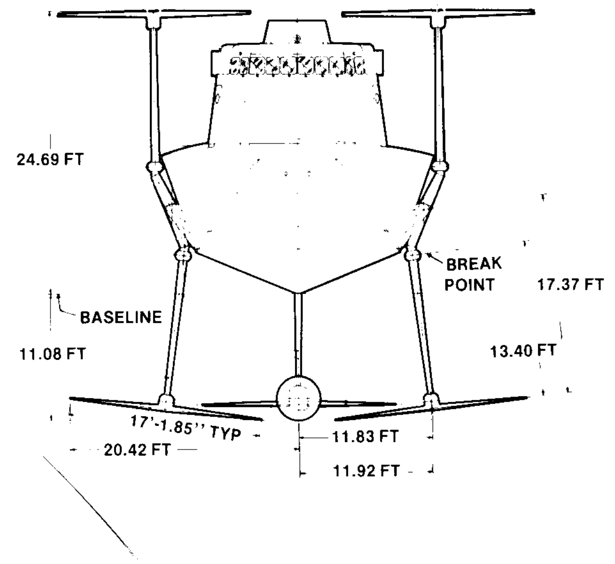
Fig. 4 FLAGSTAFF/SHIMRIT Comparison

The general arrangement of SHIMRIT shown in Figure 5 is virtually identical to FLAGSTAFF. It has 2 forward struts/foils and a single aft strut/foil. Foilborne propulsion is via a four-bladed controllable pitch propeller driven by an industrial gas turbine through a four-gearbox main transmission system. Hullborne propulsion is achieved via two hydraulically driven sterndrives with hydraulic and electrical power provided by two auxiliary power units. The vessel is equipped with an advanced Automatic (Flight) Control System (ACS) and a unique Engineering Monitoring and Control System (EMCS).

Performance of the vessel is exceptional with a foilborne cruise speed well in excess of 40 KN. Maximum speed and range are classified. Foilborne turning is outstanding. Take-off times as short as 31 seconds have been achieved with a 94 ton ship in calm sea.

Hull and Deckhouse Construction

The SHIMRIT hullform shown in Figure 6 is similar to FLAGSTAFF's except for an increase in side flare which produces a beam of 24 ft. The hull is an all-welded design constructed of 5456



aluminum. This alloy provides the best as-welded strength properties of all 5000 series alloys. Filler material is 5356, which provides a greater resistance to cracking than the 5556 alloy used on previous 5456 aluminum hulls.

Basically the hull is constructed of H-111 temper, integrally-tee-stiffened extruded planks welded to some 33 transverse frames and seven transverse water-tight bulkheads. These seven transverse and two longitudinal bulkheads divide the hull into 10 water-tight compartments. An analysis of the water impact and bending loads resulted in the selection of three gages of integrally stiffened planking, a typical section of which is shown in Figure 7. The lightest section had a 0.140-in. thick flat skin with a 1-5/8-in. high tee with a 1-in. flange width. This was utilized to fabricate main deck, platform deck and side shell subassemblies.

A similar section was used to fabricate the mid and aft bottom shell; here the skin thickness remains 0.140-in. but the integral tee was 2-1/2-in.

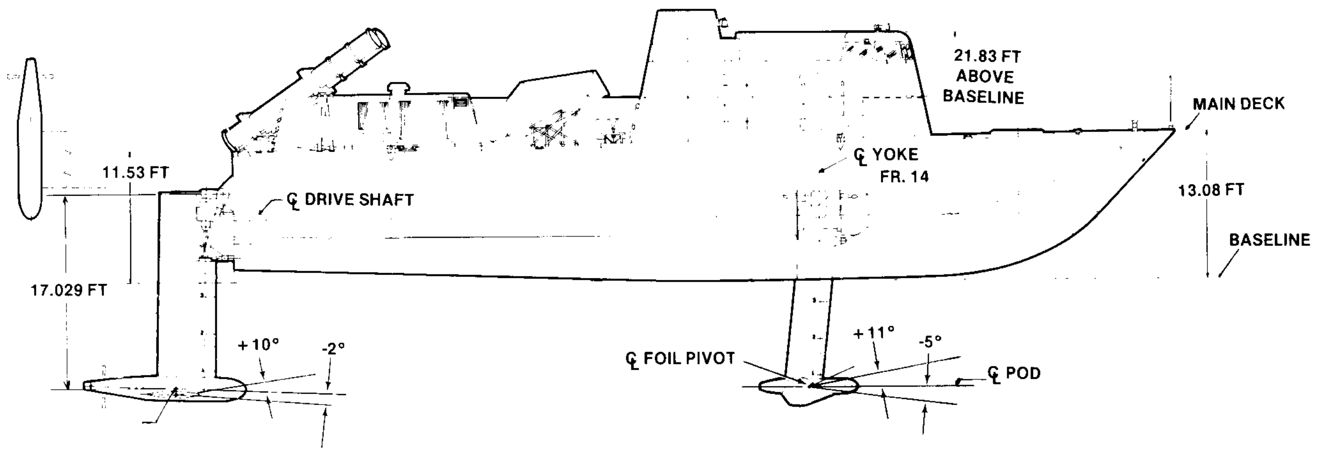


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Fig. 5 SHIMRIT General Arrangement

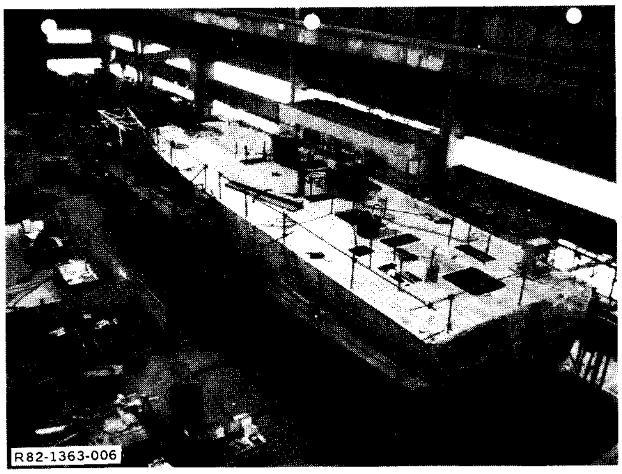

Fig. 6 All-Welded Aluminum Hull During Fabrication

deep, with a 1-1/2-in. wide flange and the skin was locally thickened (haunched) at the base of the tee to provide increased transverse bending strength. The heaviest tee stiffened extruded plank was utilized in the forward bottom shell. Here, the skin thickness was increased to 0.156-in., the 2-1/2 in. deep tee had a 2-in. wide flange and the skin was haunched at the base of the tee.

A combination of hand and machine welding was utilized in fabricating hull subassemblies and constructing the hull. Pulsed-gas metal arc, spray-gas metal arc and gas tungsten arc weld processes were employed because of specific benefits of each process. Helium shielding was utilized for all spray-gas metal arc welding because it minimized weld porosity relative to helium-argon mixtures or plain argon. Approximately 500 welds comprising over 6000 linear feet were accomplished via a mechanized weld seamer. These welds were predominantly single pass; all were full penetration and all welding was performed from one side.

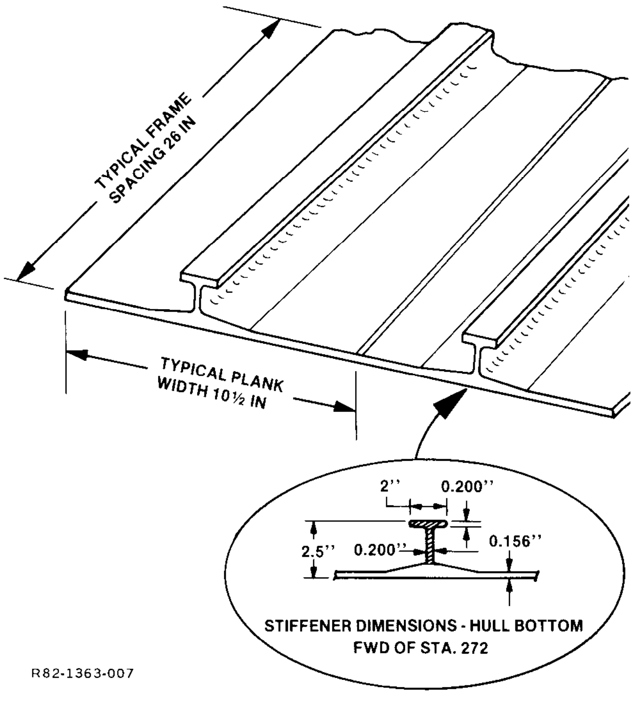

Fig. 7 Integrally Stiffened Extruded Hull Planking

Approximately 80 percent of all hull welds were x-ray inspected.

The forward deckhouse shown in an exploded view in Figure 8 contains the pilot house, bridge and air conditioning machinery. It was originally conceived as an all-welded structure; however, after careful evaluation the welded 5456 construction concept was abandoned in favor of a riveted 6061-T6 sheet metal design. This decision based on alloy strength, minimum gages and maximum loading saved about 3000 lbs. of weight.

The forward deckhouse structure for Vessel No. 1 was fully constructed and assembled in Bethpage. It was delivered to Lantana, lifted into place and attached to the main deck with riveted clips. The deckhouse for Vessel No. 2 was built in Lantana, shipped to Israel and installed at ISL.

The aft deckhouse which houses engine and APU inlets and exhaust ducting is a welded 5456 structure. The structure is permanently attached to the main deck except for a removable aft section which permits access to and removal of the main engine and main transmission Hull Mounted Gearbox (HMGB) from the aft machinery compartment.

Reference 1 provides additional detailed information about the structural design, analysis and testing of the SHIMRIT.

Foils/Struts

Hydrodynamically the struts and foils of SHIMRIT are identical to those of FLAGSTAFF. They have of course been scaled to accommodate the higher loads of the heavier vessel and to maintain the approximate foil loading of FLAGSTAFF.

The hydrofoil system is fully retractable, subcavitating, fully submerged, incidence-controlled configuration. There are three foil/strut assemblies: two forward carrying about 70% of the gross

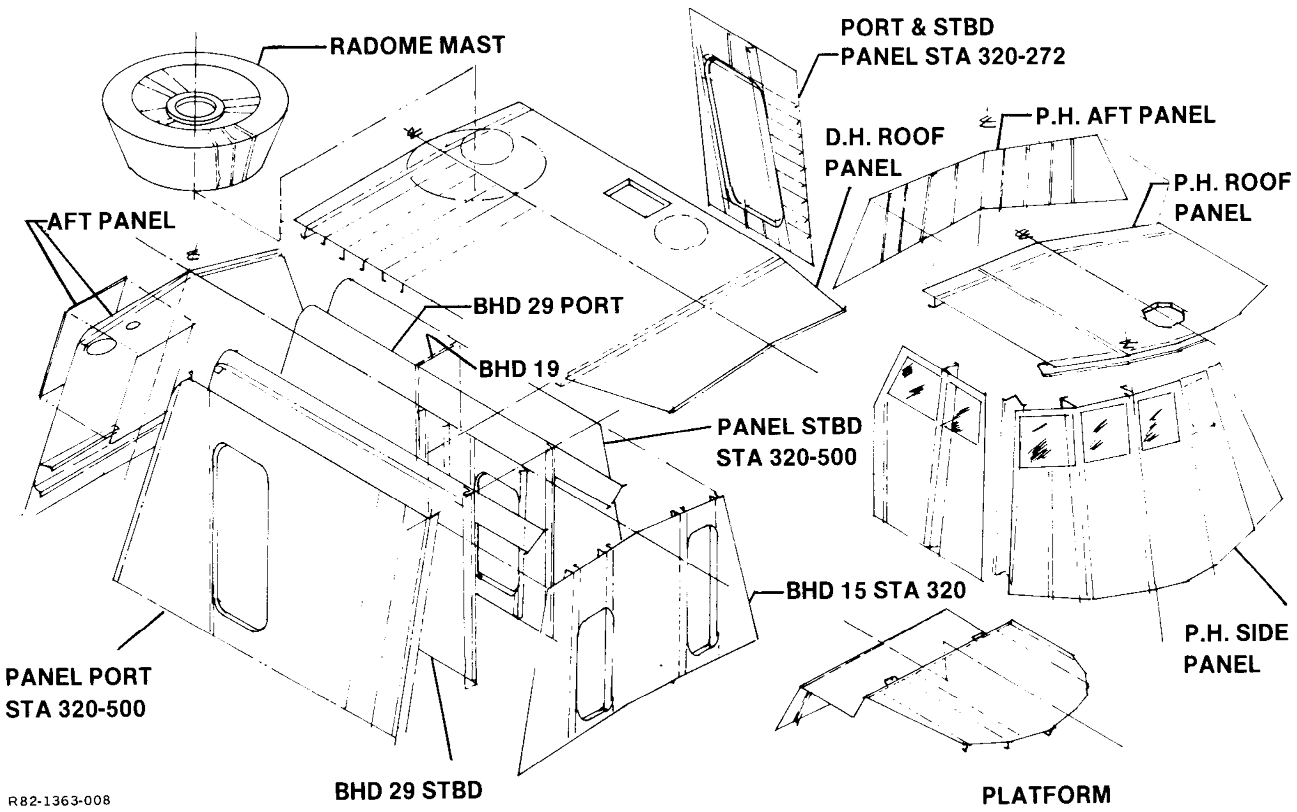

Fig. 8 Forward Deckhouse In Exploded View

weight and one aft carrying about 30% of the gross weight. The entire aft strut is steerable ± 5°, and contains a pod with two gearboxes and the controllable pitch propeller cartridge. The forward foils/struts retract outboard through an angle of 172.5° while the aft strut retracts aft through an angle of 100°.

Each of the three foils has a NACA 16 series section with characteristics defined in Figure 4. The foil pivot axis is located well forward of the center of lift such that the resultant hinge moment always acts to reduce incidence. Each foil incidence is controlled via a single hydraulic servo actuator connected to the foil through a mechanical linkage. Foil incidence is nominally +11 to -5 degrees forward and +10 to -2 degrees aft. Foils are machined from single solid 6061-T-652 aluminum forgings see Figure 9. The full-ship weight foil loading is in excess of 1400 PSF.

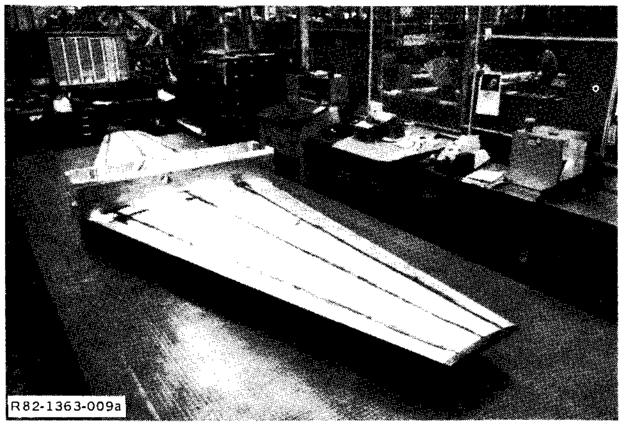

Fig. 9 Forward Foil During Manufacture at Grumman's Bethpage Facility

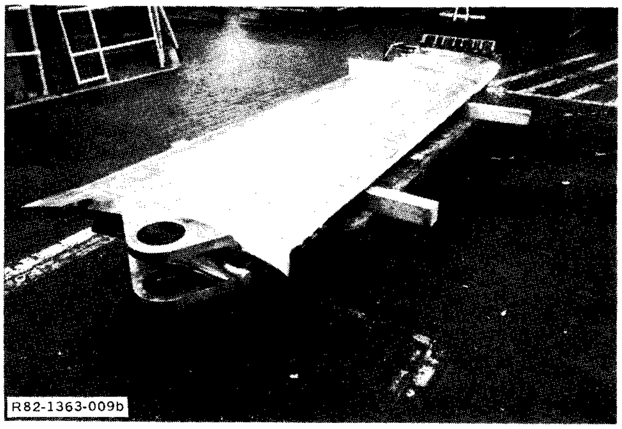

Fig. 10 Forward Strut During Manufacture at Grumman's Bethpage Facility

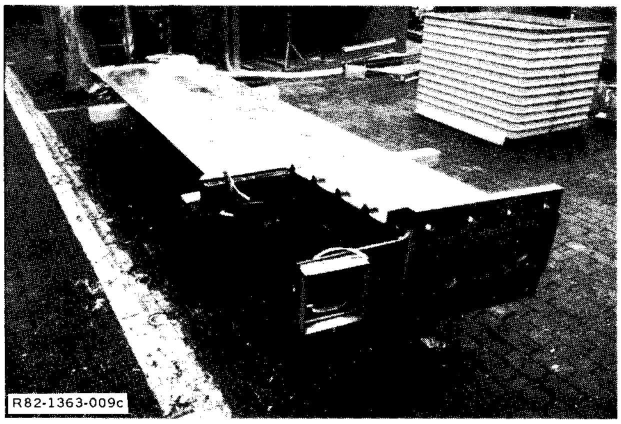

Fig. 11 Aft Strut During Manufacture at Grumman's Bethpage Facility

The forward struts are raked aft and are 40 inch constant-chord NACA -16 series section, tapered from 10 percent thick at the bottom to 24 percent thick at the interface with the yoke. The aft strut is a 60 inch constant chord NACA-16 series section, tapered from 10 percent thick at the bottom to 16 percent thick at the top. In the extended position the aft strut/pod is raked aft 1-1/2° to compensate for the normal 1-1/2° positive angle of attack of the vessel during foilborne flight. Struts are of all-welded construction utilizing high-yield HY 130 steel. Each forward strut contains a large sea water intake line with a leading edge water inlet near the bottom. The aft strut contains the vertical strut drive shaft and support bearings, numerous transmission and CP prop oil lines, and electrical conduit welded in place. Figures 10 and 11 show the forward and aft struts during manufacture at Grumman's Bethpage facility.

Pods are located at the intersection of the forward foils and struts. The forward pods are attached to the foil and move with it during changes in incidence. The aft strut supports the main pod, which contains a bevel and planetary gearbox, the CP prop cartridge, the aft foil incidence servo actuator and a fiberglass nose cone.

Struts are connected to the hull by large yoke structures which rotate with the struts during retraction. The strut-to-yoke interface provides a fused break joint for crash protection of the forward struts while the down-lock link provides protection for the aft strut. Controllable pitch propeller and incidence actuator hydraulic and lube oil enter and leave the aft strut through a large swivel joint.

Main Engine

Foilborne propulsion is provided via a four-bladed controllable pitch propeller driven through a four-gearbox transmission system developed by Western Gear Corporation. Power is provided by a single Allison model 501-KF industrial gas turbine rated at 5400 Hp.

The engine compartment is located well aft in the hull beneath the aft deckhouse. Inlets with appropriate demisters are located on each side of the aft deckhouse. The engine exhaust exits through a large single duct centrally located on the aft face of the aft deckhouse.

The engine consists of gas generator section with a 14-stage axial flow compressor, multiple combustion chambers and a two-stage turbine coupled to a two-stage axial flow power turbine. The engine is a free turbine in that the power turbine shaft is independent of the gas generator shaft. Maximum power turbine output shaft speed is 14500 RPM.

Peripheral equipment includes an Allison-supplied Engine Control Unit (ECU) which monitors critical engine parameters, provides start logic and sequencing, fuel and speed control, and automatic shut down logic. On several occasions during sea trials the unit has automatically shut down the engine after unusual occurrences.

Foilborne Transmission

The foilborne transmission system is a Grumman-owned design designated M-151 designed and manufactured by Western Gear Corporation specifically for Mark II hydrofoils. As shown in Figure 12, the system consists of four gearboxes with interconnecting shafting and has an overall reduction ratio slightly in excess of 14 to 1. The primary reduction gearbox is located internal to the hull in a machinery room immediately aft of the

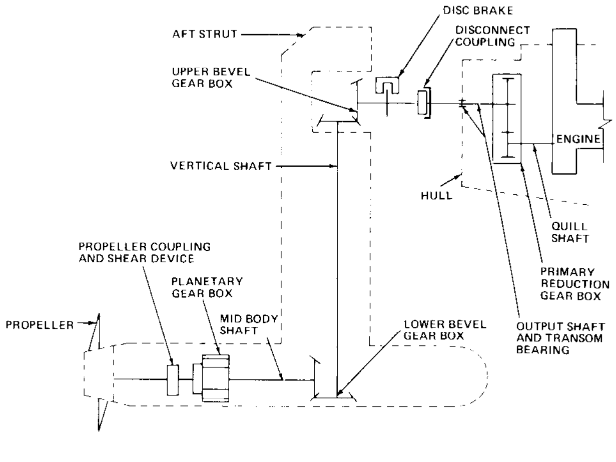

Fig. 12 MARK II Hydrofoil Foilborne Transmission Schematic

engine room. This Hull-Mounted Gearbox (HMGB) is of spur gear design with a reduction ratio of 3.1 to 1. It also provides the following accessory drives:

- Transmission lube oil supply pump
- HMGB scavenge pump
- Propeller pitch control pump
- One hydraulic pump
- Emergency A.C. and D.C. generators.

The upper bevel gear box located at the top of the aft strut is a spiral bevel box of hunting tooth design with a 1.02 to 1 reduction ratio. The only accessory drive on this box is for its own scavenge pump. Mounted on the input shaft is a hydraulically operated disc brake. The brake is used to stop the transmission during shutdown and to prevent propeller wind milling during extension and retraction of the aft strut and during strut down, hullborne operation.

The shaft connecting the primary and upper bevel gear boxes passes through the transom where a support bearing is mounted. Each end of the shaft has a crown tooth coupling to compensate for gearbox deflection under load. The upper bevel box to transom shaft coupling is accomplished with a non-lubricated Delrin* crowned spline riding in a stainless steel straight internal spline. A hydraulic actuator slides the transom shaft fore and aft to connect and disconnect the transmission immediately behind the transom. This arrangement, coupled with the transom bearing, allows main engine operation for maintenance and check out purposes with the aft strut retracted.

The lower bevel gear box is also a spiral bevel gear box of hunting tooth design with the same 1.02 to 1 reduction ratio. The accessory drives for this box include both the lower bevel gearbox and planetary gearbox scavenge pumps. The upper and lower bevel boxes are connected by a vertical strut shaft with a diaphragm coupling at the upper end, and a crown tooth coupling at the lower end. The shaft and bearings are housed in a water tight tunnel built into the aft strut. The aft strut steering axis is coincident with the vertical shaft center line. The upper and lower bevel gears, while identical, are integral with their respective shafts, and, as such are not interchangeable due to the shaft geometry.

The output shaft of the lower bevel gear box is routed through a water tight tunnel and connects to the sun gear of the planetary gear box. The planetary gearbox has a reduction ratio of 4.33 to 1 and utilizes spur gears. Power to the propeller shaft is taken from the planet carrier through a pin type shear coupling. The planetary box is scavenged by a pump driven from the lower bevel gear box.

All gear boxes are fully instrumented with vibration pickups, chip detectors, and resistance temperature detectors for all bearings and in the lube oil scavenge lines.

A pressure circulating lube oil system is used for the transmission. The system has an 85 gallon capacity, utilizes Shell Omala 68 oil, and has a single supply pump driven from the HMGB. Cooling is provided through a single oil/sea water heat exchanger. The main gear-driven scavenge pumps in each gearbox are sized to provide a ratio of scavenge capacity to oil supply of 1.5 to 1. In addition there is an electrically driven lube system of reduced capacity used to prelube the transmission, circulate oil without operating the main engine, and off load oil if required. Reference 2 provides additional information about the main transmission system.

Foilborne Propeller

The propeller is a four-bladed, controllable pitch (CP), 52 in (1.32M) diameter unit designed by NSFI** for Propulsion Systems Incorporated (PSI). Maximum operating speed is 1000 RPM. The blades were designed to be wetted at cruise but in actuality appear to operate transcavitated with a small leading edge cavity. Test data indicates blade cavitation pattern and performance is sensitive to pitch angle. Model tests in the NSFI tunnel produced cruise efficiencies approaching 70%, which appears to be about 5% above that achieved on SHIMRIT at top speed. The blades have thin leading and trailing edges, sections with high

*Delrin is a registered trademark of DuPont

**Norges Skipsforskningsinstitutt (The Ship Research Institute of Norway) camber, and a profile which is nearly symmetrical about the pitch axis.

Blade angle is attained and maintained by a servo-hydraulic system designed and built by PSI. The main components are contained within the prop cartridge shown in Figure 13 which mounts to the output side of the pod planetary gearbox. The system is a continuous flow system utilizing Shell Omala 68 oil. Oil is supplied via a single positive displacement pump driven from the HMGB. A 3-way servo-valve controls a servo-motor internal to the cartridge. The servo-motor drives the main servo, porting oil to two muscle pistons which ultimately move the blades through an eccentric cam mechanism. The muscle pistons are double acting for increasing pitch and single acting in decreasing pitch. The unit is fully flooded with return oil making the outer cowl act as a pressure vessel. The system is configured with an oil/sea water heat exchanger, electric heater internal to the reservoir and a small electric pump to drive the blades to zero pitch prior to engine start and to circulate oil during oil preheating cycles.

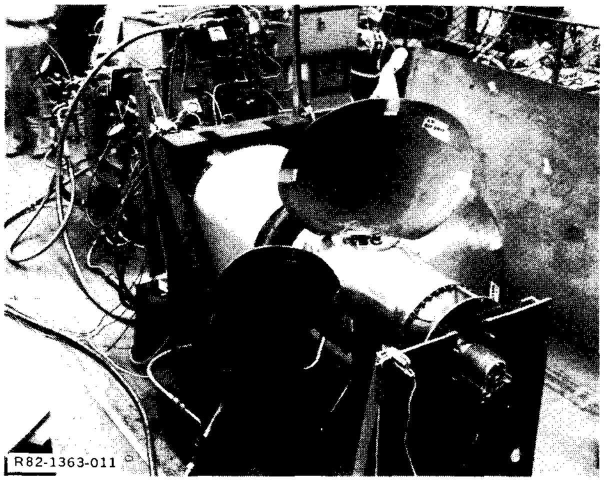

Fig. 13 Foilborne Controllable Pitch Propeller

Blade pitch is controlled by the Prop Pitch Control Unit (PPCU). This electronic servo control network senses actual blade pitch and power turbine output (blade) speed. It compares them with a pre-defined desired schedule and commands a blade angle change to minimize the error.

Hullborne Propulsion

Hullborne propulsion is provided by two hydraulically powered sterndrives mounted on the port and starboard lower outboard sections of the transom. In the extend position the lower leg of the unit protrudes below the bottom of the hull, rotating inboard 90° to its retracted position behind the transom for foilborne flight. Each unit develops 80 Hp at 75 GPM. With the three-bladed, 26 inch (0.66 M) diameter fixed pitch propellers maximum hullborne speed is in excess of 7 Kn.

The sterndrive unit shown in Figure 14 is comprised of a tilt housing which penetrates the transom below the waterline, an upper housing which rotates within the tilt housing and mounts the hydraulic motor, a steerable lower leg. Extension/retraction, locking and steering actuators and

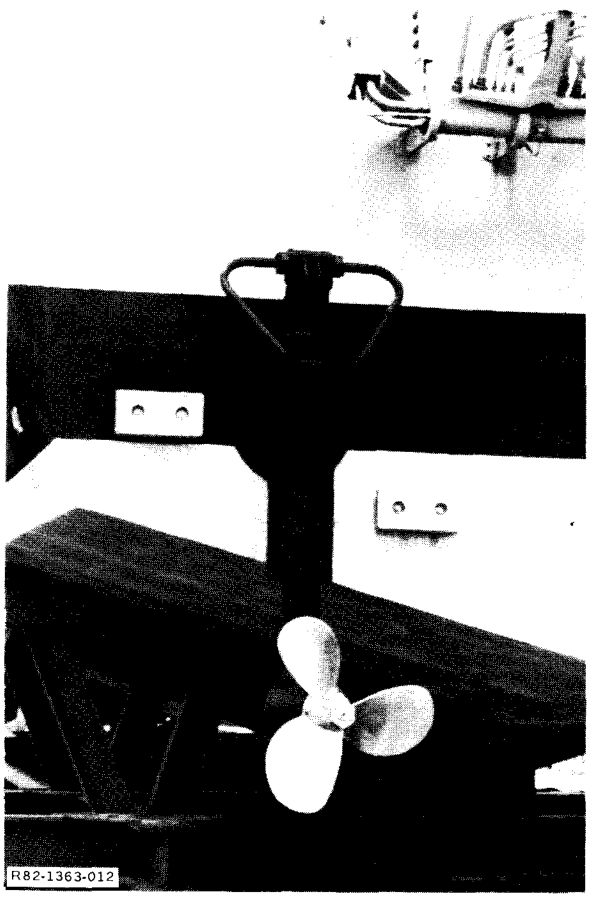

Fig. 14 Hydraulically Driven Sterndrive Installed on SHIMRIT's Transom

linkages are all located internal to the hull. External housings are A356 aluminum castings. A break-away joint is provided on the upper housing to preclude rupturing the water-tight transom seal should the lower leg strike a submerged object.

Hydraulic System

Due primarily to the sterndrives, SHIMRIT is equipped with one of, if not the largest, hydraulic system ever designed for a military vessel of its class. In flow capacity it is larger than the systems of a Boeing 747, Lockheed C-5A or the Space Shuttle. In addition to hullborne propulsion and steering, the hydraulic system supplies power for:

- Strut extension, retraction and locking
- Foil incidence
- Aft strut steering (Foilborne & Hullborne)
- Main engine start
- Sea water, fire fighting and bilge pumps
- Transmission brake/clutch
- Forward deck gun positioning.

The hydraulic system is shown schematically in Figure 15. Hydraulic fluid at 3000 psi is provided by seven Abex pumps, each with a capacity of 64

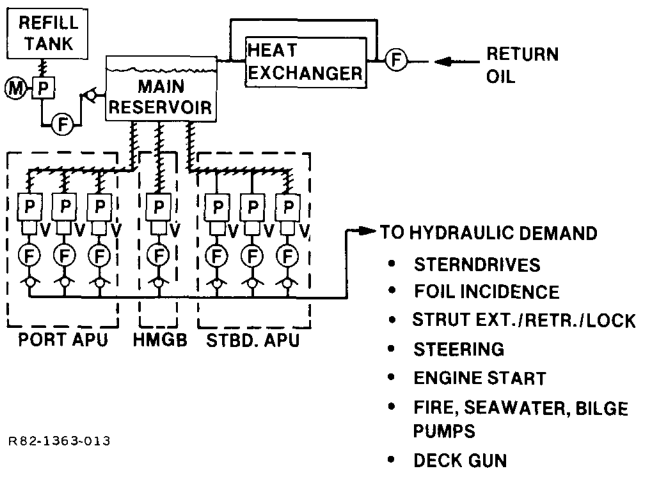

Fig. 15 Hydraulic System Block Diagram

gpm. Three pumps are located on each of two Auxiliary Power Units (APU) and one pump is driven off the main transmission HMGB.

The APU's also provide the craft's electrical power. During hull borne operation both APU's are operational. During normal foilborne flight only one APU is operational supplying all the craft's electrical and hydraulic needs. The single hydraulic pump and AC and DC generators on the HMGB accessory pads serve as emergency units should a failure require a switch over to the other APU. The craft can however operate foilborne on the emergency units only.

The system has a 35 gallon air over oil pressurized reservoir with antivortex baffles, velocity dissipation, entrained air removal and suction stand pipes. Dual level indicators integrated to the Engineering Monitoring and Control System (EMCS) provide a warning and ultimately an automatic shutdown for low oil level.

A separate tank and electric motor pump provide fluid for automatic refill of the main reservoir with filtered, pressurized fluid. It stores sufficient fluid for one main tank refill.

Hydraulic oil is fire-resistant synthetic hydrocarbon MIL-H-83282. System fluid filtration is 5 micron absolute. All filters have local and remote differential pressure indicators. Each pump has separate case drain and discharge filters. All motor case returns and all return fluid is filtered prior to passing through a single sea water cooled heat exchanger which by temperature feedback maintains oil operating temperatures between 100°F to 150°F, thereby enhancing pump life.

Electric Power System

Both AC and DC electrical power are available aboard SHIMRIT. The craft's primary service electric power system (EPS) is a 120/208 Volt, 3 phase, 4 wire, 400 Hz system, ungrounded except where the neutral leg is connected through a resistor to ground at specific points. The distribution system is of the radial type, with a single main switchboard for protection and control. Power distribution panels are selectively located near load centers to minimize cable lengths and bulkhead penetrations. The EPS may be controlled and operated locally at the switchboard or remotely from the Engineers Operating Station (EOS) via the Engineering Monitoring and Control System (EMCS). The EPS may be operated as either a split or parallel bus system with either or both generators supplying the loads in a split, tie bus or parallel configuration.

Power is supplied by 200 Kw AC generators and 200 ampere/28 Volt DC starter/generators driven by the port and starboard APUs. Each APU driving a single AC generator and DC starter/generator is capable of supplying the craft's entire electrical power needs. Under normal foilborne operation only one APU would be on line although in battle the commander may opt to activate both APU's with electrical and hydraulic load sharing.

Emergency power is available from a single 35 Kw AC generator and a single 100 ampere/28 Volt DC alternator mounted on accessory pads of, and driven by, the foilborne transmission HMGB. The emergency power available is sufficient to satisfy the essential electrical and hydraulic loads and thus maintain the craft foilborne.

The craft's main service switchboard provides for control, display and protection of the generators as well as control and protection of the power distribution system. The switchboard is located in the instrumentation room and is operated both locally or remotely from the EOS. The switchboard consists of two sections, an AC section and a DC section. Each section contains all necessary controls and appurtenances to protect and control the ship's electric power system. The switchboard is subdivided into two sections to facilitate entry and assembly into the craft as well as to minimize the effects of electrical faults.

Starting power is provided by 24 volt marine diesel starting batteries sized to provide 6 consecutive 60 second starting cycles without recharge. The batteries are recharged from the APU starter/generators or from the emergency DC generator. Dockside, the batteries may be charged by a transformer-rectifier.

Automatic Control System

SHIMRIT is designed with an advanced digital hybrid fly-by-wire automatic control system (ACS). Craft state is sensed by appropriate sensors the information of which is processed by a digital computer. The computer unit generates foil commands which, via a digital to analog interface are issued to the servo amplifier unit, the analog control for the servo actuator. Dual tandem non-redundant servo actuators, designed and built by Grumman, control flight of the boat by modulating the position of the incidence controlled foils. ACS craft altitude and motion inputs include height from two radio altimeters in the bow, vertical acceleration from an accelerometer, heading from the PL 41 gyro, roll and pitch attitude from dual redundant vertical gyros, and roll, pitch and yaw rate from rate gyros. This information is supplied to the ACS computer which compares it with desired parameters and automatically commands the desired foil incidence and aft strut turning angle.

The ACS supplies control during both hullborne and foilborne operation. Hullborne, with struts extended, the ACS provides pitch and roll compensation. Foilborne, the ACS controls take-off and landing, foilborne height (both platforming and contouring flight) and turning. The ACS also contains broach prevention logic and provisions for heading hold, both hullborne and foilborne.

In the take-off mode the ACS permits the helmsman to concern himself with only the throttle and wheel. Prior to initiating the take-off he selects the take-off mode and sets the desired cruise height and pitch attitude (normally 1-½°). During the take-off acceleration the foils automatically lift the craft to the pre-set height and pitch while the roll channel maintains teh craft's roll attitude. Once on the foils the helmsman switches the ACS to the cruise mode.

To execute automatic landings the helmsman merely reduces the throttle setting. The craft flares-out and gently settles into the water with the roll channel maintaining roll altitude.

During foilborne operation the ACS is capable of totally controlling the craft's flight path. In sea states where sufficient strut height is available to prevent wave impact on the hull a platforming mode is maintained. In this mode the height sensors detect the average height relative to the mean water surface and compare it with the height setting. The error signal is used to compensate for craft motions by commanding the forward foils. Simultaneously, pitching motions are compared with the pitch attitude setting. Deviations are corrected via commands to both forward and aft foils. Roll stability is of course maintained with differential forward foil incidence.

Contouring becomes necessary when the sea state makes platforming impractical. The basic control loops in the ACS remain the same and function as in the platforming mode. The difference is that the loops cease to be averaging devices and therefore track the sea state more closely allowing greater but properly phased deviations from the commanded height and pitch attitude. The craft rides or tracks the waves in contouring motion. Roll stability is maintained.

One of the unique features of the ACS is broach prevention logic. Broach prevention is accomplished by sensing the pressure in the sea water intake lines within each forward strut. The sea water intakes are located on the leading edges of the forward struts several feet above the foil pivot axis. On an impending broach the inlets ventilate, thus causing a loss of sea water line pressure. The ACS responds by momentarily lowering the operating height of the craft until the intake re-enters the water and pressure is re-established.

In foilborne turns the ACS is capable of automatically banking the boat at angles ranging from zero degrees (flat turn) to full allowable coordination, at design speed. Maximum coordinated turn bank angle is 15°.

When a turn is commanded, a roll command proportional to sensed turning (or yaw) rate is generated. The generated angle is the roll command reference or commanded angle of bank. The deviation between the command and the state of roll motions is evaluated by the computer which commands the main foils to supply a compensating differential incidence to suppress the deviations. The result is that the ACS holds the boat in a steady banked turn, in conformance with the degree of bank required by the yaw rate command.

Heading hold is another ACS feature which enables the operator to select a desired heading which is automatically maintained either foilborne or hullborne. Once a heading reference is selected, the system senses the actual heading from the gyro-compass. If the heading differs from that commanded, an error signal is generated followed by commands to the steering actuator(s) to modify the thrust vector of the stern strut, if foilborne, or outdrives if hullborne. In either event, the response is such as to align the craft with the commanded heading.

In calm water, the boat will achieve steady alignment with the reference signal. In a seaway, the boat will always experience a slight heading deviation. Consequently in a seaway the system constantly seeks the reference heading.

Engineering Monitoring and Control System

The complexity and sophistication of SHIMRIT's systems would under normal circumstances require that about half of its 15 man crew be assigned to systems operation, monitoring and control duties. However, with the development of the unique and revolutionary Engineering Monitoring and Control System (EMCS), a single Engineering Officer is able to monitor and control the boat's operating systems and subsystems.

The EMCS is an integrated, distributed microprocessor based system, designed to provide reliable single point management of the SHIMRIT's propulsion, hydraulic, electrical and support systems.

With an inherently small crew devoted almost entirely to the boat's tactical mission, and a hull design that is as weight/volume sensitive as a fighter aircraft, the requirement for a lightweight, power conservative system capable of monitoring and controlling 22 boat systems and subsystems was clearly established.

As a result of this requirement, a system architecture evolved that consists of six microprocessors embedded in six remote terminals (RT's) that are distributed throughout the craft in the proximity of the specific boat systems being monitored and controlled, and an Engineers Operating Console (EOC) that provides the single point through which the boat's engineer can operate the craft, (see Figure 16). Data communication between the RT's and the EOC is achieved by the use of a dual redundant MIL-STD-1553A Data Bus, operating in the dynamic bus allocation.

The EOC is a major component of the Engineers Operating Station (EOS) located in the Combat Information Center (CIC). The other components of the EOS are the Emergency Monitoring and Control Unit (EMCU), and a set of back-up throttle control levers for the main engine and the two APU's. The EMCU provides back-up monitoring and control of essential systems in the event of EMCS failure.

The EOC shown in Figure 17 consists of two plasma displays on which alpha-numeric status reports of the monitored systems are presented. Control formats are also presented that interact with microswitches located at either side of the

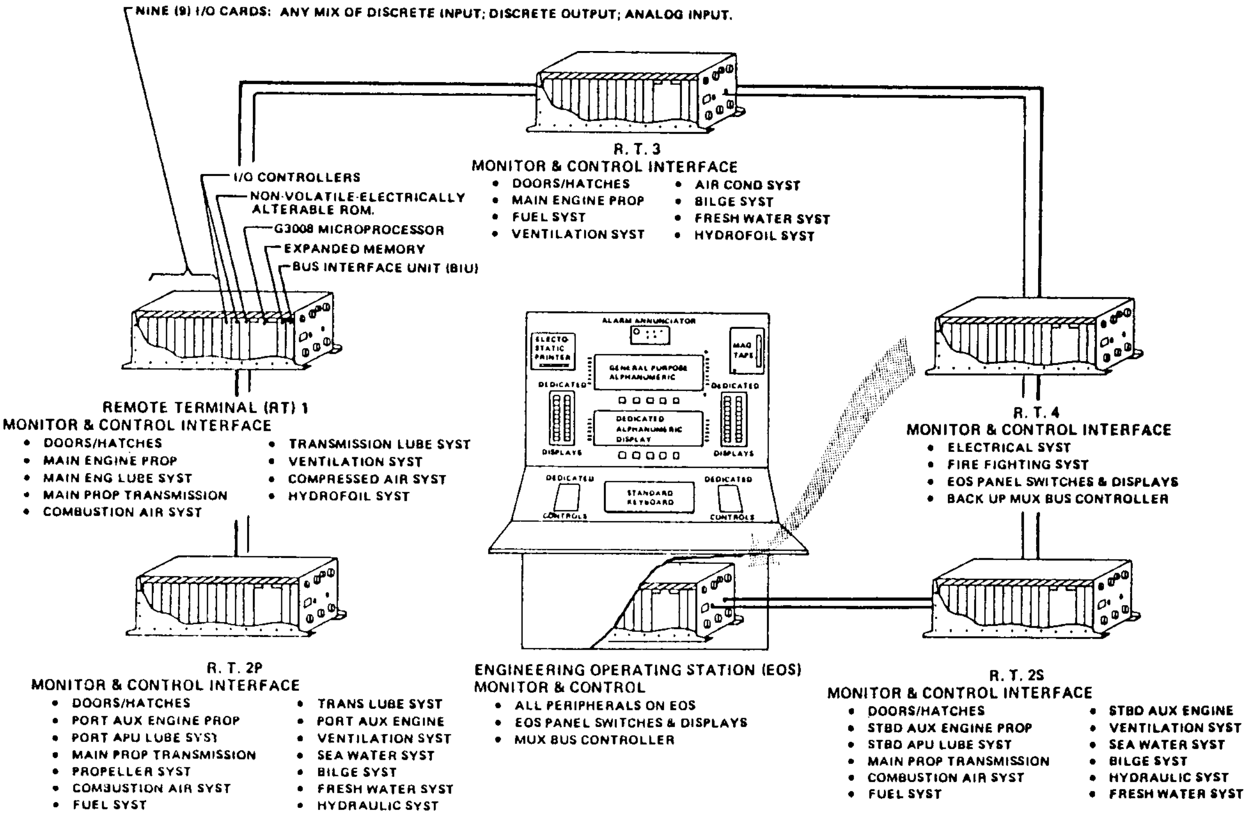

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Fig. 16 Engineering Monitoring and Control System Schematic

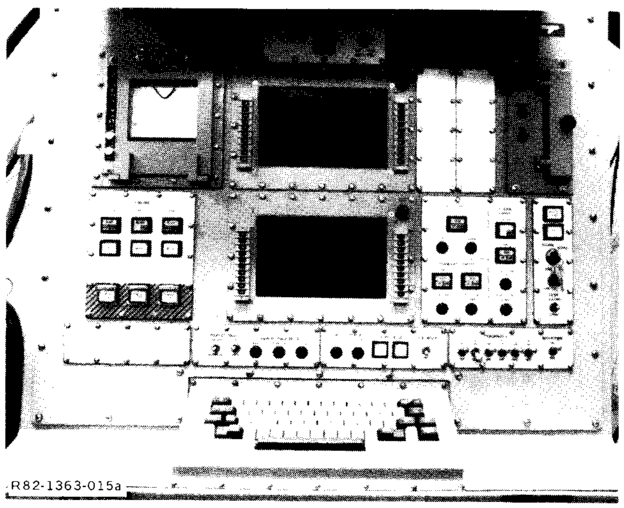

Fig. 17 Engineer's Operating Console of EMCS System

displays, providing both boat operational and EMCS functional controls.

There are seven additional control/display panels on the EOC that, with the exception of the Caution Advisory Panel, have functions dedicated to status reporting and control of specific systems on the boat. These are:

- Engine Control Panel
- Struts and Stern Drive Panel
- Display Control Panels (2)
- Power Control Panel
- Miscellaneous Control Panel.

The Caution Advisory Panel provides an annunciator function when a condition (component failure or out of limits parameter) occurs in a boat system that requires some level of advisory. The three levels of advisory are:

- Level III, Steady (red) light, non-critical
- Level II, Flashing light, critical
- Level I, Flashing light/90db tone, Critical/System Safety.

More specific fault information is obtained by selecting the fault display on one of the plasma displays.

Additional equipment found in the EOC are the Magnetic Tape Recorder and Thermal Printer used for recording operating parameters during a mission, a standard keyboard for auxiliary functions, various power supplies required for the console peripheral equipment, and two (2) of the six (6) EMCS RT's.

The Remote Terminal is the foundation of the EMCS. Each of the six RT's are electrically and electronically identical and interchangeable. However, each is programmed to perform the specific monitor and control functions associated with its physical location.

Firmware in each RT is divided into two basic segments: a common system module, and a terminal specific, "user", module. The system firmware performs the functions of initialization, built-in test, bus communication, and contains a library of common user subroutines. The user firmware comprises the bulk of the specific RT processing requirements, which include I/O control, processing monitored parameters, caution advisory, generating control commands from automatic sequences or in response to commands from the EOC, and generating displays at the EOC.

Subsystem information monitored by each RT is converted, scaled, formatted, and tested at a rate consistent with the information update requirements of the overall system. Subsystem alarm flags are set whenever an associated failure condition exists. The processed information is transmitted to one of two RT's (designated prime), located in the EOS, that share the functions of control/display processor and bus controller. All information between the RT's is accomplished via the MIL-STD-1553A Mux Bus on a fixed schedule of four (4) times a second. All information received by the non-prime control/ display processor is output to the magnetic tape unit to provide a continuous, time related, history of the monitored operational parameters. The tape will always contain the last 30 minutes of history. Operational information is displayed on the control panel, according to the modal requirements established by the operating engineer. System alarms are presented immediately in accordance with their classification.

Development Challenges

Foilborne Transmission

Historically the foilborne transmission has presented the greatest reliability problem for Grumman hydrofoils. Consequently, it was decided early in the Mark II development to subject each M-151 transmission system to a 50-hour loaded back-to-back acceptance test (see Figure 18). Eight load levels were defined (six at representative operating conditions including take-off power, one at over torque and one at overspeed) for a minimum of six hours of continuous testing at each condition. An "A" frame type test stand shown in

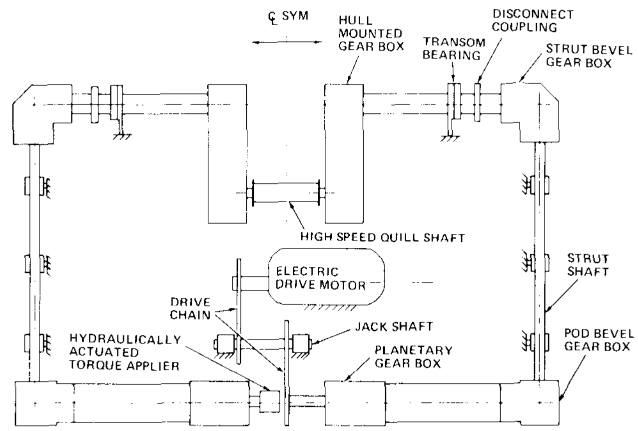

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Fig. 18 M-151 Transmission Back-To-Back Test Schematic

Figure 19 was constructed at Western Gear to accommodate two complete transmissions. The transmissions were electrically driven from one planetary gearbox output (propeller) shaft, with the load applied via a hydraulic torque applier at the second (slave) transmission planetary gearbox output shaft. Thus both transmissions are fully loaded, with one rotating in the reverse direction.

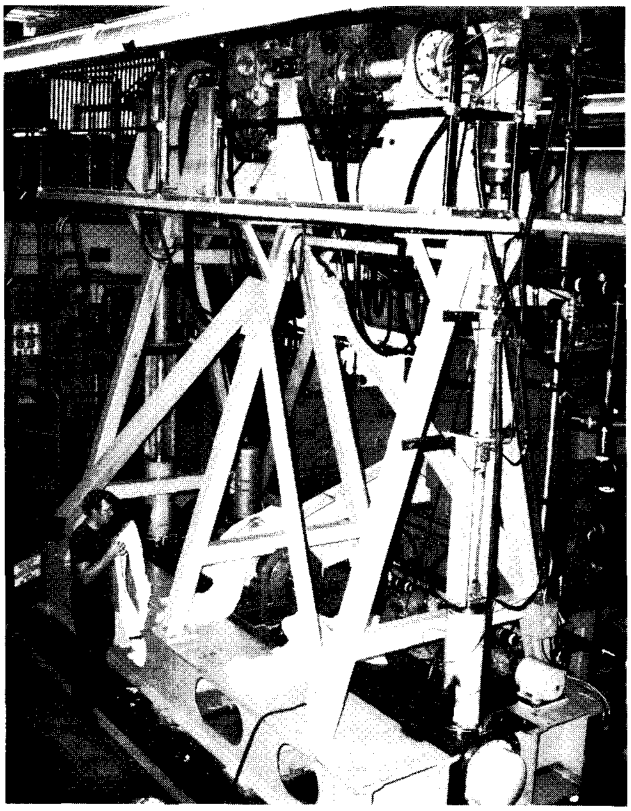

Fig. 19 "A" Frame Test Stand For M-151 Transmission Back-To-Back Testing

Prior to acceptance of the first transmission, approximately 130 hours of testing were accomplished, 90 hours at or above 70% load. Numerous problems were encountered during this testing, almost all of which were related to test stand stiffness and difficulties with the chain drive system. The test did, however, enable us to discover manufacturing-related quality problems on the HMGB output "Bull" gear of S/N 101 transmission and the PBGB pinion gear of S/N 102 transmission which otherwise would have gone undetected and failed in service. It also permitted the identification/ solution of an alignment problem with the disconnect coupling and a problem with an under strength bronze bearing cage both of which could have severely impacted transmission durability in the field. As a result of this pre-acceptance loaded testing S/N 101 transmission performed flawlessly with no failures experienced throughout the 285 hours of operation in sea and acceptance trials on SHIMRIT.

Foilborne (Controllable Pitch) Propeller

The developmental challenges with the CP prop were primarily concerned with the pitch control cartridge and electronic control unit. The prop blade contour development and model test went smoothly with the model tests at NSFI indicating a prop cruise efficiency slightly greater than anticipated.

Early developmental problems were structural in nature. The first occurred during a proof pressure check of the unit at PSI when the outer cowl yielded. The original thin skin welded design was abandoned, and Grumman assumed responsibility for the redesign of a new cast aluminum cowl. A second structural failure of an internal main shaft housing casting occurred on a subsequent test and again Grumman assumed responsibility for the redesign.

Financial difficulties at PSI caused Grumman to negotiate a termination of PSI and relocation of the CP prop work at Bird-Johnson. The subsequent assembly and test of the unit was accomplished with relatively few significant problems.

Early in sea trials a prop pitch instability was discovered wherein the blades would hunt continuously. Efforts to resolve the problem on the vessel were only partially successful and a second unit was set up in a Grumman laboratory for evaluation, see Figure 20. Analog computers were utilized to simulate Prop Pitch Control Unit (PPCU) input and feedback signals. Hydraulic power was supplied with a ground cart, and additional instrumentation was added to monitor significant parameters. An extensive laboratory evaluation resulted in changes to the PPCU gains and lead/lag network. New main servo hydraulically balanced spools/sleeves were also installed. These changes completely resolved the pitch instability problem, and the units have performed well in service.

Fig. 20 Laboratory Set Up For Foilborne Propeller Stability Investigation

ACS

The ACS development was a joint effort of GAC and Hamilton Standard. Grumman developed the control laws, specified the boat-related preflight and in-flight BITE testing, and shared in the on-site modification of all aspects of software implementation that affect boat performance. The hardware design of the CU and SAU along with the software design and implementation in the CU were the product of Hamilton Standard. Hamilton Standard also supplied all ACS sensors with the exception of the height sensors.

One of the unique features of the development effort was the use of two vendor supplied revisions of the CU, one called the PMCU/Brassboard, the other the production CU. The Program Monitor and Control Unit (PMCU)/Brassboard consists of a unit capable of patch programming and checking contents of the CU operating program (PMCU) which interfaces with a core memory CU (the brassboard). This combination was used for the major portion of the sea trials development program, and represented a powerful tool in effective ACS development. The production CU was flown in the latter stages of the sea trials using plug-in PROM boards. The "plug-in" PROMS will be used until effective operation of the finalized system is assured. It will then be replaced by hard PROM.

The sea trials development cycle dealt with the "tuning" and finalization of the foilborne longitudinal and lateral directional channels, the setting of broach prevention parameters, finalization of the heading hold channel, and firming of the take-off schedule. Of these tasks, the greatest difficulty resided in the longitudinal channels (pitch and heave). When initially set, the vessel experienced excessive pitching and heaving foilborne in following seas. Through an intensive "on-site" analytical effort and use of the PMCU/brassboard unit, the problem was resolved. The craft now possesses excellent dynamic performance coupled with virtually no tendency to broach in heavy seas.

Considerable attention has been focused on matters of safety in emergency situations. Provision of both redundant and analytically redundant sensing supplies a fail-safe operational capability in the event of sensor loss. A major computer failure results in power severance of the computer within one sample frame (1/80 sec). Power severance causes the forward foils to be driven to a preselected negative incidence, and causes the boat to land rapidly and safely. Loss of SAU power causes the forward foils to be driven to the negative stops, driving the boat safely into the water. For emergencies, such as collision avoidance, an emergency switch is located on the helm and will drive the forward foils to the negative stops when activated by the helmsman. The resulting landing brings the boat to a halt within a few boat lengths.

EMCS

The general concept of a distributed microprocessor control/monitor system, as well as most of the hardware, had been developed on a previous project. Still, several significant technical and administrative challenges were presented in the development of the EMCS.

The design goals for the EMCS were established to produce a system that:

- Would take advantage of technology advances achieved in previous years of R&D
- Was mission reliable
- Was maintainable with a limited on-board spares compliment.

Consistent with these goals, hardware/software standardization received a very high priority.

The basis of the EMCS design is derived from one of the five (5) components that constituted the Integrated Avionics Control System (IACS), a helicopter cockpit COMM/NAV Management System developed by Grumman for the U.S. Army.

The IACS Primary Central Control Unit (PCCU) was used as the basic building block of the EMCS design. By using six (6) PCCU's as remote terminals and processor/controllers, modular interchangeability and redundancy, and processor sharing of operation critical functions, a system that is maintainable with limited spares requirements and is mission reliable was configured.

One of the most significant development challenges on the M-161 was the software for the EMCS. Operational specifications for the EMCS required development of a communications protocol to allow each of the six (6) remote terminals to control the 1553A data bus once every 250 milliseconds in order to complete the transfer of over 650 associated monitor and control signals. Data recording, playback and printing of all significant system transactions, were additional specification requirements that combined to create a common timing problem.

The greatest problem associated with the EMCS software development was the incomplete boat system functional information required for the timely completion of terminal specific software. Consequently, while the EMCS was installed and operational prior to initiating sea trials, during most of the sea trial program the EMCS software was continually being revised and updated, thus giving the appearance of a major development problem.

Administratively, the two major problems in the development of the EMCS were cost and schedule. The primary contributor to these problems was the absence of a complete systems design specification at the time of Program Work Authorization. This resulted in an under estimation of the EMCS design requirements. In fact, at the time of initial work authorization, the design of the M-161 systems had not been finalized. Consequently, the 13 month delivery schedule established assumed a previous system design analysis phase had been completed. In essence a production schedule was accepted for a systems development project.

Another contributor to the schedule problems was manifest in the procurement of components for EMCS fabrication. Given a complete systems design, delivery lead times for a large percentage of the components for the EMCS precluded an on-time system delivery.

All challenges were eventually overcome, as witnessed by the successful operation of SHIMRIT by the EMCS. However, the problems incurred, both technical and administrative, did contribute to the slippage of the program milestones.

Performance

During the early phase of sea trials data indicated that at a given power the vessel was significantly below its target specification speed. Initially it was suspected that a ventilation of the aft strut was entering the propeller disk and adversely impacting performance. The NSRDC underwater dive team was employed to photograph the foils during foilborne cruise. The photography, accomplished by flying the boat through narrow course, indicating strong tip vortices coming off the forward foils and a small hydrodynamic disturbance emanating from the aft pod/foil interface. Subsequent strut and pod gear box pressure checks failed to identify a source of ventilation. A set of fences was designed and installed on the aft foils to substantially close the cavity between the foil and pod. Subsequent underwater photographs and testing showed that the fences were effective in eliminating the disturbance and produced a one kn improvement in speed at max cruise power.

Significant improvements in speed were also obtained from the following modifications:

- Polishing strut and foil surfaces to reduce drag - 2.0 kn improvement in max cruise speed
- Re-machining propeller blades to improve leading edge and blade contours - 1.5 kn improvement in max cruise speed
- Addition of propeller spinner to reduce base drag - 0.8 kn improvement in max cruise speed.

Spreading the forward struts and foils outboard to move tip vortices away from the propeller disk had no effect on speed but adversely impacted coordinated turning performance. The spread foil outboard tip was closer to the water surface and thus more susceptible to ventilation. The measures taken produced a total five to six kn improvement in maximum cruise speed.

Development Test Program Summary

On June 25, 1982 SHIMRIT completed its sea and acceptance trials program and was hauled for post test inspection and delivery preparation. All foilborne contract and specification performance parameters were achieved. A total of 549 operational hours were logged with over 288 hours on the main engine. Approximately 465 take-offs were made with a total foilborne time of 121 hours.

Figures 21 and 22 present some foilborne speed and take-off time data obtained in the latter part of the sea trials program. As evident from the data

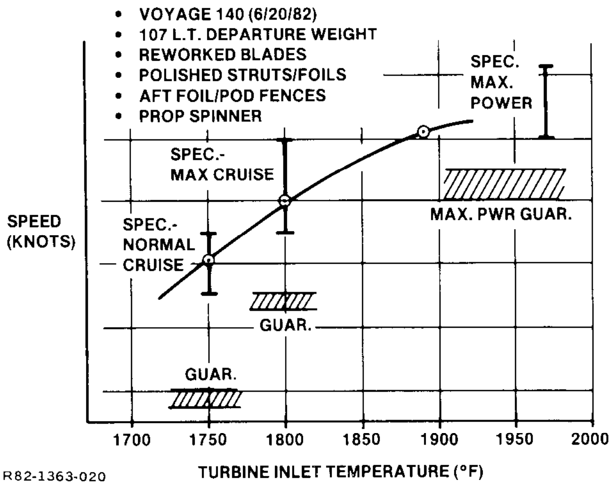

Fig. 21 Demonstrated Speed Vs. Contract Guarantees and Specification Values

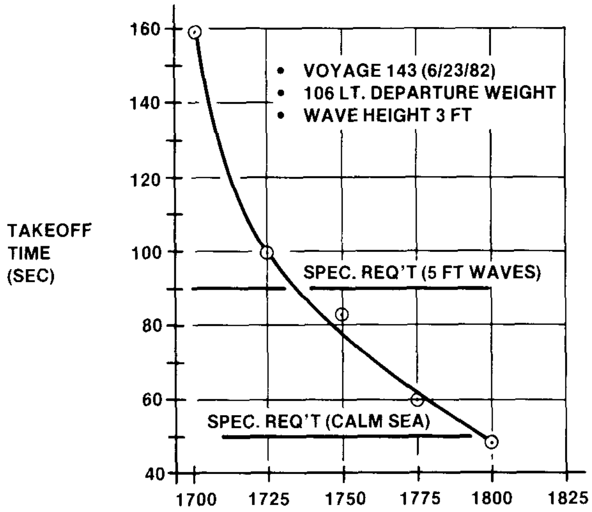

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Fig. 22 Demonstrated Take-off Times For Various Engine Power Settings Below Max Power

of Figure 21, foilborne speed at full ship weight is well above contract guarantees and within specification requirements. Take-off times demonstrated at full-ship weight in a moderate sea, as shown in Figure 22, are also within specification range. It should be noted that the data points in Figure 22 were generated for engine powers well below take-off power and consequently are not representative of minimum take-off times.

During sea trials the vessel was flown at displacements as high as 111.6 L.T. At this weight the vessel took off in 40 seconds and successfully flew with no differences in handling qualities noted. Foilborne speed was virtually unchanged, and the foilborne range with the full load of fuel was calculated at in excess of 1000 N.M.

In coordinated turning tests SHIMRIT has demonstrated turning rates substantially better than FLAGSTAFF. Excellent turning performance was achieved at weights as high as 105 L.T.

Overall the craft demonstrated a high level of reliability throughout the sea trials program. Very few failures of significance or of critical components were experienced. The large majority of hardware failures were with components (valves, sensors, etc.) which invariably were designed and built as "commercial quality." As noted previously, a great deal of time and effort was expended in developing and refining the complex systems on board. As these tasks/failures were completed/corrected the operational readiness and performance of the vessel improved, as did our confidence that the Mark II SHIMRIT was truly an outstanding military hydrofoil.

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THE EVOLUTION OF THE NIBBIO CLASS HYDROFOIL FROM TUCUMCARI

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Ingonish Beach, Nova Scotia, Canada - July 27-30 1982

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ABSTRACT

The development of the Italian SPARVIERO and NIBBIO class hydrofoils provides a special lesson. These ships were derived from the U.S. TUCUMCARI design. Their evolution offers some insight into the problems of developing a hydrofoil class that is a variant of another, successful class.

This paper includes a discussion of the evolution of the NIBBIO and its various systems from TUCUMCARI via SPARVIERO. Lessons which can be applied to other such projects are described.

INTRODUCTION

Over the years, many of us have proposed evolutionary hydrofoil designs. These involve adapting the design of a successful ship to a new mission or function.

The NIBBIO class hydrofoil is particularly interesting not just for its own characteristics but also because of its heritage: The NIBBIO is the "grandchild" of TUCUMCARI -- a successful evolutionary design. We shall trace its evolution from TUCUMCARI through SPARVIERO to NIBBIO.

This paper draws on the SPARVIERO/NIBBIO history to provide insight for those proposing similar evolutionary projects. First, we will examine some key characteristics. Then, we will study the evolution of various systems and discuss combat systems briefly. Finally, we will draw some general conclusions applicable to evolutionary designs.

The contract for TUCUMCARI (PGH-2) was let to The Boeing Co. in 1966. She was one of two ships built to serve as hydrofoil patrol gunboats (the other, PGH-1 FLAGSTAFF, was built by Grumman Aerospace Corp.). TUCUMCARI was delivered in 1968, and served on the U.S. West Coast, in Vietnam, and in the Caribbean. She made a deployment in Europe in 1971. In 1972 she was run aground, severely damaged and finally decommissioned.

In October 1970, the Italian Navy awarded a contract for the design and construction of the 928-22 class of hydrofoil missilecraft. The Contractor was Alinavi, S.p.A. which had been formed in 1964 to develop, manufacture and market military and commercial advanced marine systems, primarily in the European and Mediterranean areas. The company was owned jointly by The Boeing Company (60%), Finmeccania (30%), and Carlos Rodriquez (10%). Under the terms of a Boeing-Alinavi licensing agreement, Alinavi had access to Boeing technology for fully-submerged foil hydrofoil craft. The design of the lead ship to be produced, SPARVIERO (Swordfish), P-420, is based on that of TUCUMCARI, a Boeing product. SPARVIERO was delivered to the Italian Navy in 1974.

The NIBBIO class ships are being built in the Muggiano shipyard of Cantiere Navale Riunite. Key characteristics of TUCUMCARI and SPARVIERO are shown in Table 1.

TUCUMCARI was designed as a patrol boat. She carried a crew of 13. In the patrol mission, she could spend a considerable amount of time at low speeds and was designed to spend several days at sea. The Italian boats, on the other hand, are attack craft with only 10 crew members and short-duration missions.

ARRANGEMENTS

Because the SPARVIERO and NIBBIO class ships are designed as fast-attack craft rather than as patrol gunboats, extensive rearrangement of the basic ship was required. A simplified arrangement of TUCUMCARI is shown in Figure 1. This is compared to the view of SPARVIERO in Figure 2. The 76mm OTO Melara gun is dominant in the Italian boat. This was accompanied by the addition of the OTOMAT missiles and growth of the Combat Operations Center and electronic equipment room. The additional space required for these items was obtained by reducing space for crew support.

The difference in hull shape is interesting. The beam of the Italian boats is greater than that of TUCUMCARI. This represents an increase of volume and an increase of transverse inertia, particularly at large heel angles--required by the heavier topside loading of the combat system. The length-to-beam ratio is reduced. This is reasonable because the Italian boats would be expected to spend relatively less time hullborne than TUCUMCARI.

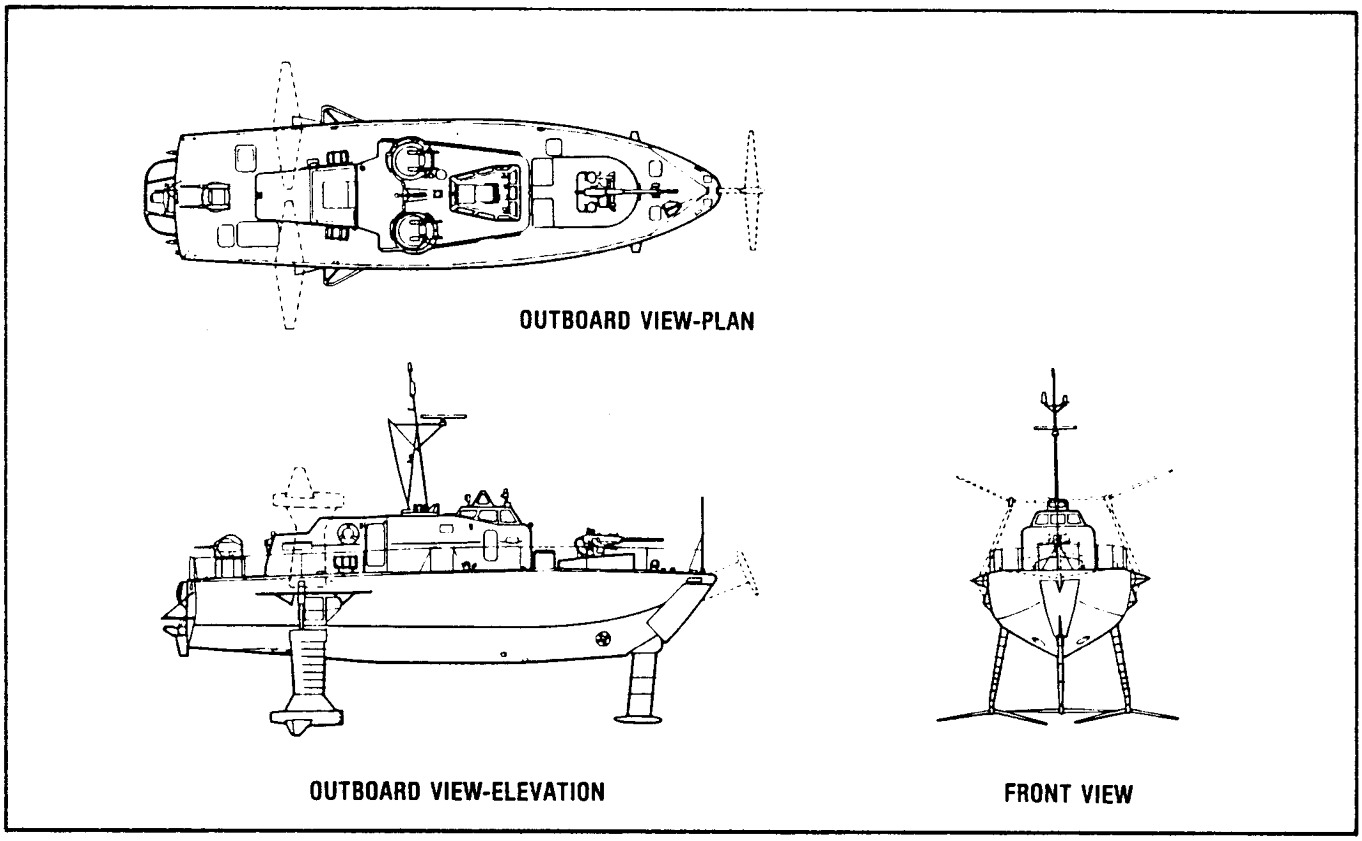

Figure 1. TUCUMCARI (PGH-2)

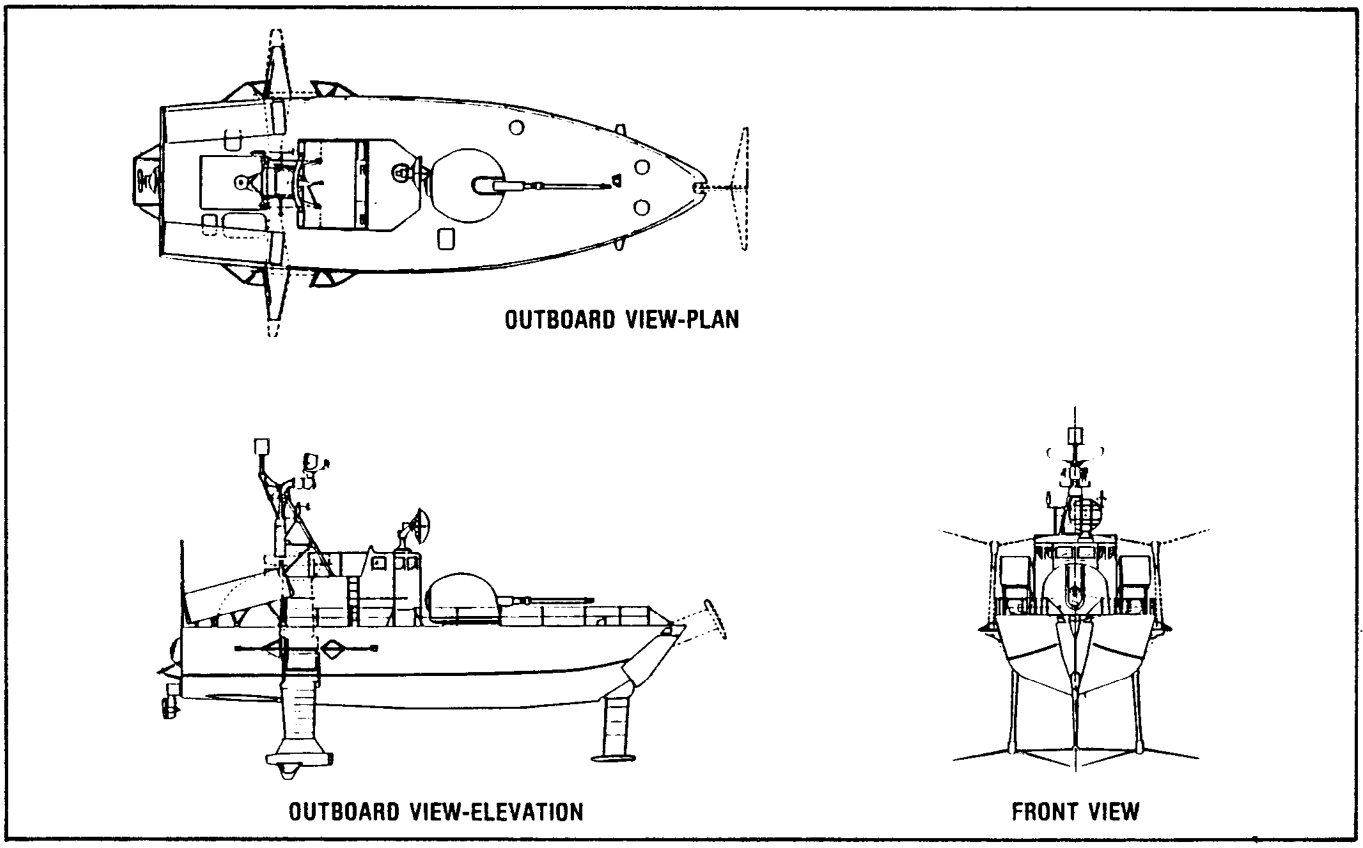

Figure 2. SPARVIERO

Crew accommodations were also affected by the different mission. TUCUMCARI was designed for patrol missions and could spend several days at sea at low speed. Her crew was comprised of one officer and 12 enlisted men. Accommodations were spartan but each man had a bunk. A small galley, six-man mess, and sanitary facilities were also provided.

The Italian attack craft are true "day-boats" (12-15 hours of operation). Despite their sophisticated combat system, there are only 10 crew members. Crew support facilities are virtually nonexistent. As a weight-saving measure, the water heater and refrigerator included in SPARVIERO were not even included in the NIBBIO and her sisters.

Thus, the desire for more combat strength together with shorter duration mission requirements resulted in a very different combat system and equipment arrangement within a similar hull. Minor changes in spaces from those of TUCUMCARI were not adequate. A very different arrangement was required, suited to the new ships' function--attack craft--and to comply with Italian Navy practice.

HULL STRUCTURE

The progression from a basic ship to a variant might seem to involve few structural problems. Indeed, when such proposals are made, hull structure is sometimes overlooked. This case illustrates that the requirements of the variant can often dictate many changes in the structure.

While the hull form of the Italian boats is quite similar to that of TUCUMCARI, the structure is different. For example, the American boat's hull was constructed of 5456 welded aluminum, while production reasons caused the use of welded 5853 aluminum in SPARVIERO and the production boats.

Further, and of great significance, is the change in combat system and its influence on the structure. The weapons on TUCUMCARI were relatively small with limited structural loading. On the other hand, the OTO Melara 76mm gun dominates the structure of the Italian variants. This rapid-fire gun imposes much larger loads on the structure. Because of this and other arrangement changes, and a desire to save weight while improving strength, the hull structure was redesigned. It was designed not only for the impact and deck loads which are usually prominent in hydrofoil design, but also for the loading imposed by the gun and the vibration associated with the gun's rapid fire use.

The gun-induced vibration can have a serious effect on instrumentation and other equipment, as well as on the structure itself. In this case, it is not sufficient for the structure to sustain the vibration. It must also transmit a minimum vibration through the structure. Minimizing the gun-induced vibration represents a significant structural challenge.

As similar evolutionary projects are proposed, structures should be carefully thought out at the conceptual stage, comparing the environments and loadings with those in which the new ships will be operating. The structure of the new ship becomes very different from that of the original ship if environment and loading are very different.

The designer cannot assume that the structural design of the original ship can be carried over to the new one.

PROPULSION

The single-engine, waterjet foilborne propulsion concept used on TUCUMCARI has been retained on the SPARVIERO and NIBBIO class ships. However, the hullborne propulsion system was changed from waterjet on TUCUMCARI to propeller on SPARVIERO. The NIBBIO and her sisters have retained the propeller hullborne propulsion concept. Table 2 illustrates the system change in the transition form TUCUMCARI to SPARVIERO. Table 3 shows how this was revised in producing the NIBBIO design.

The hullborne propulsor on these Italian hydrofoils is a propeller outdrive located at the transom. It can be rotated through 360°, providing thrust in any direction.

A retractable propeller outdrive has also been proposed for hullborne operations on the U.S. PHM hydrofoils. In addition to being more efficient than a water jet, the lighter weight would improve hullborne and foilborne range.

The designers of the Italian boats also eliminated the bow thruster used on TUCUMCARI. This probably was due to use of the 360^{o} rotatable outdrives and a potentially reduced need for low-speed maneuvering.

Although the NIBBIO class propulsion system is conceptually the same as that on the SPARVIERO, several changes have been made. Whereas SPARVIERO has many American components, in NIBBIO, Italian components have been substituted. This should improve the Italian Navy's problems with spare parts, training, and technical support. This has been done in other systems, too.

The problems with foreign supply are illustrated in the US PHM program. The PHM-1 (USS PEGASUS) had been a NATO project and contains some European equipment. Because of this, supply support has not been as attainable as desired from the manufacturers or through the U.S. Navy supply system, thus limiting the ship's availability. If a similar situation exists on SPARVIERO, though, the NIBBIO class ships should have improved availability because replacement parts will be easier to obtain.

One of the more interesting innovations in the NIBBIO is the use of (distilled) water injection in the gas turbines, which causes a 400 kW increase in maximum power. The ship can carry up to 500 kg (1100 pounds) of water, which is sufficient for up to one hour of operation. This system could provide the following advantages:

- Takeoff in very rough seas
- Takeoff in very warm air
- Takeoff with very high weight as in a fuel overload
- Increase of maximum speed in battle conditions

The potential fuel overload provided by the increased power is 1500 kg (plus 500 kg of injection water). The potential maximum speed increase is 2 kt, from 48 kt to 50 kt. Of course, each time this system is used there is some reduction in engine life, so it should be used sparingly.

This feature of the propulsion system design is consistent with short duration strike missions. The ship could be expected to spend a large amount of time during such missions at high power, burning much fuel, and needing every last bit of power. The potential increase in speed would be useful when the ship becomes engaged with other high-speed units.

Some propulsion problems were encountered in the prototype, but these have been corrected in the NIBBIO. For example, the gas turbine spray ingestion was corrected by modifying the air intake, increasing filter surface, and adding a coalescent stage. Also, the coupling between the gas turbine output shaft and the waterjet was replaced by a metastream flexible coupling. The original mechanism overheated due to misalignment. The new coupling can tolerate misalignments up to an angle of 30 minutes.

Problems with the waterjet pump of SPARVIERO included insufficient rigidity resulting in misalignment and shaft breaking. The design in the NIBBIO is improved with additional strength by using external longitudinal ribs, changing the water flow to reduce reaction torque, and employing a single waterjet shaft rather than a two-part shaft.

The specific choice of components in an evolutionary design must not be overly influenced by the existing design. This must be done to contribute to the success of the new design in performing its mission.

The designer must also take note that an evolutionary design does not eliminate risk, even in areas similar to those on the existing ship. Considerable redesign and development may be required.

ELECTRIC SYSTEM

The basic concepts of the SPARVIERO and NIBBIO electric systems are the same, each provided with total generator capacity of 225 kW. Lightweight, aerospace systems of 208/120V, 400 Hz, three-phase alternating current are used along with 28V direct current system. The Italian hydrofoil electric plants differ from the TUCUMCARI by having a much larger capacity, exclusive use of gas turbine prime movers, and compatibility with European practice.

TUCUMCARI had two generators. One was powered by a General Motors 4-53N diesel and the other by a Solar T-62T-12 gas turbine. The diesel was the primary unit, while the gas turbine was used as a standby. Both prime movers powered General Electric generators. Each generator was rated at 50 kW, 450V, 60 Hz.

The larger capacity of the electrical system on the Italian boats is needed for the more sophisticated, higher-power combat system. The 76mm gun, in particular, is a large power consumer.

The use of 400 Hz power generally saves weight. In some ships, it has restricted the choice of electrical equipment. Because this equipment is not always fully "marinized," reliability problems sometimes result.

The larger capacity system caused an additional problem on SPARVIERO. This is a very compact ship having high concentrations of electric power consumers and cabling which caused electronic interference. A number of measures were taken on both the prototype and production ships to reduce or eliminate this problem.

The use of a gas turbine for the primary power unit results in a very high fuel consumption. Although it would be a disadvantage for a ship doing long-term patrol missions, it is relatively unimportant for a ship which performs short duration, high-speed missions. In this case, the fuel consumed for electric power production is a relatively small fraction of the total. The use of a diesel was important for TUCUMCARI, which performed missions of longer duration and lower speed in which the fuel used for electric power is much more important.

The PHM hydrofoils are equipped with gas turbine generators, as on SPARVIERO and NIBBIO. The conversion of one of these to diesel has been proposed as a means of decreasing fuel consumption and increasing hullborne range. However, the PHM, unlike the Italian boats, has a requirement for long-endurance missions. In the electrical system, as in propulsion, the choice of equipment must depend on the mission of the <u>new</u> ship.

COMMAND AND CONTROL

The development of the command and control systems for the SPARVIERO and the NIBBIO class followed the same domestication mentioned earlier. Of course, the larger and more advanced combat function is reflected in this system.

The weapons on TUCUMCARI were controlled locally and had relatively simple electronics. These included a navigation radar; IFF; HF, UHF, and VHF radios; radio direction finder; depth sounder; and underwater telephone. An infrared system was also installed. In addition, a 14-station intercom system was used for interior communications.

The SPARVIERO has a more sophisticated system. The ELSAG ADT ARGO Mod 1 fire control system is used for the gun and missiles. Although an SMA radar is used, U.S. IFF equipment and a Decca navigation and tracking system are installed.

The NIBBIO class ships have the improved, Mod 3 version of the ELSAG fire control, and a new SMA combined radar has been installed. The emphasis on Italian components is illustrated by the use of an Italian (Italtel) IFF system and SMA navigation and tracking system. The Italian ships are also fitted with a low-light level television system. This electronic equipment provides a very potent system, but as we discussed above, not without its difficulties; i.e., interference due to concentration of electronics.

The automatic control system (ACS) is vital because the fully-submerged hydrofoil cannot fly without it. Although the Italian boats' ACS is manufactured by SEPA, it follows the same approach used by Boeing in TUCUMCARI. Both systems take inputs from two sonic height sensors in the bow, a vertical gyro, yaw rate gyro, and three vertical accelerometers, as well as the helm. Trailing edge flaps are used to control the depth, pitch, and roll. Steering is controlled by banking along with a steerable forward strut.

Although sonic height sensors were fitted in the PHMs, system difficulties have prompted consideration of the use of radar height sensors for those ships. However, the sonic height sensors on the SPARVIERO/NIBBIO have caused little trouble.

The automatic control system is a case in which the approach used in the original ship is directly applicable to the evolved ships. This is because this sort of system is more closely related to the ship size, configuration, and operating environment than to its mission.

AUXILIARY SYSTEMS

These systems emphasize the use of Italian equipment in the NIBBIO, as discussed above.

It is interesting to note that the use of 3000 psi hydraulics on TUCUMCARI was retained on the Italian boats, apparently to minimize weight. Reliability problems are common in high pressure hydraulic systems. Although the need for such systems is unquestioned for small hydrofoils, perhaps more conservative systems may be used on larger ships.

As mentioned above, the strut and foil system of the Italian boats is similar to the TUCUMCARI's. Like TUCUMCARI, 17-4 PH stainless steel is used for the struts and foils on the SPARVIERO/NIBBIO.

The NIBBIO class ships have incorporated two improvements over the SPARVIERO. The self-lubricating kingpost bearing suffered rapid wear and failure and was replaced by a ceramic bearing with an increased bearing surface. Gaps between the strut fairing and the struts on SPARVIERO resulted in ventilation, which was corrected in the class boats using rubber packings.

The designers of the SPARVIERO auxiliary systems were driven by the same considerations as on TUCUMCARI. Not surprisingly, they ended up with many similar systems. The NIBBIO designers were faced with correcting some deficiencies and making the ship more compatible with Italian practice and industrial availability.

WEAPONS

As discussed earlier, the SPARVIERO and NIBBIO have much more extensive combat systems than TUCUMCARI. (See Table 4.) The weapons selected in each case were suited to the ship's mission. Of course, neither the OTO Melara 76mm gun nor the OTOMAT missile were available when TUCUMCARI was designed. The OTOMAT, in particular, illustrates that very potent weapons can be mounted on small ships.

CONCLUSIONS

Although many elements of an already successful design can be applied to new ships, their selection must be based on the new craft's function and the environment in which it will operate.

It is important to remember that the nature of the mission will influence not only the combat system, but also the selection of all of the other systems. The equipment must not be automatically carried over from the old design to the new one but must be able to contribute to the purpose(s) of the complete mission.

The fact that a new design is a variant of a previously successful one does not mean necessarily that risk and development are eliminated or even vastly reduced. Some major problems and many minor ones are bound to develop in systems or equipment which may initially appear able to be transferred easily to the new design. A prototype may be necessary to identify and solve the problems before the production ships are built.

Design considerations must include both the physical environment and the operational employment.

The designer of a variant ship must also take care to ensure that spares and technical support are available to the operator. The desire to minimize cost, risk, and development tempt the designer of a variant to carry over as much as possible from the old design. However, he and the operator must do so only with extreme care if the new design is to respond to the need.

Finally, the hull, mechanical, and electrical systems do not comprise a "platform". They combine to make up part of a "ship". The systems' designs will have specific, real impact on the ship's ability to perform as required -- to accomplish a mission.

Table 1. KEY CHARACTERISTICS OF TUCUMCARI AND SPARVIERO

Dimension	TUCUMCARI	SPARVIERO
Overall Length		
Foils Retracted	80.3 ft (24.5m)	80.7 ft (24.6m)
Foils Extended	74.9 ft (22.8m)	74.9 ft (22.8m)
Between Perpendiculars	65.9 ft (20.1m)	66.0 ft (20.1m)
Maximum Breadth		
Foils Retracted	28.3 ft (8.6m)	40.5 ft (12.3m)
Foils Extended	35.3 ft (10.8m)	36.5 ft (11.2m)
Hull	19.5 ft (5.9m)	23.0 ft (7.0m)
Minimum Draft Foilborne	4.5 ft (1.4m)	5.3 ft (1.6m)
Full Load Draft Hullborne		
Foils Retracted	4.7 ft (1.4m)	6.1 ft (1.9m)
Foils Extended	14.3 ft (4.4m)	14.5 ft (4.5m)
Full Load Displacement	57.06 L. Ton (60 tonne)	61.5 L. Ton (62.5 tonne)
Manning		
Officers	1	2
Crew	12	8

Table 2. PROPULSION SYSTEM TRANSFORMATION
TUCUMCARI ——▶ SPARVIERO

ITEM	TUCUMCARI	SPARVIERO
FB PROPULSION	BYRON-JACKSON DOUBLE VOLUTE, DOUBLE SUCTION, CENTRIFUGAL	BYRON-JACKSON 928-22A DOUBLE VOLUTE, DOUBLE SUCTION, CENTRIFUGAL
FB ENGINE	ROLLS ROYCE PROTEUS 15M/530	ROLLS ROYCE PROTEUS 15M/533
FB POWER	3200 HP @ 11,350 RPM CONTINUOUS AT 27°C (80°F)	3200 HP @ 11,350 RPM CONTINUOUS AT 27°C (80°F)
HB PROPULSION	WATERJET, BUEHLER SINGLE STAGE AXIAL FLOW	PROPELLER, SCHOTTEL WERFT SRP 100
HB ENGINE	GENERAL MOTORS 6V-53	GENERAL MOTORS 6V-55M
HB POWER	160 HP @ 2600 RPM CONTINUOUS	160 HP @ 2600 RPM CONTINUOUS

Table 3. PROPULSION SYSTEM TRANSFORMATION

SPARVIERO ⟶ NIBBIO

ITEM	SPARVIERO	NIBBIO
FB PROPULSION	WATERJET	WATERJET
FB ENGINE	ROLLS ROYCE PROTEUS 15-M-533	ROLLS ROYCE PROTEUS 15-M-560
FB POWER	3300 kW (4400 HP) MAX AT 26°C (79°F)	3700 kW (5000 HP) MAX AT 26°C (79°F) WITH WATER INJECTION
FB WATERJET	BYRON-JACKSON 928-22A	TERMOMECCANICA 350 P2 D71
HB PROPULSION	PROPELLER	PROPELLER
HB ENGINE	GENERAL MOTORS 6V-55M	ISOTTA FRASCHINI ID 38 N6V
HB POWER	120 kW (160 HP) CONTINUOUS	120 kW (160 HP) CONTINUOUS
HB PROPULSOR	SCHOTTEL WERFT PROPELLER SRP 100	SCHOTTEL WERFT PROPELLER SRP 100

Table 4. TUCUMCARI AND SPARVIERO WEAPONS

TUCUMCARI	SPARVIERO
40mm Gun	76mm/62 OTO Melara Compact Gun
(2) Twin 50mm Machine Gun	OTOMAT Anti-Ship Missile
81mm Mortar	

ACKNOWLEDGMENTS

The information used in this paper was drawn from the following references in addition to private information. The conclusions drawn are those of the author and not necessarily of DTNSRDC or the U.S. Navy. Messrs. Robert Johnston, William Ellsworth, and John Monk provided valuable assistance in the preparation of this paper. Mr. Richard Brooks provided valuable comments in review.

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