SHIPS THAT
FLY ....

A STORY OF THE MODERN
HYDROFOIL.......

JOHN R. MEYER, Jr.

Courtesy of U.S. Navy

ON THE OCCASION OF "OCEAN VENTURE 1984":

> **"PHMs HAVE BROUGHT A NEW DIMENSION TO SURFACE WARFARE"**
>
> **"PHM SPEED, SMALL RADAR CROSS-SECTION, WEAPONS SUITE AND FIRE CONTROL SYSTEM PROVIDED CVBG WITH A FORMIDABLE OFFENSIVE WEAPON....."**
>
> **"PHM PERFORMANCE HAS BEEN SUPERB. YOU HAVE PROVEN PHMs CAN OPERATE EFFECTIVELY WITH A BATTLE GROUP AND ARE WELCOME BACK ANY TIME."**

COMMODORE K. G. DORSEY, COMCARGRU FOUR

FIRST FORMATION FLIGHT OF PHM SQUADRON
KEY WEST, FLORIDA - APRIL 18, 1983

This book is dedicated to the memory of my parents
John and Anna Meyer
whose sacrifices and generosity
will be long remembered.

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The author was fortunate in having a host of hydrofoil pictures and illustrations available as a result of collecting such materials over many years. Credit for many of them is due to the U.S. Navy, U.S. Coast Guard, the Boeing Company, and Jane's High-Speed Marine Craft and Air Cushion Vehicles publications, and is hereby acknowledged.

J R M Jr.

INTRODUCTION

Ask any person on the street: "What is a hydrofoil?". You will get a myriad of answers, but not many will be correct. One can expect everything from: "I dunno!", to: "Oh, I was on one of those crossing the English Channel last summer. You know - one of those boats with a big rubber bag around it and air spewing out all around". Well, our world traveler was not on a hydrofoil, but rather one of the SRN-7 air cushion vehicles that regularly transit the Channel. Other travelers will swear that they were on a hydrofoil when in actuality, it was only a catamaran. The layman's mistake in the latter case is understood since the center portion of a catamaran's hull is indeed raised above the water surface, but by its side hulls, not by a foil, or "underwater wing", which characterizes a hydrofoil craft!

One of the purposes of this book, therefore, is to make certain that the reader, whether a world traveler or not, will never make any mistake about knowing when he is on a hydrofoil, or merely some other high speed boat. Of course, the intent is really to accomplish a lot more than this. Since there is considerable romance about hydrofoils, just as there is about aviation and space travel, this element of man's fascination with ships that fly is also portrayed.

We start our story of the modern hydrofoil quite logically with its early history, affording space to only a relatively small number of the host of inventors and experimentors who provided the foundation for later work. Then came the creative Italians who reduced their patented ideas to practice. No book about hydrofoils would be complete if it did not include the highly respected work of Alexander Graham Bell, several Americans, and of course the German contributions of von Schertel and Tietjens.

During the 1950s, which has been called the "Decade of Experimental Progress", a large number of hydrofoil craft were built which provided many learning experiences in the process. For the high speeds of 80 to 100 knots that were envisioned by the more aggressive hydrofoilers at that time, it was necessary to expand the technical data base, and hence, several large scale test vehicles were built. The product of this technical information was an aggressive U.S. Navy program starting in the 1960s with the development of four hydrofoils, namely: HIGH POINT, FLAGSTAFF, TUCUMCARI, and PLAINVIEW. Simultaneously the Canadians and Europeans proceeded with hydrofoil developments, although along completely different lines than the U.S. Navy.

Culmination of the U.S. Navy developments was the Navy Fleet hydrofoil - the PHM - which occupies a special place not only in this book, but in the hearts and minds of so many of the hydrofoilers in this country. PHM's history with its early connection to the North Atlantic Treaty Organization (NATO), the program's subsequent trials and tribulations, and formation of a Squadron of six hydrofoils at Key West, Florida, is an important part of the modern hydrofoil era. The Squadron's commitment "To Go In Harm's Way" and operational success is a tribute to many devoted Navy personnel, both "bluesuiters" and civilians, and industrial enthusiasts.

For the more technically inclined reader, the chapter on why and how hydrofoils fly will be of particular interest. After all, why lift a boat's hull out of the water when for thousands of years since the dugout log canoe and Noah's Ark, mankind was satisfied to leave the hull in the water? Then too, after you lift the hull out of the water, how do you stabilize, power, maneuver and control such a craft so it doesn't crash into waves rather than glide gently above the waves? Answers to these questions and an Appendix containing sketches and drawings of many hydrofoils described rounds out the technical aspects of the book.

There are thousands of hydrofoils in operation around the world, except for the United States. These craft, and the dearth of same in the U.S. are described and explained. And of course, everyone wants to know about the future - what's next? The author humbly provides his version of the hydrofoil crystal ball.

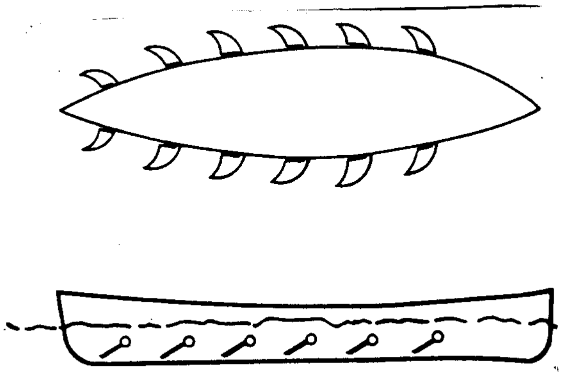
CHAPTER 1

EARLY HYDROFOILS

FARCOT AND OTHER INVENTORS

How far back does one have to go in history to see the early development of hydrofoils which eventually brought us to the scene shown on the frontispiece of this book - namely, six U.S. Navy PHM hydrofoils flying in formation off Key West, Florida in early 1983?

According to Leslie Hayward[1], who has written a most comprehensive history of hydrofoils in a 14 part series in "Hovering Craft and Hydrofoils", the first evidence of the use of hydrofoils on a boat or ship was in a British patent of 1869. It was granted to Emmanuel Denis Farcot, a Parisian, who claimed that "adapting to the sides and bottom of the vessel a series of inclined planes or wedge formed pieces, which as the vessel is driven forward will have the effect of lifting it in the water and reducing the draught". There were numerous patents during the ensuing years, all claiming, by a variety of means, to lift the vessel either partially or fully out of the water to improve speed and motions in waves. Such patents were exemplified by inventors and experimenters like Horatio Phillips, G. W. Napier, Count de Lambert, and the Meacham brothers.



Rendering From 1869 Patent by E. D. Farcot

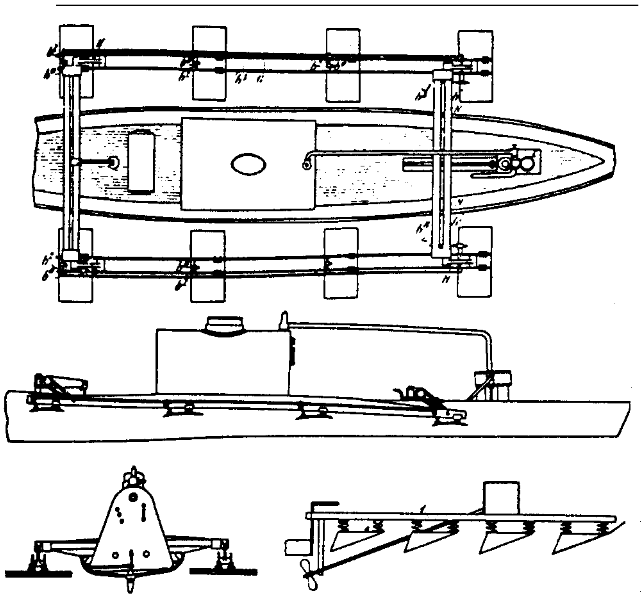
Phillips' invention of 1881 was to be applied to "torpedo boats and equally so to steam launches and other vessels propelled at high speed". The object of the invention was to "ensure an even keel by which means the resistance would be reduced and the speed thereby increased". His patent went on to describe the fitting of "plates" and the adjustment of same to obtain the desired result.

According to **Hayward,** Phillips carried out a considerable amount of experimental work with towed models on the Surrey Canal. He found that the best results were obtained when the model was fitted with "a long narrow metal blade, very slightly concave on the under side, with the front and back edges sharpened like a knife; in plan this plate or blade was wider in the center and tapered away towards each end - in fact an exact imitation of the out-stretched wings of a bird. The extremities of the blade were curved upwards in order to secure lateral stability. The blade was fixed transversely under the bottom of the boat, a little abaft of the center of gravity. The bow of the boat was lifted by a similar but very much smaller plate or blade. When the model was gliding, daylight could be seen under the boat".

Napier was an American who, in 1888, proposed fitting large adjustable foils to the sides of a ship. They were adjustable so when desired to draw less water, the forward end of the foil could be elevated. Napier also pointed out in his patent that lowering the forward end of the foil would cause the vessel to increase draft. It is not clear why the latter would have been advantageous at the time, except for the possibility of improving seakeeping.

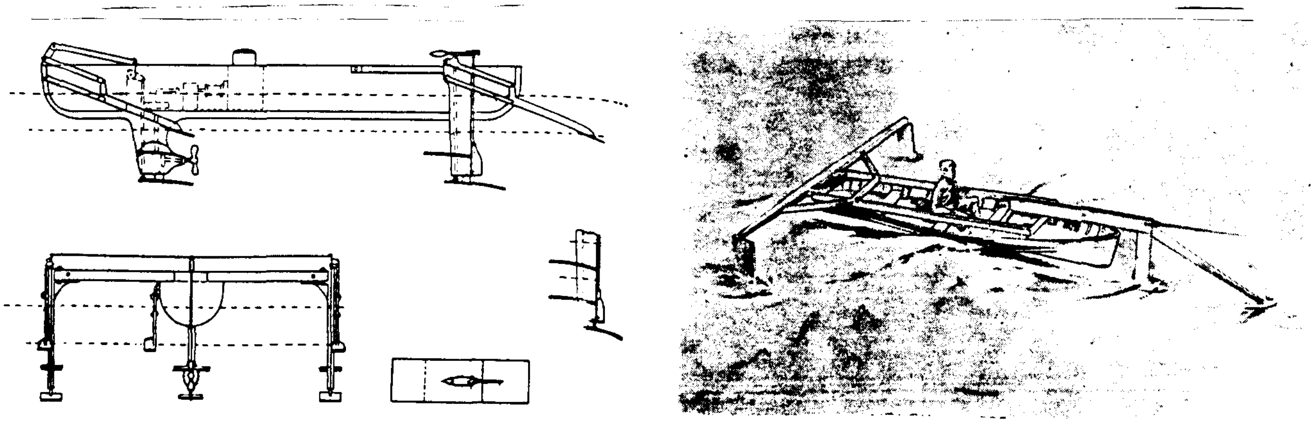
Count de Lambert, a Russian residing at Versailles, applied for patents as early as 1891. He employed a plurality of foils (or lifting planes) on each side of the vessel, each individually adjustable to raise the hull in the water as speed increased. As in the case of Napier, the location of these primitive foils did not make it possible to lift the vessel completely clear of the water.

Hayward describes the work of the Meacham brothers, of Chicago, who commenced work on hydrofoils in 1894. They were influenced by Sir Hiram Maxim's experiments in "aerial navigation" about that time, and believed that the same principle of lifting planes could be applied to "water navigation".



Count de Lambert's Hydrofoil (1891-1904)

The Meacham brothers carried out their experiments on the Chicago Drainage Canal during 1897 with tests on a 14- ft. long and 30- inch beam craft. Foils were fitted at the bow and the stern along with two small balancing foils, one on each side of the hull, as can be seen in the accompanying sketch. It is interesting to note that the foils were fully submerged and incidence controlled. A surface feeler was connected to the forward foil to provide some stabilization in waves. By 1906, the Meacham's design became more refined with controls on both fore and aft foils. Each supporting strut had two ladder foils with the upper foil fixed and the lower foil controllable through a linkage system to the surface feeler.



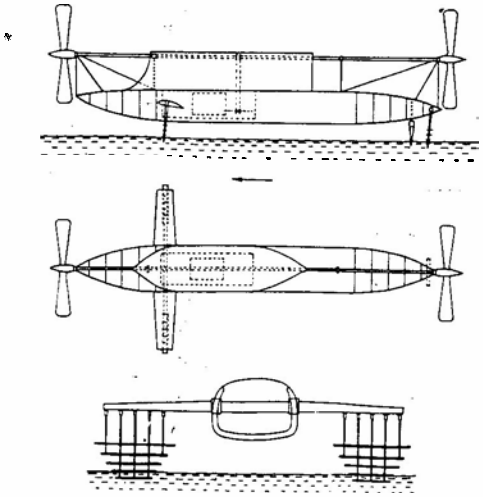
Meacham's Hydrofoil Designs (1895-1906)

It is no coincidence that much of the serious hydrofoil work started at about the same time as early powered flight. Interestingly, hydrofoil patents parallel those of aircraft inventors - the Wright brothers actually received a patent on hydrofoils applied to a catamaran hull. It appears that, as we shall see, those who were interested in developing airfoils leading to the airplane, also were intrigued by the possibility of hydrofoils and their ability to support waterborne craft above the water surface.

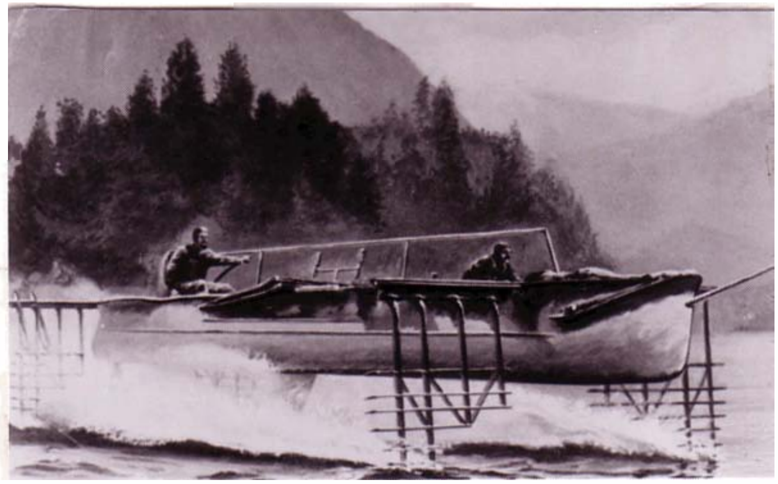
FORLANINI

We really begin the SHIPS THAT FLY story with Enrico Forlanini, an Italian engineer whose interests included airships, aircraft, and helicopters. His hydrofoil developments started in 1898 with a series of model tests from which he arrived at several simple mathematical relationships. These allowed him to proceed with the design and construction of a full-scale craft.

Forlanini's designs were characterized by a "ladder" foil system. You can see from a drawing of his concept and a copy of an old photograph what is meant by this aptly named ladder foil. Forlanini's model experiments had shown him that lift was proportional to the square of speed, therefore less foil area was required as speed increased. He conveniently obtained this decrease in foil area with the ladder scheme. The craft weighed about 2,650 pounds and had a 60- hp engine driving contrarotating airscrews. Although designed to fly at a speed of 56 mph, records, according to Hayward, show that during tests on Lake Maggiore, Italy in 1906 a speed of 42.5 mph was obtained.



Drawing of Forlanini's Hydrofoil

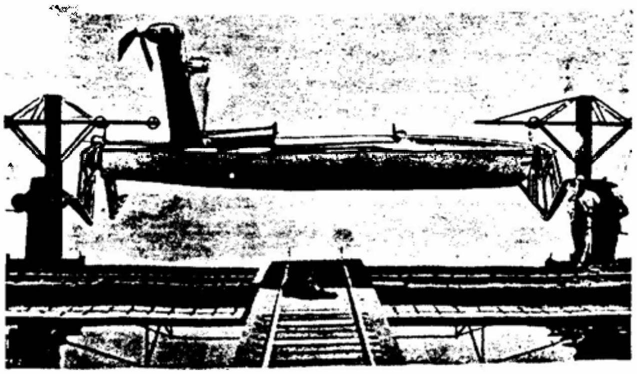


Forlanini's Hydrofoil on Lake Maggiore in 1906

Although the foil system was a rather complicated structure, Forlanini's craft operated well and represented an advancement in the state of the art. He obtained a number of British and American patents on his ideas and designs, most of which were aimed at seaplane applications.

GUIDONI AND CROCO

Another Italian, Guidoni, in the 1910 to 1921 time frame, was involved in the development of hydrofoil seaplanes. He mounted foils beneath the floats of seaplanes to reduce the impact loads and improve the landing characteristics of such craft in rough water. The aircraft Guidoni worked with usually became airborne at well below 50 knots. According to Hayward, Guidoni's work was based on that of Croco, who in 1907 experimented with marine craft supported by simple monoplane dihedral foils, but had little success in applying them to flying machines. Guidoni's ladder foil system was finally successful in executing the first take-off and landing of a hydrofoil seaplane in 1911. This was because he adopted Croco's dihedral foil feature which avoided the sudden transition from one foil to the other under varying speed conditions.



A Rendering of CROCO's Hydrofoil (1907)

ALEXANDER GRAHAM BELL

Although we see that the hydrofoil had it beginnings in Italy, probably the inventor who received the most publicity from his early work with hydrofoils was an American living in Canada: Alexander Graham Bell - yes, the same one who invented the telephone.

Born in Scotland in 1847, Bell went to Canada in his early years and later the United States to pursue his career as a teacher and scientist. Dr. and Mabel Bell returned to Canada and the rugged beauty of Cape Breton Island where he built a residence called "Beinn Bhreagh" (beautiful mountain) in 1893. This became his second home, alternating between Washington, D. C. (with its notoriously hot, humid summers) and Baddeck, where the weather was much more agreeable in the summertime. Here he constructed his famous laboratory and workshops described in detail by Arseneau[2]. One building served as Bell's boat building facility; there was another building which served as the home of Canada's first aircraft manufacturing company, the Canadian Aerodrome Company. It was in this complex that Bell worked on eugenics and the twinning of sheep, on solar stills and condensation of fog for the production of drinking water, on kites, and aeroplanes. He carried out extensive research in the areas of electricity, sound and speech, having a dedicated interest in improving the teaching of the deaf. At the other end of the spectrum, Bell applied the tetrahedral structure to shelters and towers, kites and boats. A full description of Bell's creativity in the field of man-lifting kites and aircraft requires a book in itself.

According to A. E. Roos[3], Alexander Graham Bell's attention to hydrofoils in 1906 was due, in part, to a report by one of the Meacham brothers in <u>Scientific American.</u> In connection with Bell's work on airplanes, he was concerned with the possibility of taking off and landing on water, which he considered safer than land. His experiments did not get underway until 1908, a year after the Wright brothers had considered a similar solution, as mentioned earlier. Foil sections were developed empirically by Bell's colleagues Frederick W. (Casey) Baldwin and Phillip L. Rhodes, a New York naval architect. Experiments with small- scale models and full- scale craft continued for about five years but were interrupted by a world tour that Bell and Baldwin undertook in 1911. They visited Forlanini in Italy where they witnessed tests on his 1.6 ton hydrofoil on Lake Maggiore. It is understood that Bell purchased some of Forlanini's patents.

I have taken the opportunity to excerpt material from Roos' excellent description of Bell's hydrofoil development from the HD-1 leading to the record-breaking HD-4.

"The design that Baldwin produced for this hydrodrome (as Bell's hydrofoils were called) series reflected Bell and Baldwin's view that the vessel was a hybrid, and as such, consisted of two distinct parts. One section was for progression through the air. It functioned for all intents and purposes like an aeroplane, with all parts, wherever possible, designed to constitute aerofoils. This included the main hull, as it was only useful for support in the water while at rest and once underway and out of the water should have as low a resistance to air as possible. The other section of the craft was comprised of the foils and these were designed primarily for lifting effectiveness in water and compactness. Bell and Baldwin knew that, for a hydrofoil craft, reduction in head resistance was easier in air whereas the lift should be mainly obtained from the water.

The first three hydrodromes, built between 1911 and 1914, actually looked like abbreviated aeroplanes, and their trial runs were described as resembling unsuccessful take-offs from water. The first of the three hydrodromes built prior to the HD-4 was also the fastest of these three, managing 50 mph using a 70 hp Gnome engine as a power plant. The subsequent two hydrodromes, even though they supposedly encompassed improvements ascertained from Bell's and Baldwin's previous work, did not exceed this speed. The work on the HD-3 was just beginning when the War brought all hydrodrome activity to a virtual close at Baddeck, because Bell, as a citizen of a neutral country, did not feel he could proceed with the development of a potentially military machine in a belligerent country.

Upon entry of the United States into the War this restriction was lifted, and Bell offered to develop the Hydrofoil for the U. S. Navy. His aid was not accepted, but his wife Mabel Bell, as her contribution to the War effort, decided to fund the development of a large-scale hydrofoil craft to be known as the HD-4.

Work on the design of the HD-4 was started in 1917. Bell had decided to make this Baldwin's project and did not interfere with Baldwin's design, but gave the latter his full support. Baldwin's approach to the external design of the HD-4 did not vary from his earlier perception of the function of the different parts of a hydrofoil craft, but instead of looking at the aeroplane, he looked at the dirigible as the vessel that had a shape best suited for progression through the air for a craft of the size he had in mind.

Once the proposed vessel had been roughed out on paper, a scale model was produced in 1917 for testing. This model was larger than usual, being 17 feet long and 2-1/2 feet in diameter, since Bell believed that anything smaller would not provide accurate enough data to proceed to a full-scale vessel. The results he obtained from this unpowered vessel convinced them to proceed with the construction of the HD-4.

The HD-4, once finished in 1918, had a simple yet imposing appearance. Its main hull was a 60-foot-long cigar-shaped cylinder with a maximum diameter of 5.75 feet. On either side of the hull in the cockpit area, which was approximately one third of the way back from the bow, there extended out a sponson to the end of which was attached a 20 foot-long pontoon of the same design as the hull. Each sponson served as a base support for an engine bed structure, with the two beds being inter-connected with a Phillips blind arrangement above the cockpit. The sponsons also served as the point of attachment for the main foil sets which were located directly below them. There were three foil sets on the HD-4. At the front there was a preventer set, the main purpose of which was to prevent diving and ride clear of the water once the vessel was up on its foils. A second set composed of two banks of foils, one bank under each sponson, functioned as the main load bearing foils and forward two points of the three-point support system once the vessel was underway. At the rear of the vessel, just forward of the stern, was a third set of foils that functioned as the third point of the three point support system, and also as the rudder, for these foils were constructed to pivot on a vertical axis. All foil sets, except for the preventer, were designed so that once underway there would be continuity of lift, or as Bell described it, "continuity of reefing."

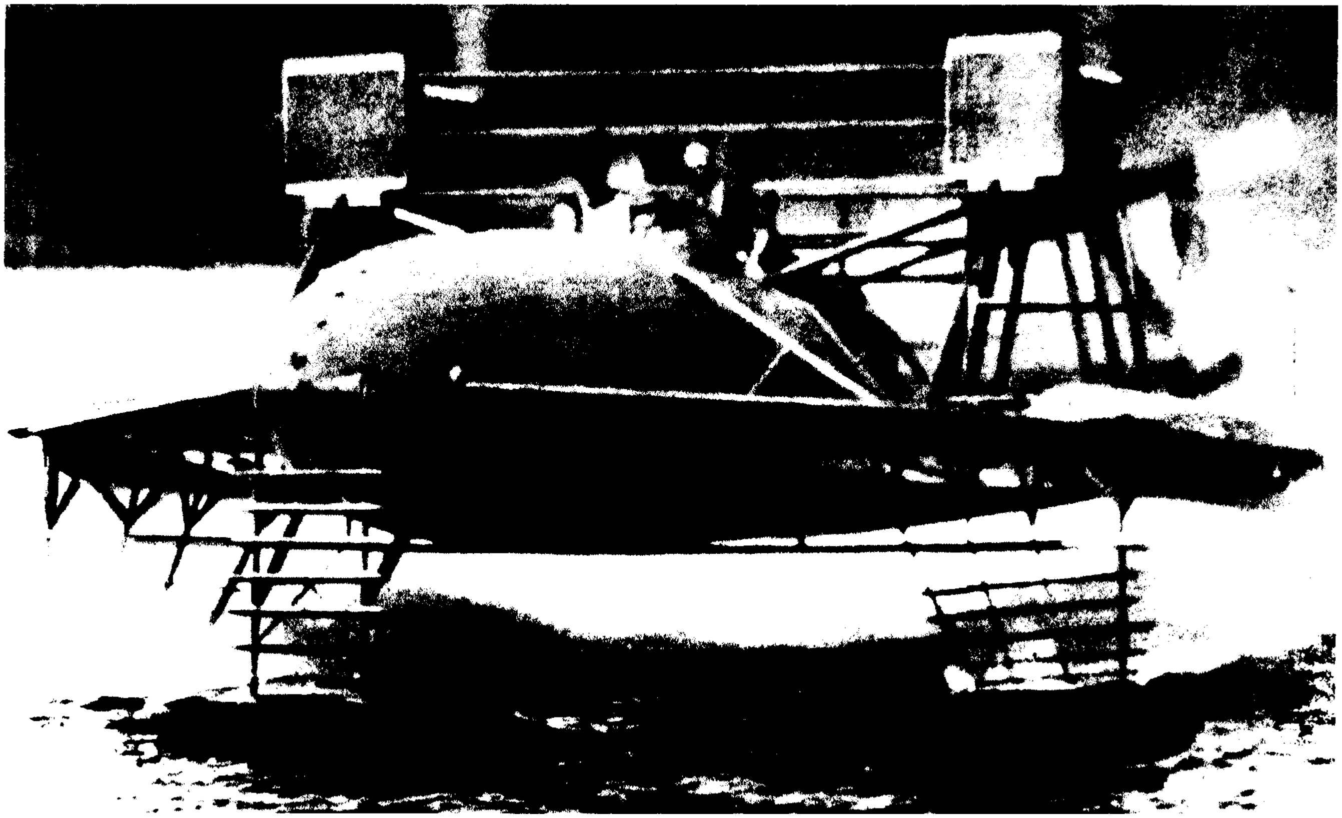
Bell argued that to obtain continuity of reefing, the foils could not extend horizontally in the lateral direction but had to slope upwards away from the center line of the boat, so that the foils on either side of the boat would form a dihedral angle. In such a system a hydrofoil comes gradually out of the water instead of leaping out like a whale. If successive foils are then so spaced that the lower end of one foil is at the same level as the upper end of the next foil below it, the lift will be continuous as the foils leave the water, or, to use Bell's phrase, continuity of reefing will result.

The HD-4 had been designed to use two Liberty engines, with air propellers as sources of thrust, that were to be obtained on loan from the U. S. Navy. Unfortunately, these were not available during the war years, and Bell and Baldwin had to settle initially for the loan of a pair

> of second-hand Renault engines. Even with these engines on board the HD-4 managed to "fly" at 53.7 mph in 1918, once the start-up problems had been solved. A report outlining the results with these engines and a set of line drawings of an HD-4 type of craft were forwarded to the U.S. Navy in 1919. It was hoped that this action would lead to an order from the Navy for a hydrofoil craft, or at the very least, the loan of two Liberty engines for future trials.
>
> This report and subsequent lobbying by Bell in Washington resulted in the loan of two Liberty engines which were installed during the summer of 1919. With these engines as power plants, that HD-4 set an official speed record of 70.86 mph on 9 September 1919. Although major external modifications were made to try to improve the performance of the HD-4, the speed of 70.86 mph was not officially surpassed. The results of this second series of tests were also tabulated, along with another series of line drawings, and forwarded to the U. S. Navy.
>
> The outcome of these reports was that both the British Admiralty and the U. S. Navy sent commissions to Baddeck in 1920 to view the hydrofoil and assess its possibilities. Unfortunately for Baldwin neither the U. S. nor Britain took up hydrofoil development.
>
> The last time that the HD-4 "flew" was in 1921, when it was pulled behind a Canadian warship to test the feasibility of towing targets fitted with hydrofoils. These tests proved successful and resulted in such structures being subsequently built. After these tests the HD-4 was beached on Bell's property across the bay from Baddeck in Cape Breton, Nova Scotia and there it rested until 1956 when it was moved indoors."

One of the many pictures of the HD-4, taken to document its design and trials, shows Bell's colleague, Casey Baldwin, at the controls of the HD-4 in 1919 on the Bras D'Or Lake in Nova Scotia. Notice that there is a set of three airfoils attached above the hull to provide aerodynamic damping to motions in choppy water, an idea which was originally proposed by Forlanini.

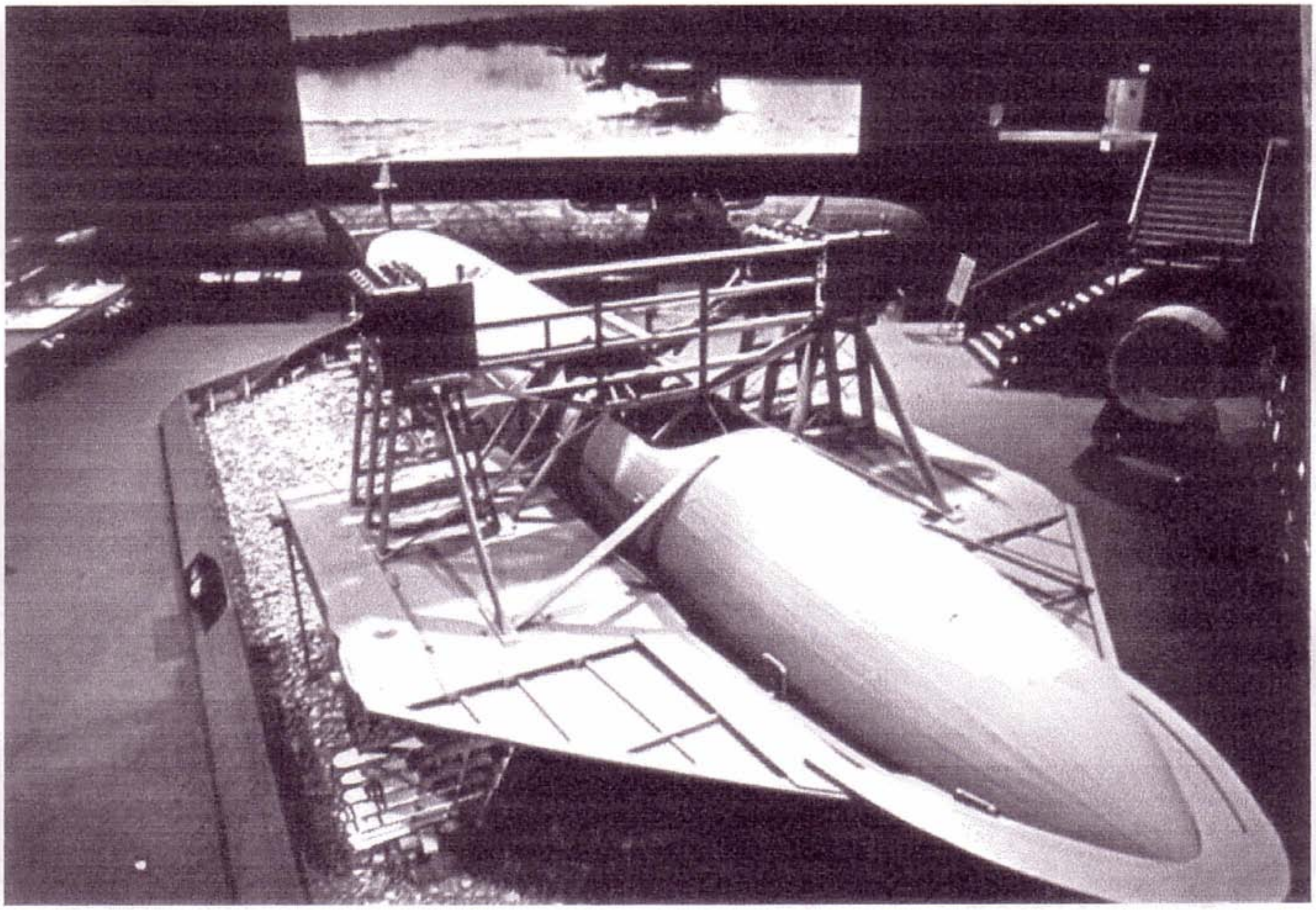
As mentioned above, over an extended period from 1918 both Bell and Baldwin made repeated attempts to interest the U.S. Navy Department in their work. It was in this connection that a young Lt. Cdr. Jerome Hunsaker, whom many Aeronautical Engineering students at M.I.T. later knew and admired as Professor Hunsaker, evaluated the HD-4 for the U.S. Navy. It was reported[4] that he said: "Its a very interesting development, but I can see no application to the U.S. Navy". In spite of this comment, the U.S. Navy and its many staunch supporters of this concept, much later proceeded along the long path to bring the hydrofoil to its present state.



Bell-Baldwin HD-4 Hydrofoil on Bras D'Or Lake

In spite of the negative response from the U.S. Navy, Bell and Baldwin's ideas were embodied in several sport and pleasure craft between 1920 and 1938 under the direction of Phillip L. Rhodes. These included the HD-12, which was 30-ft long and had a top speed of 50 knots. Also the "MISS USA", a 35 ft racing boat displacing 6500 lb, achieved a speed of 80 knots with a 650-hp engine. Unfortunately she was destroyed by fire after only two test runs.1

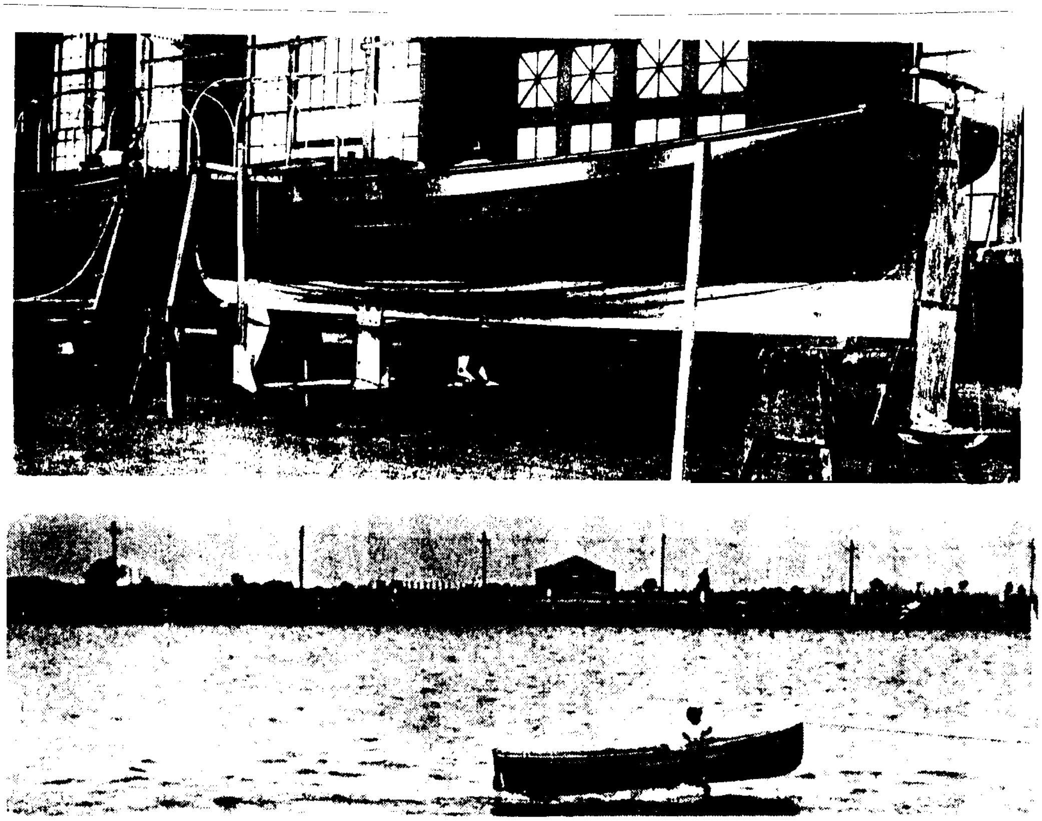
To commemorate the extraordinary and versatile mind of Alexander Graham Bell, the Canadian Government constructed a building to house the extensive collection of artifacts and relics of his experimental work. The Alexander Graham Bell Museum, making extensive use of the tetrahedral structure in its design, was opened at Baddeck in 1956. It was the daughters of Bell, Mrs. Gilbert Grosvenor and Mrs. David Fairchild who donated to the people of Canada a priceless collection, including the remains of the HD-4. Hydrofoil Hall in the Museum houses a full-scale replica of the HD-4, an impressive piece of craftsmanship in itself. A visit to this fabulous Historic Park should not to be missed by anyone venturing within several hundred miles of Cape Breton Island!



Full-scale Reconstruction of HD-4 Hydrofoil

CAPTAIN RICHARDSON'S DINGHY

The U.S. Navy, however did show an interest, although very limited, earlier than the Bell-Baldwin proposals. It was about 1909 that a young "Naval Constructor", Holden C. Richardson, fitted a set of submerged foils to a dinghy - a humble beginning to say the least. Under tow, as can be seen from the photograph, Richardson's dinghy took off and flew at six knots on the Schuylkill River in Philadelphias. He was one of the few Naval officers who believed that hydrofoils could be applied to practical seagoing craft during the period when the U.S. Navy had written them off. Captain Richardson's early interest was inspired, in part, by Forlinini; they both were interested in using hydrofoils as landing gear for seaplanes.



Captain Richardson's Dinghy (1909)

In Richardson's experiments, his craft was fitted with a set of foils consisting of a fixed ladder foil forward and a controllable foil aft. The incidence angle and the foil tips could be manually controlled. Roll control, banking into a turn, and maneuverability were achieved by this foil tip control, much in the same way as warping of aircraft wing surfaces was done during that time period. Richardson's efforts in hydrofoil supported craft continued until about **1911.** In that year he received a patent for a speed boat powered by twin air propellers with controllable fore and aft fully submerged foils.

BARON von SCHERTEL

The early years of the hydrofoil story would not be complete without a tribute to the genius, determination, and deep-rooted faith of Baron Hanns von Schertel. The gap in hydrofoil development subsequent to the Bell era was filled by "The Baron", as he was affectionately called, who began to experiment with hydrofoil craft in **1927.** Much credit for developing the hydrofoil from an unstable, unreliable, "calm-water-only" craft to today's safe, fast, and efficient mode of water transportation must be accorded to von Schertel.

It was Baron Hanns von Schertel[6] who defined a hydrofoil as:

> "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 moved through the water".

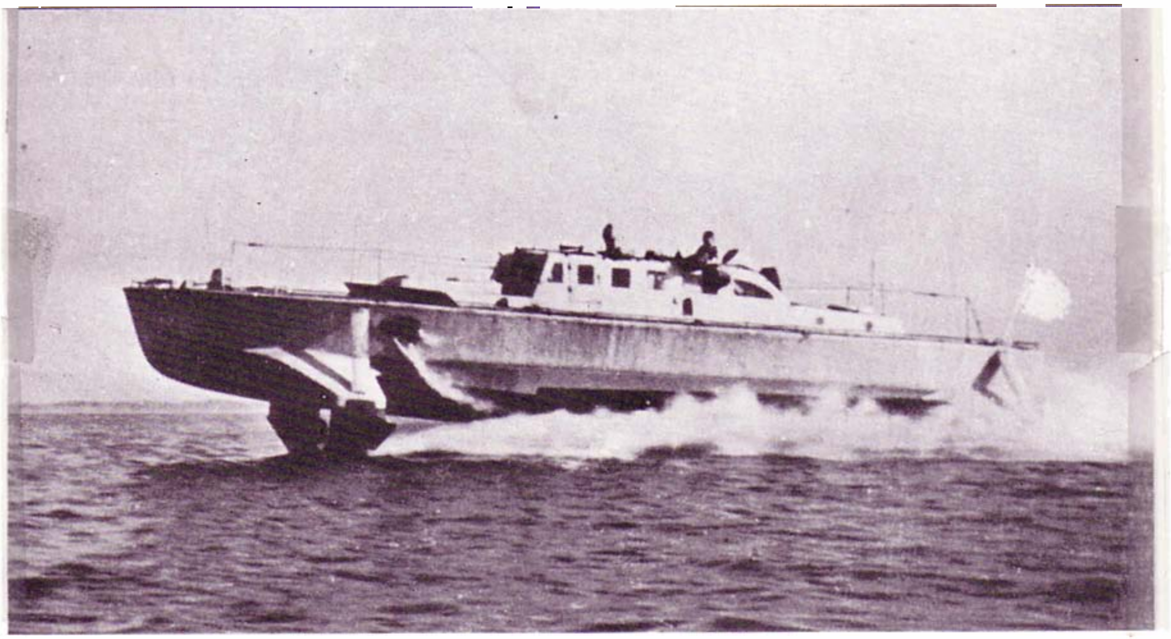
There are few who would argue with this definition, even today.

As was the case of so many of his predecessors, von Schertel started his experimental work obsessed with finding a solution for the problems of the flying boat landing gear. In the period of eight years he tested all foil configurations which appeared promising - both surface piercing and fully submerged. He originally gave preference to the fully-submerged system to get as far away as possible from the disturbing influence of the water surface waves. Von Schertel had hoped that the surface effect would be strong enough to stabilize the foil at a certain immersion depth. In Reference 6, he describes his experiences as follows:

> "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 provide enough power for take off. When I noticed that the steering control was nearly ineffective I cut off the ignition, but the engine was already so much overheated that it went on running 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 crashes with the second craft due to ventilation made it clear that the surface effect stability would not be feasible for sea going 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 a 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 compensate for the 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 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 built boat 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."

In 1937, after a demonstration trip from Mainz to Cologne on the Rhine River, the Cologne-Dusseldorf Steamship Co. placed with Gebruder Sachsenberg A.G. at Dessau, the world's first order for a commercial hydrofoil boat.



The von Schertel-Sachsenberg VS-6 Hydrofoil

To be on the safe side, the Schertel-Sachsenberg syndicate decided to build a larger test boat. It was completed at the outbreak of World War II and was later demonstrated to the German Navy. The war however, prevented the fulfillment of the original order[7].

During WW II von Schertel and the shipbuilder Sachsenberg collaborated in the construction of a number of hydrofoil boats for the German Navy. In 1941 they launched the 17-ton VS-6, a mine laying hydrofoil. It was 52.5 feet in length, was powered by two Hispano-Suiza gasoline engines of 1560 hp each and was capable of speeds up to 47 knots.

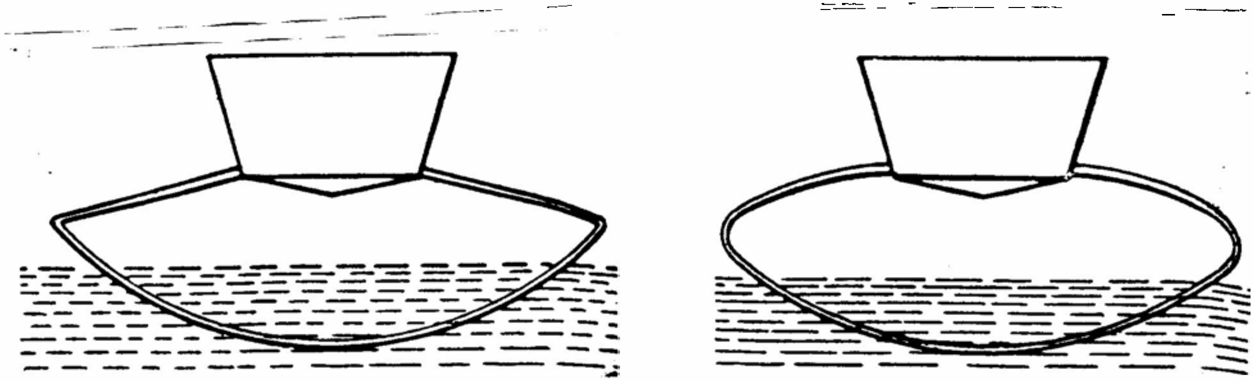
In 1943 the 80-ton VS-8 was launched. This relatively large hydrofoil was 150 feet long and was designed to carry tanks and supplies to support Rommel's North African campaign. The VS-8, although originally designed for a top speed of 45 knots, was actually limited to 37 knots. This was because the only engine that could be made available at the time was a Mercedes-Benz diesel with 1800 hp. The underpowered craft was stable in head seas but came off the foils in some tests in following waves. Furthermore, in 1944 it suffered a casualty due to sabotage and was eventually beached.

The von Schertel-Sachsenberg VS-8 Hydrofoil

The contributions of von Schertel after World War II are described in a later chapter on European hydrofoil developments

TIETJENS

Another famous name in the hydrofoil story is that of Professor Oscar **Tietjens**, who had patented a new type of foil system. The accompanying sketches show his surface-piercing hoop system which was first tested on a small speed boat at Philadelphia (probably on the Schuylkill River) in 1932. The 500 lb craft reached a speed of about 25 mph with only a 5-hp motor[1].



The Hoop Foil Systems of O. Tietjens (1931)

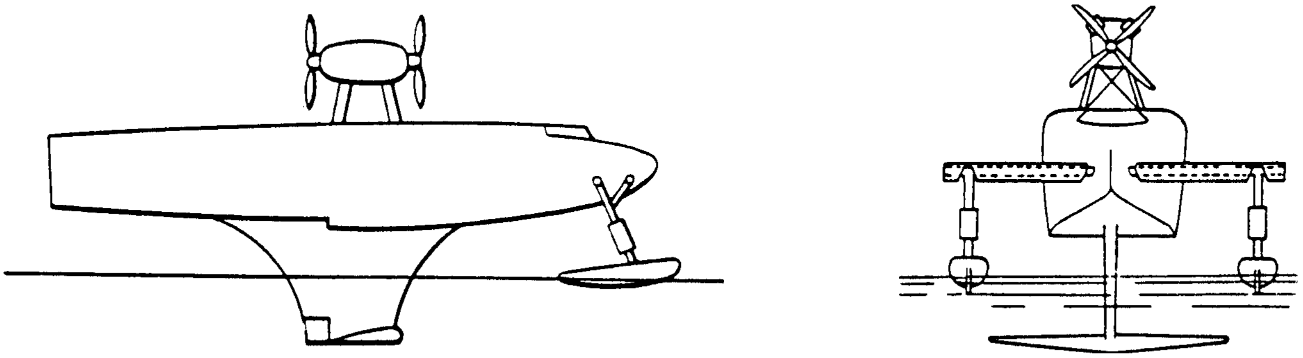
Tietjens later returned to Germany where he continued his hydrofoil development work in parallel with von Schertel. The VS-7 hydrofoil, a 17-ton craft with a hoop foil system, was built in Schleswig, Germany, at the Vertens Shipyard. The VS-7 was **built** to the same displacement and had the

Tietjens VS-7 Hydrofoil

same power as von Schertel's VS-6. The two boats were placed in competition under the auspices of the German Armed Forces. Although the VS-7 attained a speed of about 50 knots compared to the 47 knots of von Schertel's VS-6, the stability and maneuverability of Tietjen's hydrofoil was much poorer than that of the VS-6, and had difficulty with take-off.7

GRUNBERG

Wsevolode Grunberg, a Russian National residing in France, 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, shown above, were tested in the Saint-Cyr model basin in France.



A Sketch of Grunberg's Hydrofoil

In the late 1930s Grunberg came to the United States at the invitation of the National Advisory Committee for Aeronautics (NACA) to demonstrate his hydrofoil design principle.5 NACA was actually interested in Grunberg's ideas for application to seaplanes. 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 of the project prevented Grunberg, a foreign citizen, from seeing the results of the model tests. Grunberg left the U.S. and reentered as an immigrant, changed his name, and became a U.S. citizen. He has been honored as Waldemar Craig, a life member of the International Hydrofoil Society of the North American Association. It wasn't until years after World War II, when all interest in hydrofoil landing gear for seaplanes had ceased, that Mr. Craig found out how really successful the NACA model tests had been.

CHAPTER 2

THE 1950s - A DECADE OF EXPERIMENTAL PROGRESS

It was during the 1950s that a host of experimental hydrofoils were designed and built by enthusiasts on both sides of the Atlantic. Creativity in many forms flourished on very small budgets, by today's standards, but significant progress was made. Space allows for a description of only a few hydrofoil craft which made major contributions to this decade of experimental progress.

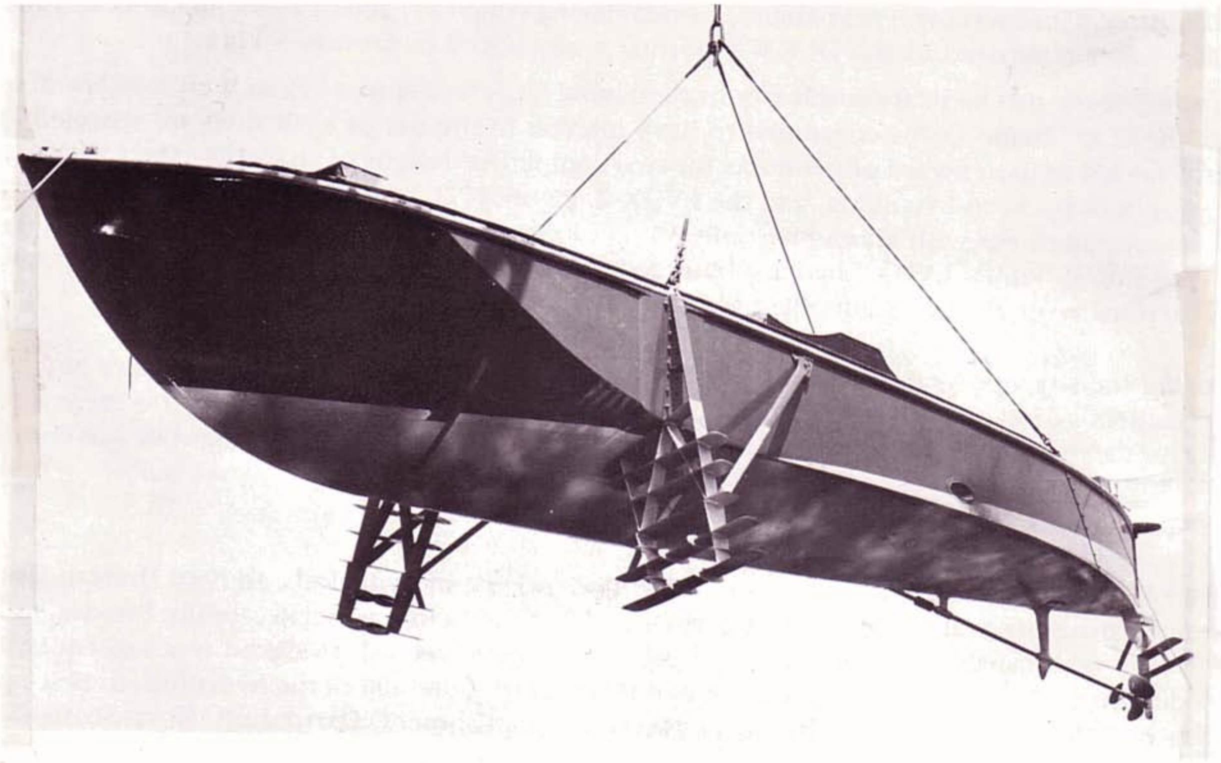
CANADIAN MASSAWIPPI, R-100

In Canada there was a rekindled interest in hydrofoils in the person of Duncan Hodgson, a former Royal Canadian naval officer. He commissioned Bell and Baldwin's associate, Phillip Rhodes, to design a hydrofoil craft capable of setting a new world speed record. However, a friend of Hodgson's, E. L. Davies, then Vice Chairman of Canada's Defence Research Board, convinced him that this was unlikely to succeed, and that a more worthy endeavor would be to design a craft to demonstrate the naval potential of the hydrofoil principle.[8]

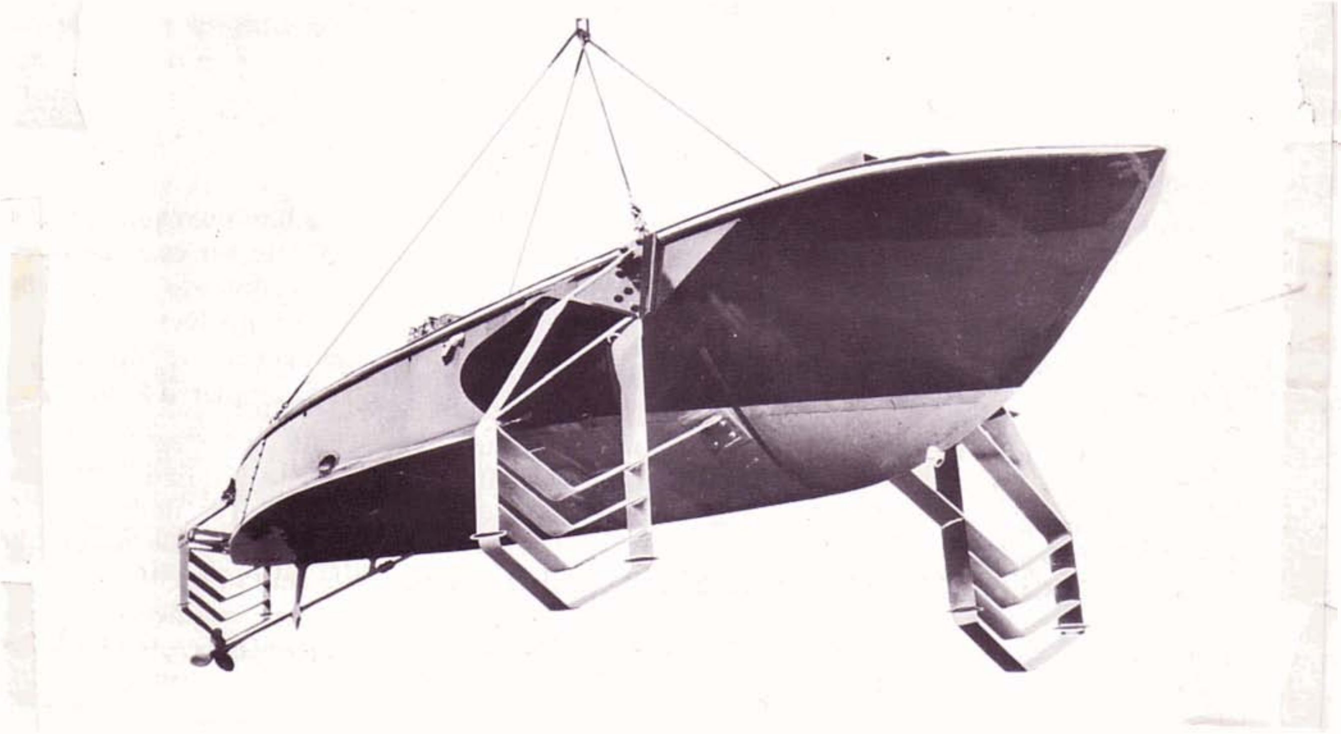
The result was a 45-foot, 5-ton craft built at Lake Massawippi in Quebec, and originally named "KCB" (after Casey Baldwin). Her foil ladders and general configuration were based on Baldwin's later designs. After a series of rough-water demonstration trials, the craft was transferred to the Naval Research Establishment at which time she became officially known as the R-100. However, the unofficial name of MASSAWIPPI was the one that prevailed throughout this hydrofoil's life.

The MASSAWIPPI was instrumented for quantitative trials to collect data for the design of larger, operationally capable ships. The original foils, when more heavily loaded, produced violent porpoising at speeds between 40 to 50 knots. A combination of cavitation and ventilation was the primary cause, and it was realized that a complete re-design was required. The modified MASSAWIPPI was quite a different boat. The foil system was designed for a 50% increase in displacement, and the main foils were moved forward to equalize the loading on all three ladder units. The craft then was a realistic

scale model of a possible ship in the 50-100- ton range, with an increased hull clearance for rough water operation.



Canadian Hydrofoil, MASSAWIPPI, R-100



MASSAWIPPI with Modified Foils

Trials in 1956 showed that the porpoising problem on MASSAWIPPI had been solved, and the boat performed well at 45 knots in 6-foot seas, a significant achievement for a 45-foot craft with surface-piercing foils. These trials also demonstrated that the foils were very effective in damping motions at slow speeds on the hull, a fact that was to become very important in later hydrofoil designs.

SAUNDERS-ROE, R-103

As a result of successful trials of the R-100, the Canadian government decided to fund another test craft to be built by Saunders-Roe in England. It was designated the R-103, and initially named BRAS D'OR, but later renamed **BADDECK,** in favor of her much larger successor which will be described later.

Canadian Hydrofoil, SAUNDERS-ROE, R-103

The R-103, a 17-ton craft, had several design features which were important at that period of hydrofoil development. These included an aluminum hull, as opposed to the wooden construction of the R-100, and built-up foils and struts of aluminum sheet riveted over aluminum ribs and stringers, compared to the solid construction heretofore. Also, a right-angle bevel gear transmission, housed in a propulsion appendage supported by a single, centrally located strut, drove propellers on each end of the pod. This represented a significant departure from the long inclined shaft used in the R-100. Power was provided by two 12-cylinder Rolls Royce Griffon gasoline engines rated at 1,500 hp.

Although BADDECK met her intended purpose of proving structural and mechanical features for the design of larger craft, her trials, which began in 1958, proved to be somewhat of a disappointment.[8] In contrast to the promise shown by MASSAWIPPI's second foil system, BADDECK's foil system was only capable of maintaining stability over a narrow range of foil angles of attack - a range too narrow for satisfactory rough-water operation.

A particularly important result from this experience surfaced which strongly influenced hydrofoil design philosophy. M. C. Eames[8] relates that, although it was almost a sacrilegious thought, particularly for a Canadian, that "Bell and Baldwin had been wrong!". It was concluded that the Bell-Baldwin "airplane" configuration was not the best approach to the design of surface-piercing hydrofoils for operation in rough seas. Very different characteristics are required of surface-piercing foils forward and aft. The forward foil should be like a feeler, relatively insensitive to angle of attack, and act as a trimming device, allowing the main aft foil to respond in advance to an on-coming wave. The forward foil should therefore be relatively small, and the main foil much larger. It was concluded that this so-called "canard" configuration would be essential to achieving good seakeeping ability with reasonable efficiency in a surface-piercing hydrofoil system.

This finding strongly influenced the design of Canadian hydrofoils that were to follow, as we shall see in later chapters.

LANTERN, HC-4

Robert Johnston, in Reference 5, relates a series of events in the 1950s that had a significant impact on the development of hydrofoils in the United States. One of them 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 only a few submarines. He directed a study seeking a solution to sustain trans-ocean operations in the event of hostilities involving a considerable number of 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.

An organization was formed to design and build a 3500-ton hydrofoil cargo carrier with a destroyer-type hull in the 1951 to 1954 time frame. The Office of Naval Research (ONR) was given the program management responsibility for the U.S. Navy, and was supported by the Bureau of Ships, the Bureau of Aeronautics, and the David Taylor Model Basin (one of the former names for the David Taylor Research Center). The research was undertaken by the Hydrofoil Corporation of America, a non-profit organization formed by Dr.

Bush. Gibbs and Cox was contracted to perform experiments that would lead to the design of the hydrofoil, and Bath Iron Works was selected as the construction yard. There were many contributors to the much needed technology to accomplish such an ambitious task, along with a series of Project Officers and Project Managers. Bob Johnston, then the ONR Project Manager, remembers the periodic personal reporting sessions with 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 at that time. In 1954 it was concluded that to develop the propulsion system for a 3,500-ton hydrofoil would tax the total capability of the U.S. industry. On this note the project ended.....It is safe to say that even 36 years later a 3500-ton hydrofoil would still be very taxing!

Although the hydrofoil cargo-carrier was put aside, a number of hydrofoil initiatives resulted from the project. Gibbs and Cox entered the hydrofoil design field and, as we shall see later in this chapter, made major contributions to stimulate hydrofoil technological development. The Hydrofoil Corporation of America assembled a technical group that derived basic hydrodynamic theories for submerged foil systems. One of the concepts that was investigated was the Constant Lift Control System (CLCS). The objective was to have the foils adjust automatically to the changes in angle of incidence due to the so-called orbital motions in waves.

This concept led to a test hydrofoil named LANTERN, which was built to evaluate the CLCS. It was designed and built by The Hydrofoil Corporation, Annapolis, Maryland, and was one of the earliest hydrofoils using electronic controls. LANTERN first flew in 1953, had tandem submerged foils, displaced about 10 tons, was 35 feet long with a beam of 22 feet.

LANTERN, HC-4

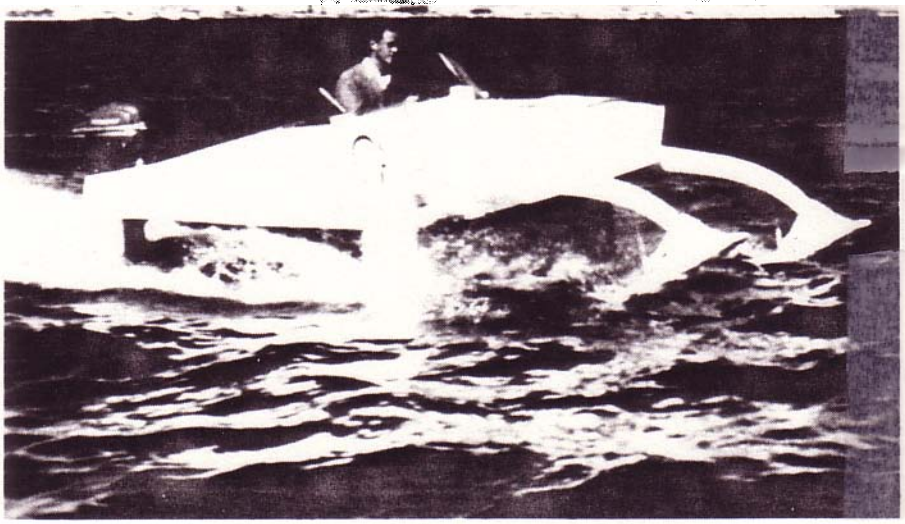
The control system was a straight adaptation of an aircraft automatic control system. We will see in a later chapter why such a control system was necessary. The craft was unusual from another point of view - the foils struts and hull were all the same shaped section, namely a symmetrical 24% thickness ratio NACA airfoil section. LANTERN was powered by a 200 horsepower Chrysler marine engine, had a takeoff speed of 14 knots and a maximum speed in calm water of only 18 knots. As one can see from the illustration, the designers were enamored with a 24% thick airfoil section and used it throughout the craft. The reason for this is not known, or understood by the author. From what we know now, it would be predicted that the foil performance could have been better and a higher speed attained, if a thinner foil section had been selected.

For a time there was interest in LANTERN for use as a photographic platform to assess the changes in harbor bottoms, but the interest waned and the program ended.

ICARUS

Christopher Hook, a name well known in the hydrofoil community the world over, had studied naval architecture and aerodynamics in occupied France during World War II. He managed to escape first to Lisbon and then Kenya where he carried out numerous hydrofoil experiments under extremely austere conditions. Hayward describes three craft that Hook built there, all of which attempted to solve the foil control problem by the use of mechanically connected floats arranged to skim along the water surface in advance of the lifting foils. In 1945 Hook returned to England where he set up a research establishment at Cowes to further pursue hydrofoil model and full scale testing.

In the early 1950s, Christopher Hook decided to exploit some of his ideas in America. He brought with him a small test craft called "ICARUS" shown here. As with his previous designs, feelers were used ahead of the craft to sense the oncoming waves. These feelers, linked to the forward submerged foils, controlled their incidence,



Christopher Hook's Hydrofoil ICARUS

and thereby, it was intended to stabilize the craft. It was reported that the ICARUS was quite maneuverable and stable in waves. These aspects of ICARUS' success lead to the collaboration of Christopher Hook and the Miami Shipbuilding Corporation on several hydrofoils.

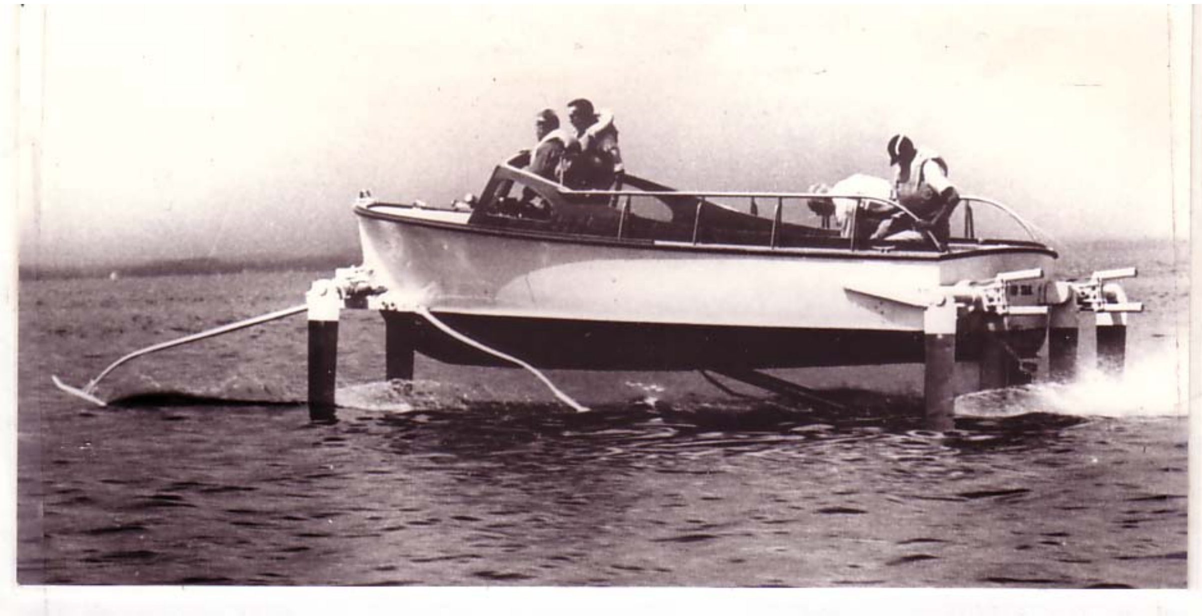
HIGH POCKETS - HIGH TAIL

In 1951 the Office of Naval Research contracted with the Baker Manufacturing Co. of Evansville, Wisconsin for the construction of two 24-foot hydrofoils. These projects were directed by Gordon Baker, who has been described as a mechanical genius. The first of these hydrofoils was "HIGH POCKETS", with a surface piercing foil configuration. The craft had four retractable "V"-foils which could be steered and rotated to provide a capability of banking into a turn.

HIGH POCKETS

HIGH POCKETS was demonstrated extensively to the U.S. Navy to show the capability of hydrofoils. Also, HIGH POCKETS can be proud of the fact that it was the first hydrofoil to embark the then Chief of Naval Operations, Admiral Carney, in the summer of 1953.[5]

The second Baker hydrofoil, known as "HIGH TAIL"[9], had a controllable fully-submerged foil system. The three-foil system; one forward and two aft, had three mechanical sensors, one touching the water ahead of each foil. These sensors provided the input for controlling foil lift. Propulsion was provided by a propeller driven by an inboard marine engine through an angled shaft. The forward foil and struts were mounted on a vertical axis which provided steering while flying. The foils, sensors, and propeller were all hydraulically retractable for operating in shallow water. Since the foils were quite small, lift control was obtained by changing foil incidence, or angle, relative to a fixed reference using a mechanical-hydraulic autopilot.



HIGH TAIL

The Table below provides a summary of the physical and operating characteristics of Baker's HIGH POCKETS and HIGH TAIL.

	HIGH TAIL	HIGH POCKETS
Type of Foil System	Fully Submerged	Surface Piercing
Length (Hull)	24 ft.	24 ft.
Beam (Hull)	7 ft.-6 in.	7 ft.-6 in.
Draft (Foils Down)	3 ft.-5 in.	3 ft.-5 in.
Cruise Speed	22 kts.	30 kts.
Max Speed	30 kts.	35 kts.
Power Installed	115 hp	115 hp
Displacement	6000 lbs.	6000 lbs.
Payload	915 lbs.	950 lbs.
Turning Diameter	250 ft.@ 22 kts.	360 ft. @ 32 kts.

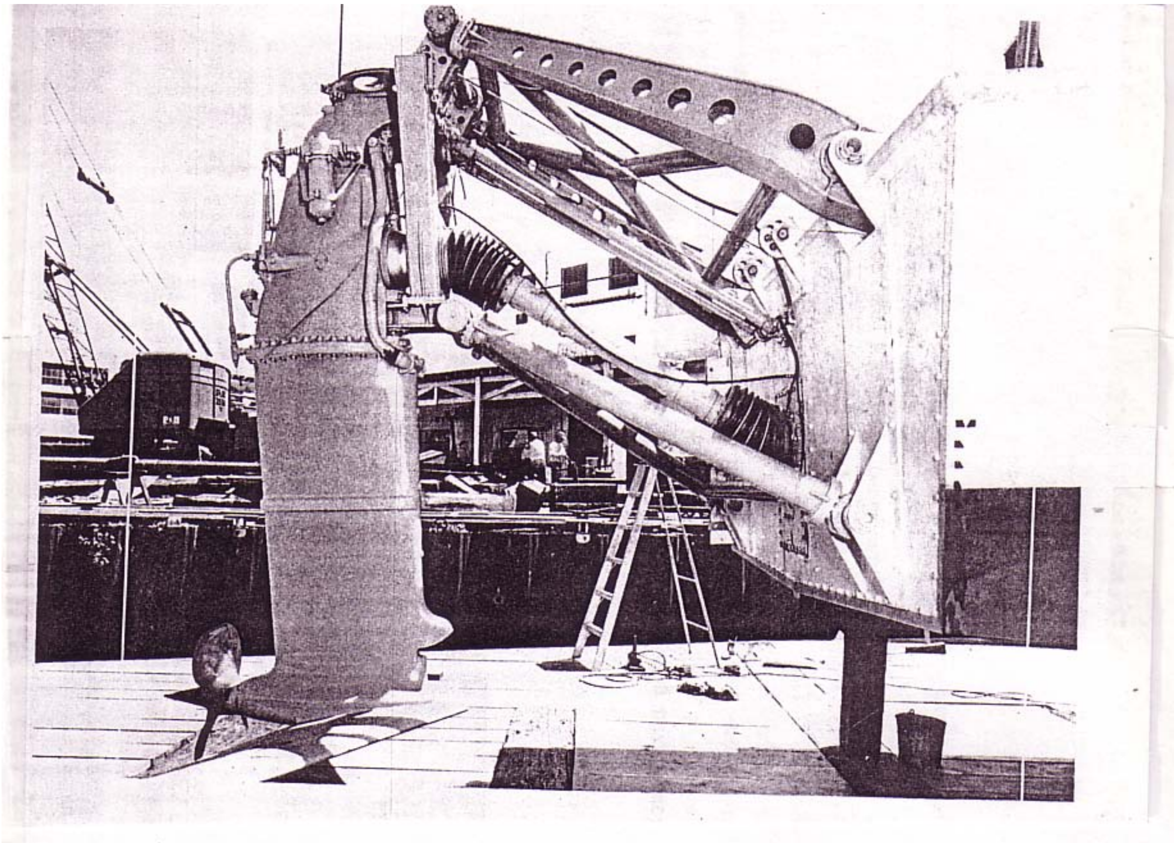
Even though Baker's mechanical genius led to a very workable mechanical-hydraulic autopilot, the conclusion was that future autopilots should be electro-hydraulic. Gordon Baker's contributions during this experimental stage of hydrofoil development was considered significant and helpful for future design decisions.

Another craft which contributed to the development of the modern hydrofoil is known as "HALOBATES", designed and completed in 1957 by the Miami Shipbuilding Corporation. This development grew out of a desire of the Marine Corps to increase the speed of approach to landing on the beach. They noted that these speeds during the Korean War landings had not changed perceptibly since William the Conqueror headed for a beach in 1066. As a result, a program was initiated in 1954 to evaluate a hydrofoil-supported landing craft, designated LCVP.

One version of the craft is shown here with "feeler" arms adapted from the Hook system. The name, HALOBATES, was suggested by the Marine Laboratory of the University of Miami since *halobates* is a sea going insect which has forward extending feelers. The hydrofoil HALOBATES, a modified small landing craft, was 35.5 feet long with a beam of 11.7 feet and a full load displacement of 31,000 pounds. A 630 hp gasoline engine provided power for the craft which demonstrated speeds up to 34 knots in 5-foot waves.[5] The design was complicated by the use of many ball and screw actuators necessary to provide retraction of the foil and propulsion system for the landing craft requirement. However, in spite of its relative success, this configuration led to a comment which in essence said: "If this is the way hydrofoils are to be built, we have no use for them in the Navy!".[4] The feeler concept was certainly objectionable, and so, feelers went their way.

HALOBATES with Feeler Arms

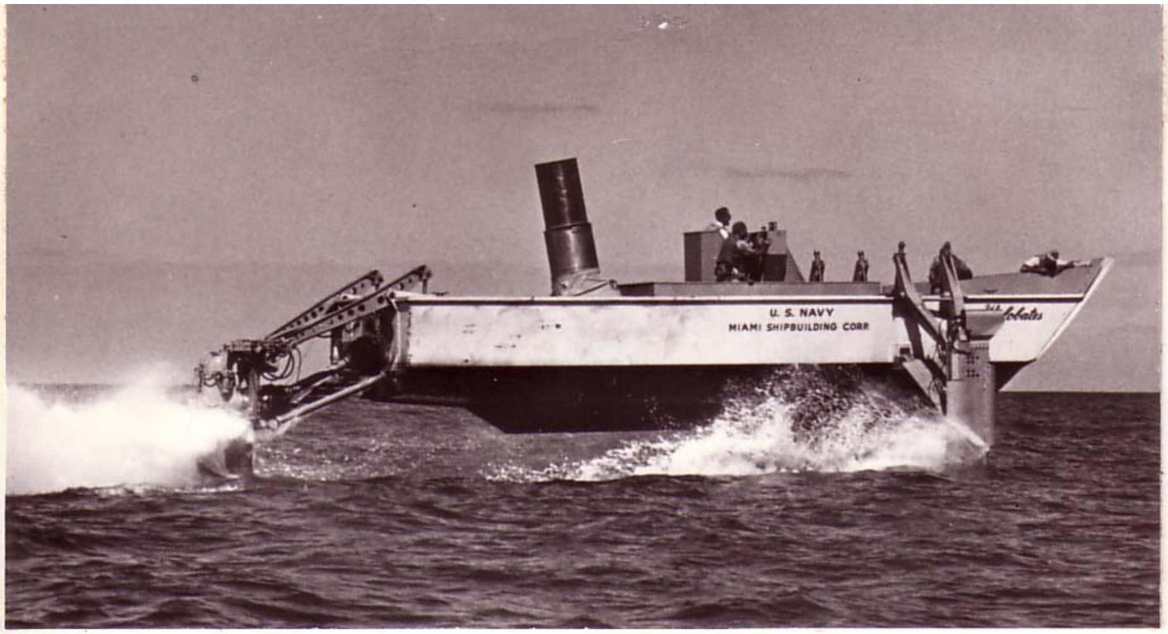
An interesting aspect of the HALOBATES design was associated with the landing craft requirement. Not only did the foil and propulsion systems have to retract, but they were to continue to operate during the retraction process, that is, the craft was to be capable of flying continuously from relatively deep water up to the point it became hullborne as the water became very shallow. The aft propulsion "out-drive", shown in the accompanying picture, had not only to provide thrust during retraction, but remain steerable at all times.



HALOBATES' Retractable, Steerable Propulsion System

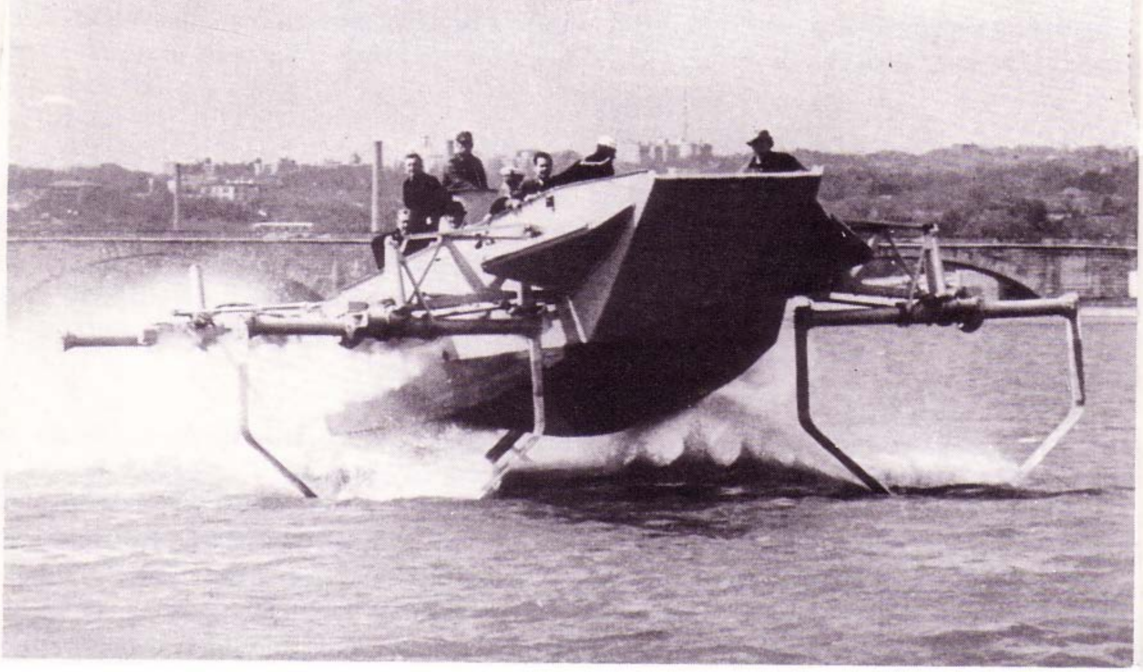
Because of objections to its feelers, HALOBATES was reconfigured with an electronic automatic foil control system. The feelers were removed and a step-resistance incorporated along the leading edge of the two forward struts. This feature provided a height signal, based on wetted length, to the autopilot, which in turn controlled foil lift. Also, it was decided to replace the reciprocating gasoline engine with an Avco T-53 gas turbine engine providing about 1,000 hp.

The photo on the next page shows the reconfigured craft. Note that the smokestack is not a steam boiler, but the exhaust duct for the gas turbine. The gas turbine installation in HALOBATES marked a notable technological "first" for hydrofoils in particular, and in the marine field in general.



HALOBATES with Gas Turbine and Automatic Control System

The second LCVP(H) was built by Baker Mfgr. Co. in the early 1960s and was named HIGH LANDER. It had four surface-piercing V-foils which were retractable and it could carry a payload of 8,000 pounds to the beach at 40 knots. It was also a modified LCVP and was designed along the lines of HIGH POCKETS, but weighed about 10 tons in the light condition.



Baker Hydrofoil, HIGH LANDER, LCVP(H)

During this period the U.S. Army also became interested in the potential of foils to increase the speed of their amphibious DUKW. Miami Shipbuilding, working with Avco-Lycoming, was awarded a contract in 1957 to demonstrate a "flying" DUKW. An Avco T-53 gas turbine engine was installed along with an electronic autopilot like that in HALOBATES. Retractable submerged foils were attached to complete the modification. Trials were run near Miami, Florida during which a speed of about 30 knots was achieved in calm water compared to the DUKW's normal water speed of only 5 knots.

Miami Shipbuilding Flying DUKW

Avco-Lycoming Hydrofoil Amphibian LVHX-1

In spite of the mechanical complexity of the Flying DUKW, as well as other disadvantages, the U.S. Marine Corps continued to have interest in the use of hydrofoils on wheeled amphibians. This led to their award of contracts for two competing designs of an LVHX. The LVHX-1, was built by Avco-Lycoming, and the LVHX-2 by FMC. Both were designed to meet the same requirement with aluminum hulls 38 feet long and a capability of carrying a

5-ton payload at a speed of 35 knots. LVHX-1 had a submerged foil system and LVHX-2 employed surface-piercing foils forward with a single submerged foil aft.

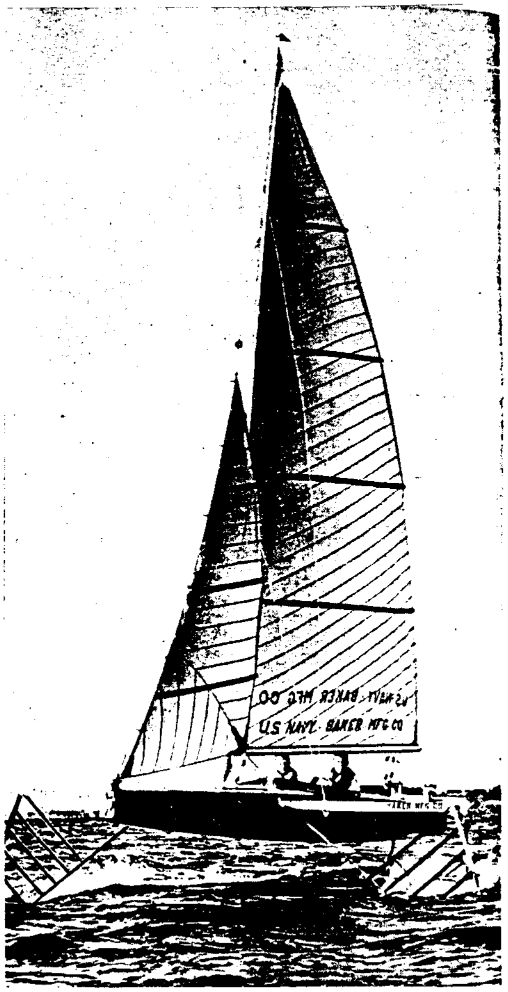
During the trials program that followed it finally became clear that the complexities and costs of such features as foil retraction and high speed gas turbine propulsion presented too great a penalty to pay for the increased water speed. As a result, further pursuit of hydrofoil landing craft was terminated.

FMC Hydrofoil Amphibian LVHX-2 Foilborne

FMC Hydrofoil Amphibian LVHX-2 On Wheels

MONITOR

All of Gordon Baker's mechanical genius was not expended on military hydrofoil applications. About 1950 he was interested in using hydrofoils for sailing purposes, having built a three V-foil cat boat with an airplane foil configuration (two foils forward and one aft).[5] This craft attained remarkable speeds while beating into the wind reaching 20 knots. Speed ratios of over 1.5 times the real wind velocity were recorded. However, it had a tendency to "pitch pole" when running before the wind and would go into "irons" when coming about. These undesirable characteristics led Baker, with U.S. Navy backing, to develop the MONITOR, a sloop with two ladder foils forward and a submerged foil aft. The forces of all the stays were fed into a mechanical computer. Based on these inputs, the computer determined and then set, through a linkage system, 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.



MONITOR

MONITOR first flew in 1955 and a pace boat clocked her at 25 knots. In October of the following year she was paced at 30.4 knots. It was reported that MONITOR attained speed to true wind speed ratios of just over 2.0, and at times unofficial boat speed measurements close to 40 knots were observed.[10]

It is interesting to note that the U.S. Navy backing of MONITOR was motivated by its objective to learn more about the foil structural characteristics and construction methods used by Baker.

Reference 10 is an excellent treatment on the subject of hydrofoil sailing and is highly recommended for anyone wishing to pursue this exciting sport.

CARL XCH-4 HYDROFOIL

The U.S. Navy, in its early development work, evaluated a hydrofoil configuration having ladder foils, described earlier, on the XCH-4 (Experimental Carl Hydrofoil No. 4). This 16,500 pound, 53 foot craft, was known as the "Carl Boat", after its principal designer, William P. Carl. It had a seaplane-type hull supported by two sets of foils forward and a single strut and foil aft. Two 450 hp Pratt and Whitney R-985 aircraft engines with two-bladed controllable pitch propellers 8 feet in diameter provided the thrust to carry this craft to the highest speeds since those achieved by Alexander Graham Bell's HD-4.

The Carl XCH-4 Hydrofoil

During trials of the XCH-4 in 1953, its design speed of 65 mph was exceeded in three to four foot waves. It is interesting to note that many of the tests were run on the Great South Bay between Sayville, and Patchogue, Long Island, and also in the open sea off Montauk Point, Long Island.[11] The U.S. Coast Guard furnished an escort boat for each of the tests. A humorous aspect of XCH-4 testing occurred one day when an innocent bystander, after observing the craft running back and forth for several days, called the Coast Guard to report that a seaplane had been trying unsuccessfully to take off, and undoubtedly needed some assistance. This is an understandable error in view of the craft's appearance.

Later, a maximum speed of 74.4 mph was recorded, which in 1954 was a speed record for hydrofoils, exceeding Bell's 1919 record of 70.85 mph. The good performance, stability and favorable seakeeping characteristics of the XCH-4 encouraged U.S. Navy officials to continue hydrofoil development.

Shortly after final tests of the XCH-4, Bill Carl left J. H. Carl and Sons to form his own company, Dynamic Developments, Inc. His partner in this venture was Robert Gilruth, who was also a hydrofoil enthusiast. They initially developed and produced a hydrofoil kit for conversion of small runabouts. Grumman Aircraft Engineering Corp. purchased an interest in the company and later acquired it as a base for their entry into the hydrofoil market.

SEA LEGS

During the early 1950s, the well-known naval architectural firm of Gibbs and Cox of New York had assembled, with U. S. Navy support, a highly respected technical team for the design of a versatile hydrofoil test craft. It was built by Bath Iron Works and aptly named BIW. The craft, 20 feet long with a 5-foot beam, displaced about 1800 pounds and had a 22-hp outboard engine. BIW was successful in testing different foil arrangements, different control schemes including manual, mechanical and electronic, and different height sensors used in the control system. The most important outcome of this work was the potential for an electro-hydraulic autopilot and the decision to design and build SEA LEGS.

SEA LEGS

In 1954 Sutton and Browne undertook the modification of a Chris Craft hull. A foil system was added and propulsion system changes were made. An electronic autopilot stabilization system, developed by the Draper Laboratory at the Massachusetts Institute of Technology, was installed to control the fully submerged foil system. This electronic autopilot contained 160 vacuum tubes! Remember them? A signal input to control the flying height of SEA LEGS was obtained from a bow-mounted sonic height sensor. This device provided a continuous measurement of the distance between the bow and the water surface. But more about that in Chapter 7.

The original design of SEA LEGS called for about an 8,000 pound displacement, but as the design and construction developed, the weight grew to 10,550 lbs. This trend seems to be inherent in the design of high technology craft, and continues to plague designers even today. The foils were made of aluminum and arranged in a canard configuration with about 30% of the lift on the forward foil and the remainder on the larger aft foil. Each foil had a trailing edge flap which was hydraulically actuated.

SEA LEGS made its first flight in 1957 and demonstrated its excellent seakeeping performance in rough water up to speeds of 27 knots. During the latter part of 1957 and early 1958 the craft continued its demonstration flights for Navy and civilian visitors in the New York area. It was in June of 1958 that the Chief of Naval Operations, Admiral Arleigh Burke approved a demonstration trip to the Washington, D. C. area. Arrangements were made to have SEA LEGS escorted by a Navy torpedo boat, the PT-812.

After a false start and a return to the Gibbs and Cox pier in New York for repair of a foil control attachment, the craft got underway for Cape May, New Jersey on 15 July 1958. After stopping over night and refueling, SEA LEGS proceeded through the Delaware Canal to the Navy's small boat facility on the Severn River in Annapolis, Maryland where it and the PT boat arrived on the afternoon of 16 July. During the open-ocean portion of the trip the boats experienced waves up to 4 or 5 feet, but SEA LEGS was able to maintain an average of 23 knots. It clearly demonstrated to the participants the superior seakeeping capabilities of this hydrofoil. The dry and comfortable ride they experienced would be impossible to duplicate on a comparably sized conventional craft.[5,7] The conditions during this part of the trip were quite different on the PT boat which had been outrun by SEA LEGS in the bargain. It might be asked: who was escorting whom?

After a week of successful demonstrations in the Annapolis area, SEA LEGS undertook the 170-mile run to Washington on 26 July. A Navy representative and crew arrived at the Naval Gun Factory in the afternoon after an uneventful trip down the Chesapeake Bay and up the Potomac River. The following day, Sunday, 27 July, the small hydrofoil took aboard the Chief of Naval Operations, ADM Arleigh Burke, along with a host of other high-level Navy dignitaries. It was recalled that 15 or 20 minutes before the CNO party was due to arrive, the autopilot "blew a tube" on the warm-up run and SEA LEGS crash landed. One of the crew managed to fix the system in the nick of time just before the Admiral arrived! This was undoubtedly one of SEA LEGS' most important demonstrations. It lasted about an hour and 15 minutes, during which time all of the VIPs took a turn at the helm, and had the satisfaction of flying a hydrofoil. The trip to Mount Vernon and back was completed without a hitch to everyone's satisfaction.

During the days that followed, SEA LEGS continued to display her unique capabilities to a wide variety of visitors. These included many Navy officers of flag rank, congressional representatives, including Senator Saltonstall of Massachusetts, and numerous members of the press, radio, and television. The craft returned to New York, arriving there on 20 August after covering 1851 miles of which 1751 were on foils. The visitor "box score" for this all-important demonstration included 3 Congressmen, 17 Admirals, 3 Marine Corps Generals, 3 Assistant Secretaries, and numerous other important civilian and military personnel for a total of 375. This was an impressive accomplishment and one that had a significant impact on the Navy's future course of action in the hydrofoil arena. Richard Browne[12] provides a detailed, running account of the travels of SEA LEGS between New York and Washington and return. The account also describes the ingenuity of the crew and dedication that has characterized so many hydrofoilers.

SEA LEGS on Cradle

In 1962 and 1963 SEA LEGS underwent a more detailed evaluation by the David Taylor Model Basin, more recently known as the David Taylor Research Center. The craft was extensively instrumented to provide at-sea data for future hydrofoil designs. This marked the beginning of the change from when hydrofoils were carried out on a "cut-and-try" basis to a more scientific approach of collecting design data and establishing design criteria. This information was much needed for the hydrofoil ships that were to follow. After the trials, SEA LEGS was retired with honors and refurbished for the Smithsonian with the financial aid of Gibbs and Cox.[5] SEA LEGS is on display at the Mariners Museum, Newport News, Virginia. She is shown here on a cradle in the process of being transported to the museum sometime about 1975.

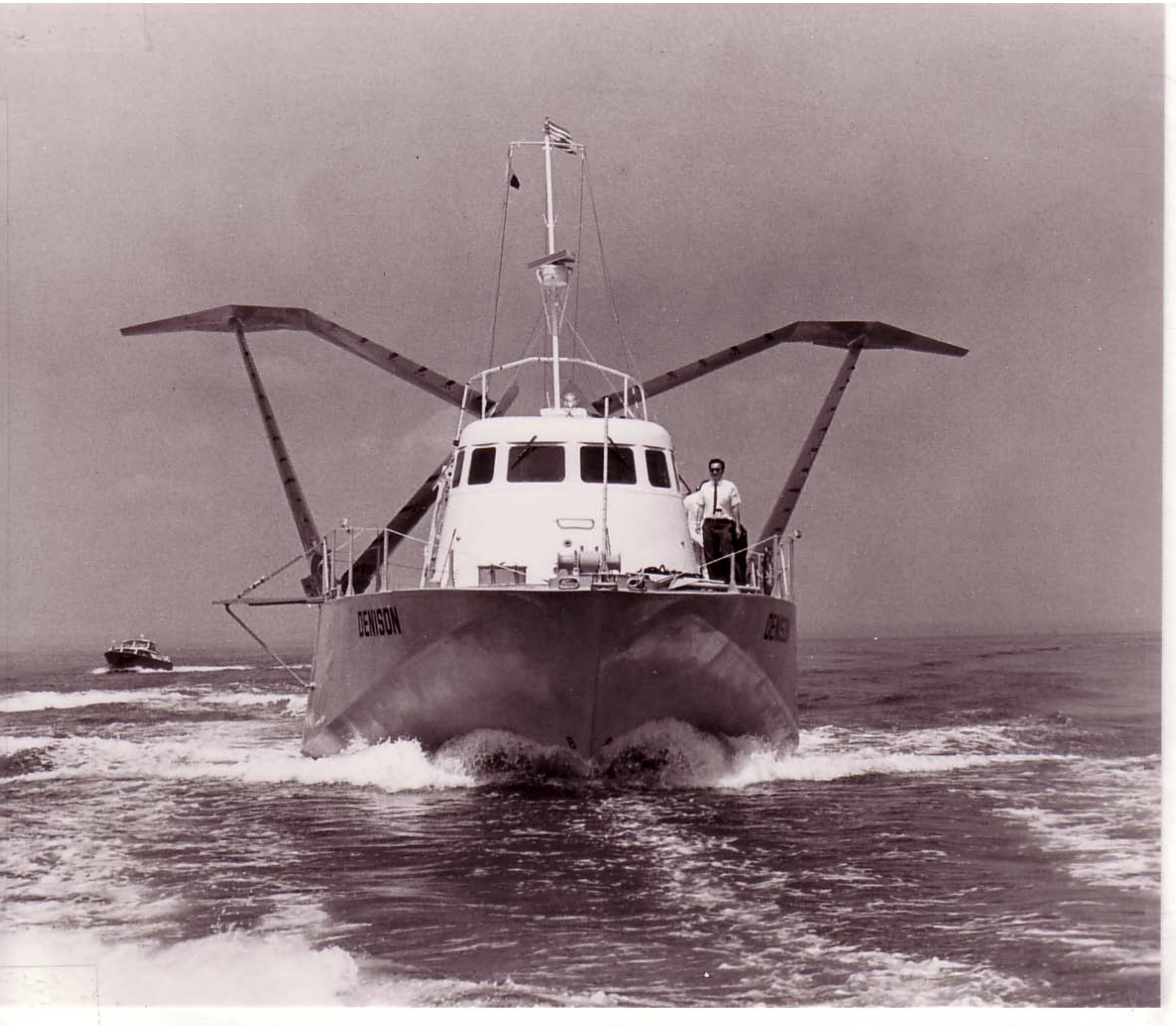
DENISON

Overlapping the events just described in connection with SEA LEGS was a series of developments within the Maritime Administration (MARAD) that started in 1955. These were sparked by the commercial application of hydrofoils in Europe and the research being sponsored by the U.S. Navy. The Maritime Administration Coordinator of Research, Charles R. Denison, was enthusiastic about the future commercial potential of the hydrofoil and in 1958 sponsored an extensive parametric study carried out by Grumman Aerospace Corporation and its affiliate Dynamic Developments, Inc. The purpose of the study was to determine the type of hydrofoil craft best suited to future express-cargo and passenger applications and establish design criteria for such craft. Speeds of 50 to 200 knots, displacements from 100 to 3,000 tons, and ranges from 400 to 3,600 nautical miles were considered. Foil section shapes and arrangements, power plants and propulsors, hull form, and control systems were treated including several preliminary designs for oceangoing ships. Based on the favorable results of this study, MARAD contracted with Grumman in 1959 for design studies for two test craft. One was to have a conventional powerplant and the other a provision for a *lightweight aircraft nuclear power* source when such a system became available. Now that's <u>really</u> planning ahead!

Subsequently, in January of 1960 MARAD placed a contract with Dynamic Developments, Inc. to build an experimental hydrofoil capable of speeds up to 60 knots with gas turbine engines. Provision was made for a second phase where the subcavitating foils would be replaced with supercavitating foils. The intent was to achieve speeds up to 100 knots with the same power plant. Unfortunately, Charles Denison, whose vision and enthusiasm was in great part responsible for the program, suffered an untimely death before the ship got beyond the early design stage. It was in his memory that the ship was later christened HS DENISON.

Although MARAD had contracted with Dynamic Developments, Inc. to build DENISON, Gumman Aircraft Engineering Corporation, because of expanding interest in hydrofoils, purchased interest in and eventually acquired all of Dynamic Developments, Inc.

DENISON was launched by Grumman on 5 June 1962 at Oyster Bay, Long Island, and began sea trials only four days later. The picture below shows the ship hullborne with its unique foil system retracted. The 95-ton DENISON had surface piercing foils forward carrying 85% of its weight, and a single fully submerged tail foil aft carrying the remaining 15%. The ship's length overall was 104.6 feet, maximum hull beam was 23 feet, and maximum draft hullborne with its foils extended was 15.4 feet.



HS DENISON Hullborne with Foils Retracted

It is significant that the main propulsion for foilborne operations was provided by a General Electric gas turbine engine rated at 14,000 horsepower. It was a marine version of GE's J-79 aircraft jet engine. MARAD had obtained two J-79 engines from the Navy and then bailed them back to GE who then provided the marine version by the addition of a so-called free power turbine to take energy out of the jet. This arrangement was interesting in that it was accomplished for the total sum of *one dollar*. This proved to be a wise long-term investment on the part of the General Electric Company because it was the basis for their later so-called LM series of marinized gas turbine engines which are extensively used in Navy ships today.

The above financial arrangement was not entirely unique on the DENISON program because although MARAD contributed $1,500,000 for design and construction, Grumman and 73 other companies invested from $5M to $7M of their own funds. Now <u>that's</u> cooperation!

The design of a propulsion system capable of putting 14,000 hp into the water through a single high speed propeller was a considerable challenge at the time. Power was transmitted from the gas turbine engine through a right-angle bevel-gear drive to a supercavitating propeller mounted at the bottom of the aft strut. The spiral bevel gears, 20 and 21 inches in diameter and turning at 4,000 rpm, were designed and built by General Electric Company and represented the most stringent requirement of any which previously had been manufactured.[7]

A series of trials were carried out at speeds of 50 to 60 knots as the ship demonstrated its ability to be stable and highly maneuverable. DENISON was also a good performer in rough water under high winds and low temperatures. The temperatures on some tests were below freezing, but no icing problems were encountered during either hullborne or foilborne operations. In comparison, it was reported that a 30-foot escort boat was unable to proceed out of sheltered waters during that time due to heavy icing on its deck and superstructure. Again we have a case of who was escorting whom?

Following these trials, the U.S. Navy and MARAD had planned to proceed with the next high-speed phase of the DENISON program incorporating a supercavitating foil system. All seemed to be on track when the Navy decided to change course and proceed with the design of their own high speed foil research craft, designated FRESH-1 (described in the next Chapter). Since the Navy withdrew their financial support, MARAD decided to terminate the program and not pursue development of commercial hydrofoils any further.

Maritime Administration Hydrofoil HS DENISON Foilborne

It has been said that the MARAD program, and more particularly the HS DENISON, contributed in large measure to the growing technology base for the design of hydrofoils. Many of the DENISON's subsystems were at the leading edge of the state-of-the-art, and knowledge gained was invaluable in further developments by the U.S. Navy. It is unfortunate that it did not also fulfill the bright future originally forecast for the employment of commercial hydrofoils in U. S. service.[7] But more about that later.

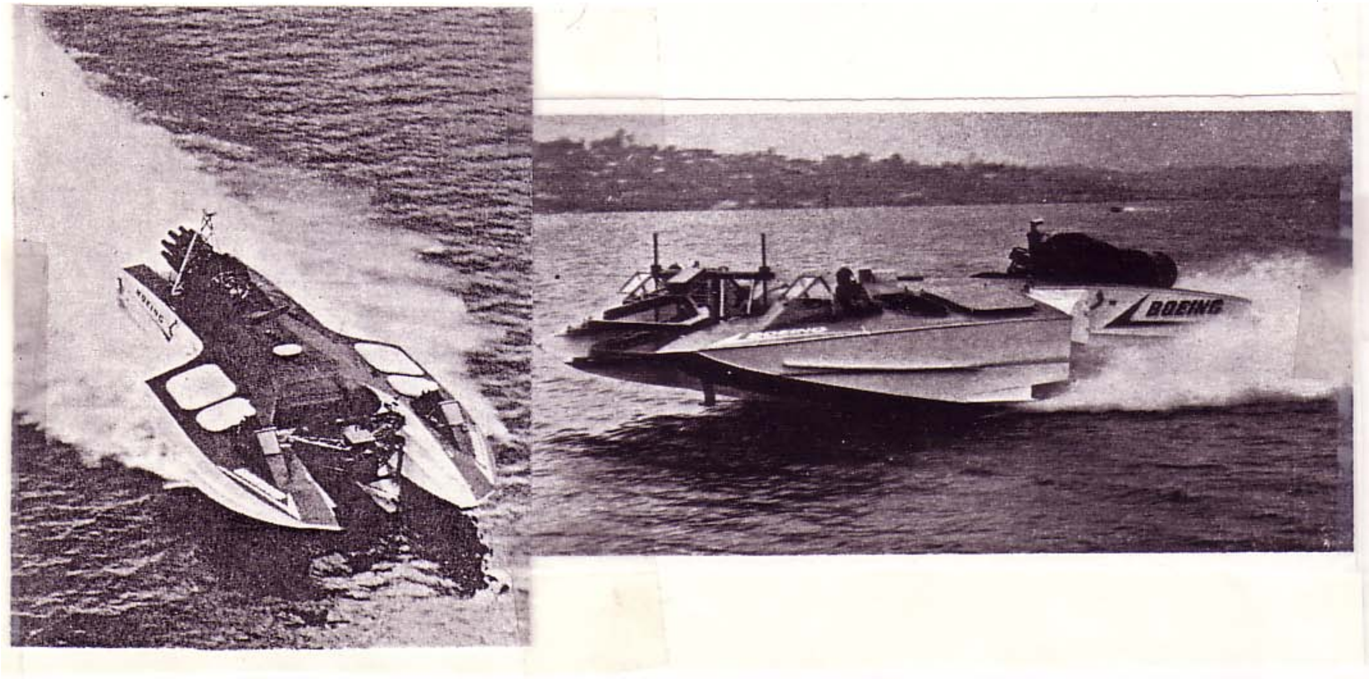
CHAPTER 3

LARGE SCALE TEST HYDROFOILS

We have now entered the era when small experimental hydrofoil craft have given way to large scale test craft built specifically to identify and solve major hydrofoil technical problems. The technical data base for committing the hydrofoil community to speeds of 80 to 100 knots did not exist, therefore industry, the U.S. Navy, and the Royal Canadian Navy joined their talents and financial resources to build the test craft described in this chapter.

HYDRODYNAMIC TEST SYSTEM

The Boeing jet-propelled research hydroplane, or Hydrodynamic Test System (HTS)[13], was put into operation in 1961. This lobster-shaped craft had provision for placing foil models of about 0.50-square feet and other shapes in the water between the "claws". This 16,000 pound, 38-ft long craft with an Allison J-33 turbo-jet engine having a thrust of 4,600 lb, was capable of speeds up to about 80 knots.



Boeing Hydrodynamic Test System

The starboard cockpit carried the driver, and the test observer was in the port cockpit. The instrumentation of the craft was such that a complete polar plot (lift and drag versus angle of attack) at one depth and speed could be obtained in a run time of 30 seconds.

The HTS operated on Lake Washington on calm, quiet water during daylight hours. It proved to be indispensable in adding to the knowledge of hydrodynamics of high speed foils at that time.

FRESH-1

The Foil Research Experimental Supercavitating Hydrofoil, known as FRESH-1 was designed and built by the Boeing Company, under Navy contract, in the 1962 to 1963 time frame. The purpose of this 53-foot long test vehicle was to evaluate a variety of foil designs and foil system arrangements at high speed. The twin-hull catamaran arrangement provided a large clear space between the hulls, within which different foil systems could be mounted. Unlike the HTS, these foils actually supported the 16.7-ton test vehicle in the foilborne mode of operation. There was complete freedom for the arrangement and location of foils relative to each other.

FRESH-1

FRESH-1 was powered by a Pratt & Whitney JT3D-3 turbofan engine having a rating of 17,000 pounds of thrust. It was selected because it was a relatively expedient way of obtaining the required high speed thrust; overall efficiency was not an important consideration, and it permitted the investigation of foil systems without interference from propellers or waterjets.

During the early trials of FRESH-1, there was concern over the possible problems of flutter, divergence, and rudder reversal. To examine these hydroelastic phenomena, it was necessary to examine a series of test conditions interpreting and evaluating results at each stage before moving on to the next. To overcome the delays in such a procedure, a telemetry system was employed to provide instantaneous data in a mobile shore station. With this system, it was possible to move more rapidly through various tests.

Extensive hullborne and foilborne trials were conducted by Boeing during the first half of 1963. On May 3, 1963 the craft attained a speed of 80 knots, exceeding the hydrofoil speed record set by the XCH-4 in 1954 of 63 knots. The FRESH-1 hydrofoil speed record of 80 knots still stands unchallenged at this writing.

In July of 1963 a series of test runs were made, and at a speed of 70 knots[7] the craft went out of control and completely turned over! Fortunately, the two man crew and a member of the Trials Board, who were on the craft at the time, sustained only minor injuries. Damage to FRESH-1 was light except for considerable deformation of the first stage blading in the jet engine, and later extensive corrosion of other metal parts of the engine.

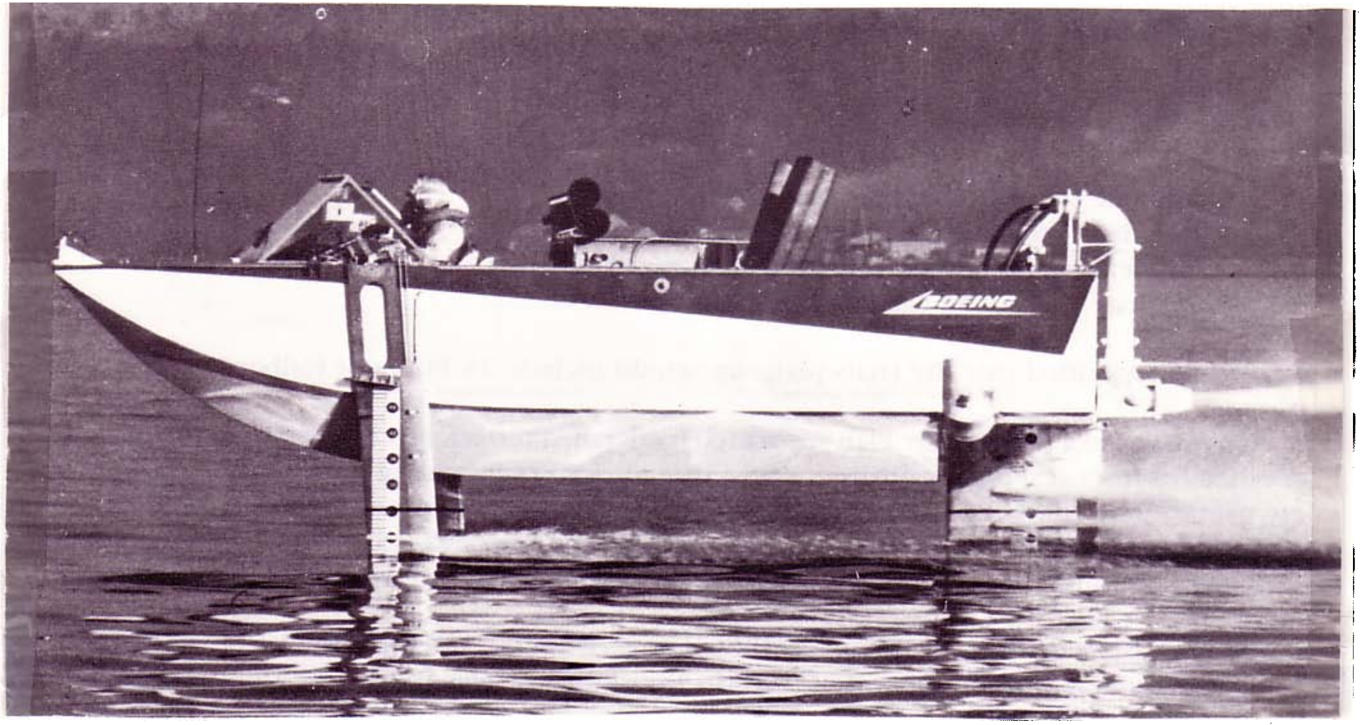
As mentioned above, FRESH-1 was extensively instrumented so an analysis of the data made possible a complete reconstruction of the events leading up to the accident. It was reported that a loss of flap effectiveness due to the formation of cavities in the flow permitted a gradual increase in flying height during the run and this was not detected until the foils were in the near-broach condition. At the very shallow foil submergence, the craft lacked both the lateral stability and rudder effectiveness and went into a divergent yaw to starboard. Ultimately, the port foil was completely overloaded and stalled with a resulting rapid roll to port causing the craft to capsize.

Following the accident, the FRESH-1 was completely refurbished and changes were made to prevent a recurrence of a loss of directional stability. The JT-3D jet engine was replaced with a reconditioned YTF-33 jet engine acquired from the U.S. Air Force. Upon completion of this work, additional trials were successfully conducted by Boeing, and then accepted by the U.S. Navy in July 1964. Tests continued only for a short time before the craft was laid up due to the de-emphasis of the 100 knot goal in preference to a reliable 50 knot hydrofoil.

LITTLE SQUIRT

It was also about this time that designers were intrigued with the idea that a waterjet could propel a hydrofoil boat. Advantages were simplicity through elimination of gears and light weight. This lead to the design and construction of a company-sponsored research craft by the Boeing Company. It was called LITTLE SQUIRT, and consisted of a small 5,500 lb, 20 foot run-about with a stepped W-form hull.

The boat used a centrifugal pump producing a flow rate of 3,600 gallons of water per minute out the stern; hence its name. The pump in turn was powered through a reduction gear by a 425 hp Boeing gas turbine engine. It was at that time that this small gas turbine as one of Boeing's product lines, and they anticipated wide use of such engines on trucks and small craft.

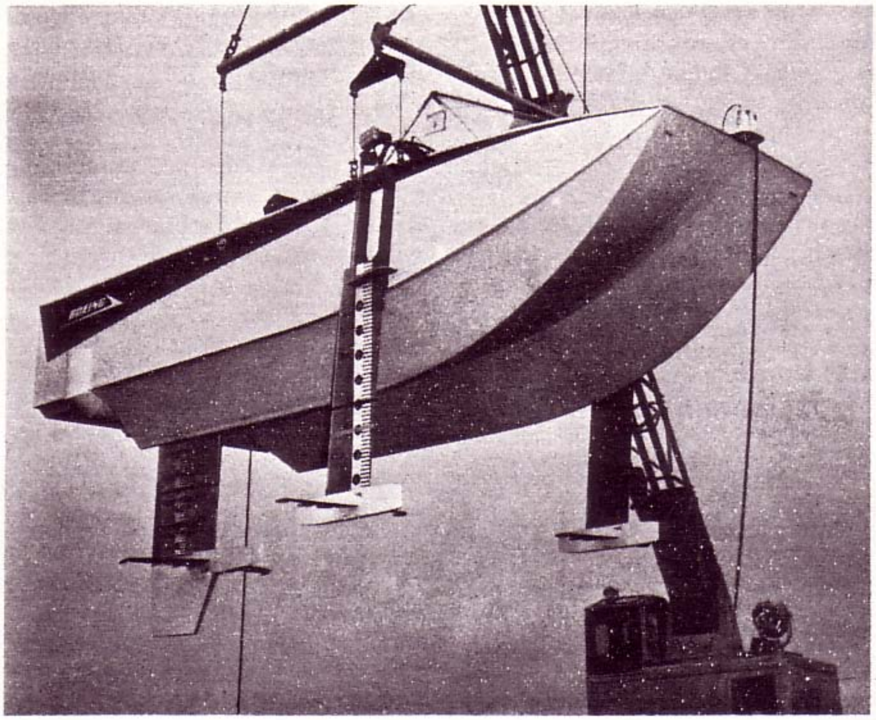


LITTLE SQUIRT

The following table describes the principle characteristics of LITTLE SQUIRT.

Length Overall		20 ft.
Beam		8 ft.
Foil Span:	2 Forward	3 ft. -1 in.
	1 Aft	4 ft. -6 in.
Strut Length		2 ft. -9 in.
Displacement:	Full Load	2.6 L. Tons

Two foils were placed forward on the craft and one aft, as seen in the illustration.[13] It is interesting to note that the area of the single aft foil was equal to the sum of the areas of the two forward foils. Each foil had trailing-edge flaps, but in addition, lift was controlled by changing the incidence of each foil. The flaps were used for lift augmentation during takeoff and were retracted for the cruise, foilborne condition. The automatic control system used an acoustic height sensor. It measured the distance between a fixed point on the bow of the boat to the mean, or average water surface.

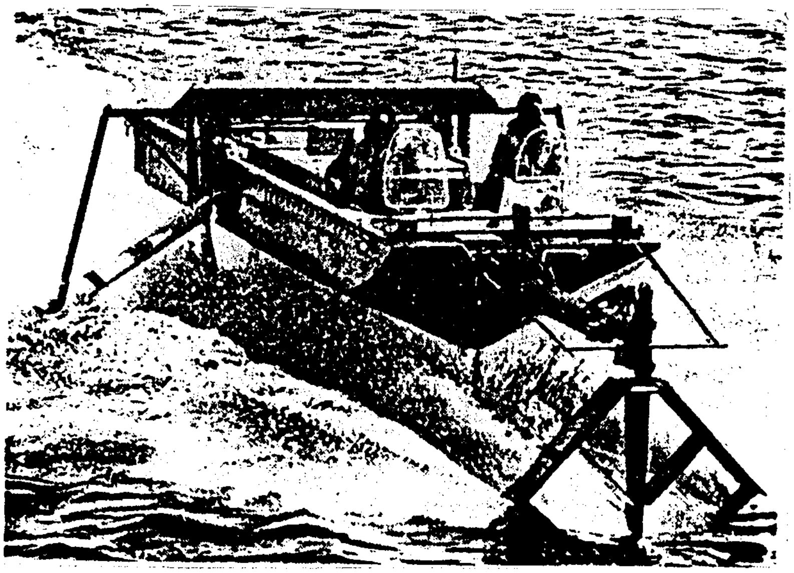


View of LITTLE SQUIRT Showing Foils

This test craft accumulated about 110 hours of foilborne operation on Lake Washington and Puget Sound, sometimes operating in 3-foot waves. LITTLE SQUIRT achieved speeds of up to 45 knots and established the technical basis for proceeding to the waterjet propulsion designs for the gunboat, TUCUMCARI, subsequently the U.S. Navy PHM hydrofoils, and also the Boeing's commercial hydrofoil passenger ferry, JETFOIL.

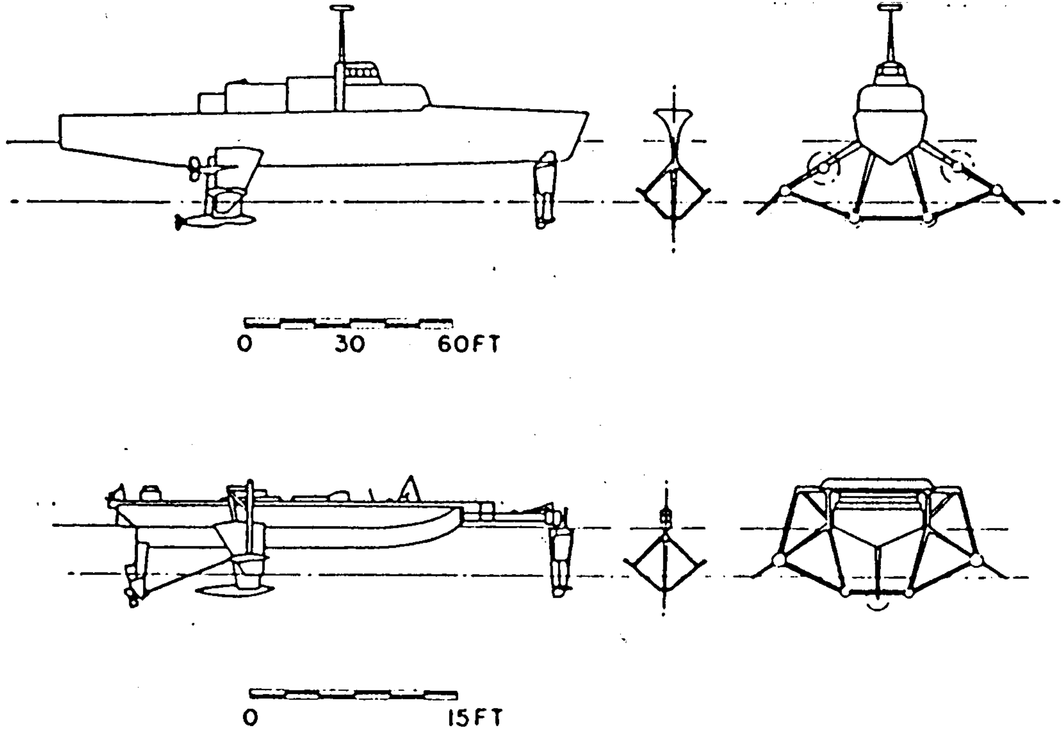
CANADIAN R-X CRAFT

In 1960 the Naval Research Establishment (NRE) of the Canadian Defense Research Board proposed a 200-ton, 50-to 60-knot, open-ocean Anti-Submarine Warfare (ASW) hydrofoil ship for the Royal Canadian Navy. This hydrofoil became known as the HMCS "BRAS D'OR" (FHE-400), designed by DeHavilland Aircraft of Canada Ltd. One of NRE's major contribution to this project was the use of a 3.5-ton research test craft, R-X.[14]



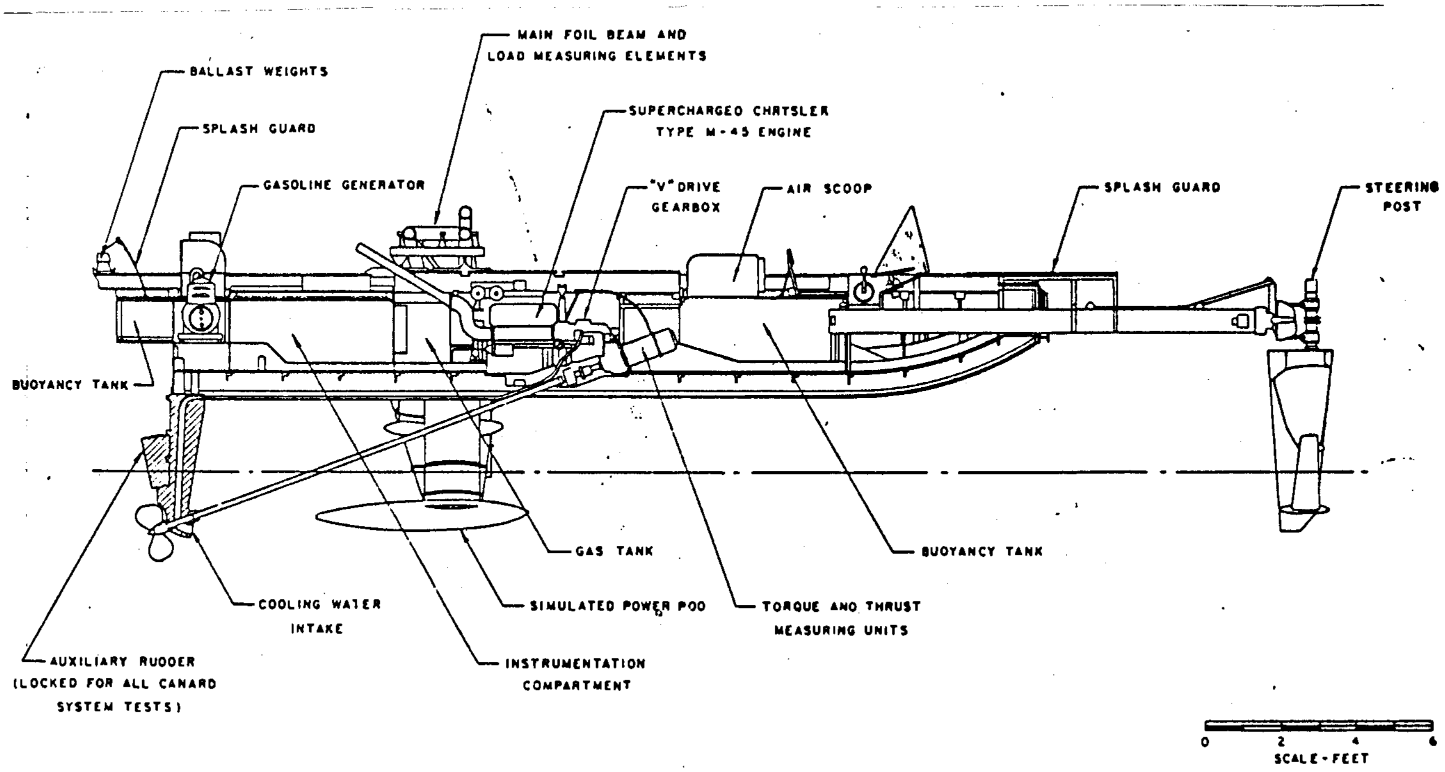
R-X Test Craft with FHE-400 Foils

R-X was designed and constructed to investigate the characteristics of different hydrofoil configurations and to allow rapid change of hydrofoil design features. Her major use was a long series of tests in connection with the FHE-400, the details of which are described in a later chapter. For this purpose the R-X was equipped with a canard foil system and was operated as a quarter-scale dynamic model of the FHE-400. The accompanying diagram shows the similarities between the R-X craft and its larger counterpart.



Outline Comparison of R-X and FHE-400 Hydrofoils

The original intention was to use the R-X primarily to check DeHavilland's analog computer and design predictions for the dynamic behavior of the BRAS d'OR foilborne in waves. However, as tests evolved the R-X had a more important role to play in demonstrating problem areas that might have been overlooked by conventional design and model test approaches. Reference 14 describes the design of the R-X and its equipment along with its use in developing the FHE-400 hydrofoil system.



R-X Test Craft Hull Cross Section

The craft had a hull length of 25 feet, a beam of 6 feet, and a depth of 3 feet. A water-cooled Chrysler Imperial Type M-45 marine engine, with modifications to increase its power rating to 365 hp, was used to drive a conventional propeller on an inclined shaft. As can be seen from the hull cross section diagram, the engine and fuel tanks were located at the craft's center of gravity, just forward of the main foil.

The foil system of the R-X was designed by DeHavilland at a very early stage of the development program. The bow foil, in particular, was modified many times from the original design to reflect full-scale design progress. These changes were required to alleviate the craft's pitching motions in waves. It was recognized at the outset that the design of a diamond-shaped surface piercing bow foil, carrying 10% of the ship's weight, for operation at 50-knots in waves would present many difficulties. Fluctuations of immersion and angle of attack due to wave action and ship pitch would be more pronounced at the bow than at the main foil and could lead to ventilation and cavitation.

The R-X was instrumental in providing solutions to these difficulties, and lead to designs which made the BRAS D'OR a successful hydrofoil ship. One of the important lessons learned was the value of open-water tests with a manned model as an integral part of the design process for advanced marine vehicles.

We will see in later chapters how these test craft, and the Research and Development hydrofoils that were to follow, provided the technical basis for commercial and U.S. Navy Fleet hydrofoils of the 1980s.

CHAPTER 4

U.S. NAVY DEVELOPMENTAL HYDROFOILS

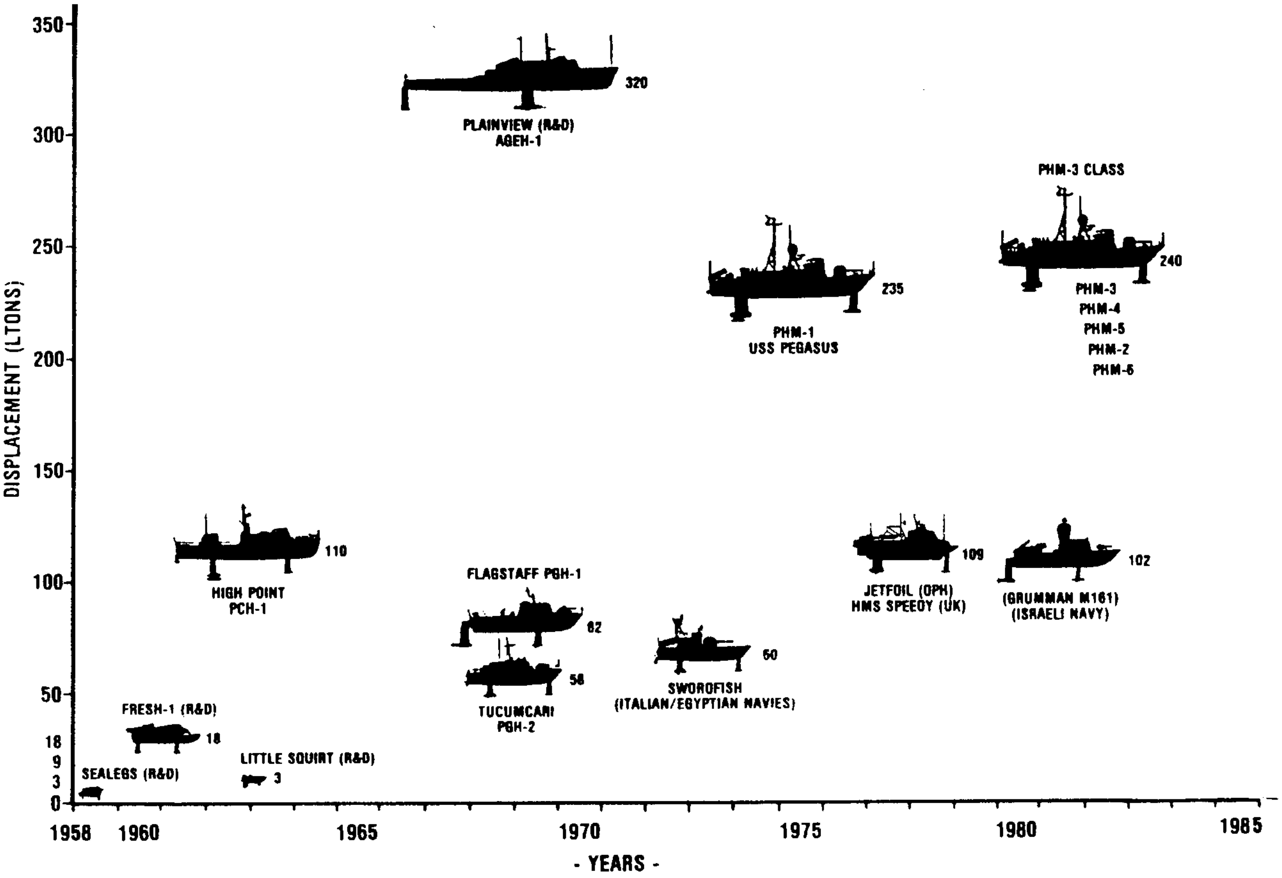
Before describing the hardware aspects of the Developmental Hydrofoils in this chapter, it is essential to convey to the reader that there were several U.S. Navy organizations and dedicated people that made this all possible.

William M. Ellsworth, in "Twenty Foilborne Years"[7], describes in great detail the involvement of the many devoted people who were the backbone of the U.S. Navy's hydrofoil research and development program. He points out that as early as 1961, James L. Schuler played a key role in not only hydrofoil development but other advanced marine vehicles as well in one of his positions as Program Manager for Hydrofoil Research and Development in the BuShips Research Directorate. "His involvement was to have a profound impact on the future of hydrofoil development in the years to come." But Jim Schuler was not alone in this endeavor.

In April of 1966 The David Taylor Model Basin (later to be known by several names, but most recently DTRC, The David Taylor Research Center) assumed the responsibilities as BuShips Technical Agent for the Hydrofoil Program. A Hydrofoil Development Office under the leadership of William M. Ellsworth was established. A long lasting partnership between Bill Ellsworth at DTRC and Jim Schuler at what became the Naval Sea Systems Command (NAVSEA) continued for several decades all during the developmental hydrofoil days and the PHM hydrofoil program that followed. Bill was ably assisted by a host of technical experts over the many years exemplified by such hydrofoilers as Robert Johnston, William C. O'Neill, and the members of the Hydrofoil Special Trials Unit, but the complete list would very extensive.

Then too, there was the industrial base which performed the detail design, construction and provided the technical experts involved in the comprehensive testing of these ships. Boeing and Grumman were the major contributors to this effort along with their many subcontractors who provided the subsystem hardware to bring it all together.

One of the best ways to see the entire scope of the U.S. Navy hydrofoil development is by way of a plot of ship weight against time over the time frame of 1958 to 1985. At the lower left corner of the illustration we see SEA LEGS, FRESH-1, and LITTLE SQUIRT. These, as described in previous chapters, provided the technical basis for the four U.S. Navy Research and Development hydrofoils, the subject of this chapter, and later the U.S. Navy's PHM-1 Class hydrofoil ships.



U. S. Hydrofoil Military Development: 1958 to 1985

HIGH POINT (PCH-1)

HIGH POINT, named after a city in North Carolina, was designed by the U. S. Navy Bureau of Ships, built by the Boeing Company under Navy contract, and delivered in August of 1963. The ship was 116 feet long, had a maximum hull beam of 32 feet (38 feet across its foil guards), a draft of 8.5 feet with foils retracted, 19.0 ft with foils extended, and displaced about 125 tons. Power for foilborne operations is provided by two British-built Rolls Royce PROTEUS gas turbine engines driving four propellers, two at the bottom of each of two aft struts. A diesel engine provided power to a steerable out-drive for hullborne, low speed maneuvering. The canard foil system had a forward foil with a span of 20 feet and an aft foil with a span of about 36.5 feet.

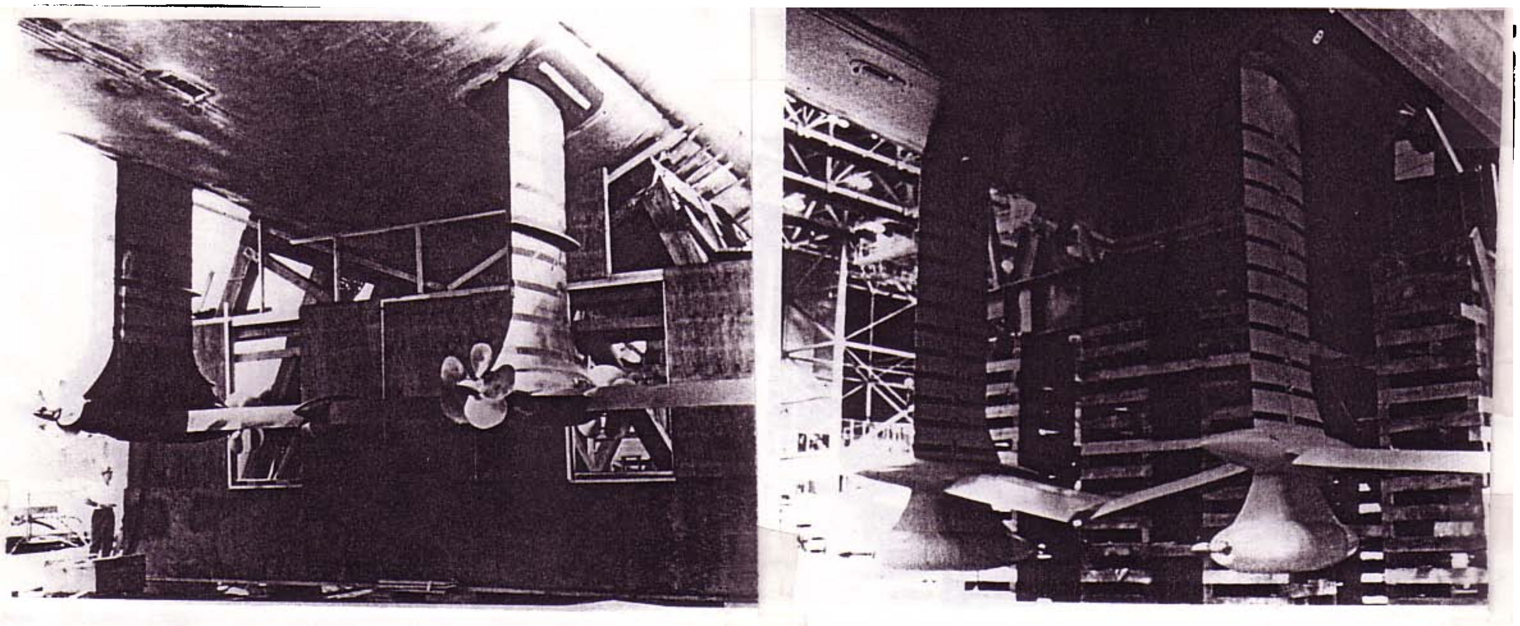
HIGH POINT was originally intended for off-shore Anti-Submarine Warfare (ASW). The concept was to use the PCH-1 as a small, high-speed sonar platform, equipped with ASW torpedoes to sortie from harbors in advance of a convoy. Using its speed to move quickly over a larger area, the PCH-1 could protect the departing convoy and its larger ASW escorts at its origin when they are most vulnerable. In this connection the ship was to be delivered to the Pacific Fleet for operation by the Mine Force. However, development of a sonar suitable for effective utilization of the ship's unique capabilities was never prosecuted. But instead, HIGH POINT underwent Navy tests immediately after construction during which time numerous technical problems were uncovered.

Boeing-Built HIGH POINT (PCH-1)

Delivery to the Pacific Fleet was therefore postponed because it was recognized that the hydrofoil state-of-the art was not adequate to produce a fleet hydrofoil with acceptable operational reliability. In spite of this, the initial version of HIGH POINT underwent extensive calm and rough-water trials.

Because the ship still displayed some shortcomings, a decision was made in October of 1964 to perform extensive repairs and refurbishment. Much was learned during subsequent trials and operations which lead to major modifications proposed and made by The Boeing Company starting in 1971 under the "MOD-1" (modification) program. Among the many changes, the major ones included steering and automatic controls, hydraulic system improvements, relocation of the propulsion pods, redesigned gears for the foilborne transmission system, new propellers, and the incorporation of strain gauges and video cameras at critical locations for gathering data during trials.

Shown below are comparison photographs of HIGH POINT on blocks before and after major modification of the propulsion pod and foil to strut intersection arrangement. These changes were made because of unforeseen effects of cavitation on the foils, transmission pods and propellers. Subsequent to MOD-1, HIGH POINT attained a level of availability that was significantly higher than that previously experienced.

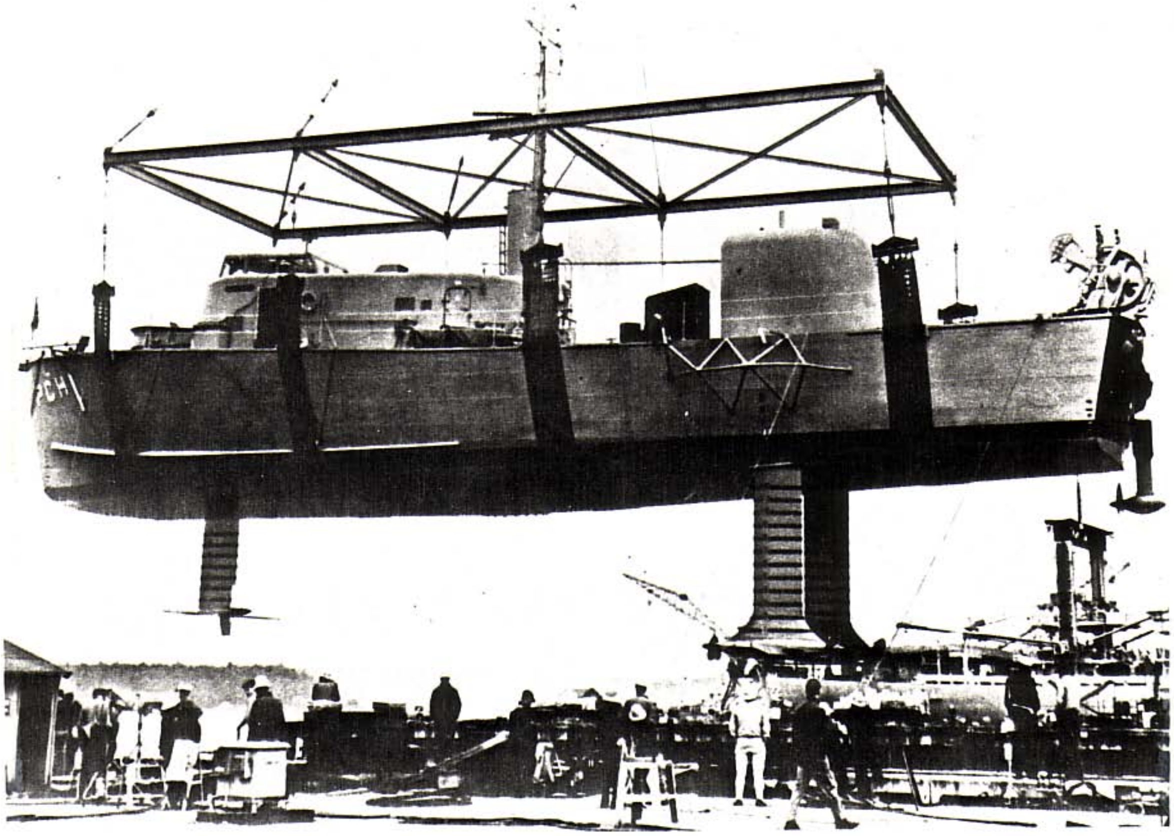


HIGH POINT Propulsion System Before and After MOD-1

One may wonder how a hydrofoil of this size and weight can be moved back and forth from pierside to blocks for such major changes and other work that cannot be accomplished with the ship in the water. The photo on the next page serves to illustrate how this is done. Pictured here is the ship supported by a strongback, or frame, and four straps judiciously placed. A shipyard hammerhead crane provides the lift and transport of the ship to it's resting place. Some appreciation for the size of the foils and struts can be gained from the comparison with the shipyard workers.

As indicated before, an excellent, comprehensive treatment of HIGH POINT is provided by William M. Ellsworth in "Twenty Foilborne Years"[7]. He describes the events leading up to this ship's acquisition, detailed design, construction, and trials. Its utilization as an R & D ship to refine the criteria for future hydrofoil designs, and to explore the mission utility of hydrofoils and other high speed advanced vehicles is also portrayed.

HIGH POINT has been the "work horse" of the hydrofoil research and development community for almost three decades, and accumulated almost 2,000 foilborne hours before it was placed in the "Inactive Fleet".



HIGH POINT Being Lifted at Pierside

HIGH POINT participated in demonstrations of equipment and was used for the evaluation of mission capabilities of hydrofoil ships on many occasions. The HARPOON missile firing illustrated here was a major milestone, but was one of many such demonstrations of hydrofoil capabilities.

HIGH POINT During First Firing of HARPOON Missile from a Hydrofoil

Shown below is HIGH POINT in another demonstration of its capabilities conducting a vertical fuel replenishment exercise from a CH-46 SEA KNIGHT helicopter in which fuel was transferred from the CH-46 to HIGH POINT.

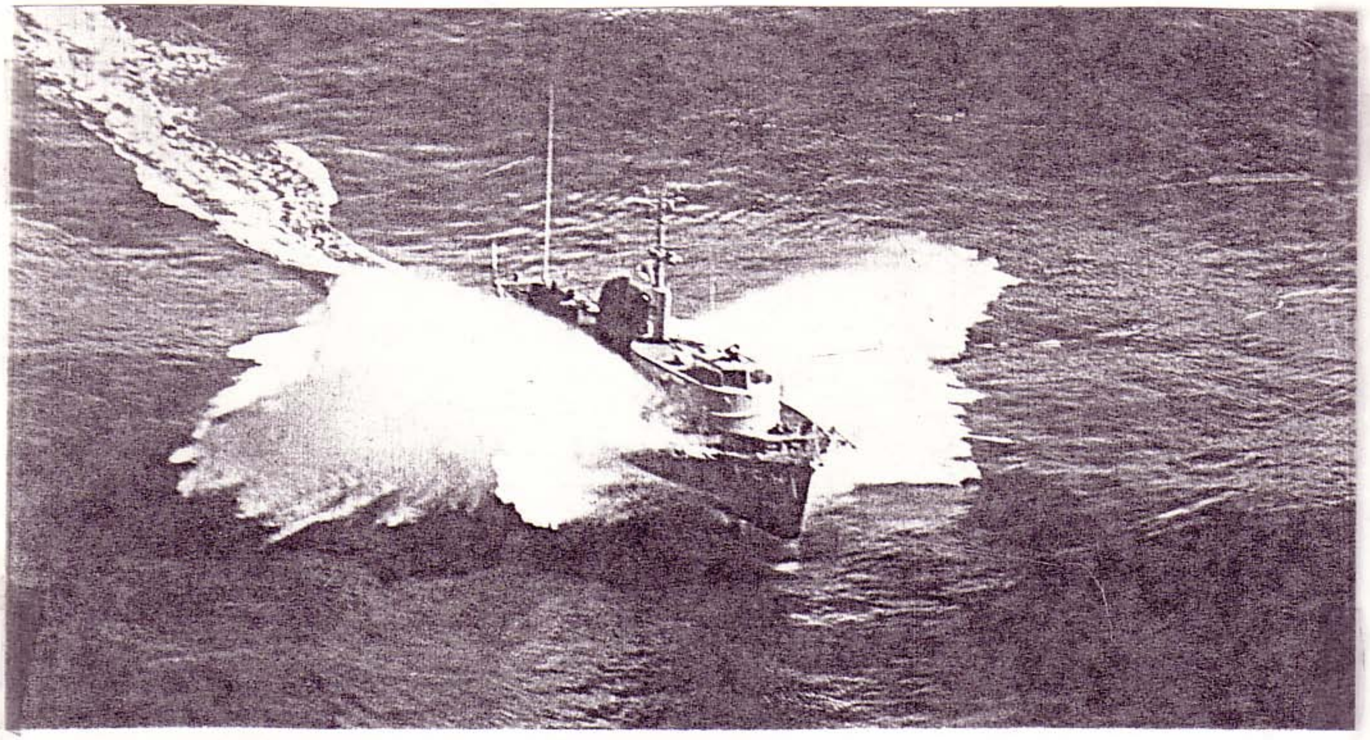
HIGH POINT Vertical Replenishment with a CH-46 Helicopter

In May of 1971 HIGH POINT made a transit to an area north of Port Angeles, Washington, and made a rendezvous with a SEA KNIGHT from the Naval Air Station at Whidbey Island. The ship was run at various speeds, hullborne and foilborne, at various turn rates, and wind directions as the helicopter attempted to maintain a safe altitude to avoid striking the ship's mast with its rotors. The trials had been run in calm water. To introduce realism into the operation which someday would have to be carried out in the open ocean under adverse weather conditions, the hydrofoil control system was manually cycled to simulate rough water action on HIGH POINT. After several attempts, the trial was successfully completed. There were no adverse effects on the ship from the close proximity to the helo noise and the rotor downwash. The crewmen reported that the deck was a very stable platform on which they had to work while handling a 1-1/2 inch fuel hose while foilborne at 38 knots with 45 knots of wind across the deck. The CH-46, however, was reported to have restricted pilot visibility when hovering over the stern of the hydrofoil during the initial hook-up operations.

In April 1975, HIGH POINT was turned over to the U.S. Coast Guard for the evaluation of the hydrofoil in several coastal roles. The ship was officially commissioned as the Coast Guard vessel WMEH-1, complete with a new coat of white paint and the conventional red "racing stripes" as shown below.

HIGH POINT in U.S. Coast Guard Colors

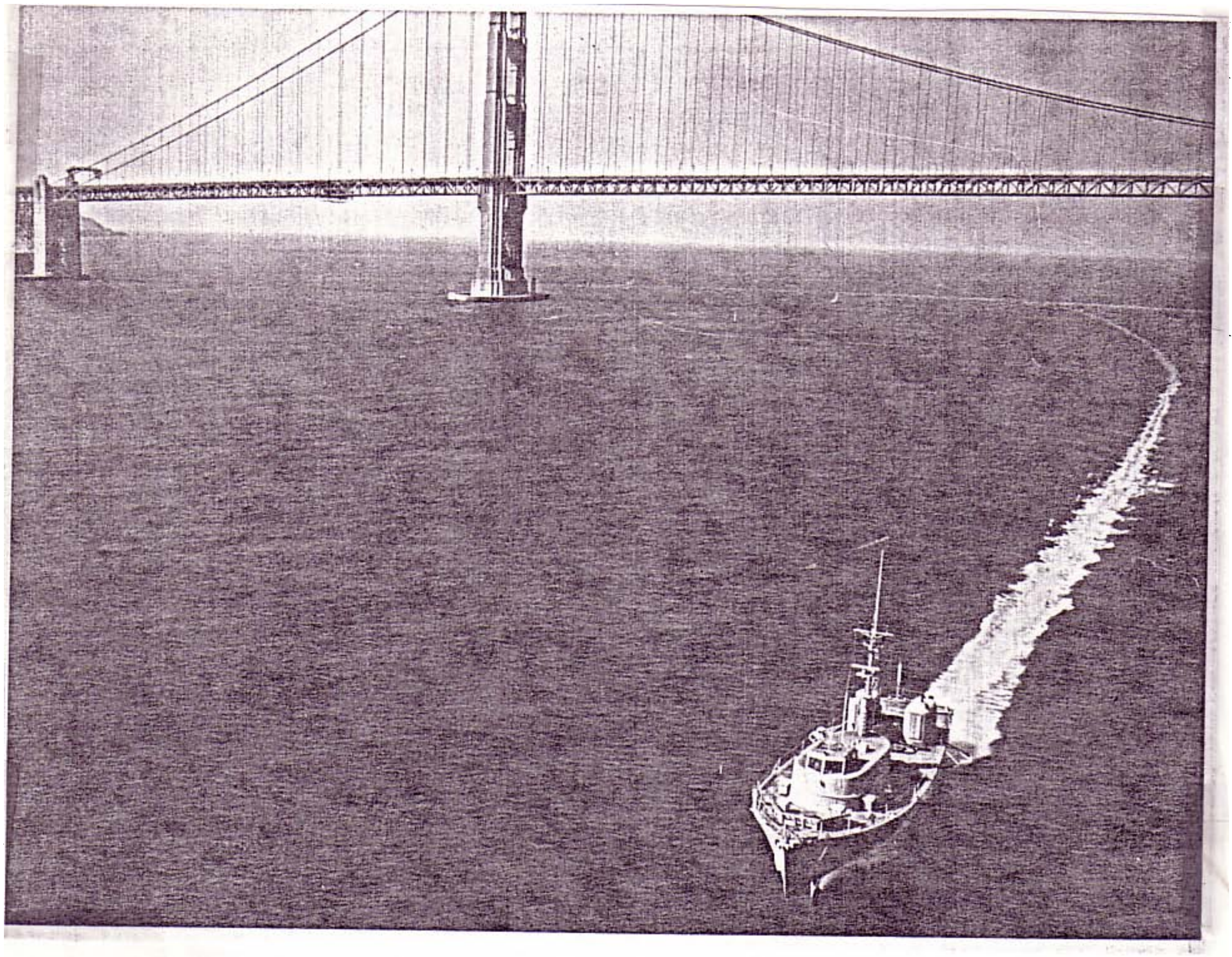
During the voyage to its operating base at the Naval Air Station at Alameda, near San Francisco, California, the WMEH-1 stopped at Astoria, Oregon. It had just completed it 280 mile voyage from Bremerton, when on crossing the Columbia River Bar, it ran into a huge wave. The picture shown here gives some indication of the nature of this experience.



HIGH POINT Crossing the Columbia River Bar at Astoria, Oregon

HIGH POINT's forward foil broached, the ship slowed down as the hull crashed into the water. The craft rolled about 26 degrees and pitched down 6-1/2 degrees, with the bow becoming submerged in the face of the next oncoming wave. The ship and crew recovered from the experience and the Coast Guard learned something the Navy crew had long known, namely, that the HIGH POINT was a very forgiving ship. The total transit distance from Bremerton, Washington to San Francisco was 855 nm and took a total of 31 hours running time. Of this, 17.4 hours were on foils.

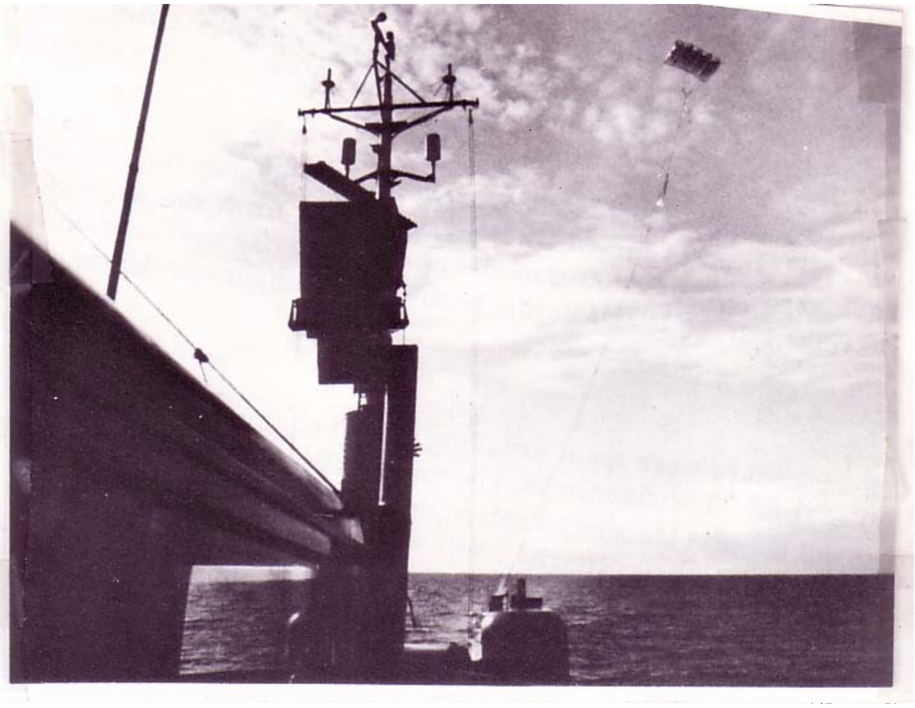
One of the many missions that the WMEH-1 accomplished during the Coast Guard evaluation was a fisheries patrol. She was ordered to proceed in pre-dawn hours to locate the Soviet fishing fleet off the San Francisco coast. HIGH POINT found the fleet operating about 40 miles to the Southwest, remained foilborne and maneuvered through the fleet, photographing and identifying over 40 vessels in about 1-1/2 hours. It was estimated that this would have taken 12 to 14 hours to accomplish with conventional Coast Guard surface units. Similar patrols and Search and Rescue missions continued during this period, and the ship demonstrated excellent potential for hydrofoils to enhance Coast Guard mission capability.



HIGH POINT Cuts a Narrow Swath Under The Golden Gate

On several occasions during its colorful career, HIGH POINT was used as a high speed tow ship-towing either airborne or submerged bodies having considerable drag at hydrofoil speeds. A hydrofoil has a lot of excess power built into it to enable the ship to take off, especially in rough water, and attain high speeds. HIGH POINT was well endowed in this respect, even able to take off on one of its two gas turbine engines if necessary. With both gas turbines operating, HIGH POINT could tow objects on a long towline at high speed.

In 1971 during a Southern California deployment, HIGH POINT conducted a test to determine the effectiveness of using a towed parafoil to raise an antenna to an altitude which would provide over-the-horizon, direct line-of-sight communication for surface ships. Parafoils were used routinely as an alternative for a parachute, offering greater directional control in free-fall, and were also used as a kite to lift weather instruments from a fixed location. Insofar as was known at the time, parafoils had not been deployed from a moving towpoint prior to this test on HIGH POINT. The parafoil was airborne at a speed of 14 knots into the wind to give a relative wind speed at the parafoil of 22 knots. This was adequate to get the parafoil aloft with the antenna attached as can be seen in the photograph. The ship then went foilborne and demonstrated stable operation up to speeds of 36 knots. Similar tests were carried out successfully on conventional Navy ships such as the USS SCHOFIELD (DEG-3).



Parafoil Being Towed by HIGH POINT

HIGH POINT with Towing Gear on Stern and Cable Deployed

A more recent example of a HIGH POINT towing mission during 1987 is shown on the previous page in a close-up of the ship towing a high-speed sonar body (which is about 100 feet below the water surface) at speeds higher than ever achieved by other ships. With its high speed, coordinated turn capability, this hydrofoil and its tow could successfully maneuver while the body maintained a given depth and trailed directly behind the ship.

It was during 1988 that hard decisions concerning HIGH POINT had to be made. U.S. Navy funding for hydrofoil Research and Development projects had been reduced to an all-time low - namely, zero. Hence projects requiring the talents of the "old work-horse" were non existent in the hydrofoil community.

Along with this "non-development", came a decision to close David Taylor Research Center's Hydrofoil Trials Branch on 9 December 1988. This organization had been the mainstay of U.S. Navy R&D hydrofoil operations in the Bremerton/Seattle Washington area for over 22 years. The group had been originally established in 1966 as the David Taylor Research Center Hydrofoil Special Trials Unit, or affectionately called HYSTU, at the Puget Sound Naval Shipyard.

The contributions of the HYSTU hard working and devoted group of Navy civilians and earlier, Navy military personnel, cannot be adequately described in only a few pages. William M. Ellsworth provides some of the laurels in reference 7. Suffice it to say that HYSTU was inextricably connected with testing of many of the hydrofoils described in these chapters - including the all-important Navy acceptance testing of PHM described in a later chapter. The author's close association with such HYSTU personnel as Sumi Arima, Don Rieg, and Vern Whitehead for over a decade will long be remembered with great appreciation for a "job well done".

For about five years PCH-1 had received "tender loving care" from Boeing under U.S. Navy contract. She was docked at the Boeing plant in Renton, WA at the southern end of Lake Washington. Early in 1989 a decision was made to take HIGH POINT out of service and transfer her to the Navy Reutilization Facility at the Puget Sound Naval Shipyard, Bremerton, WA. HIGH POINT's last voyage, with Arlyn Harang (of Boeing) in command, was on 11 May 1989 and consisted of a transit from Renton, up Lake Washington, through the Lake Washington Ship Canal and Hiram M. Chittenden Locks and into Puget Sound. She then put on a real show for the television media. A helicopter-borne video camera captured some of HIGH POINT's sharpest maneuvers and were for all to see that evening on the late news.

FLAGSTAFF (PGH-1)

Two hydrofoil patrol gunboats were built for U.S. Navy fleet operational evaluation in the late 1960s. Although they were designed and built to the same performance specification, their configurations were different. PGH-1 was propeller driven and had a conventional (airplane) foil configuration, whereas TUCUMCARI (PGH-2) was waterjet propelled and had a canard foil arrangement. Delivered to the Navy in 1968, they both saw service in Vietnam between September 1969 and February 1970, making them the first U.S. Navy hydrofoils in combat.

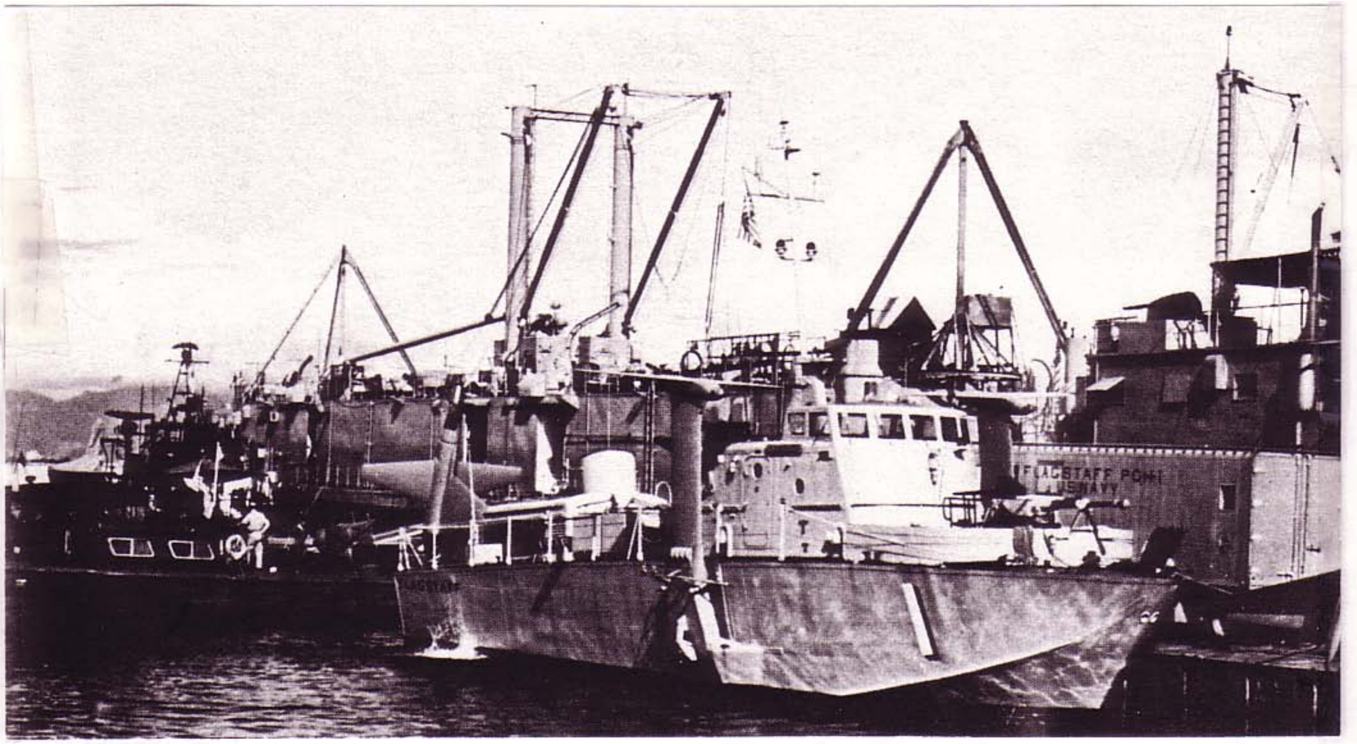
Grumman-Built PGH-1, FLAGSTAFF

FLAGSTAFF, named after a city in Arizona, was designed and built by Grumman Aerospace Corporation. The ship was 74 feet long with a maximum beam of 37 feet and a displacement of about 69 tons. Draft was 4.2 feet with foils retracted, and 13.5 feet with foils extended. This 69-ton hydrofoil, with its conventional foil configuration, carried 70% of the lift on the forward, main foils and 30% of the lift on the aft foil. Manning consisted of 4 officers and 12 enlisted men.

Power for foilborne operation of FLAGSTAFF was provided by a single Rolls Royce TYNE 621/10 marine gas turbine engine with a maximum continuous power rating of 3,450 hp at 14,500 rpm. This drove a single 45-inch diameter variable pitch supercavitating propeller located on the lower end of the aft strut through a set of right angle bevel gears. Hullborne propulsion consisted of two Detroit diesels at 160 hp each driving Buehler waterjets.

FLAGSTAFF was launched from the Grumman facility in Stuart, Florida early in 1968 and underwent sea trials. Delivery to the U.S. Navy took place at West Palm Beach, Florida on September 14, 1968 with an accumulated foil- borne time of 85 hours. The ship was then transported to the west coast and in February 1970, FLAGSTAFF was assigned to operate as part of the Amphibious Forces based in San Diego. It was here that she went through a series of tests by the Navy referred to OPEVAL, or Operational Evaluation.

After completion of these trials, FLAGSTAFF was transported to Vietnam for riverine operations. The photo below shows the ship at a pier in Danang. Note the clearly marked support vans in the background which were transported along with FLAGSTAFF to provide the crew with spare parts and maintenance equipment. Operations in the area were very successful. The crew was particularly impressed with the ships ability to operate under adverse conditions, and had occasion to fly through many monsoons near South Vietnam's Demilitarized Zone.



FLAGSTAFF Docked at Danang, Vietnam

FLAGSTAFF completed its tour in Vietnam early the following year having added 138 foilborne hours to its log and completing 22 missions. She was returned to San Diego to resume her operations there.

One of the important features of a hydrofoil is its ability to withstand the impact of an underwater explosion in its vicinity. The accompanying picture shows this quite vividly as FLAGSTAFF was snapped during a test to demonstrate this characteristic.

FLAGSTAFF Underwater Explosion Demonstration

In late 1974 the Navy loaned FLAGSTAFF to the U.S. Coast Guard for several months for evaluation in performing their expanded 200-mile offshore coastal patrol role. The Coast Guard commissioned the ship, manned it with their personnel, maintained it, and evaluated her in actual and simulated missions while operating out of San Diego and other Southern California ports.

During its sojourn there, it was FLAGSTAFF to the rescue! A 40-foot cabin cruiser, several miles off shore late in a winter evening, was reported to have an electrical fire on board. Minutes later, cutter FLAGSTAFF was dispatched from her dock at Port Hueneme (wah-nee-mee) near Oxnard, and proceeded at about 55 mph to the search area. A private sailboat reported no signs of survivors on the cruiser, which had quickly burned to the waterline. An accompanying Coast Guard chopper flew a search pattern of the area, dropping flares; but there wasn't a sign of survivors. When the chopper had to return, FLAGSTAFF's skipper took over command of the search operation, and shortly the crew spotted a hatch cover and other debris in the water. Time was of essence! The 55 degree water temperature was no time for a slow boat! Coast Guardsmen entered the water shortly after a shout from one of the survivors.

Later, the official Coast Guard report stated: "Reaction time of FLAGSTAFF-type craft allowed timely arrival of surface craft to participate in an offshore maritime distress".

It was the very next day that a similar distress message was received and FLAGSTAFF again took off in 40-knot winds and 3 to 5-foot seas to rescue two men whose boat had capsized. In both of these rescues it was the hydrofoils high speed capability in adverse weather that was the deciding factor in saving lives.

FLAGSTAFF in U.S. Coast Guard Colors

Subsequent to its evaluation of both the HIGH POINT and FLAGSTAFF, the U.S. Coast Guard concluded that the hydrofoil's ability to achieve and maintain high speed in a given sea state are an asset for those missions wherein this feature can contribute. These include: Search and Rescue and Enforcement of Laws and Treaties. The conclusions of reference 15 continue by saying that hydrofoils are not mysterious craft; Coast Guardsmen from the field, without aviation training, can operate and maintain them with a minimum of additional training and familiarization. The training and experience requirements of hydrofoils are no more demanding than that of the modern conventional cutter. However, the speed factor introduces new concepts of crew response and interrelation. Further, improved navigational and collision avoidance systems are mandatory for high speed craft of all types."

As a result of this favorable experience, agreement was reached in 1976 to turn over the ship to the Coast Guard for operation off the New England Coast. It was recommissioned as a Coast Guard Cutter with the designation WPGH-1 on March 2, 1977 at the U.S. Coast Guard Support Center, Boston, Massachusetts. The ship was employed to evaluate the use of hydrofoils for Coast Guard duties.

FLAGSTAFF was decommissioned in September 1978 due to problems with its propulsion machinery, lack of spare parts, and problems related to being one-of-a-kind ship. In an article in *High-Speed Surface Craft* of December 1983 it was reported that FLAGSTAFF sat afloat at a small boat pier in a salvor's possession at Warwick, Rhode Island in what was described as "a rather disreputable condition". It was an unfitting end for a true "Trail Blazer".

But was it really the end? No, thanks to a real hydrofoiler, who in 1988 was successful in acquiring FLAGSTAFF. John Altoonian was amazed to find that in spite of pigeon droppings and mud, the "ole girl" was still pretty much intact. He had FLAGSTAFF raised and towed her to Point Judith, Rhode Island. With all the foils raised, and two small leaks repaired, he towed the craft to his residence on the Inter-Coastal Waterway at Grassy Sound, New Jersey. One can understand that as people on ordinary boats pass by, FLAGSTAFF always gets a second look. John has renamed his hydrofoil "THE GOLDEN EAGLE" since it is a golden oldie; the Eagle represents flight and the USA where it was built.

TUCUMCARI (PGH-2)

The second hydrofoil gunboat built for U.S. Navy operational evaluation was the Boeing-built TUCUMCARI which means, in Apache, "to lie in wait". It was named after the city of Tucumcari, New Mexico. Many of this hydrofoil's major features were purposely different from FLAGSTAFF. Instead of a conventional, or airplane, foil arrangement, the PGH-2 had a so-called "canard" configuration, like HIGH POINT, with 30% of the ships weight on the forward foil, and 70% of it on the aft foil. Another difference was that the foils had individual flaps for lift control rather than FLAGSTAFF's incidence control. Instead of propeller propulsion, a waterjet provided the thrust for foilborne operations of TUCUMCARI. Its water inlets were located at the juncture of each aft strut and foil, and the waterjet exhaust nozzle was on the underside of the hull just forward of the transom. The jet of water can be seen in the photo of TUCUMCARI.

Boeing-Built PGH-2, TUCUMCARI

TUCUMCARI on a High Speed Run

Both the FLAGSTAFF and TUCUMCARI gunboats had gas turbines for their foilborne propulsion systems. In the case of PGH-2, a PROTEUS engine provided 3200 hp to give this 57-ton hydrofoil a speed in excess of 40 knots. It was 72 feet long had a beam of 35.3 feet, with a draft of 4.5 feet with foils retracted and 13.9 feet with foils extended. The crew consisted of 1 officer and 12 enlisted personnel.

In the photograph below we see one of the characteristics of a hydrofoil that sets it apart from conventional boats and even other advanced vehicles. Here HIGH POINT and TUCUMCARI are cutting high-speed tight circles around each other. It is evident that they were on a collision course, and as you can see HIGH POINT had to make a course correction to avoid disaster!

TUCUMCARI and HIGH POINT in High Speed Turns

The design of TUCUMCARI was started with a contract award to Boeing in April of 1966. By July of the following year the hull of PGH-2 was built in Portland, Oregon, then transported to one of Boeing's plants in Seattle, Washington for completion and outfitting. Delivery of the ship to the U.S. Navy took place on March 8, 1968 at a cost of $4 million.

As mentioned before, TUCUMCARI was deployed to Vietnam along with FLAGSTAFF in November of 1969 for riverine operations out of Danang and evaluation in a wartime environment. Total time underway in Vietnam was about 318 hours, 203 hours of which were foilborne; she covered a total of 9,073 nm before returning from RVN in February of 1970.

Following its deployment to Vietnam, TUCUMCARI was deck loaded on USS WOOD COUNTY for transport to Europe for a North Atlantic Treaty Organization (NATO) tour and demonstrations. From April until October 1971 she operated in European waters, while performing numerous demonstrations and combat exercises. These exercises undoubtedly had a significant influence on the later decision to procure a NATO fast patrol hydrofoil.

TUCUMCARI chalked up some very impressive statistics during her deployment to Europe. She logged 659 hours underway, 396 hours of which were foilborne, and covered over 17,000 nm in European waters, visiting seven NATO countries (a total of 17 port visits). These accomplishments played a major role in greatly enhancing confidence in the potential of hydrofoil ships.

Upon return from Europe, TUCUMCARI was assigned to the Amphibious Force in the Atlantic Fleet. However, it was a sad ending to a distinguished period of performance, when in November of 1972, while conducting night exercises with the 2nd Fleet in the Caribbean, she ran onto a coral reef at Caballo Blanco, Vieques Island, Puerto Rico. Fortunately there were no serious injuries to the crew. The ship was salvaged and transported to her base in Norfolk, Virginia where it was decided not to attempt repair of the extensive damage. In 1973 she was transported to the David Taylor Research Center for structural and material testing. In spite of this rather inauspicious ending, TUCUMCARI can take credit as one of the hydrofoils which provided the technology base and confidence to proceed to the PHM program.

PLAINVIEW (AGEH-1)

In December 1960, the U.S. Navy Bureau of Ships issued a requirements document for a hydrofoil research ship designated the AGEH-1. This designation stands for Ocean-Going Auxiliary (A), General (G), Experimental (E), Hydrofoil (H). It was to be be a 50-knot hydrofoil with provision for future conversion to achieve speeds up to 90 knots! This was to be accomplished by addition of two more gas turbines and a supercavitating strut foil system. Its purpose was to provide criteria for design of future Navy hydrofoil ships and to explore the utility of such ships for Anti-Submarine Warfare (ASW) and other Navy missions.

W. M. Ellsworth[7] summarizes the long and sometimes agonizing history of PLAINVIEW acquisition, construction and trials. He relates that proposals were submitted by a number of contractors. Grumman Aircraft Engineering Corporation (now named Grumman Aerospace Corporation) was selected as the contractor based on their submission which consisted of two different concepts. One had fixed foils which could be retracted only with a crane at dockside. The other had a fully self-contained foil retraction system. The fully-retractable design was selected and, on 26 October 1961, Grumman was awarded a cost-type contract for the guidance design of AGEH-1. There was a provision in the contract whereby, if the Navy did not like Grumman's estimate of the cost of detail design and construction, they had the option to go out for bids in a new competition. The Grumman team included Newport News Shipbuilding Corp. and General Electric Co. Grumman was designated the Program Manager and principal designer and it was proposed that they build the foils and install the transmission. Newport News was to be involved in the design of the shipboard systems and the hull, and would be the hull builder and outfitter. The General Electric Co. had the responsibility for the propulsion system.

The guidance design took about one year, followed by preliminary design and weight estimates submittal and approval in February 1962. The contract drawings and final draft of the specifications were signed off by the Navy on 9 October 1962. Grumman's estimate for detail design and construction was about $17M. Since the Navy had budgeted only $12M, they exercised the option to recompete the procurement. Additional bids were received, all of which were in the neighborhood of $17M, except for the bid of Puget Sound Bridge and Drydock Co. in Seattle, Washington (later to become Lockheed Shipbuilding and Construction Co.). They bid just under $12M and, on 9 July 1963, were awarded a fixed-price contract for detail design and construction. The contract for this 320-ton advanced hydrofoil, the largest ever built, was only seven pages long. As it turned out, the actual cost of the ship, including changes, was close to $21M.

There were numerous contributors to the design and construction of PLAINVIEW under the overall responsibility of Lockheed Shipbuilding and Construction Co. These were W. C. Nickum & Sons for engineering and detail design, Rucker for the design of the hydraulic system, General Electric for the design and construction of the hullborne and foilborne transmissions, Hamilton Standard for the automatic control system, and Lockheed California for design and construction of the strut/foil system.

The keel was laid on 8 May 1964 and the ship was launched on 28 June 1965. It was christened PLAINVIEW in honor of Plainview, New York and Texas. The ship made its first foilborne flight of 11-1/2 minutes on 21 March 1968 but, it was nearly a year later, on 3 February 1969, that it began Preliminary

Acceptance Trials. On 1 March 1969, the Navy took delivery and assigned the ship to the Navy Hydrofoil Special Trials Unit (HYSTU) located at the Puget Sound Naval Shipyard in Bremerton, Washington for administrative and technical control. This was nearly 3-1/2 years later than the originally projected delivery date. Much of this delay was due to 3 major strikes during the construction period. PLAINVIEW was far from problem free at time of delivery. The Navy decided that its best course of action was to undertake its own program of deficiency correction if the ship was ever to become fully operational. Final Contract Trials were begun on 21 January 1970, and on 2 March 1970, the Navy accepted the ship.

PLAINVIEW Foilborne During Trials

This 320-ton hydrofoil was characterized by its long, slender hull as can be seen in the above photograph. One might wonder why there was no "A" on the hull of PLAINVIEW in view of its AGEH-1 designation. It turns out that it is not customary to include the "A" on the hull of Navy auxiliary ships.

The ship had a length of 212 feet and an extreme beam with foils down of 70.8 feet. It attained foilborne speeds of over 50 knots from two General Electric LM-1500 gas turbine engines driving two supercavitating propellers. Two Packard diesel engines drove propellers for low-speed hullborne operations.

The photograph below shows the ship with its foils retracted. From this one can see that the large foils were forward, and a smaller foil aft which puts the PLAINVIEW foil arrangement in the conventional, or airplane category.

PLAINVIEW With Foils Retracted

PLAINVIEW possessed many unusual characteristics, the most significant of which were:

- The largest hydrofoil ship in the world at that time. It has subsequently been surpassed by the Soviet BABOCHKA hydrofoil at about 400 tons.
- The largest high-speed aluminum hull.; the highest subcavitating foil loading at 1460 pounds per square foot.
- The largest vehicular hydraulic system with a pressure of 3,600 pounds per square inch at 1,000 gallons per minute.
- The highest power Zee-drive transmission incorporating two 15,000 horsepower units.

- The largest high-speed supercavitating propellers with a diameter of 5.2 feet and a design rotational speed of 1,700 rpm. A visitor to the David Taylor Research Center will see one of these propellers (as pictured below) mounted on a pedestal near the Center's main entrance. The propeller's titanium structure remains sparkling bright through all the elements wrought by the Washington, D. C. weather!
- The highest design sea state capability at high speed. PLAINVIEW could essentially maintain its design speed through ten-foot waves with little difficulty.

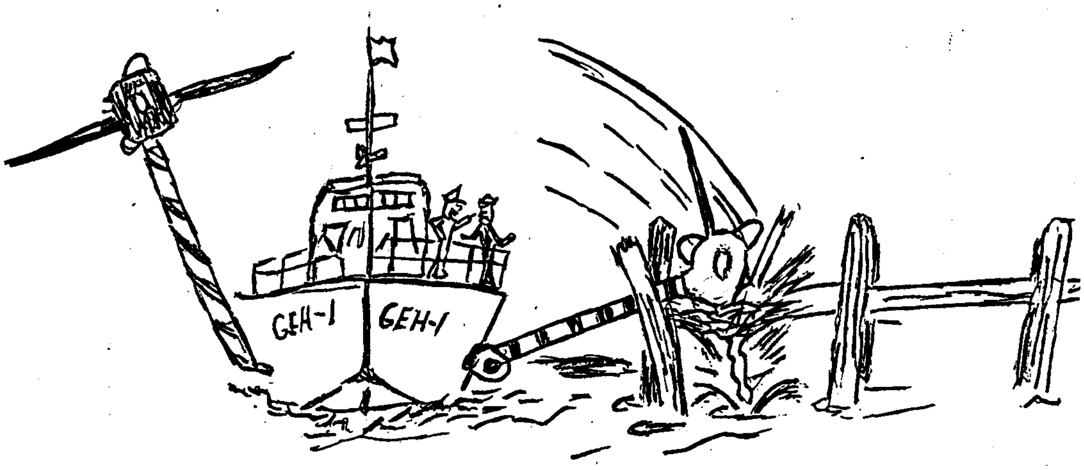
Pilot House of PLAINVIEW

PLAINVIEW's Titanium Propeller

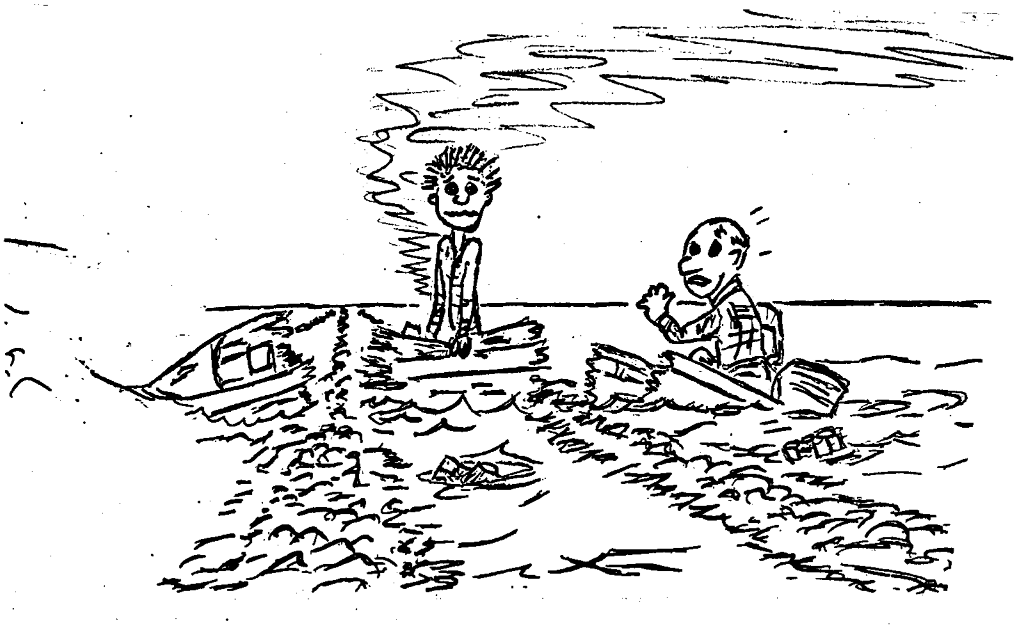
From the photo above one can see that the pilot house of PLAINVIEW looks more like the cockpit of a jet airliner. This happens to be typical of all modern hydrofoils since, after all, they were designed by aircraft manufacturers who were not brainwashed in their thinking about the traditional ship's bridge.

As can well be appreciated, PLAINVIEW's assignment to HYSTU was a considerable additional burden on the Unit, particularly since there were many problems and deficiencies to overcome. This was to be expected, however, with a first-of-a-kind, one-of-a-kind, sophisticated and complex system. Fortunately, at the time of PLAINVIEW's delivery, the problems with HIGH POINT had become much more manageable and the focus of attention could be directed more to the bigger ship during this early period.

Some humor was injected with the serious business of solving the technical problems on PLAINVIEW. This is evident from two of several cartoons generated during that period, and are show below.



"That is <u>NOT</u> the Way We Secure The Ship to the Pier, Filstrup!!"



"So <u>THAT'S</u> the PLAINVIEW!!!"

One can be assured that many of the small boat owners on Puget Sound did not want to argue with PLAINVIEW when it came to right-of-way!

During the four years after delivery of PLAINVIEW, the story of trials and tribulations was a repeat of the early problems with HIGH POINT. Finally, on 16 May 1974, what was to be a two-year overhaul and modification effort, was begun at Todd Shipyard in Seattle. This included the following major items: A new hydraulic system with all welded piping; disassembly and refurbishment of the main struts and foils; a new incidence control system; a new tail strut of HY-130 steel, built by Grumman; a Hydrofoil Universal Digital Autopilot, taken from PCH-1; and a radar height sensor in place of the sonic unit.

The story of PLAINVIEW is told in much more detail in a paper entitled "A Ship Whose Time Has Come--And Gone," by R. J. Johnston and W. C. O'Neill.[16] As mentioned before, one of the objectives of the ship was to demonstrate the applicability of hydrofoils to Navy missions. In addition to many of the technical aspects of the ship's design, the authors described several operations which include the launching of torpedoes, the firing of missiles, such as the Sea Sparrow, the launching and retrieval of remotely piloted vehicles (RPV), underway replenishment/personnel transfer, and multiple ship close formation flying.

Firing of SEA SPARROW Missile from PLAINVIEW

Johnston and O'Neill point out a feature of hydrofoils that make RPV operations intriguing; namely, that the hydrofoil's foilborne speed is greater than the stall speed of an RPV. It is possible to maneuver a hydrofoil under a flying RPV and retrieve it with both vehicles operating at the same speed. This is called zero-relative-speed recovery which, coupled with the hydrofoil's excellent motion characteristics, benefits RPV operations.[16] The speed of a hydrofoil also simplifies the launch procedure for the same reason.

Another one of PLAINVIEW's demonstrations was in connection with evaluating vertical replenishment and personnel transfers from a helicopter to a foilborne hydrofoil. Shown below is a photo of such an operation with a Boeing-Vertol CH-46 SEA KNIGHT. Transfers such as this demonstrated that aircraft and personnel safety are enhanced with increased wind across the deck and a steady foilborne platform.[16]

Personnel Transfer Between CH-46 and PLAINVIEW

There are Navy mission requirements where close formation, foilborne operations of multiple hydrofoils is desirable. A variety of minimum distances of separation at high speed were explored by PLAINVIEW in cooperation with HIGH POINT and other hydrofoils such as USS PEGASUS and the Boeing JETFOIL. With strict rules established before each "flight", the crews of the various ships became comfortable operating at close quarters.

PLAINVIEW and HIGH POINT in Close Formation Flight

USS PEGASUS Approaches PLAINVIEW for Close Formation Trial

The most significant Anti-Submarine Warfare tests conducted by PLAINVIEW were those demonstrating the firing of torpedoes. A number of MK46 torpedoes were fired at different foilborne speeds and angles of entrance into the water, and clearly established the feasibility of such operations.[16]

Firing of a Torpedo from PLAINVIEW

Unfortunately, soon after returning to the trials program with significantly increased availability, and many successful operations in it's log, PLAINVIEW fell victim to the Congressional budget knife. She made her last foilborne flight on 17 July 1978, ending with a total of 268 foilborne hours and without ever being tested to the limits of her rough water capability. The ship was officially inactivated on 22 September 1978 and towed to the inactive fleet at Bremerton, Washington. In May of 1979, the hull, without the struts and foils, gas turbines, and other special equipment was sold to a private party for the sum of $128,000. The engines, foils and transmissions were retained by the Navy for possible use on another prototype hydrofoil or another advanced naval vehicle. It was understood that the ship was to be converted for use as a fishing boat. This was either unsuccessful or was never attempted. The final indignity for this once-proud and beautiful ship was being relegated to resting on a mud flat near Astoria, Oregon.

A comparison of physical and performance characteristics of the four U. S. Navy developmental hydrofoils described in this Chapter and the PHM-1 can be found in Appendix A.

CHAPTER 5

CANADIAN AND EUROPEAN HYDROFOIL DEVELOPMENTS

During the time that the U.S. Navy was developing hydrofoils described in the previous chapter, rather significant advancements were also being made in Canada and Europe. There was a strong tie technically between the hydrofoil enthusiasts on both sides of the Atlantic. This was fostered by the International Hydrofoil Society through their technical publications and meetings. Several significant hydrofoil developments will be treated here as examples of Canadian and European accomplishments during the 1960s.

CANADIAN BRAS D'OR, FHE-400

The Canadian requirement for a hydrofoil centered about the Anti-Submarine Warfare role which demands an extremely versatile ship. Michael Eames, in his paper reviewing hydrofoil developments in Canada[8], points out that an alternative to improving sonar range (on large ships) is to provide a significantly larger number of sonars economically - the so-called "small and many" concept. Initial detection requires long endurance at slow search speeds; interception and attack require short bursts at speeds exceeding those of conventional ships. The stability of the hydrofoil, hullborne and foilborne, makes it the smallest ship capable of sustained operation in the open ocean.

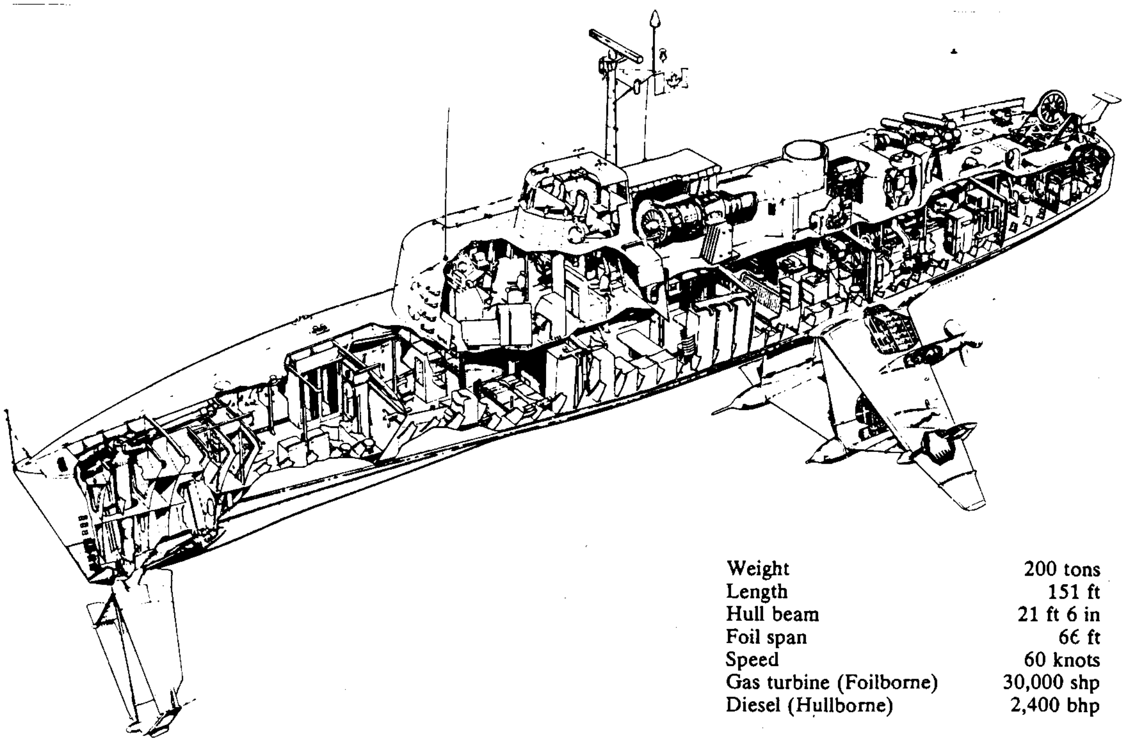
With this philosophy firmly in mind, and continued confidence from their earlier developmental effort, the Canadians undertook in 1959 a study of design requirements for a nominal 200-ton ASW hydrofoil ship designated R-200. The design concept that resulted was reviewed in January 1960 by experts from the United States, United Kingdom, and Canada with the conclusion that the concept was sound. By this time the U.S. was well underway with their program to construct a 120-ton ASW hydrofoil, HIGH POINT, with a fully-submerged foil system and autopilot control. It was agreed that the U.S. and Canadian approaches would be complementary in expanding the data base and providing the opportunity for comparison of two quite different designs.

In August 1960 a contract was awarded to DeHavilland Aircraft of Canada to carry out engineering studies and to determine the technical feasibility of the R-200 design. Based on the positive conclusions that resulted, a second contract was awarded to develop a preliminary design. Other work was also supported to carry out model tests and an in-depth examination of some of the more critical system details. In May 1963 this led to award of a three-phase contract to DeHavilland which called for preparation of contract plans and specification, detailed design and construction, and the conduct of performance trials. DeHavilland, in turn, subcontracted fabrication of the hull and installation of ship systems to Marine Industries Ltd. in Sorel, Quebec. Hull construction of BRAS D'OR commenced in 1964, but during construction, on 5 November 1966, there was a disastrous fire in the main machinery space which almost caused termination of the program. In spite of the delays and cost increase, however, the ship, designated FHE-400 and named BRAS D'OR, was completed in 1967.

Canadian BRAS D'OR, FHE-400, at 62 Knots

The surface-piercing foil system of this hydrofoil is very evident from the photo and diagrams. The main foil carries about 90% of the lift, whereas the small bow foil carries the remaining 10%. The latter is steerable and acts like a rudder for both foilborne and hullborne operations. It can also be adjusted in rake, enabling the best angle-of-attack to be selected for foilborne or hullborne operation under whatever load or sea conditions that may exist.

As in many hydrofoil designs, the different power levels involved in hullborne and high-speed foilborne operations dictate separate propulsion systems. The accompanying illustration shows the layout of BRAS D'OR's propulsion system. For the lower-power, long endurance hullborne system, fuel weight is a critical factor which made the selection of a high speed diesel engine a logical one. A Paxman 16 YJCM diesel rated at 2,000 hp drove two three-bladed propellers on pods mounted on the main anhedral foils. These 7-foot diameter, fully-reversible, controllable-pitch propellers were 30 feet apart in the lateral direction which provided excellent maneuverability at low speed through differential pitch control.



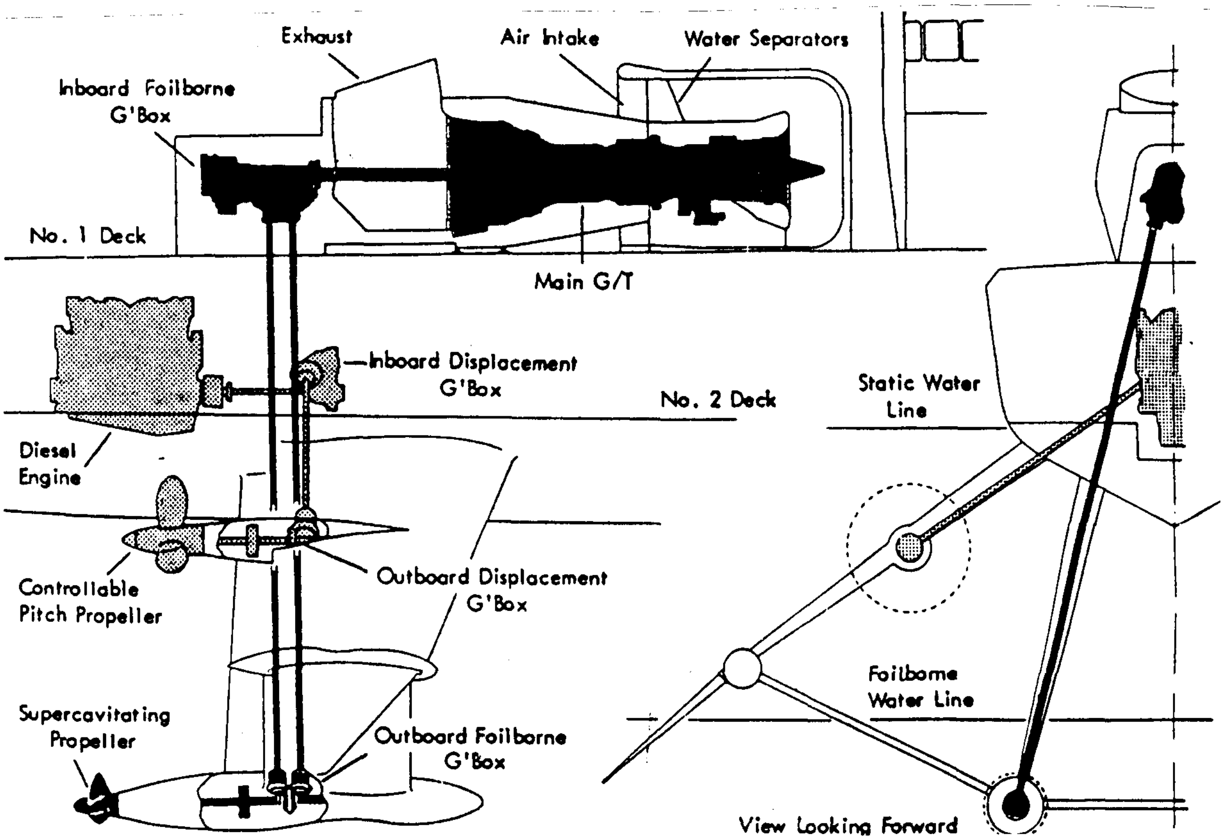
Weight	200 tons
Length	151 ft
Hull beam	21 ft 6 in
Foil span	66 ft
Speed	60 knots
Gas turbine (Foilborne)	30,000 shp
Diesel (Hullborne)	2,400 bhp

HMCS BRAS D'OR Features and Particulars

The foilborne propulsion system consisted of a Pratt & Whitney FT4A-2 gas turbine engine, rated at 22,000 hp, driving two fixed-pitch, three-bladed propellers 4 feet in diameter. The propulsion drive system was similar in many ways to the PLAINVIEW propulsion layout as described in Chapter 4.

BRAS D'OR arrived in Halifax, Nova Scotia on 1 July 1968 to begin a long series of trials. From September of 1968 until July 1971, when the trials terminated, the ship logged 648 hours, 552 hullborne, and 96 hours foilborne. The most operationally representative trial was a 2,500 mile voyage to Hamilton, Bermuda, and Norfolk, Virginia, in June 1971.

The biggest disappointment, albeit from a scientific point of view (but not the sailor's aboard), was that the amount of significant rough-water data collected was regrettably small. At no time during the trip were limiting rough-water conditions experienced, either hullborne or foilborne.



BRAS **D'OR** Propulsion System Layout

This was not to say that BRAS D'OR did not encounter rough water! According to Michael Eames, who describes highlights of these trials in Reference 8, HMCS FRASIER, a 3,000-ton frigate sailing in company during a rough water trial sent a signal as follows:

> "Weather conditions were considered most unpleasant, heavy seas and 15-20 ft swell, wind gusting to 60 knots, ship spraying overall with upper deck (of FRASIER) 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 maneuverability. The almost complete absence of spray over the focasle and bridge was very impressive."

Foilborne, BRAS D'OR exceeded her calm-water design speed, achieving 63 knots at full load in 3 to 4 foot waves. Sea trials included a comprehensive set of seakeeping and motions data, all of which prompted the Canadians to conclude that BRAS D'OR showed its performance to be quite remarkable for a surface-piercing hydrofoil ship.8

A variety of teething problems interfered with the progress of BRAS D'ORs 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 of these proved to be insurmountable problems however, and steady progress was made in overcoming them.

In July 1969, BRAS D'OR was docked to repair persistent foil-system leaks, and a large crack was discovered in the lower surface of the center 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 substructure. A replacement foil element was constructed, but later, it too developed severe cracking.

This Canadian hydrofoil project was not curtailed and the ship laid up due to foil cracking, as some believed. Success of the trials was recognized, and it was appreciated that a production class of this ship would not employ the same foil material. The real reason for the curtailment was a change of defence policy announced in the White Paper on Defence issued in August 1971. It assigned priority, not to Anti-Submarine Warfare (for which the BRAS D'OR was designed) but to the protection of sovereignty and the surveillance of Canadian territory and Coastlines.

The FHE-400, although no longer operational, remains even today the most sophisticated and advanced design of a surface-piercing-type hydrofoil. Its design and extensive trials program contributed significantly to the technical data base and this was invaluable in complementing the U.S. development program.

SUPRAMAR PT SERIES HYDROFOILS

The SUPRAMAR series of hydrofoils was an outgrowth of Baron von Schertel's work prior to and during World War II in Germany, which was described previously in Chapter 1. It was the Russians' good fortune to capture most of von Schertel's hydrofoil team after the War. They became the backbone of hydrofoil development in that country where large numbers of surface-piercing hydrofoils have been built and provide much needed high speed water transportation on the myriad of rivers and lakes of that vast country.

Von Schertel managed to escape the Russian's. This, combined with the fact that after WWII it was forbidden in Germany to build boats with speeds in excess of 12 knots, led von Schertel and his partner Sachsenberg to move to Switzerland. There, in 1952, at a small shipyard in Stansstad, they completed the PT-10, FRECCIA D'ORO, (Golden Arrow). This 7-ton craft had 32 seats and was capable of speeds up to 35 knots. On 29 May 1952, the

Konsortium of Schertel and Sachsenberg joined with the Kredit and Verwaltungs-Bank Zug, to form Supramar, A.G. based in Lucerne. That same year the FRECCIA D'ORO began the world's first regular hydrofoil passenger service on Lake Maggiore, between Switzerland and Italy. You may remember that this is the same lake on which Forlanini made his noteworthy hydrofoil experiments half a century earlier.

FRECCIA D'ORO had an enthusiastic reception, mainly from the Italian public. The PT-10 proved that a hydrofoil could successfully compete with land vehicles as was done when it and an auto began a race from Arona to Ascona. According to von Schertel: "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."

SUPRAMAR Hydrofoil PT-10, FRECCIA D'ORO

In 1954 **Supramar** arranged their first license to build hydrofoil craft of their design with the Leopoldo Rodriquez Shipyard in Messina, Italy. Later, the PT-20 and PT-50 were licensed to be built in Japan, Norway, Holland, and Hong Kong.

Rodriquez started production of the 32-ton PT-20, a 72-passenger hydrofoil with a cruise speed of 35 knots, in 1955. The foils were a standard Schertel-Sachsenberg, surface-piercing type, with 58% of the lift provided by the bow foil and the remaining lift supplied by the aft foil. The angle of incidence of the bow foil could be manually adjusted within narrow limits from the helm position. This was convenient for adjusting for the effects of passenger load variations and sea conditions. Power was provided to a single propeller through a reversible gear by a supercharged, 1,100 hp, 12- cylinder MTU diesel engine with an exhaust turbo-compressor.

The first of the PT-20 series was named FRECCIA del SOLE, which opened a passenger service across the Straits of Messina.[17] It was built to satisfy maritime regulations and became the first passenger hydrofoil to receive certification authority for carrying passengers at sea.

The FRECCIA del SOLE reduced the port-to-port time from Messina to Reggio di Calabria to one-quarter of that of the conventional ferry boats. This hydrofoil, which completed 22 daily crossings, soon proved its commercial viability. It has been reported[17] that average time between major overhauls of the PT-20 engines is approximately 10,000 hours, a notable achievement at the time.

SUPRAMAR Hydrofoil PT-20

Success of the PT-20 commercial passenger hydrofoil, from both its operation and profit aspects, led to development of the PT-50. Designed for offshore and inter-island operations, the prototype of this 63-ton hydrofoil was completed early in 1958, and production versions have seen extensive use in regular passenger services in various areas including the Baltic, the Mediterranean, and the Japanese Inland Sea.

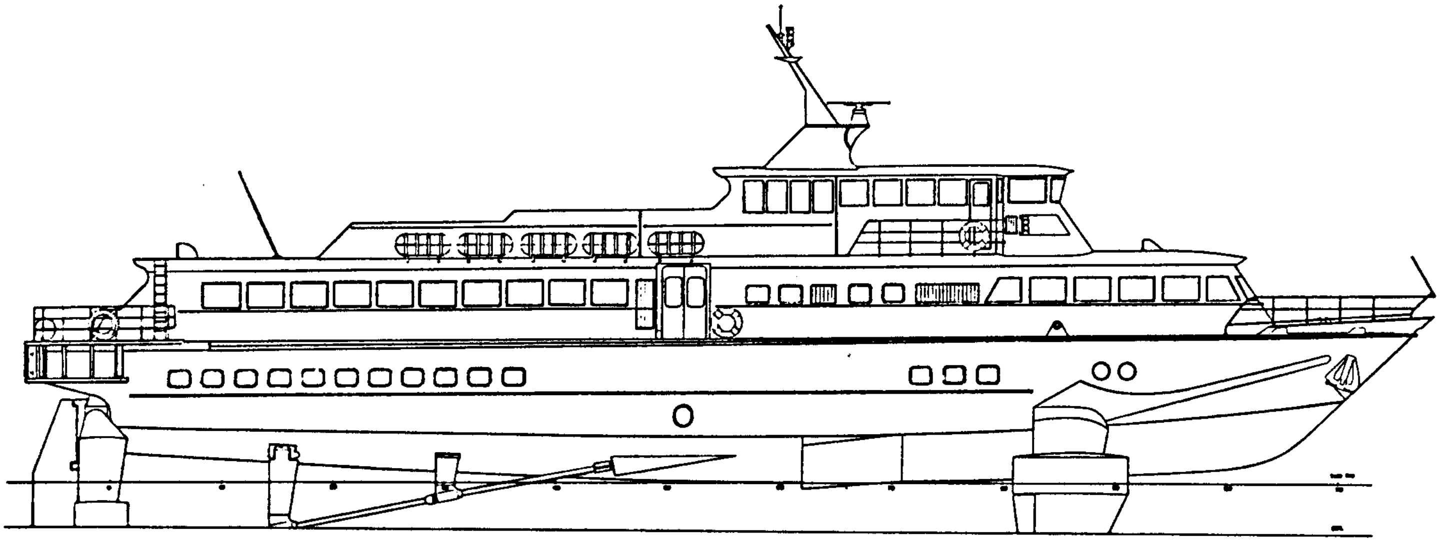
SUPRAMAR Hydrofoil PT-50

The foil system of the 91-foot long PT-50 was larger, but very similar to that of the PT-20 in general arrangement. Both craft had about the same maximum speed of 34 knots. The PT-50 of course had two 1,100 hp MTU diesels, instead of the single one for the PT-20, and drove two three-bladed propellers.

Following the PT-50, several other craft in the extensive PT Series of SUPRAMAR hydrofoils were developed including the PT-75 with a displacement of 85 tons. This was an advanced version of the PT-50. Also the PT-100, in turn a variant of the PT-75, was designed for short-haul commuter routes and accommodated 200 passengers.

The next major SUPRAMAR hydrofoil design was the PT-150 MkII with a displacement of 165 tons. It carries 250 passengers, and at a length of 124 feet, the PT-150 was the largest sea-going hydrofoil passenger ferry in the free world at the time it was launched.

The PT-150 represented a departure for SUPRAMAR with respect to the design of the foil system. Instead of the usual surface-piercing type fore and aft, the PT-150 foil configuration combined a surface-piercing foil forward with a fully-submerged foil in the aft location. Reference 17 points out that the bow foil, which provides the necessary static transverse stability, is of the Schertel-Sachsenberg surface-piercing "V" design and provides 60% of the lift. The rear foil provides the remaining lift and utilizes the Schertel-Supramar air stabilization system. The angle of attack of the rear foil can be also manually controlled hydraulically both during take-off and when foilborne.



SUPRAMAR Hydrofoil PT-150

The air stabilization system referred to above feeds air from the atmosphere through small ports on the foil upper surface (the low pressure side), thereby decreasing the lift. The amount of lift is varied by the quantity of air admitted to the foil, and it is controlled by valves actuated by signals from a damped pendulum and a rate gyro. Since the system is installed on both port and starboard foils, a stabilizing roll moment is produced by decreasing the available air volume on the more deeply submerged foil and increasing the air available to the foil on the opposite side. This system was a rather ingenious invention of Von Schertel, but has never been widely adopted; the industry prefers to retain the more reliable system of either incidence or flap controls which are elaborated on in Chapter 7.

The PT-150 was also a major departure from its passenger ferry predecessors in terms of it's powerplant. Two 20- cylinder MTU supercharged diesel engines, each rated at 3,400 hp were installed to provide a cruising speed of 36.5 knots. It has been reported that the maximum permissible wave height in the foilborne mode at full power for passenger acceptability is 10 feet.[17]

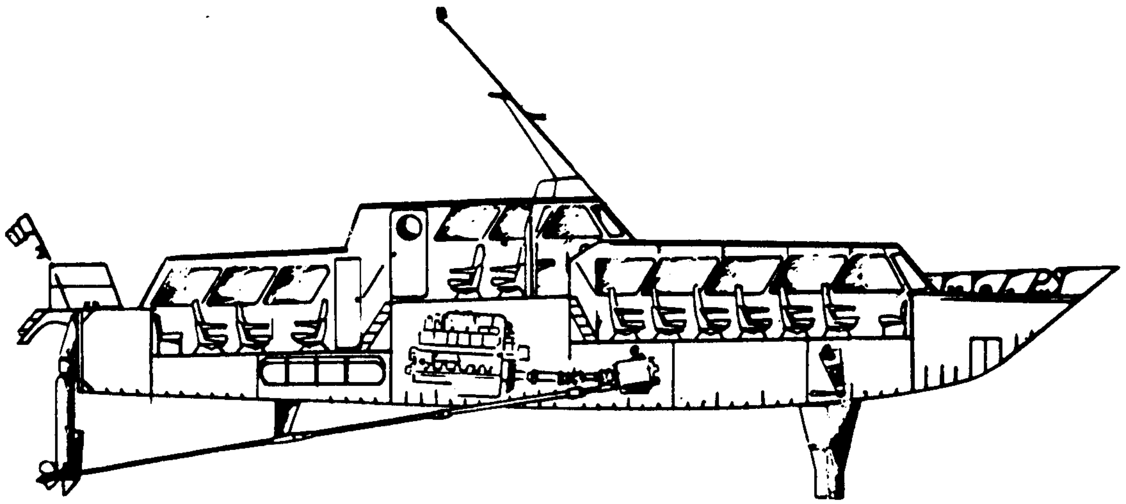
More than 150 hydrofoils have been built under license to SUPRAMAR of which by far the largest number were built by Rodriquez up until 1971.

RODRIQUEZ RHS SERIES HYDROFOILS

Cantiere Navaltecnica SpA, formerly known as Leopaldo Rodriquez Shipyard, was the first in the world to produce hydrofoils in series.[17] Their accomplishments, under the leadership of Carlo Rodriquez, in connection with the PT series has just been described. However, this was just the beginning of one of the most successful hydrofoil operations to date in the free world. Subsequent to building the PT series of hydrofoils under license to SUPRAMAR, Rodriquez undertook production of their own craft which were designated the RHS series (Rodriquez Hydrofoil Ship).

A listing of the RHS series hydrofoils include RHS-70, -110, -140, -150, -160, and the latest and largest hydrofoil passenger ferry of the series, namely, the SUPER JUMBO RHS-200. As pointed out by Loepoldo Rodriquez and Dino Di Blasi in Reference 18, the evolution of European commercial hydrofoils 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 routes over a period of more than 25 years. All of this has given rise to improvements in performance and craft of greater size. There was a demand for commercial utilization of hydrofoils in open, and sometimes rough waters, along with the ability to carry more passengers.

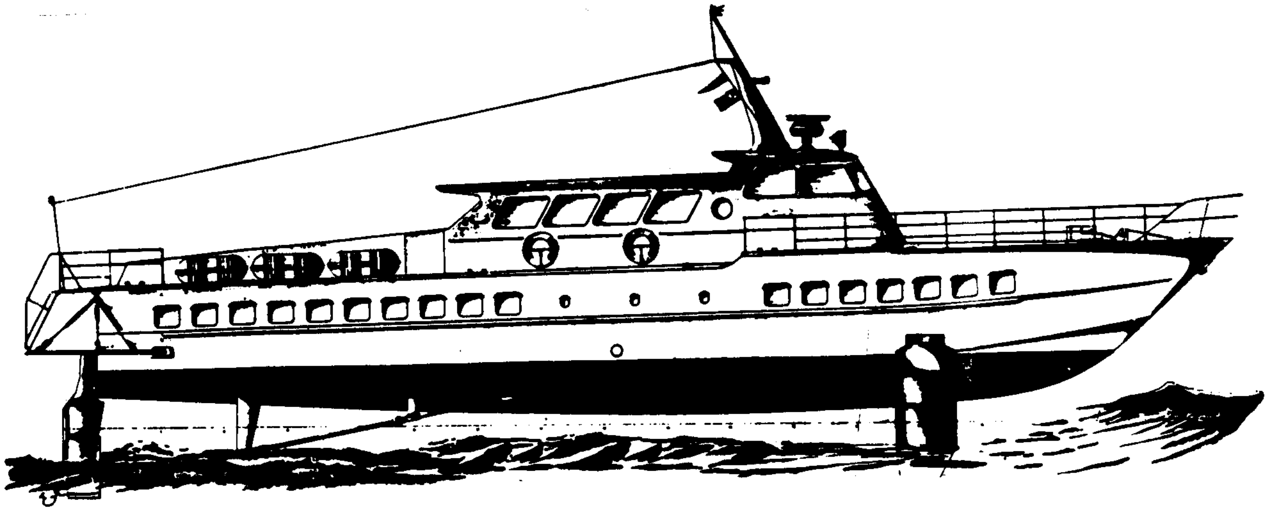
The RHS-70 was a 32-ton coastal passenger ferry with seats for 71 passengers. With a length of over 72 feet, its 1,350 hp MTU diesel engine provided a speed of about 32 knots. The surface- piercing foils were used both fore and aft. However, the forward foil angle could be adjusted within narrow limits from the helm position to properly trim the craft for load and sea conditions.



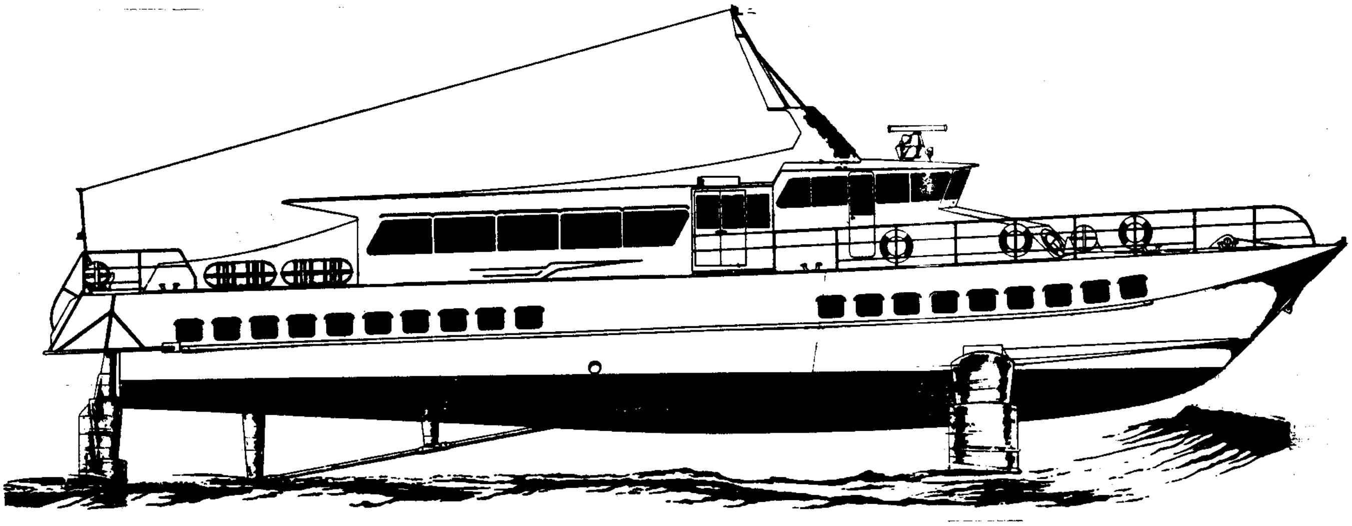
RODRIQUEZ RHS-70 Hydrofoil

At 54 tons, the RHS-110 hydrofoil ferry could carry a maximum of 110 passengers over routes of up to 300 miles at a cruising speed of 37 knots. This 84- foot hydrofoil was powered by two 12-cylinder supercharged MTU diesels, each with a maximum output of 1,350 hp. The surface-piercing foil system of the RHS-110 was different from its predecessor in that flaps, attached to both the forward and aft foils, were adjusted automatically by a Hamilton Standard Seakeeping Augmentation System (SAS). This system provided damping of heave, pitch and roll motions of the craft in rough water conditions.

The next larger hydrofoil passenger ferry produced by Rodriquez during its evolutionary process was the 65-ton RHS-140. It had a passenger seating of up to 140 and had a cruising speed of 32.5 knots. With essentially the same propulsion system as the RHS-110, there was an expected reduction in maximum speed for this larger hydrofoil.

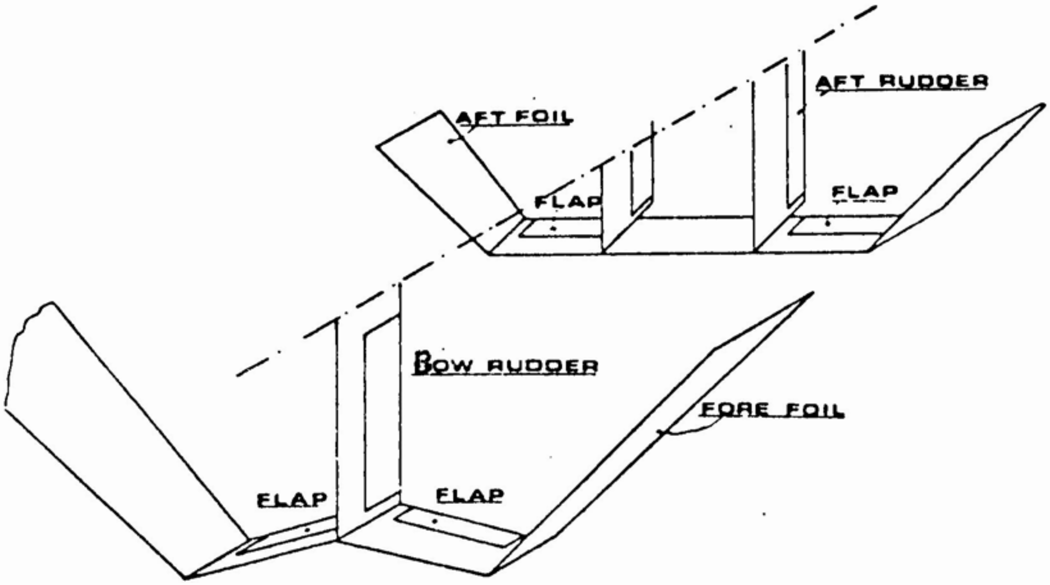


RODRIQUEZ RHS-110 Hydrofoil



RODRIQUEZ RHS-140 Hydrofoil

Illustrated on the next page is the 101 foot long RHS-160 passenger hydrofoil which is configured to carry from 160 to 200 passengers. At 85 tons, its two supercharged MTU diesel engines with an output of 1,950 hp each, give this hydrofoil a speed of 36 knots. The configuration of the RHS-160 foils was somewhat unique in that, although, surface-piercing in design, they appeared as a "W" from a bow view. The craft featured a bow rudder for improved maneuverability, that worked in conjunction with the aft rudders. Hydraulically-operated flaps on the forward and aft foils were adjusted by a Hamilton Standard electronic SAS as used on the RHS-110.



RODRIQUEZ "W"-Shaped Foil System

RODRIQUEZ RHS-160 Hydrofoil

The latest commercial hydrofoil in this series is the SUPER JUMBO RHS-200 which can carry up to 254 passengers. First constructed in 1978, this 120-ton ferry, with a length of 116 feet, has a cruise speed of about 37 knots. To achieve this speed with a hydrofoil of this size, the propulsion system had to be a step beyond that of the RHS-160. Two 2,415 hp supercharged MTU diesels driving two supercavitating, controllable-pitch propellers are employed in much the same overall system layout as its predecessors. The surface-piercing foils are of a "V" configuration, and are fitted with flaps controlled by the Seakeeping Augmentation System developed for the RHS-160 hydrofoil.

RODRIQUEZ RHS-200 Hydrofoil

Some interesting observations can be made as a result of tracing the development of hydrofoils on the West European continent in contrast to such developments in North America. First, there is the difference in high speed goals, and the associated powerplants necessary to achieve these speeds. Second is the operating environment and the associated motions that were believed to be acceptable.

In the 1960 to 1980 time frame there was never much argument that diesel engines, due to their wide-spread use, relatively low cost, and acceptance in the marine community, were considered low-tech compared to the relatively new and unfamiliar gas turbine engine. The European community therefore adopted the diesel engine for their hydrofoil designs and accepted the lower speeds that such powerplants could provide. The United States Navy and the Canadians, as pointed out in Chapter 4 and the beginning of this Chapter, had much higher speed goals and a need to operate in open ocean areas. As will be pointed out in Chapter 7, hydrofoils with speed requirements greater than about 40 knots are destined to use light-weight, high power-density gas turbines for foilborne power. Diesel engines, as currently constituted in terms of weight and power capabilities, cannot do the job.

Similarly, the surface-piercing foil system was favored by the Europeans because of its relative simplicity in that it provided inherent stability, and therefore did not require an automatic control system to keep the hydrofoil in an upright position when foilborne. As we shall see in Chapter 7, a fully-submerged foil, although little affected by the surface waves encountered in the open ocean, requires automatic controls, not unlike those of a high performance aircraft.

As we have seen, the PT and RHS series hydrofoils grew in size and ventured into waters which subjected their inherently stable surface-piercing foils to forces not previously felt under the benign environment offered by rivers, lakes, and coastal regions. During this evolution it was realized that some degree of motion control was required to provide an acceptable ride to hydrofoil passengers. Hence, the introduction of Rodriquez's Seakeeping Augmentation System (SAS) which has been successful in alleviating heave, pitch, and roll motions in rough water.[18]

CHAPTER 6

THE U.S. NAVY FLEET HYDROFOIL - PHM

Why and how did the U. S. Navy build six hydrofoils as a part of its fleet of 600 relatively large ships? This chapter will trace the history of the Patrol Hydrofoil Missile (PHM) ship through its early years as a North Atlantic Treaty Organization (NATO) concept, problems of USS PEGASUS, the follow-on ships, and the success of the PHM Squadron.

THE NATO CONNECTION

In 1970 NATO indicated a need for a fast, seaworthy missile ship to operate in the Mediterranean, North Sea, and Baltic waters. One of the needs was to counter the Soviet OSA KOMAR missile boats. Comparisons were made between planing hulls, catamarans, hydrofoils and hovercraft. The hydrofoil was identified as best at meeting the requirements based on proven U.S. Navy technology, as we have seen in previous chapters. The NATO group that subsequently drafted the military requirements for the PHM realized that a modern hydrofoil, when equipped with antiship missiles became a formidable surface combatant. This was because of its unique capabilities for high-speed, all-weather operations over distances and mission durations consistent with operations of the more conventional fast patrol boats. An excellent description of NATO and U.S. requirements for the PHM is given by Captain John W. King.[20] The PHM program was launched in November 1971 with a letter contract to the Boeing Company for PHM-1. Italy, Germany and the United States Navy became partners under a Memorandum of Understanding a year later.

In the late 1971 to early 1972 time frame it was necessary to determine the feasibility of designing a hydrofoil to meet the performance goals of the three participating governments. The objective was examined from the standpoint of three alternative combinations of weapons, in particular the surface-to-surface missiles. The feasibility baseline design and parametric studies were to provide the data and alternatives which would allow the participating governments to select the primary performance and major configuration characteristics to be incorporated in the standard design. Baseline ship cost estimates were also developed to provide information on the effect of configuration choices on cost.

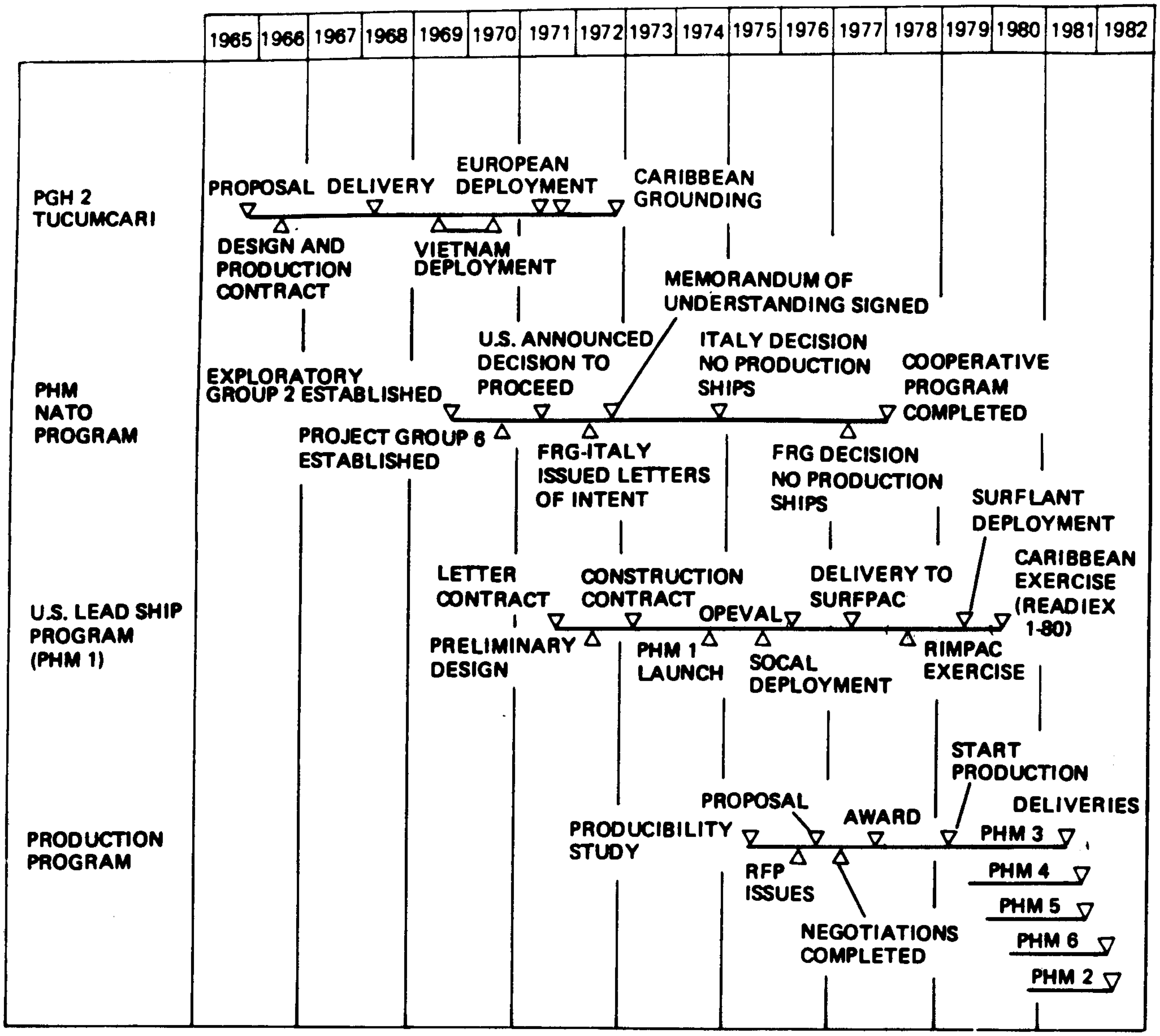
A $42.6M contract was awarded in 1973 to the Boeing Company[7] for the feasibility study, the design and construction of two PHM hydrofoils. While the initial contract called for two ships initially, program cost growth forced the suspension of work on the second ship in August 1974. The completion of PHM-2 was later incorporated into the production program as shown in the schedule of major PHM events on the next page.[21] The keel of USS PEGASUS was laid on 9 May 1973, and she was christened and launched on 9 November 1974. She made her first flight on 25 February 1975. However, before delivery of PEGASUS to the U.S. Navy in 1977, Italy and Germany had decided to drop out of the program. Because of higher than anticipated costs, only one ship was completed at that time.

USS PEGASUS (PHM-1) Foilborne

PHM BEGINNINGS

The U.S. Navy ship acquisition process historically requires about a 7-year development cycle for the definition, design and first unit construction of a new ship platform. As the schedule of major events shows, about six years elapsed from the signing of the contract for the design and construction of the lead ship and its commissioning and delivery to SURFPAC (short for Surface Forces, Pacific).

It is interesting to note that the NATO patrol missile hydrofoil (PHM) was the first U.S. Navy ship program to complete all aspects of the design, construction, technical evaluation, and independent operational evaluation as required by Department of Defense "fly-before-buy" policies required of selected DOD system acquisition programs. The extensive predelivery test and evaluation program, including problem resolution and corrective actions, accounted for more than a 2 1/2 year time span from launch to delivery.

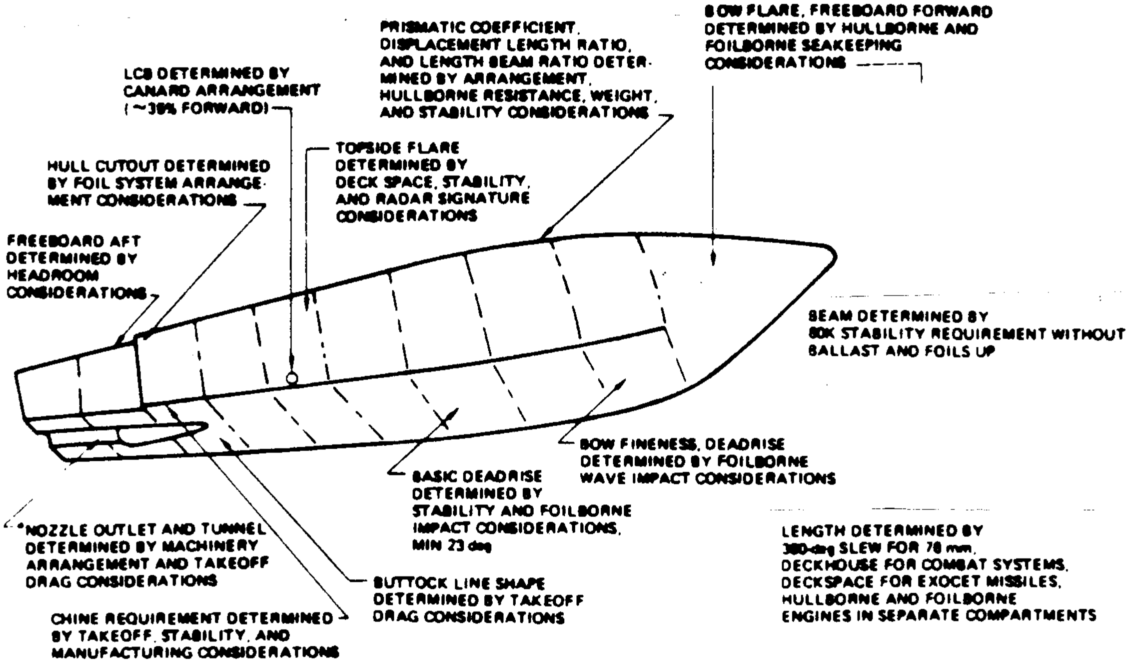


Major Events Leading to the Operational PHM Squadron

The following is a description from reference 19 which provides some of the alternatives that were considered during the early design phases. It indicates the type of thinking and trade-off considerations required at this stage of a major hydrofoil design.

The initial effort determined that the performance goals could be attained with any of the three mission suites, but the displacement in each case was greater than a target value which had become 170 tons. In fact, by the time the feasibility baseline design was completed in April 1972, the design full load displacement was established at 228 metric tons including a 9.5 metric ton margin for growth during the service life.

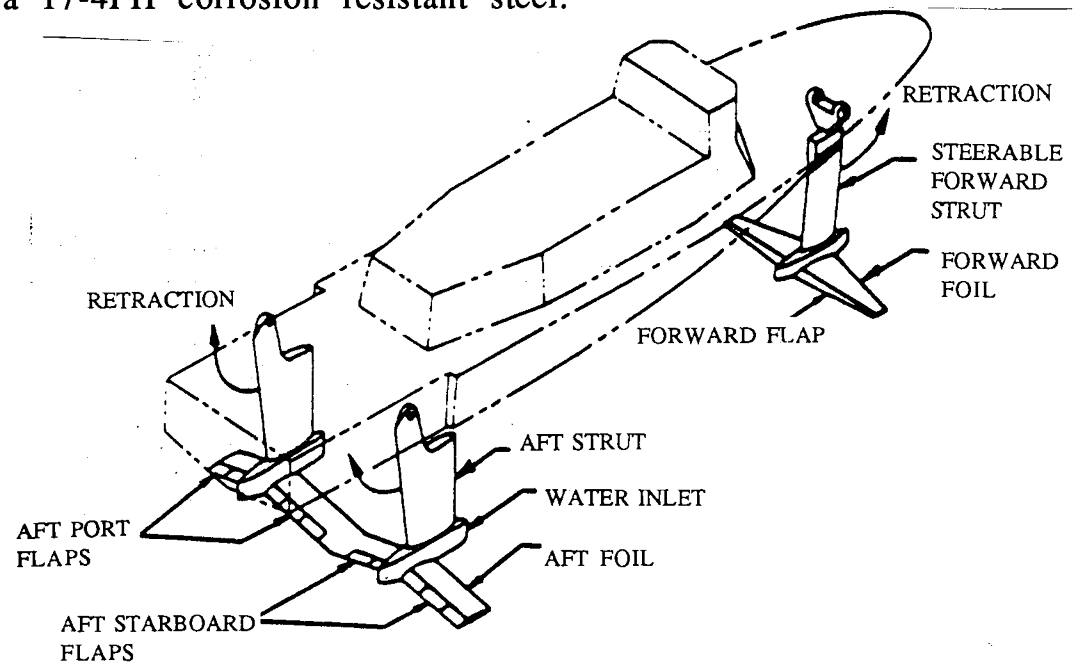
Another major task in the first days of the hydrofoil contract was to study the feasibility of designing and constructing the ship using metric units in order to achieve the objectives of a cooperative design in the most cost-effective manner. The approach involved review of each major element of the design specifying metric units for new elements and using imperial units for elements already developed in those units. The initial cost impact was estimated to be about five percent on design, five percent on procurement and an initial ten percent impact on maintenance and support items. The decision to "go metric' was later viewed as very favorable. The engineering designers had no problem in changing their thinking to metric equivalents. This represented a significant first in U.S. shipbuilding experience.



PHM Hull Design Considerations

The hull lines were developed to satisfy considerations related to accommodations, weight, intact and damaged stability, a two-compartment flooding criteria, seakeeping, hullborne resistance, takeoff resistance, and foilborne wave impacts. The hull was designed as an all-welded structure fabricated primarily from 5456 aluminum alloy.

The use of a canard foil system was established at the outset of the program. The forward foil/strut system has a steerable tee configuration which stows ahead of the bow in the retracted position. The aft foil system was an upside down pi (Greek letter Π) configuration with retraction rearward behind the transom for shallow-water, hullborne operation. These retraction constraints along with the strut length requirements dictated by sea state, determined the location of the foils relative to the hull. The final distribution of foil area, fore and aft, was then determined by the ship center of gravity location. The length of the struts was chosen to allow foilborne operation in 5-meter maximum height waves. The basic material chosen for the foils and struts was a 17-4PH corrosion resistant steel.



PHM Foil System Arrangement

The propulsion plant went through more of an evolutionary process during the feasibility baseline design period than any other major system. The foilborne propulsion system was initially conceived as two double-impeller centrifugal waterjet pumps driven through two combining reduction gearboxes by four General Electric LM500 gas turbines. The hullborne system designs initially consisted of a single Avco TF25A gas turbine engine driving a controllable, reversible-pitch propeller through a V-gearbox.

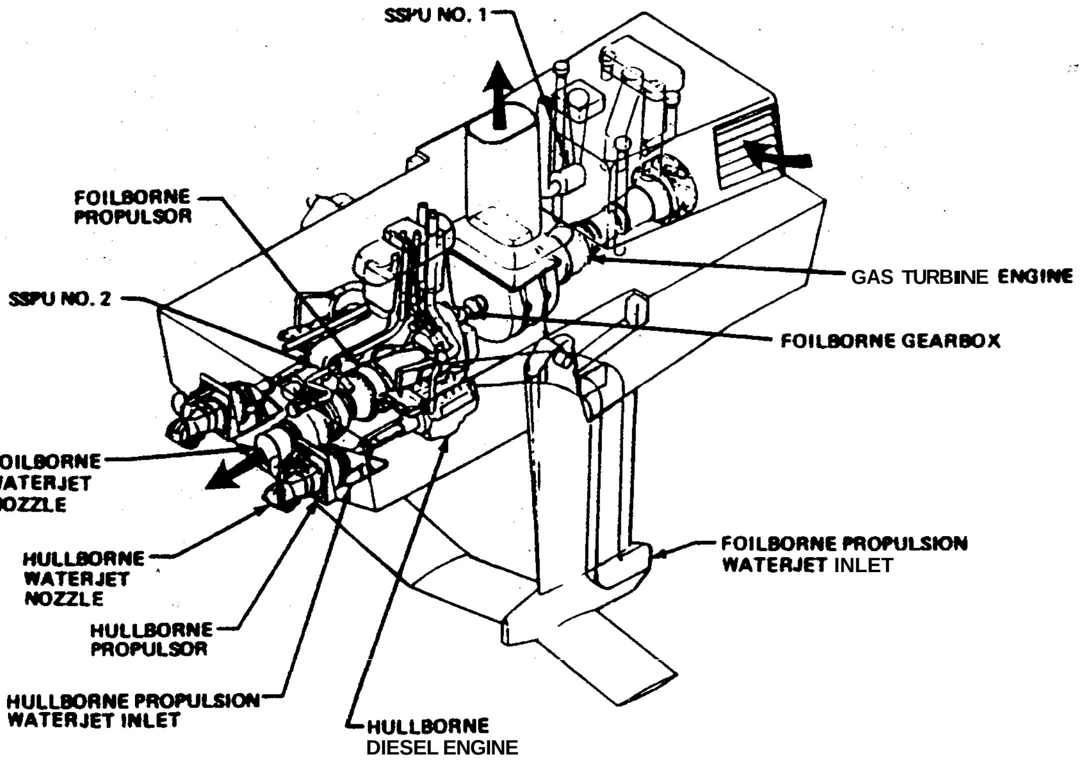
Since the foilborne propulsion system has a major cost impact on the ship, its selection was of primary importance. The hullborne system was of secondary importance and was largely dictated by the foilborne system. Criteria used in the selection process were many, but the important considerations included risk, availability, cost, arrangement/access, other commercial and military applications; and performance.

The LM500 gas turbine engine was not a U.S. Navy-qualified marine gas turbine engine at the outset of the PHM development program, and it was estimated that appreciable cost would be required to accomplish its qualification. Other engines considered at the time were the LM1500 and LM2500. Both resulted in heavier ships, increased machinery weights, larger machinery spaces, larger intake and exhaust ducts, and higher per-engine costs. The LM1500 was a first- generation turbine which GE planned to phase out of production. On the other hand, the LM2500, while more costly, was a second generation engine with a substantially higher compression ratio and turbine inlet temperature resulting in much lower fuel consumption, even when operated at lower power levels. The decision to select a single LM2500 engine was based upon the desire to standardize gas turbines in use by the U.S. Navy since LM2500 engines are used in the PERRY- Class Frigate (FFG) and SPRUANCE- Class Destroyer (DD-963). The LM2500 engine is rated at considerably higher power output than necessary for a ship sized to meet the PHM specification. The engine fuel control was therefore modified to limit the power output to the 17,000 horsepower needed to meet the specification performance, and the propulsor and gearbox were designed for the reduced power.

For the foilborne propulsor the choice of the single engine, mounted on the ship centerline, narrowed the selection of waterjet pump to a single or a twin-pump consideration. The twin-pump system required a complex power train system which included gearboxes, flexible couplings and shafting spanning the beam of the ship. This twin configuration was initially adopted as the feasibility baseline design. However, complexity and technical risk caused the later selection of a single pump with integral gearbox, direct-driven by the engine, with the water ducting spanning the ship. Either a single centrifugal or a mixed-flow pump could have satisfied this configuration decision.

One company proposed a mixed-flow, single-stage pump; the second proposed a mixed-flow, two-stage pump; and the third (the TUCUMCARI supplier), proposed a double-impeller, centrifugal pump. After consideration of risk, cost, and performance, the second proposal was chosen. The foilborne propulsor has been very successful with no changes in performance but with some changes in materials and fabrication techniques between the lead ship and production PHM hydrofoils.

The foilborne gearbox on the lead ship experienced some problems early in testing. These problems were analyzed, and corrections were made. The production ship design accounted for these corrections, and the following design modifications were made: 1) capability was increased from 16,200 to 17,000 metric horsepower with a battle override rating of 19,680 metric horsepower, 2) rolling element bearings were changed to journal bearings, 3) increased geartooth strength resulted in decreased stresses, and 4) all main gear elements were made integral with their shafts.



PHM Propulsion System Arrangement

After the selection of the single foilborne propulsor, the hullborne propulsion system became a twin system. Twelve candidate hullborne systems were quickly reduced to three. They were: two ST6J-77 gas turbine engines and controllable-pitch propellers; two MTU (Motoren-und Turbinen-Union) MB8V331TC80 diesels and controllable-pitch propellers; and two MB8V331TC80 diesels and waterjets. The MTU diesels were selected due to lower cost, low specific fuel consumption and good availability. The diesels also had excellent cold start and response time capability, a desired attribute for cold weather operations. Also, early in the program, there was a desire to find some potential Federal Republic of Germany equipment suppliers to increase the European equipment content in the ship. The choice of diesel has proven to be excellent. The only changes from lead ship to production have been a change in designator, MB 8V331TC81, and a very minor increase in continuous power from 750 to 815 metric horsepower.

The choice of hullborne waterjet propulsor over a controllable- pitch propeller was based on least cost, best availability, simplicity, direct access for maintenance, and very low underwater damage vulnerability.

The electrical system feasibility baseline design called for two redundant gas turbine driven generator sets of 200-kW each. Power would be 1201208-volt, three-phase, 400-Hertz a.c. The required 450-volt, 60 Hz a.c. power; the 120-volt, three-phase, 60-Hz a.c. power; and the 28-volt d.c. power would be obtained through power conversion equipment. An auxiliary power unit would provide 60-kW of 400-Hz a.c. power for in-port use, battery charging, and emergency supply to navigation and radio equipment.

The hydraulic and automatic control systems are worthy of mention because: 1) they have proven reliable and functionally well-suited for a hydrofoil ship, 2) they combine proven aircraft system equipment applications with unique hydrofoil equipment applications, and 3) they are essential to all operations; foilborne, hullborne, and docking.

The hydraulic systems operate at a standard 3,000 psi constant pressure. Proven aircraft hardware, mostly from the Boeing 747 aircraft, was used where possible. The hydraulic pumps, tube fittings, tubing material, and filters were all taken directly from the 747.

Because the hydraulic systems are crucial to both foilborne and hullborne operation, the design employs multiple levels of redundancy to assure continued operation in the event of system failures. Four separate systems supply the required power to the various hydraulic equipment users which include the foilborne and hullborne control actuators, strut retraction and lock actuators, bow thruster, anchor windlass, and emergency fuel pump. Systems No. 1 and No. 2 supply hydraulics to the forward part of the ship while systems No. 3 and No. 4 supply the after part. Two separate supply systems feed each user, with provisions included to transfer the user from its primary supply to its alternate supply in the event of loss of primary supply pressure.

In the case of the foilborne control and hullborne steering actuators, an automatic shuttle valve was specifically developed for the hydrofoil program which rapidly transfers the user actuator from a failed supply to the alternate, thus assuring continued safe foilborne operation.

The hydraulic actuators on the PHM were for the most part specifically designed and developed for this program. The four foilborne control actuators, the hullborne steering actuator, two hullborne thrust reverser actuators and the strut retraction actuators all were designed, manufactured and qualified to military specifications including rigorous environmental and life testing.

While the automatic control system (ACS) derived much of its basic approach from the earlier TUCUMCARI and HIGH POINT designs, major technology advances as well as considerable electronic equipment obsolescence had occurred during the intervening years. At the same time, the then current performance and equipment requirements were considerably more extensive and stringent than for the previous programs. Therefore, the foilborne control system and hullborne steering systems were designed and developed specifically for the PHM program.

USS PEGASUS (PHM-1) was the first of this new Class. She is 138 feet long with a maximum beam of 28.2 feet at the deck, displaces 235 tons, and has a crew of 23 officers and enlisted men. The actual design speed of the PHM-1 Class ships is classified, as is range, endurance, and turn rate. The ship is heavily armed for its size carrying 8 HARPOON missiles and a 76 mm gun. A tabulation of many of the ship's particulars is given in Appendix A.

An interesting aside in this part of the PHM story is that although the first of the PHM-1 Class has been referred to as PEGASUS, it nearly had a different name. Captain Karl Duff, USN (retired), then Commander Duff, who served as Deputy Project Manager of the PHM program under Captain James R. Wilkins, tells of a fascinating episode early in the life of the ship.[22] According to Duff no one ever succeeded in changing the name of a U.S. Navy ship, especially the lead ship of a new class, after the Secretary of the Navy had officially announced it. CDR Duff had written a memorandum requesting a change in name of the lead ship of the PHM class of hydrofoils. As he wrote in Reference 22:

> "Secretary Middendorf had decided that the class of ships would be named after constellations and that the lead ship would be named "Delphinus", which means "Dolphin" in Greek, perhaps an apt name for a high speed surface ship that travels sometimes in and sometimes above the water. The problem was that Delphinus was a perfectly awful name for a ship manned by a bunch of sailors. Sailors like to be proud of their ships and the name is an important factor, since many ships also pick up abbreviations or nicknames and no one wanted to be associated with a name that reflected poorly on the character of the ship or her crew. Delphinus was about as effeminate a name as has ever been coined for a U.S. Navy ship."

Karl Duff further describes a series of events involving several Executive Assistants, Admiral Kidd, Vice Admiral Robert Gooding, and Secretary Middendorf leading to an agreement on the part of the latter to change the name of the lead PHM ship - and proposed USS PEGASUS. He told Admiral Kidd's Executive Assistant that "it was a great name, perfect for the class of ship it was to typify".

The original NATO plan was to build two lead **PHM's** prior to a total ship production of thirty. As mentioned previously, costs became high, the second PHM hull was abandoned, and all of the remaining resources were concentrated on PHM-1. Its construction was completed in early **1974.**

Launching of the PHM hydrofoil is somewhat unique when compared to that of other Navy ships. USS **PEGASUS** is seen here being transported on a specially- built cradle from the Boeing hangar at **Renton,** Washington, where it was constructed, to a ramp leading into Lake Washington. It was at this ramp that the christening ceremony took place. The champaign bottle was broken over the starboard forward foil extremity rather than more conventionally at the bow of the ship.

USS PEGASUS on Cradle

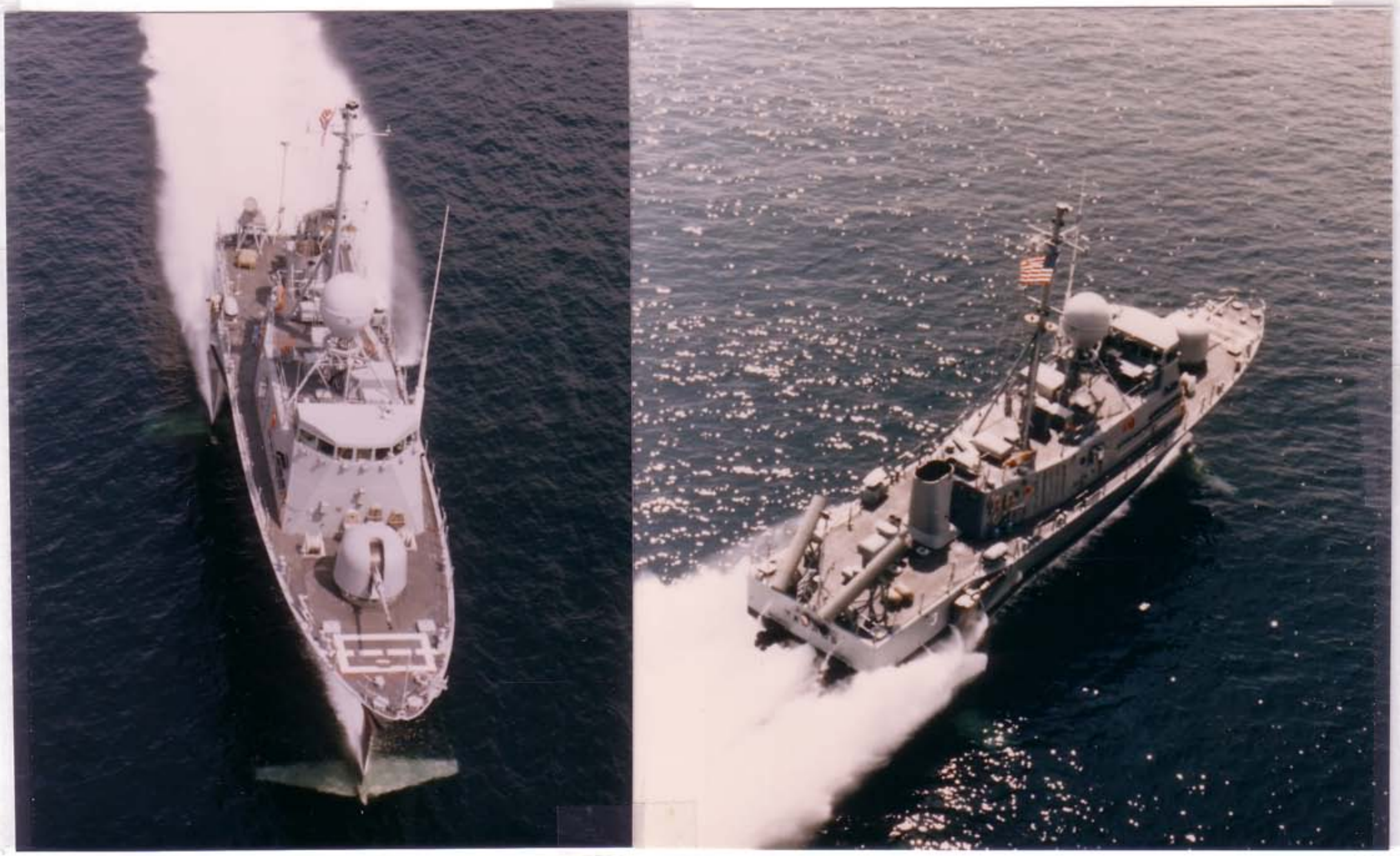
Subsequent to launching in February 1974, the ship transitted from Lake Washington, thru the Lake Washington Ship Canal and Hiram M. Chittenden Locks, into Puget Sound, and to the David Taylor Research Center Hydrofoil Special Trials Unit Facility at the Puget Sound Naval Shipyard, Bremerton, Washington. There a series of trials were performed under the watchful eyes of U.S. Navy personnel leading to Navy acceptance of the ship.

USS PEGASUS Launching

As can be seen from some of the accompanying photographs, the eight (four each port and starboard) live HARPOON missiles which are normally carried on operational PHMs have been replaced by dummy cannisters to simulate the total weight of the HARPOON load during technical and operational evaluation of the ship.

Trials of PHM-1 continued for several months as the performance of the ship was determined and compared with the specifications to which it was designed and built. The many photographs taken at the time provide a vivid impression of the ship's unique characteristics of high speed and maneuverability.

USS PEGASUS on a High Speed Run on Puget Sound



Bird's Eye Views of PHM

USS PEGASUS Accompanied by Helo and Fixed Wing Aircraft

Dramatic Display of Spray During PHM Emergency Landing Demonstration

USS PEGASUS Displays its Rough Water Capability

USS PEGASUS TRIALS AND TRIBULATIONS

Trials of USS PEGASUS were completed with much tribulation. To those intimately involved in the trials phase of her operations on a day-to-day basis, this is probably an understatement. Karl Duff, Hank Schmidt, and Mike Terry, in Reference 23, remind us that PHM-1 was the first U.S. Navy ship to be procured under the "fly-before-buy" Department of Defense policy. As a result there was a test phase referred to as Initial Operational Test and Evaluation (IOT&E) followed by an independent series of tests called Operational Evaluation (OPEVAL) by the Commander, Operational Test and Evaluation Forces (OPTEVFOR) headquartered in Norfolk, VA.

A relatively short period of time of 90 days was originally planned early in the program when two PHMs were to be available. However when one ship was cut from the program due to cost problems, all tests had to be performed on USS PEGASUS. A heavy test load was placed on the ship, her crew, and test personnel, the results of which would either support a favorable production decision by the government or lead to an early end of the hydrofoil program.

A very elaborate test program was developed for not only the ship itself, but much of the equipment used on board. Both critical and so called non-critical items were identified. In the critical area were such items as major foilborne

PHM Shows Off Its Maneuverability

propulsion components, hullborne propulsion system, automatic control system, foils, struts and pods, and hydraulic actuators. Included in the "non-critical" items were, for example, the ship's gyro compass, seawater pumps, life rafts, speedlog, communications equipment, fuel-water separators, and window deicing.

Government- furnished equipment selected for the PHM also underwent extensive testing to qualify for use on the ship. Both the gun fire control system and the 76mm rapid fire gun were modifications of foreign weapon development programs by the Dutch and the Italians. The first system had been under development and test for a number of years in the Federal Republic of Germany and installation on the FRG Navy fast patrol boat S-143 Class. In parallel, the U.S. built version of the this fire- control system with a MK 92 U.S. designation, was built by Sperry and underwent tests on the U.S. Navy frigate USS TALBOT (FFG-4) to determine its suitability for both the FFG-7 and PHM production programs.

The Italian OTO MELARA 76mm gun had been used by many foreign navies for small- ship armament including use on board the Italian Navy hydrofoil ship SWORDFISH, a variant of the U.S. Navy Hydrofoil TUCUMCARI, described in a previous chapter. This gun, with a MK 75 designation, underwent a rigorous technical evaluation at the Naval Surface Weapons Center, Dahlgren, Virginia. In parallel, another OTO MELARA- built MK 75 gun was placed aboard USS TALBOT for an operational evaluation along with the MK-92 fire control system.

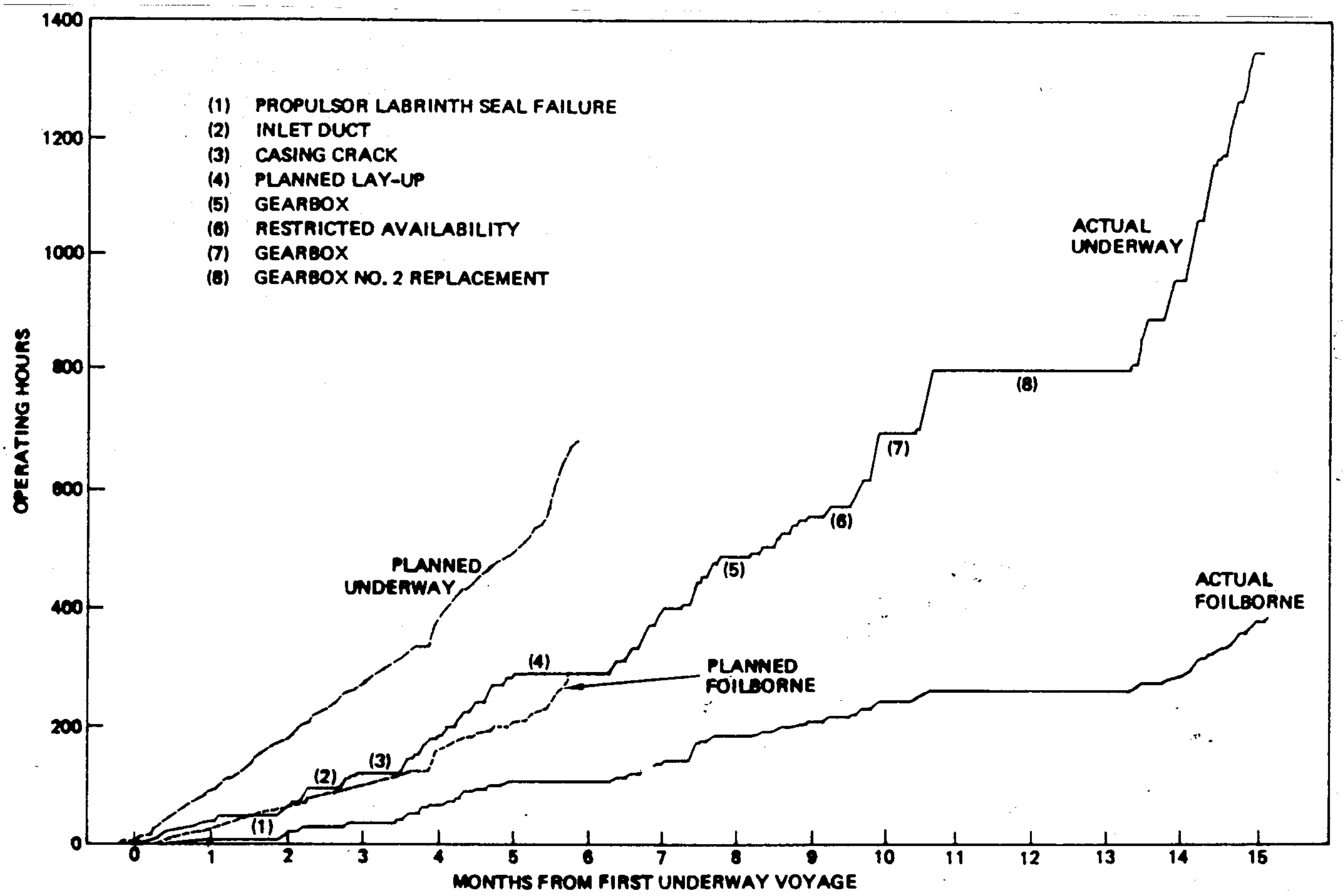
In a previous chapter, the HIGH POINT was shown firing a HARPOON missile. This was one of the tests that provided confidence in the use of a fixed cannister launcher for this weapon on a hydrofoil operating at high speeds. The HARPOON surface-to-surface missile, built by McDonnell Douglas, is the primary weapon for the PHM.

Engineering and performance trials started with the launch of the ship in November 1974. Platform trials consisted of both dockside tests and underway trials. The first foilborne flight of USS PEGASUS was on March 25, 1975 with performance trials starting the middle of the next month. The test and evaluation plan contained 48 individual engineering tests and 44 individual contract performance tests to be completed during the latter stages of construction and the dockside portion of testing. Shipboard testing was performed under both calm water and rough water conditions. There were 119 individual tests associated with the underway trials.

In addition to all the previous testing of the combat systems, USS PEGASUS went through an elaborate series of trials to demonstrate that all of these systems would operate satisfactorily on board this unique vessel. Tests were carried out in the Puget Sound area and in an operational area off Point Mugu, southern California. Although some development problems were experienced, corrective actions were taken, the system retested to verify system readiness for the PHM OPEVAL. These trials were conducted over a period of seven months which included 41 trial days.

PHM Firing A HARPOON Missile

All during this test period, which ran from March 1975 into May 1976, the major cause for lost trial days was the main foilborne propulsion system. First there was the waterjet propulsor labrynth seal failure, followed by water inlet duct problems, propulsor casing cracks, and propulsor gearbox problems which ultimately required a changeout during the Christmas holidays of 1975. It was concluded that although the PHM trials program suffered severely from failure to have an adequately qualified propulsion system prior to ship launch, the maturity of the applied hydrofoil technology, selection of combat systems, management of systems integration, and the test program planning saved the program and demonstrated that the ship was ready for OPEVAL.



USS PEGASUS Trials Operation Profile[23]

And indeed the OPEVAL did take place successfully in May and June of 1976! It was during this time that rough water trials were carried out with an impressive quantity of valuable data collected. In fact, the motions information showed that the ship performed better than that required by the specifications. Again the superior seakeeping and comfortable ride qualities of the hydrofoil concept was vividly demonstrated.

In reality, the most strenuous tests of USS PEGASUS were still to come. The ship and its sister ships were destined for operations out of their home port at Key West, Florida, a mere 5,000 miles away from Seattle! But before that PEGASUS, then assigned to the Surface Forces, Pacific (SURFPAC), was to participate in a trans-oceanic exercise. This deployment and fleet exercise was known as "RIMPAC-78". She was the first commissioned hydrofoil to join a mid-Pacific multi-national fleet operation as an integral unit of a U.S. Navy battle group. This historical event represented an operational and logistic milestone for a small combatant at it demonstrated trans-oceanic long deployment sustainability while at the same time maintaining a full and continuous combat readiness status.

Thanks to Anton Maier, of Hydrofoil Support Applied Technology, Inc., this phase of PEGASUS' trials and tribulations was thoroughly documented.[24] He reported that USS PEGASUS' initial role was to serve as a surface escort in company with six amphibious ships enroute from San Diego to the mid-Pacific exercise area. A simulated submarine threat scenario required a nine day transit due to frequent course changes. A speed of advance of 12 knots was maintained by the convoy formation with USS PEGASUS keeping station from 30 miles ahead to 30 miles astern using a "sprint and drift" technique.

The term known as "sprint and drift" is peculiar to advanced, high performance ships such as hydrofoils. What this means is that when traveling with other conventional monohull ship which cannot maintain a high speed economically, PHM would "fly" at speeds around 40 knots from a rear position of the accompanying ships, and then get so far ahead so quickly, it would have to "land" and essentially drift (or travel at very low speed) until the more ponderous ships would finally catch up. Of course PHM could fly circles around the accompanying ships as they made their slow pace across the Pacific, but this would require an excessive amount of fuel and more frequent refuelings.

Underway replenishments of USS PEGASUS were accomplished every two days from one of the amphibious LPD ships. On April 4, 1978 she joined the main group of a four-nation naval exercise involving 41 ships, 225 aircraft, and 22,000 personnel. This was Exercise "RIMPAC-78" involving the Rim of the Pacific nations maritime forces from the United States, Canada, New Zealand, and Australia.

The statistics of the first major deployment of a U.S., Navy fleet hydrofoil are impressive - in spite of the many difficulties the ship had in the way of spare parts and transfer of same from the support ship, USS SAN BERNADINO. Tony Maier points out that due to lack of PHM operating experience at that time, many parts that were required were not on board USS SAN BERNADINO, and many of the parts that had been taken, were not actually required during the 49 days of operations. Covering 9028 miles, PEGASUS operated for 554 hours with 121 of these foilborne. It was during this time period, in fact on April 25, 1978 that USS PEGASUS played host to the then Chief of Naval Operations, Admiral Hayward and the newly selected CINCPACFLT, Vice Admiral Davis. She showed her flying colors with a successful demonstration of speed and agility; both admirals were impressed with the ship's performance and their visit to the machinery spaces while hullborne.

Tony documented daily successes and tribulations all during the exercise and concluded that there were inadequate spare parts for a trans-oceanic deployment/transit and exercise and also a critical shortcoming of special equipment and tools. This type of exercise was quite different from previous deployments like the long distance transit from Seattle to San Diego. The latter was carried out relatively close to the coastline (30 to 50 miles offshore) so a short diversion to a nearby port was always an option when required for parts, equipment, or supplies.

Of course, unlike conventional U.S. Navy ships, the PHMs were designed and built with a logistic and operational philosophy more like an aircraft than a ship. PHM hydrofoils are weight sensitive - after all, they have to fly! Consequently it cannot go to sea with a large storeroom full of parts and extra personnel on board to replace and repair everything that could go wrong. But more about that later when we describe the PHM Squadron operations.

CONSTRUCTION OF REMAINING PHMs

At the same time that USS PEGASUS was going through its initial introduction to the fleet, plans were underway for the construction of the 5 remaining hydrofoils to round out a squadron of six ships.

However, this was not a smooth and straightforward process. As pointed out by Stephen Chapin[25], "politics and procurement do not mix". By December of 1976 Italy and Germany had dropped out of the program even though each had contributed about $13M to the project. But fortunately by this time the PHM program had garnered the U.S. Navy's support.

Chapin goes on to explain the ups and downs of the PHM procurement process. The request for PHM acquisition funds was to pass through the Defense System Acquisition Review Council (DSARC) before being forwarded to the Secretary of Defense for approval. The PHM met a major funding challenge rather than a challenge to its ability to perform its mission. The DSARC recommended disapproval of the PHM package to the Secretary of Defense. PHM advocates called upon the Office of the Assistant Secretary of Defense for International Affairs (ISA) to "expound" upon the international importance of this shipbuilding program. After listening to ISA arguments, the Deputy Secretary of Defense supported PHM funding over the objections of the DSARC.

In January 1977, there was a change in administrations. Almost immediately upon entering office, President Jimmy Carter's Secretary of Defense, Harold Brown, decided to take the PHM program "under advisement". Next, Brown cancelled funding for the PHM Squadron support ship, the USS WOOD COUNTY (LST-1178). Then in April 1977, he decided to cancel the entire program. It was at this time that the West German government declared that they would be unable to enter into PHM production. It seemed that the PHM hydrofoil's fate had been decided, but not so!

Chapin describes a further twist in this unorthodox acquisition process by stating that one could make an argument that it was President Richard Nixon who reversed the fortunes of the hydrofoil and saved the PHM program. This was because earlier, during his term as President, he refused to spend the funds that Congress had allocated for certain programs, and Congress passed the National Budgeting Impoundment Act of 1974. This law states that if the President does not desire to spend appropriated funds for programs, he must submit a Memorandum of Recision to Congress asking it to abbrogate the approved funds. If no action is taken by the House of Representatives within 45 days, the President must then spend the money for the purpose originally stated in the appropriations act.

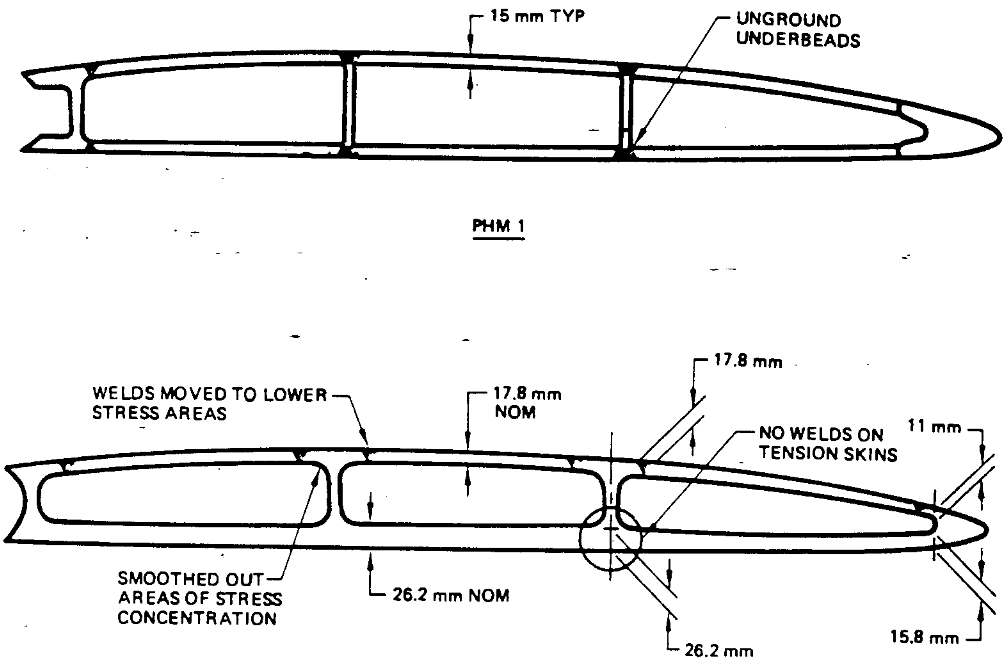
Because Congress had already approved funds for the PHM, Secretary Brown, via President Carter, provided the Memorandum of Recision, and a Bill was drafted. The future of the Navy's PHM program looked bleak indeed because the House Appropriations Committee (HAC) was somewhat hostile toward the program for earlier cost increases. However, several key personalities helped to change this situation. It was Congressman Norman D. Dicks (D-WA), of the district in the State of Washington where Boeing was to build the ships, who spoke very highly of them and urged the committee to defeat the bill. It was also from one of President Carter's own appointees that the greatest support from the program came. The former president of Southern Railroad, then Secretary of the Navy W. Graham Claytor, Jr, had sent two detailed memoranda to the Secretary of Defense prior to Brown's April decision urging him to allow the PHM program to proceed. Following the April decision, Claytor was bound to support the Secretary of Defense before Congress. However, his memos found their way to the HAC staff and were read into the record before Claytor's testimony was given. With a vote of nine to one, the committee rejected the Bill of Recision, and the PHM program prevailed against Brown's attempt to dismantle it.

The production contract was not signed until October of that year, so the program suffered about an eight month delay which took its toll in further increased costs.

With a production contract for five PHM ships in hand, Boeing proceeded with construction of the PHM-3 Series hydrofoils. One may wonder why PHM-3 rather than PHM-2 since only PHM-1 was completed and delivered to the Navy! Well, the Navy is very sensitive to Hull Numbers. Remember that PHM-2 had been started, but due to cost escalation, it had to be disbanded. But the hull was still in Renton, WA, and the Navy system could not tolerate two hulls with the same number. Hence, a fresh start was made with PHM-3, and a designation of PHM-3 Series of the PHM-1 Class hydrofoils. But later when the old PHM-2 hull was scraped, the last of the ships to be delivered was, you guessed it, PHM-2! So much for that!

Obviously there were many things that Boeing and the Navy learned from PHM-1. To most observers the configuration of the PHM-3 Series production ship looks identical to the PHM-1. The arrangement of the ship is essentially the same except for certain items and operators stations in the Command and Information Center (CIC) which was rearranged. The officer's wardroom was eliminated allowing a larger crew messroom, and the two head facilities were combined creating a much needed crew storeroom.

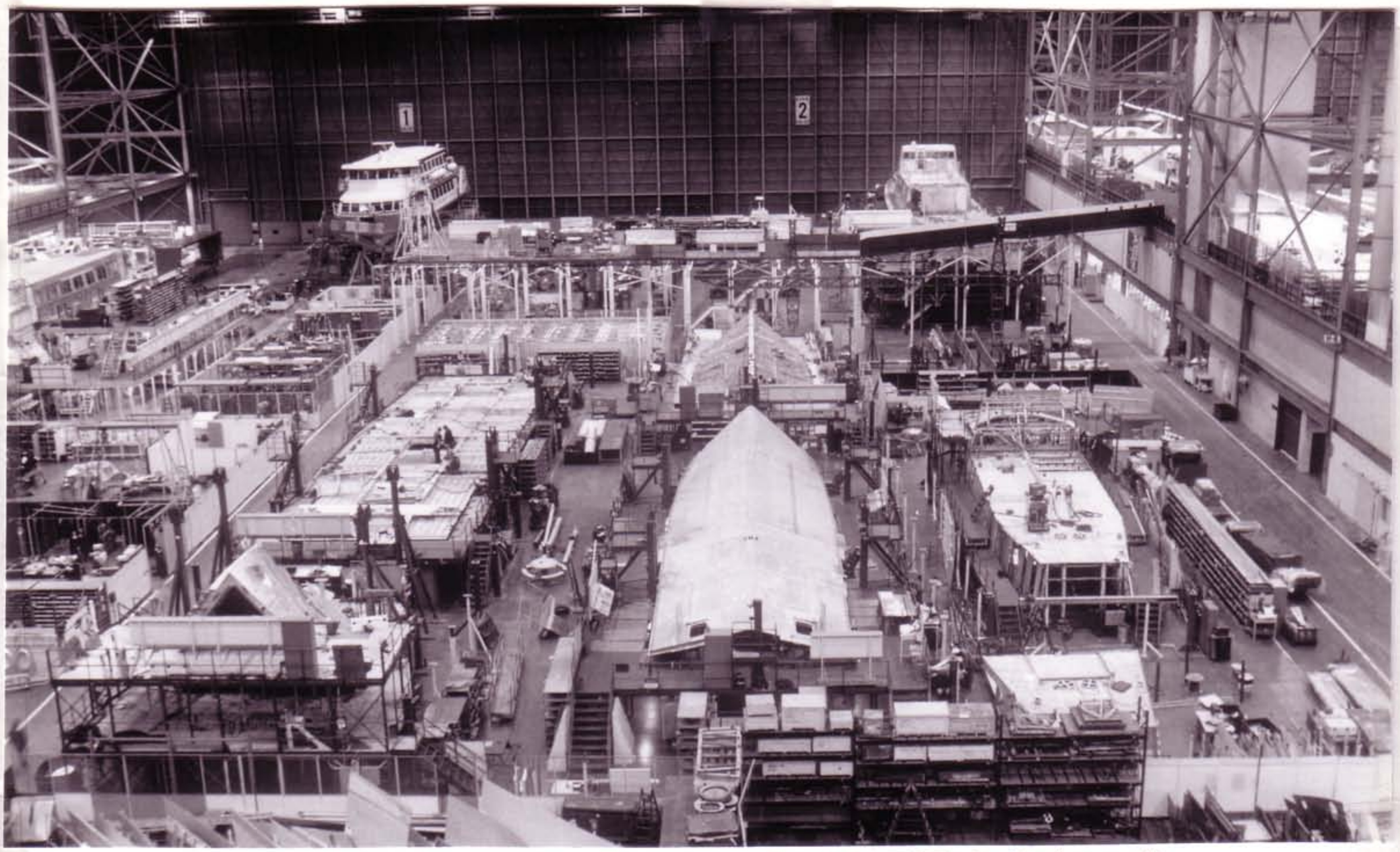
However, the more significant and major differences were in hull construction details to improve producibility and the all-important foil/strut system. Early in the operational life of PHM-1, cracks appeared in the skins of the foils. Detailed investigations showed that material fatigue was the major source of failure. Load information on the foils was obtained from tests, and the struts and foils redesigned to lower the stresses in the material and smoothing out stress concentrations. The result was a completely new foil and strut system for the ship. As seen in the accompanying figure, the foil structure was created from a large, thick billet. Numerically controlled machines fashioned the interior as well as the exterior surfaces to their proper shapes. The only welding was on the upper, rather than the lower surface of the foil to avoid welds in tension.



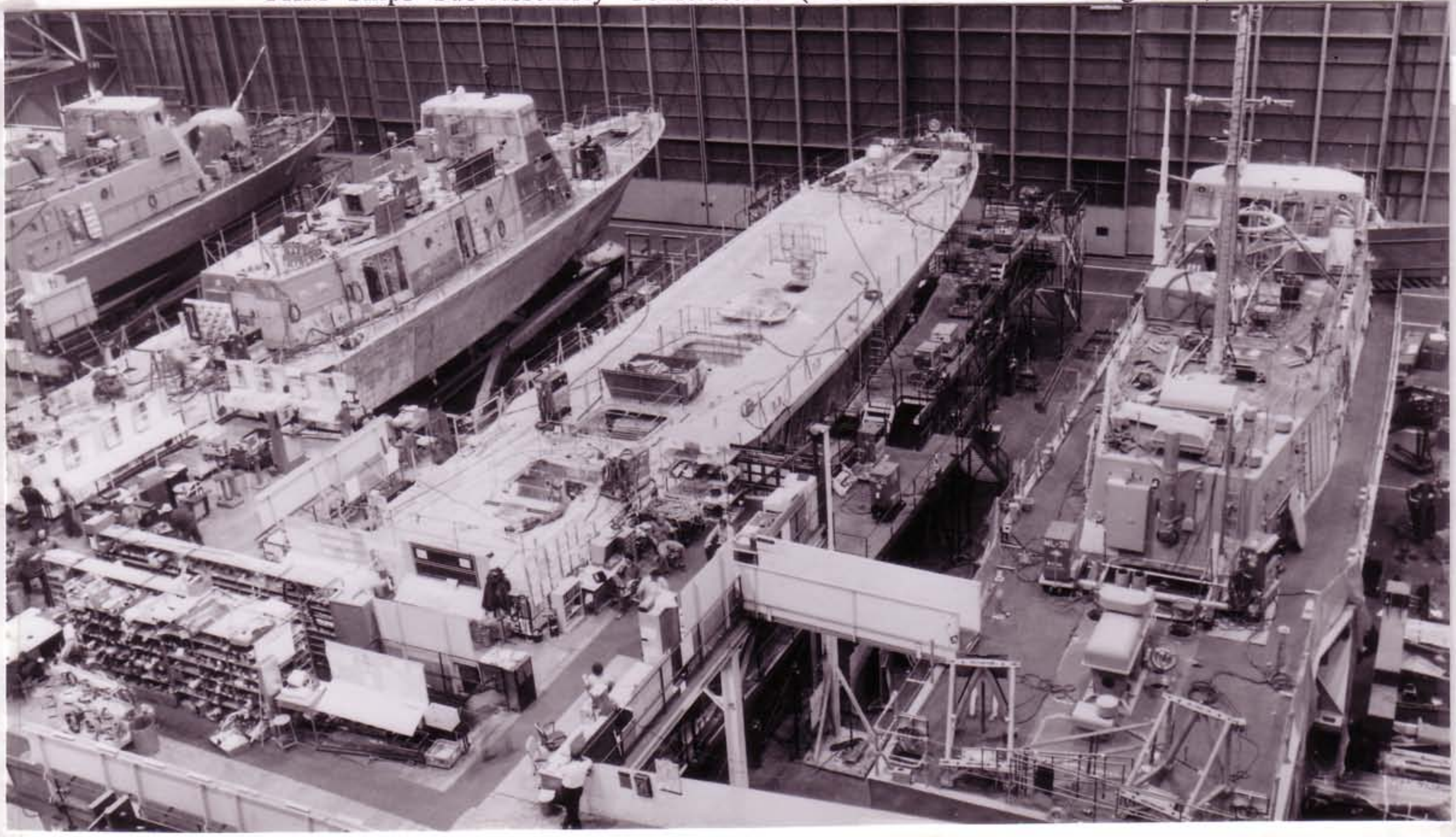
PHM 1

PHM-3

Comparison of PHM-1 and Production Ship Foil Construction



PHM Ships Sub-Assembly Construction (Note JETFOIL In Background)



PHMs Take Shape

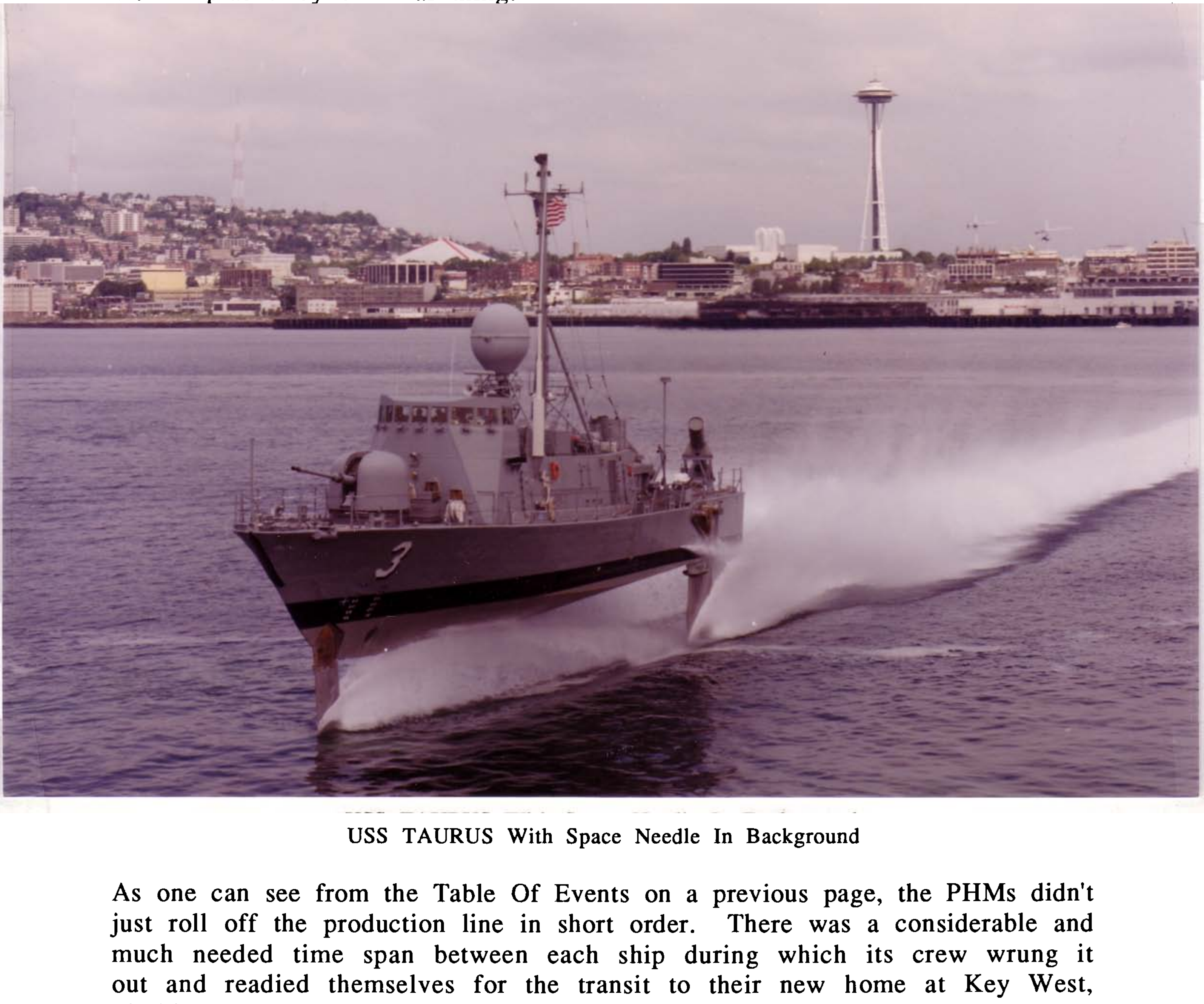
The author had the opportunity on several occasions to see the PHM ships under construction at Boeing's Renton plant - PHMs on one side of the wall and Boeing 727s on the other. These "small combatants" did look big in the aircraft assembly hangar as one can gather from the photographs.

PHM-3 Nears Completion

The table below summarizes the significant dates associated with all of the PHM ships. As mentioned before, the PHM ships were to be named after constellations. With about 88 to choose from, the Navy decided to follow "The Winged Horse" with HERCULES "Son of Zeus", TAURUS "The Bull", AQUILA "The Eagle", ARIES "The Ram", and GEMINI "The Twins".

SHIP	KEEL LAYING	LAUNCH	DELIVERY	COMMISSIONING DATE	ARRIVAL IN KEY WEST
PHM-1 (PEGASUS)	9 MAY 73	9 NOV 74	21 JUNE 77	9 JULY 77	17 JULY 80
PHM-2 (HERCULES)	12 SEP 80	13 APR 82	17 SEP 82	15 JAN 83	17 FEB 83
PHM-3 (TAURUS)	30 JAN 79	8 MAY 81	7 OCT 81	10 OCT 81	11 AUG 82
PHM-4 (AQUILA)	10 JUL 79	16 SEP 81	26 JAN 82	26 JUNE 82	11 AUG 82
PHM-5 (ARIES)	7 JAN 80	5 NOV 81	10 MAY 82	18 SEP 82	15 DEC 82
PHM-6 (GEMINI)	13 MAY 80	17 JAN 82	29 JULY 82	13 NOV 82	17 FEB 83

Subsequent to construction, each ship underwent a series of trials in the Puget Sound area. Following the launching ceremonies the PHMs were transferred to the Navy's David Taylor Research Center Hydrofoil Special Trials Unit (HYSTU) Detachment at the Puget Sound Naval Shipyard in Bremerton, WA. A host of great photographs were taken by the Navy and Boeing during this period. The Space Needle from Seattle's 1962 Worlds Fair usually found itself as an ideal backdrop for the PHM, whatever it was doing. Note that the Navy had not changed its mind about the number of HARPOONs the ship was to carry. The two cannisters at the stern of the ship during this phase of testing simulated the weight of the eight missiles, and of course later were replaced by the real thing.



USS TAURUS With Space Needle In Background

As one can see from the Table Of Events on a previous page, the PHMs didn't just roll off the production line in short order. There was a considerable and much needed time span between each ship during which its crew wrung it out and readied themselves for the transit to their new home at Key West, Florida as a unit of PHMRON TWO, the subject of the next section.

USS TAURUS from a Helo

Wheelhouse/Bridge of PHM

USS TAURUS In A Tight Turn

THE PHM SQUADRON IS COMPLETE - HYDROFOILS JOIN THE FLEET

USS PEGASUS departed San Diego, CA on 4 June 1979, set a speed record transiting the Panama Canal, and arrived at her first East coast home port at Little Creek, Norfolk, VA on 3 July. At that time the plan was to have the entire Squadron of PHMs at that location. However, the plan was later changed. Rather than have the PHMs operating too close to sources of major support afforded by one of the largest Naval bases on the East Coast, the ships and it's Mobile Logistics Support Group were put to the test of self reliance by selecting the most southern U.S. outpost, namely, Key West, Florida. Also, the Caribbean was increasingly becoming a focus of the U.S. Navy's Atlantic Fleet.

However, before that change took place, a memorable event occurred during PHMs early East Coast operations. An article from a "Survey of Selected Grounding Incidents" documents, as Case Number Forty-Three[26], the USS PEGASUS grounding on 20 August 1979. She got underway from the Naval Amphibious Base (NAVPHIBASE), Little Creek, Virginia at noon, en route to Yorktown as part of a fleet exercise. The weather was overcast with isolated rain showers, and the visibility was 2 to 5 nm in haze. After clearing the harbor, the PHM became foilborne while outbound in Thimble Shoal Channel and then proceeded to Yorktown via the Chesapeake Bay and York River entrance channels.

There were fishing craft, fishing traps, and shoal water in the York River area. With an indication that water depth was sufficient, the ship was landed because of the concern about the fishing boats and the nets ahead. Unfortunately there was actually only 13 feet of water forward. Successful salvage operations freed PHM-1 by mid-morning the next day. Damage was limited to strut and foil assemblies, with no structural damage to the hull. All other major equipment remained operational. Three months later she was flying again.

The first PHM to arrive in Key West was, of course, USS PEGASUS on 17 July 1980. There was a considerable gap in time (about 31 months) until all of the remaining ships arrived. You will note from the table of significant dates for the ships that TAURUS and AQUILA made the transit together in the summer of 1982.

The PHM Squadron Two, known in short as PHMRON TWO, in Key West, Florida finally received its sixth ship (PHM-2!) in February 1983. Since each ship has only a crew of 23 and limited space, it is supported in much the same way as are aircraft operating from a fixed base. At Key West this "fixed base" is the Mobile Logistics Support Group (MLSG) of about 170 persons established on the Squadron pier. The various shops, offices, and storage areas are housed within about 74, forty-foot vans - many of them interconnected. When a PHM returns from a mission, the ship's crew files reports with the MLSG who provide personnel to the ship for repairs and maintenance.

View of PHMs and MLSG From Squadron Building, Key West

One may wonder why the first squadron of PHMs has a "two" in its designation. This is because all U.S. Navy Squadrons on the East Coast are even-numbered, whereas, those on the West Coast are odd-numbered. Hence, if a second squadron of PHMs was to be formed on the East Coast, it would be designated PHMRON FOUR.

PHMs Flying in Formation

Operations of PHMs from Key West have been varied from independent routines in the Caribbean Basin, participating with the Fleet in major exercizes, and cooperating with the U.S. Coast Guard.

Officially the Squadron's mission in peacetime is to conduct surveillance, screening, and special operations. In wartime the PHM squadron is to operate offensively against major surface combatants and other surface craft. In particular, tasks assigned to the Squadron include detection and engagement of enemy surface forces with surface-to-surface missiles and secondary armament; conduct surface surveillance and blockade operations in coastal areas, straits and narrow seas; screen coastal convoys against surface attack; and screen large mercantile or amphibious force convoys against surface attack during arrival or departure operations.

One must remember that the Patrol Combatant Missile (Hydrofoil) PHM Class was designed to augment the capabilities of the U.S. Navy surface forces, particularly in the Mediterranean and Caribbean Seas and in other narrow seas and coastal waters. The PHM characteristics of all-weather capability, significantly higher foilborne speed relative to normal surface ship speeds, and high sea state operational capability lend themselves uniquely to geographic area surveillance, choke point interdiction, barrier patrol, sea lanes of control protection, and detection of and attack on enemy forces.

PHM SQUADRON MATURES - READY "TO GO IN HARM'S WAY"

Captain Frank G. Horn was the first hydrofoil Squadron Commodore to have six hydrofoils under his wing. He, the Squadron personnel, and all of the ship's crews were eager to demonstrate the Squadron's ability to be a reliable, powerful element of Navy seapower wherever they were ordered to operate. As suggested by the Squadron's emblem, PHMs were designed "To Go In Harm's Way".

It was during the time period of 1983 through 1984 that Captain Horn moved aggressively to prove and develop the Squadron's at-sea techniques and multi-ship tactics.[28] Application of "big-ship" thinking and approaches had to be tested and validated for the PHMs, or else innovative alternative approaches invented. Major emphasis was placed on "keep 'em sailing", or flying in the case of the PHMs.

Captain Horn emphasized "operating successfully is the big payoff for all our efforts in building, equipping, training, and maintaining this squadron of new ships. Some of the operational techniques that are basic doctrine for larger, slower ships have to be tested and validated for PHM's. For example, what is the best speed for underway replenishment? How do we tow the PHM? How do we tow other ships?"[29] The objective at this stage of operations at Key West was to develop a mature, proven body of sea skills for the PHM that every Navy ship class needs.

As the new Squadron operated at sea, the PHM's excellent sea-keeping characteristics in heavy weather became apparent. Also, although the ship was designed to operate for only five days with two days at the pier for upkeep, early experiences indicate that a ten-day at-sea period at slow speed while hullborne was well within their capability - an excellent characteristic for surveillance missions. It became evident to Captain Horn and all of the ship's crews that there was an opportunity to exploit the ships small radar cross section, its high speed, big "punch", and capabilities to provide the surface Navy with a potent weapon and act as a force multiplier.

USS HERCULES - Ready For Action

Mentioning "speed" of ships brings up the age-old question: Is there value in speed? Speed, as the classic element of surprise, has always been and still is a prime element of tactics. A high-speed naval vessel can react quickly to an unforeseen application of the enemy's strength. It can cover wide areas while engaged in search of defensive barrier operation, for example. Such a high speed ship can project an offensive capability quickly and unexpectedly. It can control the time, place, and to a certain extent, the conditions of any potential engagement. Speed enables the PHM to cover large areas and return to base after attack with minimum exposure. The common argument that a homing anti-ship missile traveling at supersonic speeds can perceive no difference in a target travelling at 15 knots or one at greater than 40 knots has been said to be an over-simplification. A target, maneuvering at high speed and at high turn rates injects a degree of complication into the over-the-horizon targeting problem. Seizing the initiative, going on the offensive, and striking unexpectedly are the PHM's decided advantages in any engagement. These are some of the important elements in the maturing of the PHM Squadron that Captain Horn fostered.

Although the PHM success story of tactical maneuvering actually took place earlier on USS PEGASUS during OPEVAL off the Pacific Missile Range, Pt. Mugu, CA, it equally applies to the entire hydrofoil Squadron operating off Key West. Vernon Salisbury[30], of Boeing, relates that CDR Erich Ashburn, the Commanding Officer of PEGASUS at the time, was the first to learn to defeat jet fighters.

Salsibury pointed out that tactical maneuvering in the face of the enemy means simply being in position to hit and not be hit. Tactical maneuvering of the PHM in a wide variety of circumstances is essentially the same as for any other ship. However, a foilborne PHM with accurate gun control adds a new dimension to tactical maneuvering of surface ships against aircraft. To conduct high-speed runs against the ship, the services of A-4, A-6, and F-4 aircraft were obtained from NAS Miramar on the Pacific Missile Range. If the pilots had fuel and time remaining on station when their required exercises were completed, they usually asked for and received "free time." To take advantage of this time and learn how to fight a PHM, the pilots were encouraged to attack the ship in any manner they considered effective.

CDR. Ashburn quickly recognized the advantages of fighting the airplanes at his highest foilborne speed. Adding a very long extension cord to his inter-comm, he was able to keep the airplanes in sight by moving around the pilothouse and out on the 01 level of the ship as needed. The Tactical Action Officer (TAO) and the Combat Information Center (CIC) team directed the gun and monitored the aircraft ranges and bearings.

When attacking, the aircraft were watched visually and as soon as they were committed, it was possible with practice to estimate the phase of the attack, angle of approach, weapon release point, and pullout maneuver, and determine the best killpoints on both the approach and retirement. This became a game and pilots showed up just for the "free time". It was rumored that NASA pilots flying in the naval reserve also came out to see this ship that could outmaneuver them.

On the day of the demonstration for Admirals Bird, Monroe, and Walters during PHM DSARC II OPEVAL., CDR. Ashburn put a high-intensity flashing light into the breech of the gun. It was a yacht life jacket 100,000 candle power zenon lamp, so that the flashes could be seen down the bore. He also had the ballistics control dialed out of the gunfire control system. He reasoned that this would aim the gun directly at the pilot. With the admirals aboard, he carefully explained his game plan for the aircraft's "free time". Afterward, one of the admirals radioed to the pilots and asked them if they had seen the flashing light. They replied: "Oh yes, Admiral, on every run." It had worked at every Mach number. Salisbury reported that the practice, Tactical Action Officer (TAO) and Combat Information Center (CIC) coordination, discussions with naval aviators, and the ship's maneuverability all combined to make the demonstration a success.

During the early early years of Squadron operations, the concept of the Fast-Attack Surface Action Group (FASAG) was used to take advantage of the PHM's strengths while avoiding her weaknesses (short range and relatively short mission time). The FASAG combines PHMs with an antiair warfare-capable warship that can act as a refueling and supply ship while underway. The FFG-7 is a natural for this role since she has adequate room to support a detachment of the MLSG, and there is a significant amount of commonality between the two ships. This includes the LM2500 gas turbine engines, HARPOON missiles, the MK-92 fire control system, and the Mk-75 76 mm. gun.

The FASAG concept was successfully carried out during an operational exercise called "Urgent Fury". Whereas the FFG provided extended command, control, communications, and endurance for the PHMs, the PHMs provided extended sensor and weapons performance for the FFG.

It was during a Caribbean Exercise called "Ocean Venture 1984" in which the PHMs participated, that Commodore K. G. Dorsey, COMCARGRU FOUR, stated that:

> **"PHMs HAVE BROUGHT A NEW DIMENSION TO SURFACE WARFARE. PHM SPEED, SMALL RADAR CROSS-SECTION, WEAPONS SUITE AND FIRE CONTROL SYSTEM PROVIDED CVBG WITH A FORMIDABLE OFFENSIVE WEAPON. PHM PERFORMANCE HAS BEEN SUPERB. YOU HAVE PROVEN PHMs CAN OPERATE EFFECTIVELY WITH A BATTLE GROUP AND ARE WELCOME BACK ANY TIME."**

With missions like this and the recognition of Fleet Commanders "under its belt", Captain Horn was certain and confident that the PHM Squadron was "Ready To Go In Harm's Way".

The Squadron went on to plan and execute many more successful operations, the subject of the next section.

PHMs Operating With A Carrier in 1984

Hullborne PHMs Maintain Position On A Carrier

OPERATIONAL SUCCESS

We have described in very broad terms the PHM's mission and the establishment of the Squadron of six ships at Key West, Florida. What have these ships done and what is their future in the Caribbean and perhaps elsewhere?

R. H. Smith, in an article in the Naval Reserve Association magazine[27], describes several of the PHM's successes. He characterizes PHMs as having successfully carried out their responsibilities, having been integrated in all major fleet operations in the Western Atlantic. They have operated routinely with other surface forces, and have performed effectively in coordination with naval helicopters and maritime patrol aircraft. PHMs have demonstrated reliability, ruggedness, versatility, and the ability to perform a wide variety of tasks across a challenging spectrum of conditions.

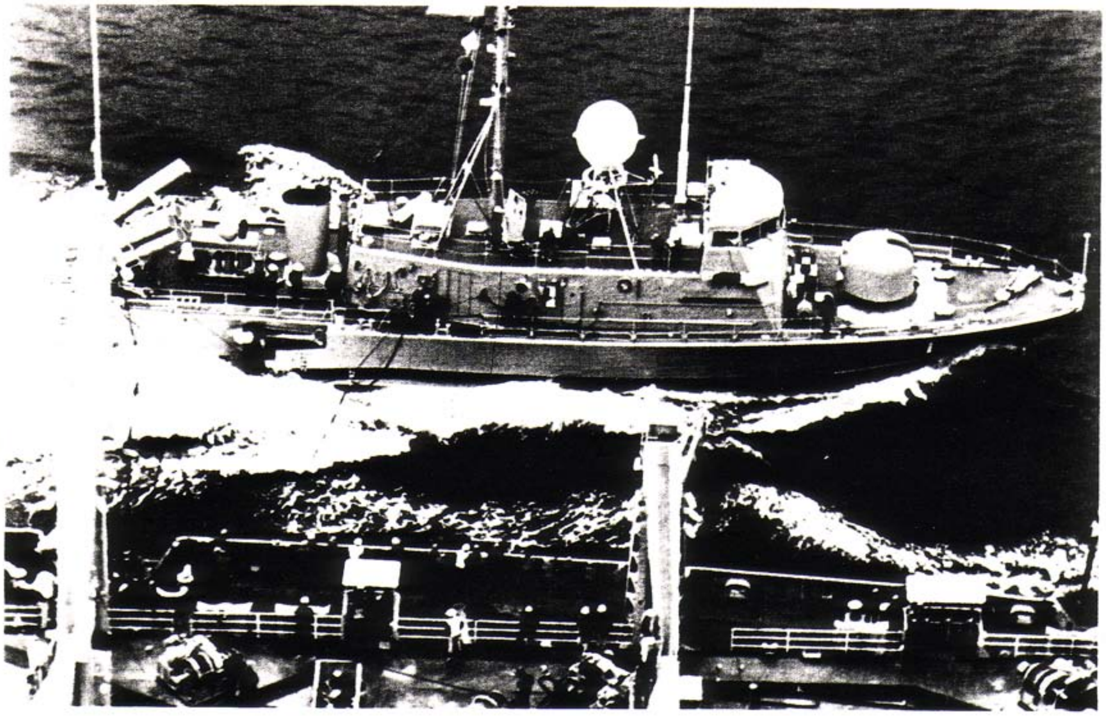
USS TAURUS Operating In The Caribbean

During the invasion of Granada in 1983, for instance, these hydrofoils maintained surveillance of Cuban ports. The PHMs have been the major, and often the sole, enduring naval force across a broad region in which the interests of the United States demand not merely presence, but readiness for conflict. Smith goes on to remind us that in a case of war in Europe, sixty percent of U.S. merchant traffic would traverse the Straits of Florida along with 100 percent of our initial petroleum needs. To keep these sea lanes open and free from the threat of intruders, the PHMs would play a major role.

As an example of operational success, the USS GEMINI (PHM-6), which serves as a typical member of the PHM SQUADRON TWO family, took part in many fleet exercises in the Caribbean and Atlantic areas. In 1985 alone, GEMINI took part in fleet exercises such as READEX, UNIVERSAL TREK, UNITAS, AND MOBEX, all code names for Navy operations.

For instance, after READEX, RADM James H. Flatley, Commander of Caribbean Group Eight, said of PHM:

> **"I APPRECIATE YOUR INITIATIVE AND AGGRESSIVE EXECUTION---YOU STRUCK FIRST, MOVED FIRST AND TOOK ON ALL IN YOUR PATH"**
>
> **"(YOU)--- PROVIDED A FULLER APPRECIATION FOR THE TACTICAL POTENTIAL AND IMPRESSIVE CREDENTIALS OF THE PHM---WELL DONE---"**



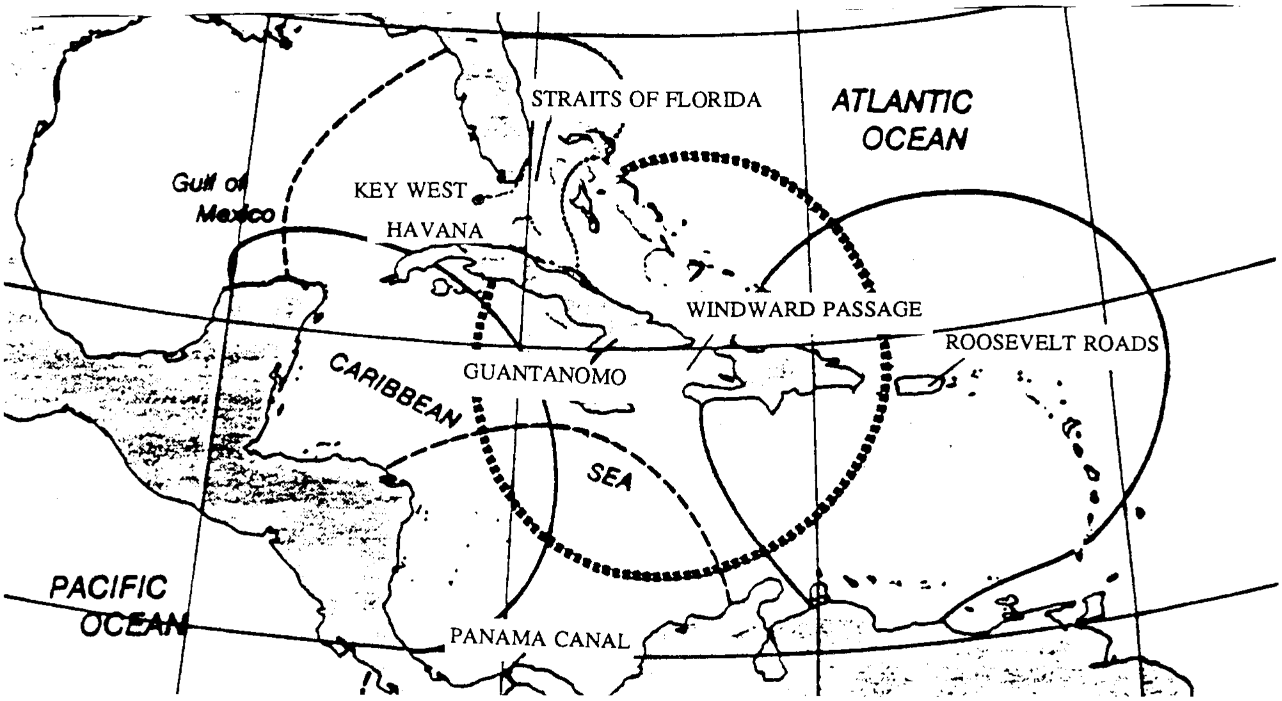
PHM Undergoing Refueling Operations

PHMs demonstrated another success in its Caribbean operations in 1988. Under the Command of Captain Stephen Hamilton, three ships, USS TAURUS, USS ARIES, and USS GEMINI established that the squadron is definitely a part of the nation's rapid deployment resources. Called "ALLADIN'S CARPET", the plan to deploy three PHMs to Grenada and the surrounding area was an exemplary exercise in teamwork involving interservice and international considerations. Although plans had started sometime before, it really all began on 12 February when USS LA MOURE COUNTY (LST 1194) began to load

33 vans and personnel from the Mobile Logistics Support Group (MLSG) in Key West. These vans of course held the parts and equipment that the ships required while deployed from their home base, and this LST served as primary support for the PHMs during this time.

While LST 1194 made its journey to a remote site on the island of Grenada and the 60 man detachment made ready for the PHM's arrival, USS TAURUS, USS ARIES, and USS GEMINI combed the eastern Caribbean conducting drug interdiction operations and visited diplomatic ports of call. Shortly after their arrival in the port of Saint Georges, Grenada on 21 February, the ships took full advantage of their temporary forward base by visiting 15 islands in the Leeward and Windward Island chains. They worked with maritime law enforcement agencies or the governments of those islands, sharing vital tactical information and enforcement techniques. A "ship rider" agreement was worked out with the government of Grenada operating within the 12 mile limit of that country. In addition, the PHMs operated with and visited the Venezuelan Navy in the nearby port of La Guaria. The USS NEWPORT (LST 1179) acted as tactical support ship for the Squadron during the last six weeks of the deployment. On the whole, the 1300 mile trek to Grenada was a great success in many ways and answered the question about availability. The PHMs answered the question resoundingly with a 100 percent availability over the 90 day deployment which ended on 12 May 1988.

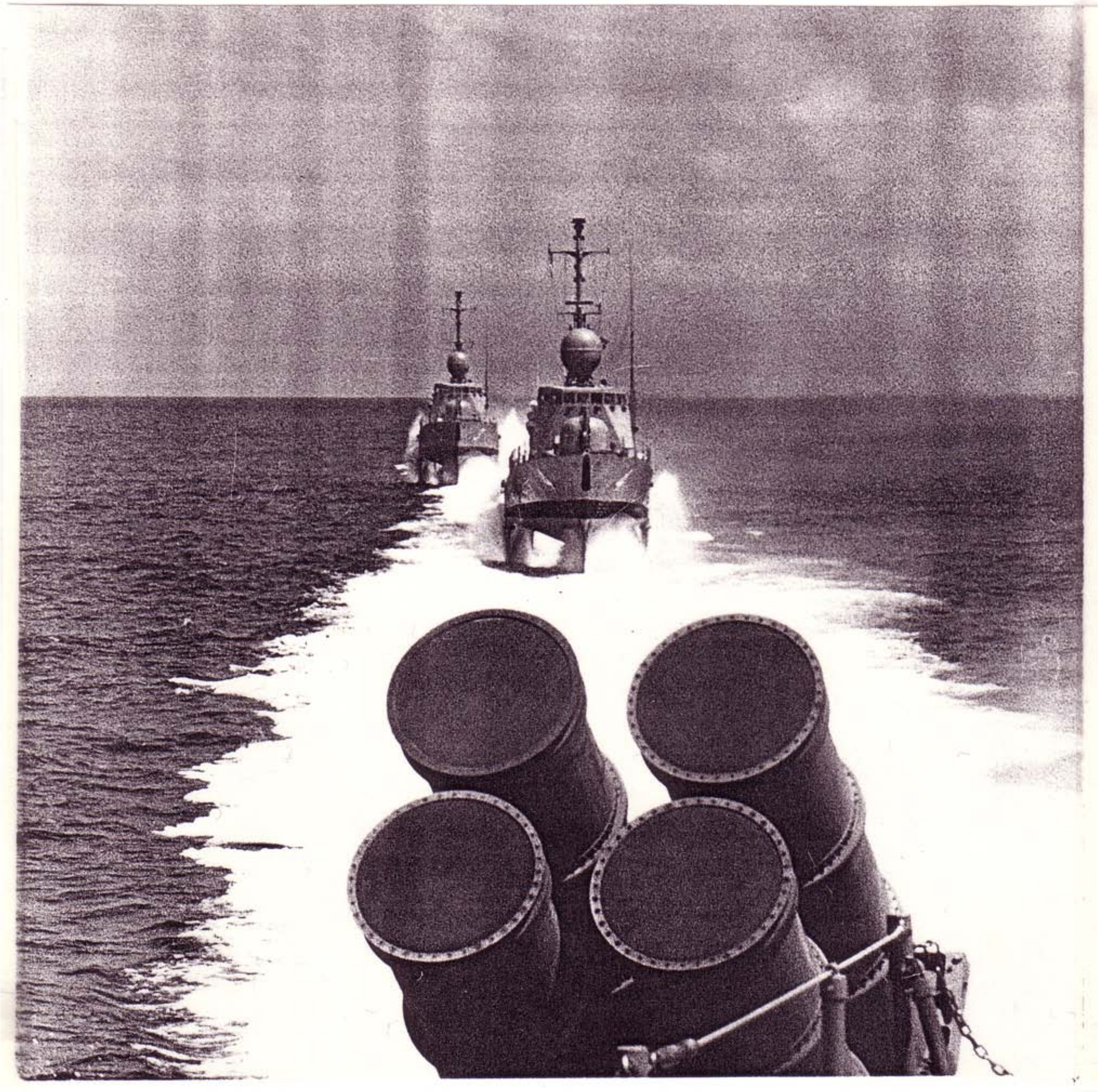
The accompanying map[31] shows areas in the Caribbean where the PHM can conduct so-called "denial" operations. These can be carried out from U.S. Naval



Map of the Caribbean Area

installations, such as Key West, Roosevelt Roads, and Guantanamo, or from friendly countries such as Grenada mentioned above. Also a floating mobile center can be established for operations from a support ship.

A trend which demonstrates the increased confidence the PHM crews have in their ships is the change in the amount of foilborne time the ships accumulate as time marches on. In the 1983-1984 time frame the PHMs were foilborne for only about 23 percent of the time they were out operating. By 1989 this figure reached almost 50 percent. This was far higher than had been anticipated when the ships were designed and placed in the Fleet, but proves that the hydrofoil crews like to fly!



PHMs Follow the Leader

It must be remembered that tactical employment of the PHMs is a new science which is receiving input from a relatively small portion of the naval community. The last several years has provided the Squadron the opportunity to learn fast. Every mission, exercise, and deployment involving the PHMs add to their understanding of the ships capabilities and limitations. Compared to the centuries of naval warfare experience with conventional ships, the PHM is only hours old!

DRUG BUSTING WITH THE U. S. COAST GUARD

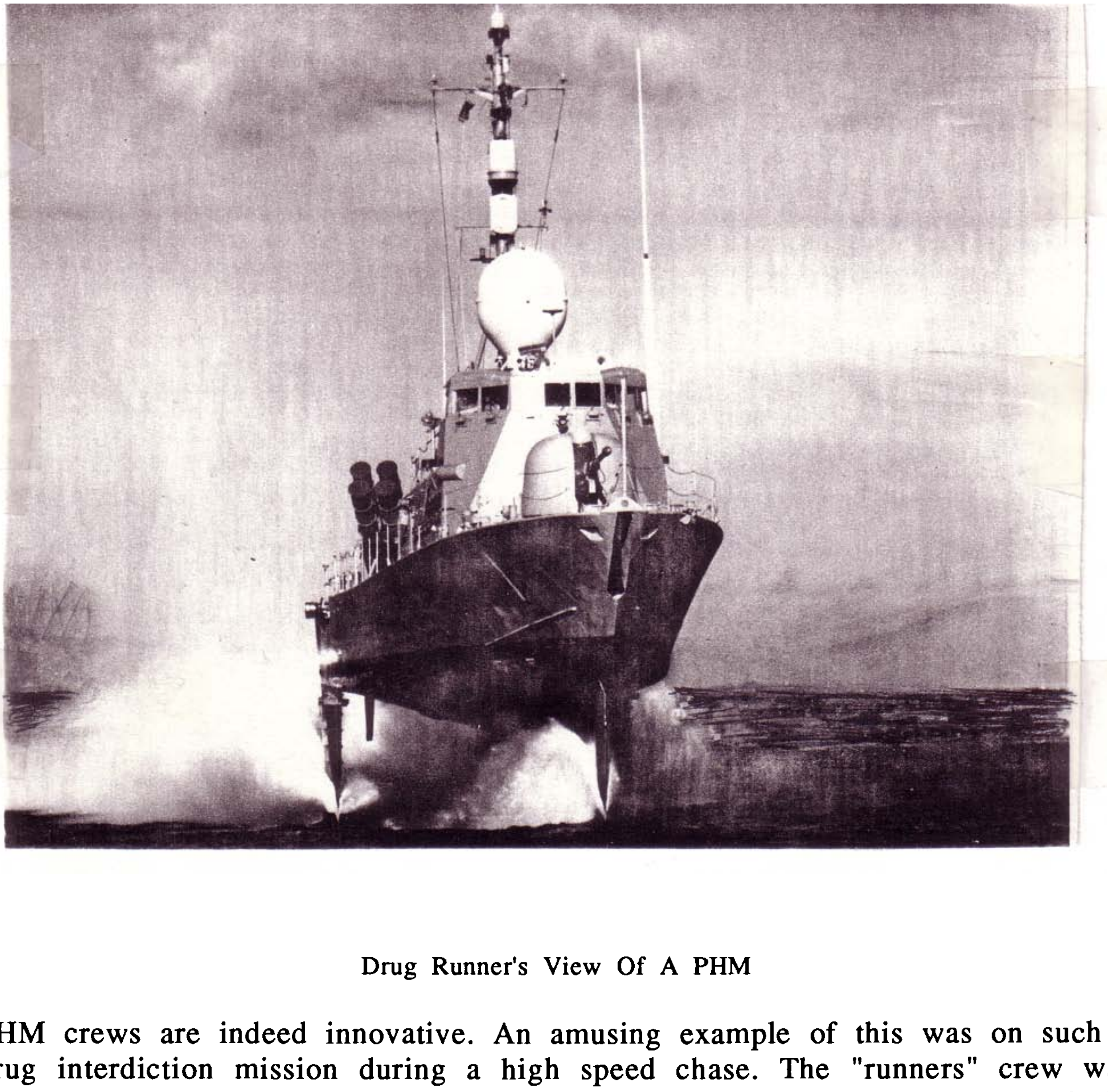
Basing the PHM Squadron Two in Key West, and particularly at Trumbo Point, establishes an ideal situation for drug busting in the Caribbean Basin. In addition to the obvious geographic area, is the fact that the U.S. Coast Guard Station is also located on an adjacent pier. In any such exercise utilizing the PHMs, it is necessary that Coast Guard personnel be present to play an active role in apprehending personnel and confiscating illegal materials.

Nicknamed "El Terror Gris que Vuela" (The Grey Terror That Flies) by drug smugglers of the Florida Keys, the PHM's drug interdiction efforts have been most impressive. The PHMs are uniquely suited to such "hand-to-hand" combat. With speeds in excess of 40 knots in any weather, they are the only U.S. ships which can outrun the "go-fast boats" used by the smugglers.

There have been numerous cases in which the U.S. Navy and the Coast Guard have cooperated in drug busting operations. However, the "Navy News" of 17 April 1987 reported a particularly interesting story. It was about the USS GEMINI (PHM-6) on its first such interdiction on April 6 and 7, 1987.

PHM-6 worked with not only the Coast Guard, but also the U.S. Marine Corps and U.S. Customs Service to apprehend seven people and seize three boats, an airplane, 500 pounds of Cocaine, and 1,500 pounds of marijuana. A Marine OV-10 BRONCO aircraft spotted a private airplane dropping packages to two boats off the Florida Coast and alerted U.S. Customs officials. USS GEMINI and a Customs boat chased and stopped the two "Cigarette-Type" craft. The Coast Guard team that was embarked on GEMINI boarded and discovered an estimated 500 pounds of cocaine. Five U.S. citizens were arrested and the two boats seized. Meanwhile, a Customs helicopter chased the airplane to Bimini Island where it landed. The two men aboard ran into the woods and avoided arrest. A U.S. Customs Service spokesman in Miami said that "this is the quintissential example of interagency cooperation". The following day, on April 7, 1987 GEMINI and the U.S. Coast Guard Cutter "CAPE GULL" pursued another drug runner. Coast Guardsmen from the GEMINI boarded the boat, while CAPE GULL crewmen retrieved 1,500 pounds of marijuana from the water.

The characteristics of the PHMs that make them particularly valuable in the Drug Busting role are speed, maneuverability, and staying power at high speed compared to the boats that run drugs to the Florida coast. Since the Coast Guard does not have comparable assets, it relies on PHM SQUADRON TWO to supplement its own capabilities in the Caribbean. Unlike aerial surveillance which can only track smugglers, PHMs can bring the business end of a 76 mm rapid fire gun to bear should the situation warrant it. No wonder the experienced Coast Guard law enforcement officers state candidly that drug smugglers fear the PHM more than any other vessel.



Drug Runner's View Of A PHM

PHM crews are indeed innovative. An amusing example of this was on such a drug interdiction mission during a high speed chase. The "runners" crew was somewhat stubborn, refusing to slow down and recognize the warnings of the authorities embarked on the PHM. Rather than destroy the drug runner with a blast from the PHMs 76 mm cannon, the crew thought it would be even more impressive if they would merely pass close by, pull in front of the "runner" and proceed to spray it unmercifully with PHMs foilborne waterjet. Although this event was not captured on film, perhaps the reader can imagine the reaction of the crew on the "runner" boat when confronted with a high speed water blast at the rate of 95,000 gallons per minute coming over their bow!

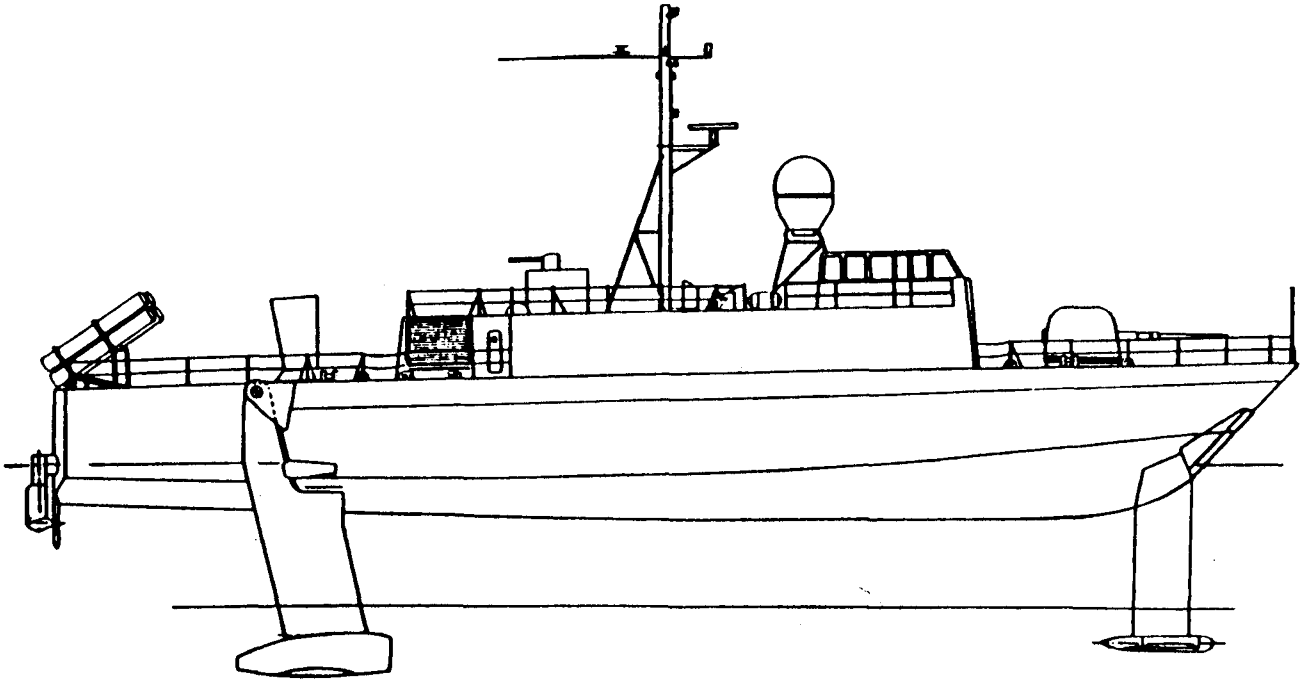
Another technique which puts the speed and staying power of PHMs to use is in a case where the drug runner's boat top speed is relatively high. Unless his boat is specially designed for high speed over a long period of time, and for rough water, it will easily "burn out". That is, if forced to run at full throttle for a long duration, the engines will probably fail and make the crew and their contraband sitting ducks. The PHMs can provoke a "runner" to keep his "throttles to the wall" by just staying on his tail until the time comes that the culprit can be approached at a leisurely speed. Some idea of what the drug runner will see through his binoculars as he peers astern is seen in the above photograph of a PHM and it's 76 mm cannon bearing down at high speed.

FUTURE OF THE PHMs

So, what is the future of the PHM hydrofoils? The ships currently in the squadron are scheduled to continue operations as presently configured until the year 2003. Improvements can be made in these ships to increase their range, improve their motion control system, and introduce a variety of payloads to broaden their mission applications, among other things. However, it is costly to do so. Also, since in 1989 and subsequent years there were even greater constraints on funding for both research and development, and product improvement, it is not expected that these improvements will be incorporated in the PHMs in the near future.

One would expect that with the turn of events in 1989 which has suddenly changed the U.S. perception of the Soviet threat, combined with the continuing escalation of "big" ship costs, that there would be greater emphasis in the minds of Navy planners to reconsider "small" ships and their relative affordability. It is clear that the PHM provides more "bang for the buck" than many of the ships in the "Six Hundred Ship Navy". One must ask: "In view of the 1990s threat, wouldn't it be smarter to build smaller, more capable, and affordable ships like the PHM or improved versions of these hydrofoils?"

An example of such an approach is the PHM "Growth" hydrofoil design shown below. The ship is 400 tons instead of 240 tons, and is "stretched" from 138 feet to 160 feet. As in the aircraft world, Boeing has suggested putting a 22 foot long plug in the hull. The ship would use the full available power of the LM 2500 gas turbine engine, namely 25,000 hp, to maintain the PHM's speed, and carry more fuel. All of this would result in a larger payload, or combat system, and greater range and endurance. References 32, 33, and 34 describe a wide variety of PHM variants and the roles that these ships could play in the real world.



PHM Growth Hydrofoil

Additionally, an alternative approach has been taken to improving the PHMs and extending their life through a so called "mid-life conversion". The Hybrid Hydrofoil concept described in Reference 35 builds upon the PHM experience and provides substantial improvements in hullborne and foilborne range, plus the capability to operate efficiently in the hullborne mode in the 15 to 16-knot speed regime, as well as a major increase the ship's weight-carrying capability. The author suggested this alternative design for not only a mid-life conversion of the PHM-1 Class ships, but also as a candidate for follow-on procurement to a more demanding specification.

The Hybrid Hydrofoil concept consists essentially of the current PHM hull with the addition of a large buoyancy/fuel tank, and changes to the foil system, hullborne and foilborne propulsion systems. This PHM Hybrid Hydrofoil's increased fuel capacity, combined with more than a 50 percent improvement in hydrodynamic and propulsive efficiency, has a considerable impact in terms of hullborne and foilborne range, and fuel/military payload tradeoffs. By-products of this innovative design also include low foilborne wake signature, potential for sonar installation in the lower hull's nose section, minesweeping, increased military payload potential, reduction of weight constraints, refueling cycle improvements, world-wide ferry operations, and the possibility of current PHMs and a Hybrid Hydrofoil operating as a team wherein the latter serves as a fuel "tanker" for today's PHMs.

Candidate For Long Term PHM Product Improvement[35]

However, it is not a foregone conclusion that more PHMs will be built. If it does come to pass, it is hoped that the further improvements in this already very capable ship will be incorporated. Also, a large number of small hydrofoil ship alternatives, described in Chapter 9, are potential advanced marine vehicle candidates for the Navy of the future.

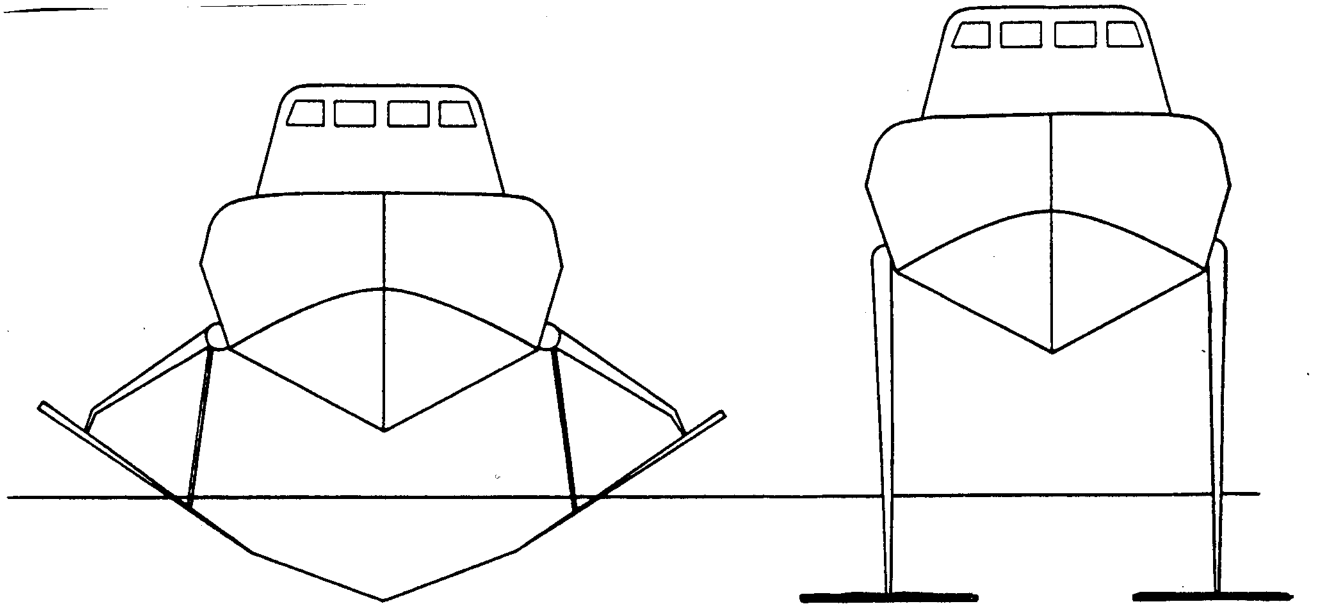
CHAPTER 7

WHY AND HOW DO HYDROFOILS FLY?

The purpose of this chapter is to treat the more technical aspects of the hydrofoil which may make the other chapters more meaningful. However, it is not intended to be a textbook on hydrofoil theory. The listings under "Additional Reading" and "References" should be examined if the reader wishes to further pursue this aspect of the hydrofoil subject.

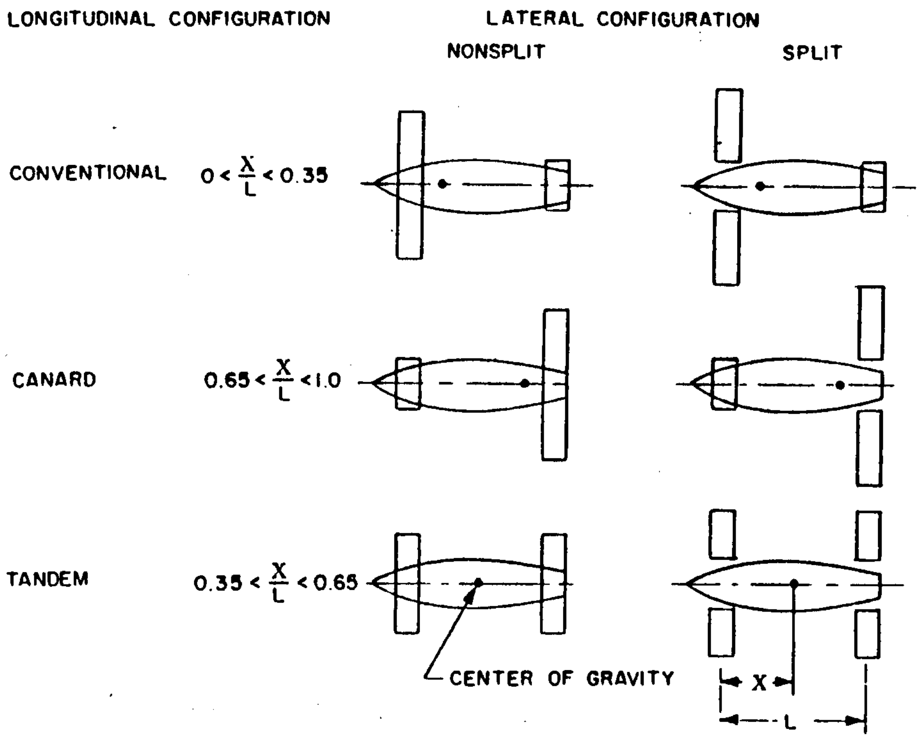
FOIL ARRANGEMENTS

As mentioned in previous chapters, the principle underlying the hydrofoil concept is to raise the ship's hull out of the water to reduce the effect of waves, and also reduce resistance and power required to achieve and maintain high speeds. The hydrofoil depends on forward speed to generate dynamic lift on its foil surfaces. There are basically two general classifications of hydrofoil arrangements, namely, surface- piercing and fully-submerged as shown in the accompanying diagram.



Comparison of Surface-Piercing and Fully-Submerged Foil Systems

In the surface-piercing arrangement, portions of the foils are designed to extend through the air/sea interface when the hydrofoil is foilborne. Struts connect the foils to the ship's hull with sufficient length to support the hull at a moderate height above the water surface when operating at design flying speed. As the hydrofoil accelerates, lift is produced on the submerged portion of the foils and angled struts to the point where less foil area is required to overcome the weight of the craft. When the surface-piercing foil encounters a wave, varying amounts of the foil surfaces are submerged, and in order to maintain total lift equal to ship weight, the craft must either pitch, roll, or heave (or a combination of all three). These changes occur automatically, and therefore a surface-piercing foil system is said to be self-stabilizing. It therefore requires no active controls for height, longitudinal or roll stability. But it is this very attribute of the system that forces the hull to move and therefore places a limit on its ride quality if the ship is required to operate in very rough water. Modern surface-piercing hydrofoils have augmented their inherent stability with electrohydraulic control systems to enable them to operate in higher sea states with a ride that is acceptable to the personnel aboard.



Foil Arrangements

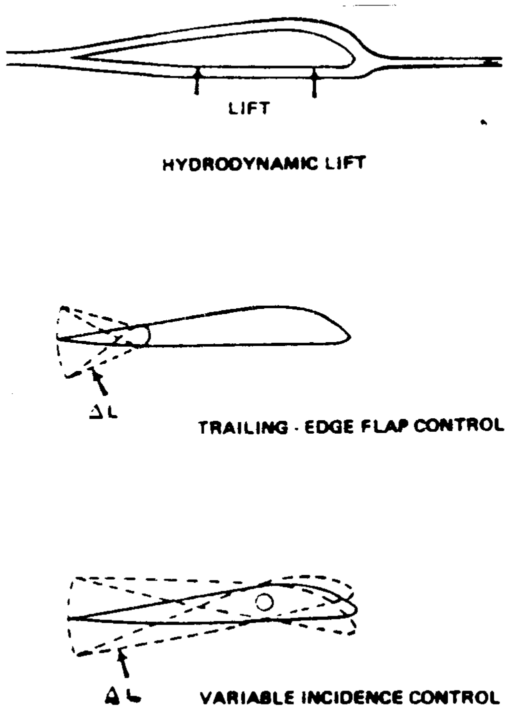
As the name implies, the foils of the submerged type system operate at all times under the water surface. The struts of the system are essentially vertical, do not contribute any dynamic lift to the ship, and therefore any vertical forces generated by them due to changes in buoyancy as waves are encountered are comparatively small. On the other hand, the system is not self-stabilizing, and therefore an automatic control system is required to maintain straight and level flight. The major attribute of the fully-submerged system is to provide a unique operational capability whereby the ship is essentially decoupled from the sea surface and the effect of its waves.

Foil geometric arrangements on the hull have varied but the major ones are shown in the sketch on the previous page.

The conventional, or sometimes called "airplane" arrangement is when most of the foil area is located forward on the hull, as is the case for most airplane wings. The balance of the foil area is then located aft. The canard type is just the opposite; most of the foil area is located aft. When the foil areas are split more evenly, it becomes a tandem configuration. This arrangement can be useful in very large hydrofoil designs where it is desirable to keep foil spans from becoming inordinately large.

AUTOMATIC CONTROL SYSTEM

It is particularly difficult, if not impossible, to manually control a high-speed hydrofoil craft with a fully submerged foil system, particularly operating in rough water. Such craft therefore depend on an automatic control system (ACS) that constantly adjusts foil angle of attack, either through changes in foil incidence or flap angle. See the accompanying sketch. These adjustments are made to both port and starboard, as well as fore and aft foils, to maintain trim and keep the hull at a given height above the mean water surface in the presence of disturbances. In order to achieve as high a lift-to-drag ratio (or minimum drag for a given amount of lift) as possible in the cruise condition, the foils are designed to operate with relatively small mean incidence or flap angles. This then provides adequate reserve to generate the required control forces. This is necessary because of the changes in foil angle of attack resulting from the orbital velocities of waves which, if not compensated for, could produce significant ship motions.



Hydrodynamic Force Control[19]

These excitations must be compensated for by the control system if the hydrofoil is to fly straight and level and remain foilborne in large waves without excessive cresting of the hull or broaching of the foils. The latter refers to a condition when a foil breaks through the water surface, loses its lift, and can cause the craft to go hullborne with a loss of speed. The hydrofoil has to then reaccelerate and become foilborne again.

There are two modes in which a hydrofoil control system operates, namely, platforming and contouring modes. As the name implies, in the former mode the craft flies at a given height above the mean water surface, as illustrated below, and is controlled automatically so that there is minimum ship motion. The limit on this mode is a function of wave height and foil system strut length. When wave height exceeds a value where the ship can no longer "platform", the operator resorts to the contouring mode in which the hydrofoil flies approximately parallel to the smoothed contour of the sea surface or essentially follows the wave contour.

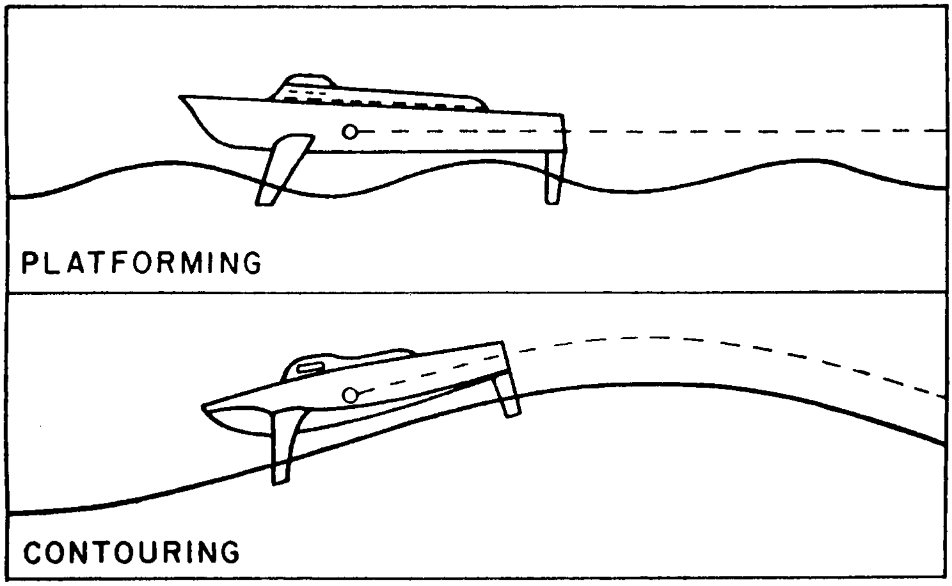
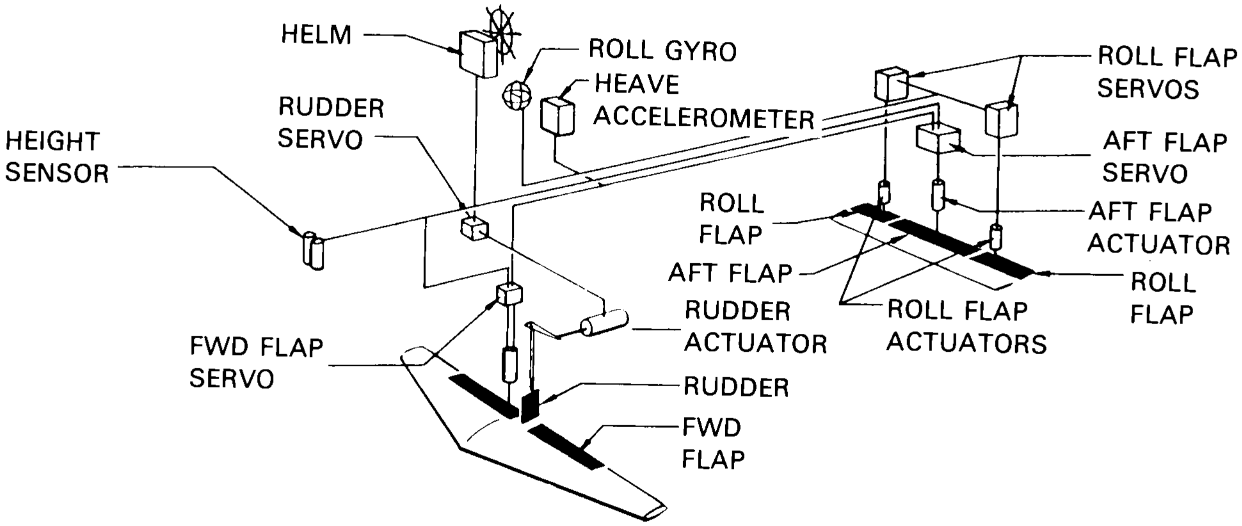


Illustration of Hydrofoil Platforming and Contouring Modes

During early developments of hydrofoils, control systems utilized input sensors for spatial anticipation of oncoming waves. These mechanical devices known as "feelers", or as a stinger-like slipper projecting ahead of the craft, and were described in an earlier chapter of the book. In modern hydrofoils, such as the U.S. Navy PHM, the time constants of the control system are sufficient to handle both the platforming and contouring modes of operation. The control system uses either a sonic or radar height sensor, or both. These devices continually measure the distance to the water surface and input signals to the control system, which, together with other autopilot inputs, provide signals to the hydraulically actuated foil system. The control system motion sensors are the following: a vertical gyro which measures ship pitch and roll angular motion; a rate gyro which measures yaw rate; three vertical accelerometers located at the top of each strut; and a height sensor which measures the height of the bow above the water surface.

An improvement in one of these sensors has been experimented with by Boeing and shows promise. This is called a Forward Looking Radar Height Sensor. It is a device that will determine wave height well ahead of the hydrofoil and in sufficient time, switch automatically from one mode (platform or contour) to the other to minimize not only ship motion, but loads imposed on the foil, hydraulic systems, and hull.

The accompanying illustration shows the layout of a hydrofoil control system with the various components identified.[7]



PCH-1 HIGH POINT Automatic Control System Schematic

Functionally, the foilborne control system provides continuous automatic control of the ship during takeoff, landing, and all foilborne operation. Pitch, roll, and height feedback loops provide automatic stabilization. The ship is automatically trimmed in pitch over the entire operating envelope, and roll trim is accomplished by helm inputs. To steer the ship the helmsman simply turns the helm, and the ACS automatically provides a coordinated turn with turn rate being proportional to the helm angle. The ship, such as PHM, employs a swiveling forward strut for foilborne steering and an inverted "W" foil aft which enhances directional stability and maneuverability. Trailing-edge flaps on all the foils are actuated by hydraulic actuators to provide the necessary control forces.

To further improve ride quality aspects of a fully-submerged foil system, acceleration feedback is provided to the forward and aft flap actuators. A heading hold system was developed to satisfy long-term steering and navigation relief requirements. Dual sensors, power supplies, electronics and hydraulic actuators were incorporated to meet the foilborne safety requirements. An automatic failure detection system and an "auto land" system are used for the same safety reasons.

All of these complexities have resulted in a hydrofoil with superior seakeeping and ability to provide an extremely comfortable ride for the personnel aboard. With modern electronics, these systems can be built in compact packages and with high reliability.

But even with such a great foil system and its controls, it takes a power plant to give them and the entire hydrofoil life, so the next section will describe the part of a hydrofoil that really makes it go.

PROPULSION SYSTEMS

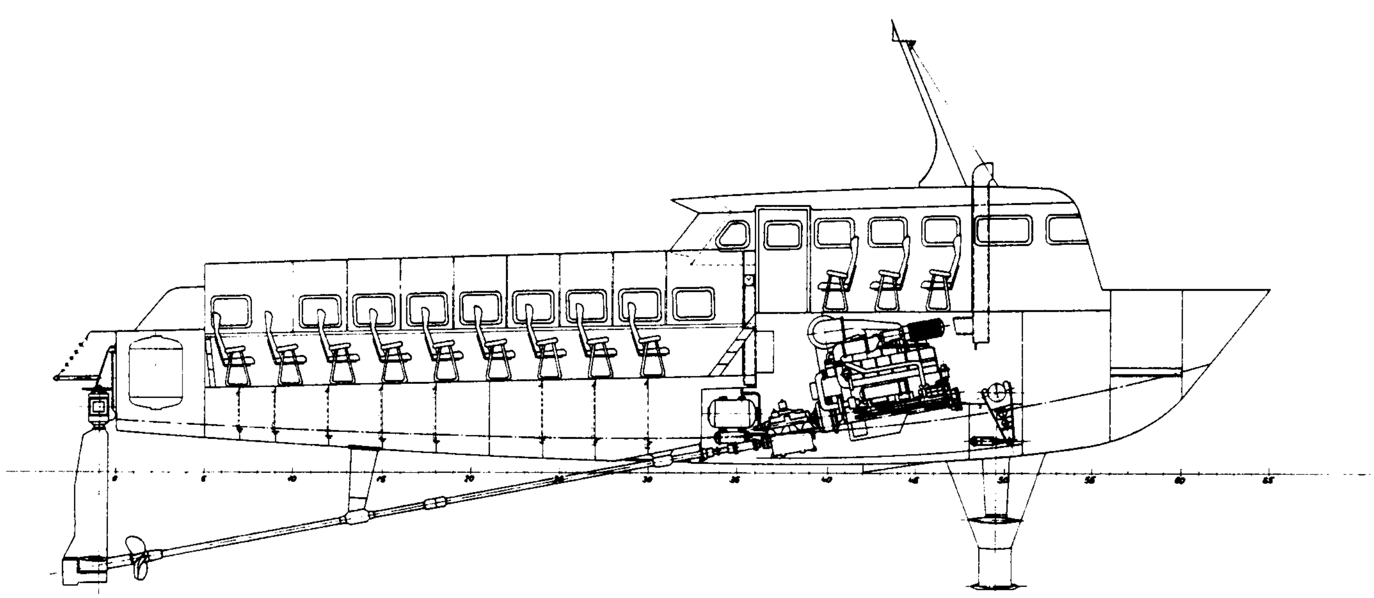
The propulsion system of a modern hydrofoil consists of three major components: the engine (or prime mover), the transmission system that transmits the power to the third element, namely the propulsor (or thrust producer). Each of these will be described in order.

Modern hydrofoils have only been possible by the development of light-weight diesel engines and gas turbine engines. It stands to reason that if the engine is too heavy for each unit of power it develops, the ship will never fly, or if it does it won't fly long because it can't carry enough fuel, or it will not be able to carry much "payload", or both. Therefore a more efficient propulsion system provides a more efficient hydrofoil for transportation of a given load.

Light-weight diesels have been developed to the point where the specific weight (or pounds of engine weight per horsepower produced) is about 6 to 8 pounds per horsepower. But these are high values compared to gas turbines where a comparable number is 0.5 lb/hp (or less than a tenth of the diesel engine). Gas turbine engines have been a by-product of the aircraft industry, however, the basic gas turbine in each case had to be modified specifically to operate in a marine environment, that is, it had to be "marinized".

It has been found that hydrofoils which rely on diesel engines for their foilborne power are limited in cruise speed to about 30 to 35 knots. These craft are usually of the surface-piercing type, and the same diesel engines (or one of them) can be used for relatively slow hullborne operations when desired. However, for hydrofoils where higher speeds are demanded, a gas turbine engine is used for foilborne operations and another, completely independent propulsion system is built into the ship for slow speed operations when on the hull. This may seem like a waste, or duplication, but the state of the art does not allow the hydrofoil designer to produce a gas turbine propulsion system that can handle both speed regimes efficiently.

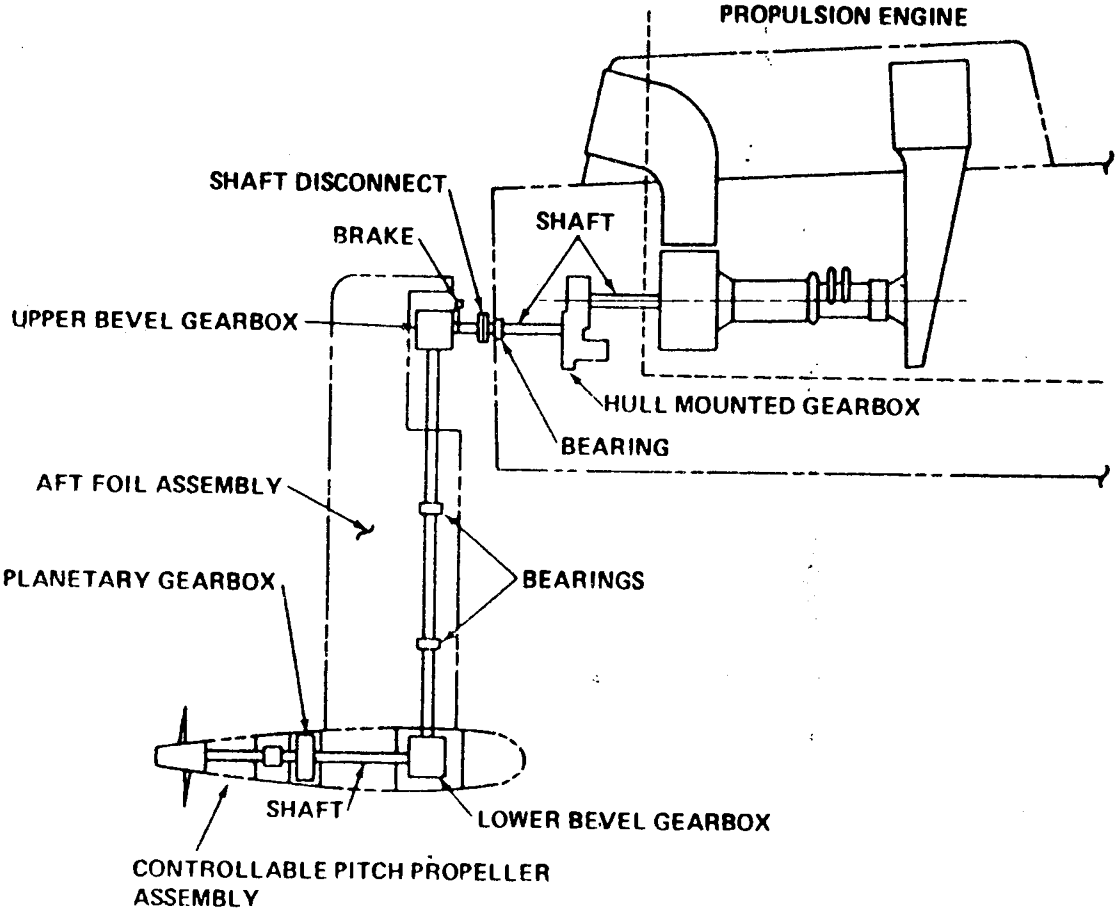
An example of a diesel engine installation is shown in the accompanying sketch. Note that in this case there is no separate propulsion system dedicated solely to either hullborne or foilborne operation. The diesel engines are used throughout the entire speed range of the hydrofoil. This is because such craft are usually designed as passenger ferries. Hence, they operate at high speed most of the time; low speeds being only necessary when maneuvering in and around the pier, around other boats or through narrow passages.



Hydrofoil with a Diesel Engine, Angled Shaft and Propeller[17]

An example of a foilborne gas turbine driven propulsion system is shown in the illustration of the FLAGSTAFF foilborne propeller propulsion system. Here the gas turbine is mounted in the aft section of the hull in such a way that the air intake is located forward. The exhaust stack is positioned further behind in the hull and the exit is directed aft so as not to contaminate the intake air or raise its temperature. A gas turbine requires much more air than a diesel engine of comparable power. Adequate intake ducting for the air is required to keep flow rates below certain limits. Likewise the exhaust air duct must be large enough so as not to produce undesirable back pressure on the engine which can adversely affect its operation.

Although not shown in the FLAGSTAFF propulsion system installation, there are two small waterjets driven by small diesel engines to provide thrust for hullborne operations.

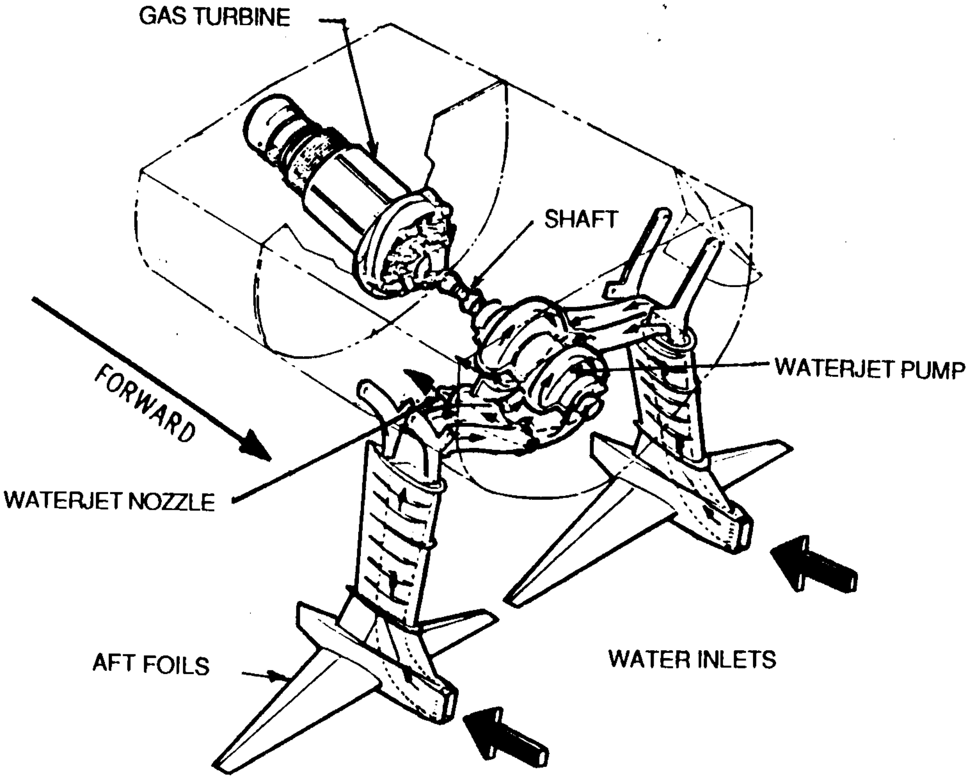


FLAGSTAFF Gas Turbine Foilborne Propulsion System

When it comes to transmission systems, we find that the scheme selected depends upon the propulsor that is desired.

Waterjet proponents will contend that a transmission system for this type of propulsor is much simpler than that for a propeller thruster. A typical waterjet installation is shown below with the major components identified.

The water, in the case of a foilborne hydrofoil, has to be taken in at the bottom of the aft struts, carried up through the struts into the hull, and into the waterjet pump. The latter is driven by the gas turbine engine through a gearbox and shaft. The pump discharges the water through a nozzle, located near or on the transom, thereby producing thrust.



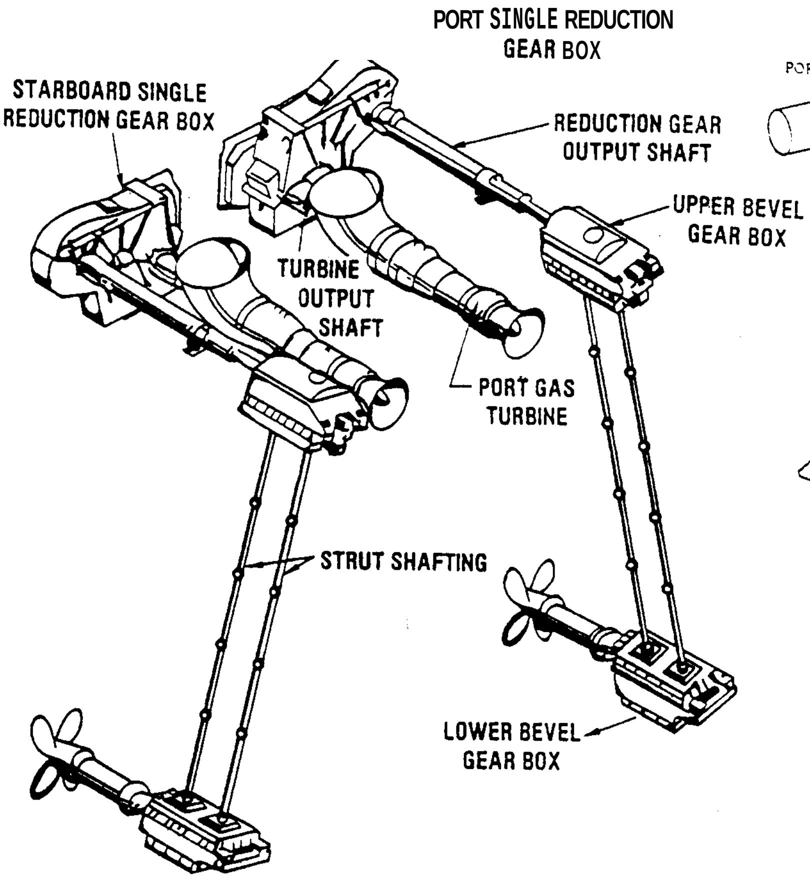
TUCUMCARI Waterjet Propulsion System

The example shown here is the system from the TUCUMCARI, but as you know from Chapter 6, PHM also employs a waterjet propulsion system.

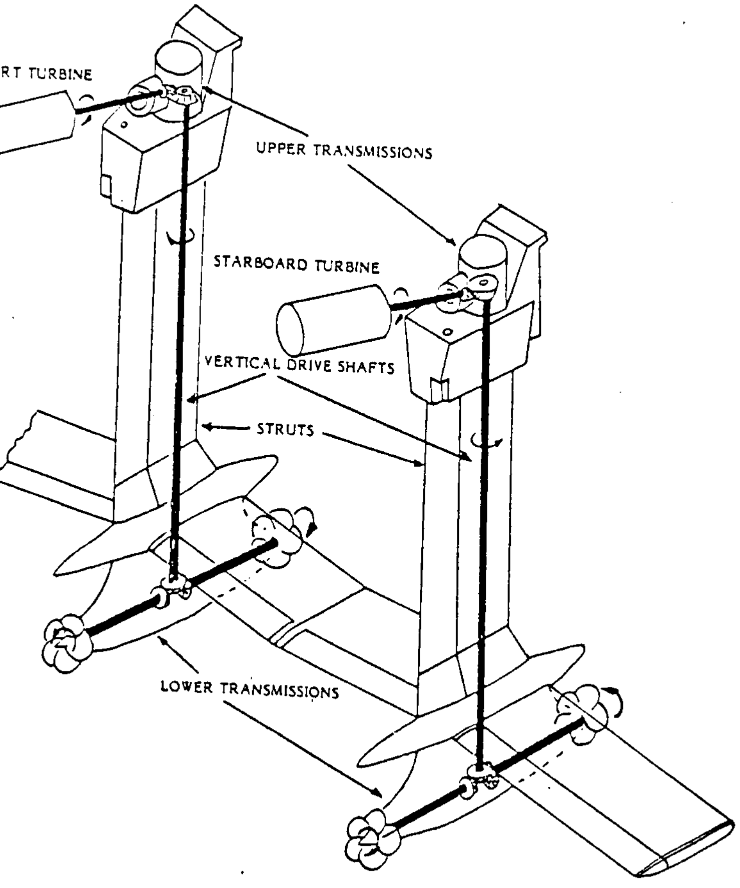
A hydrofoil with fully submerged foils and long struts poses a challenging problem for the mechanical engineer to transfer power from the engine located in the hull to one or more propellers located at or below the foils. From the illustration earlier in this chapter for a surface-piercing foil and relatively short struts, an angled shaft is used. However, for the former case, a Z-drive is depended upon to transmit the power. This means that a series of gearboxes and shafts are required to turn all the corners to transfer power from the hull level to the lower level at the bottom of the strut or struts. Hence, the use of the term "Z-drive".

A previous illustration of the FLAGSTAFF propulsion system is a relatively simple example of a Z-drive. In this case a hull-mounted gearbox reduces the relatively high gas turbine rotational speed down to a range that can be handled by conventional bearings, shafts and gearboxes. In the case of FLAGSTAFF, the rear strut retracted upward and rearward, so a shaft disconnect was introduced. The upper bevel gearbox provided one right angle turn and the lower bevel gearbox provided the other turn of the Z-drive. A shaft then is connected to a planetary gearbox for further reduction of rotational speed to the propeller.

A much more complex **Z-drive** is illustrated by the transmission systems of the PLAINVIEW and HIGH POINT. Here one can trace the transmission of power from the gas turbine engines through the various gearboxes via shafts to its final destination, the propellers at the bottom of the major struts of the foil system. Hank Schab provides an excellent overview of the AGEH power transmission (Reference 31).



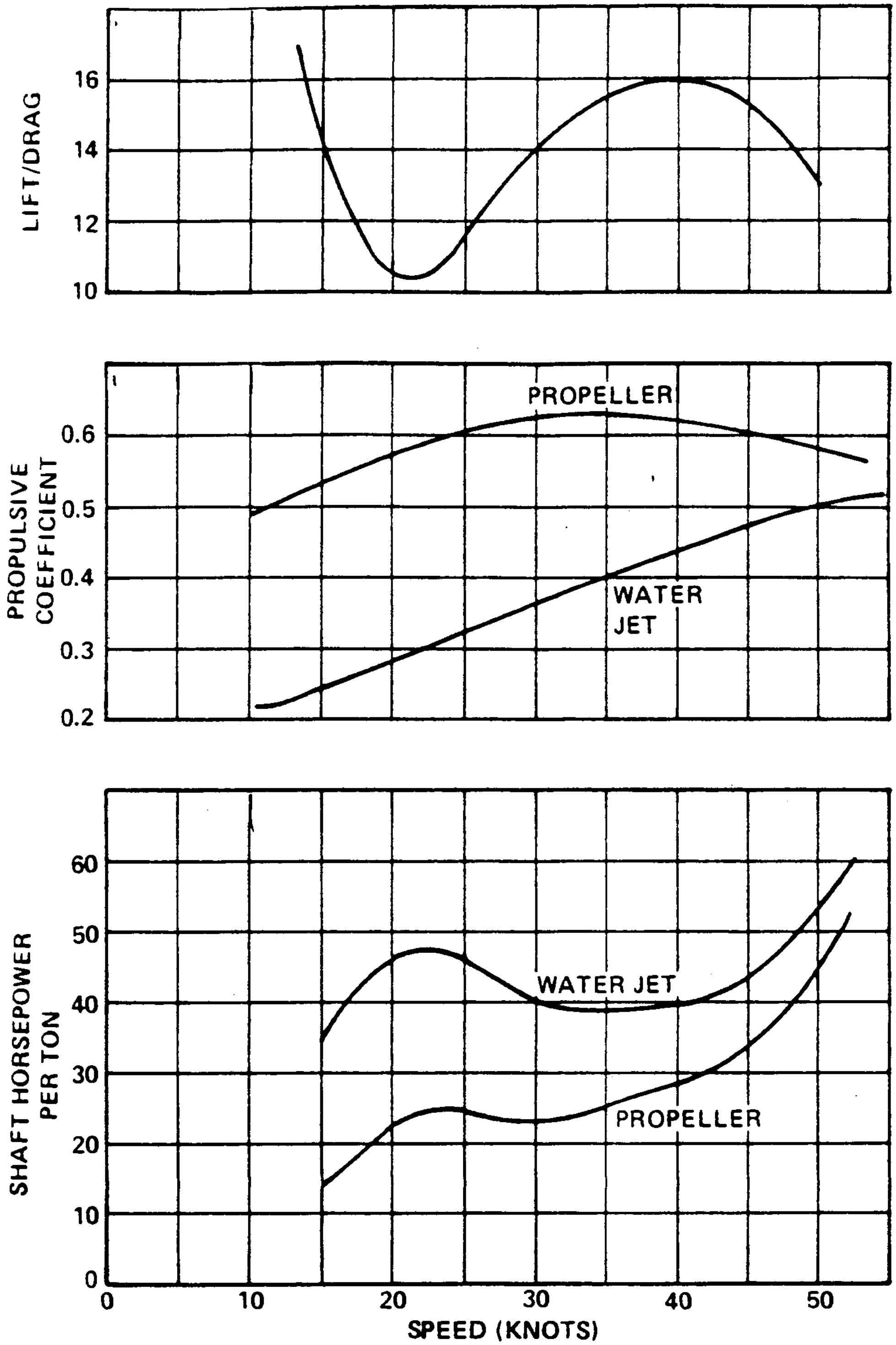
PLAINVIEW Transmission System



HIGH POINT Transmission System

Obviously, the **waterjet** and propeller systems each have their pros and cons which the hydrofoil designer must consider during the feasibility and preliminary design of a given hydrofoil. Much has been learned from the various hydrofoils and their particular propulsion systems built to date. An illustration that tells a lot about the two basic systems is shown here in terms of several hydrofoil performance parameters.

Note the large difference between "propeller" and "waterjet" for both propulsive coefficient and shaft horsepower per ton. The former parameter is a measure of the efficiency of the propulsion system, or how well the system transmits power from the engine to the water. The second parameter, engine shaft horsepower per ton of ship weight, is a result of combining the efficiency values and the lift-to-drag ratio characteristics of the foil system.



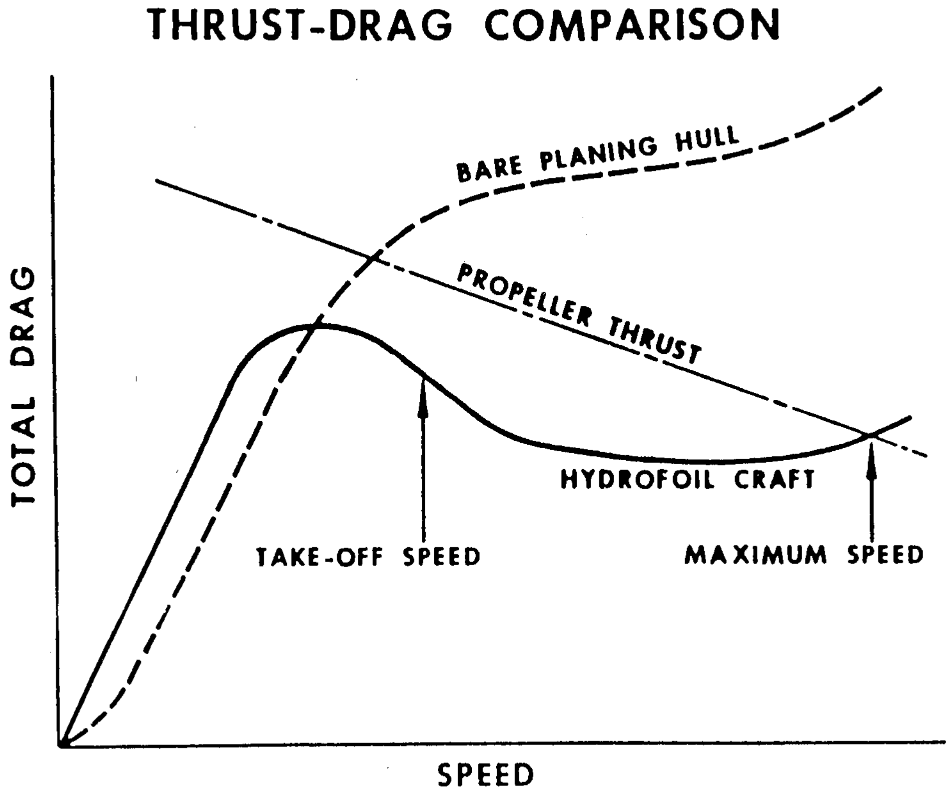
Typical Hydrofoil Performance

Thrust-Drag Comparison - A way for one to better understand the drag characteristics of a hydrofoil is to compare it with something we all know about, that is, the usual "garden variety" boat having a planing hull. Illustrated here in pictorial form is the difference in drag between a hydrofoil and planing hull craft. Note the difference in wake. Although the craft are about the same size, FLAGSTAFF produces a much narrower wake, and hence less disturbance to the water. This also implies that less power has to be provided to propel the craft through the water at a given speed.

FLAGSTAFF Foilborne with Two Planing Hull Craft

The accompanying plot of curves for a planing hull and hydrofoil craft bears this out. The implication of the term "bare" on the planing hull curve means that it does not include the drag of appendages such as propeller shaft, shaft supports, and rudders. On the other hand, the hydrofoil craft curve does include everything that is in the water.

The "propeller thrust" line is a typical trend line representing the reduction of propeller thrust as speed increases for a given power setting of the engine. It can be seen that the planing hull craft will require relatively more power in order to raise the propeller thrust curve upward to achieve a crossing with the drag curve at the higher speed of the hydrofoil. It can also be seen that the hydrofoil generally has a higher drag at low speeds, but upon takeoff, drag rapidly decreases, reaches a minimum, and then rises again until propeller (or waterjet) thrust available equals drag, at which time the hydrofoil reaches its maximum speed.



Typical Calm-Water Thrust and Drag Curves

The reason for the greater drag of a hydrofoil at low speeds is because of the submerged struts and foils which add to the drag of the hull. Just before takeoff, the foils are required to produce lift equal to the total weight of the craft. This is difficult to do at low speeds since large angles of attack are necessary on the foils and this produces high drag (induced drag, or drag due to lift). Since lift on the foil varies with the square of speed, foil angle of attack can be reduced quite rapidly after takeoff, induced drag decreases, and the hydrofoil speeds up, like riding down a wave or a hill. In addition, the hull is no longer in the water, and therefore its drag is eliminated which further contributes to reduction of drag after takeoff.

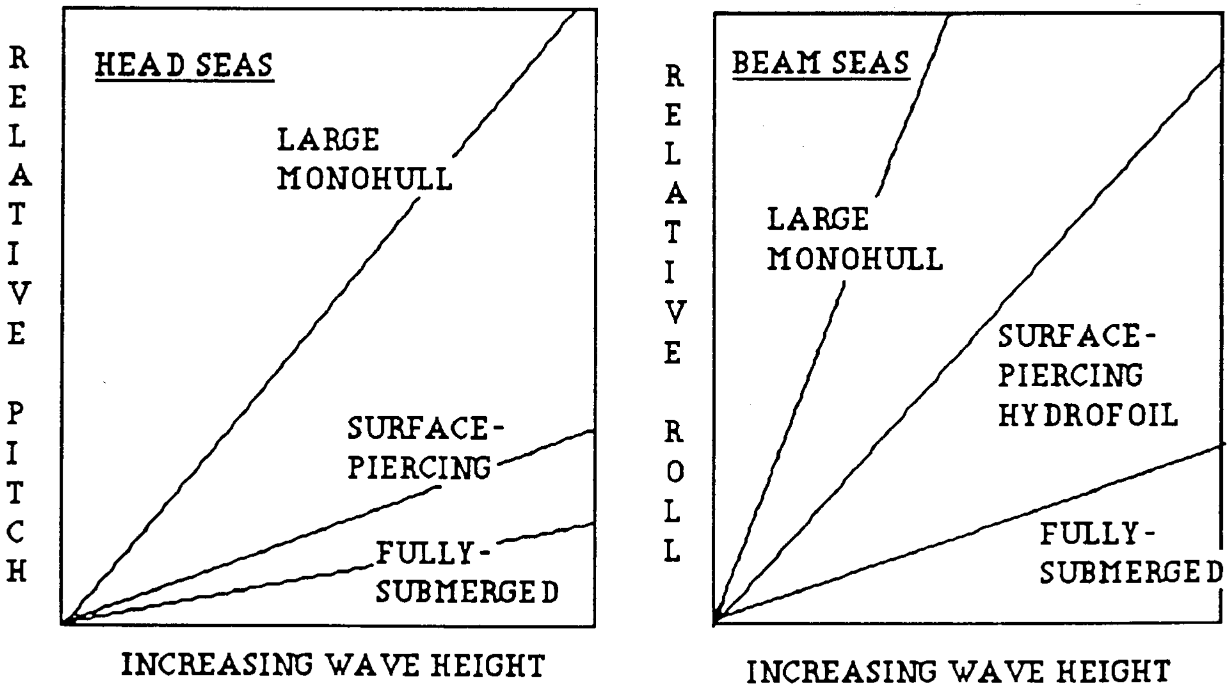
<u>Maneuverability</u> - A story about maneuverability was already related about the PHM out-maneuvering jet fighters in Chapter 6. It can be seen from a picture of HIGH POINT and TUCUMCARI during a "dog fight" that hydrofoils are indeed maneuverable! They can literally fly circles around all other ships, U.S. Navy or not, and do so at every opportunity.

Back in the days when HIGH POINT was very active in running trials on Puget Sound, it was fairly common to give the passengers of the Seattle-to-Bremerton ferry boat a "free show". HIGH POINT's captain just had to circle the ferry boat at least once before returning to his home port at the Puget Sound Naval Shipyard, Bremerton, WA. One could almost see the bulging eyes and hear the "ooo's" and "ahhh's" as HIGH POINT leaned into a sharply banked turn at 40 to 50 knots.

HIGH POINT and TUCUMCARI Cutting Circles in Puget Sound

The PHM has followed this tradition in the Caribbean area by giving passing ships a similar show of speed and maneuverability. On one occasion, with the author aboard, PHM was returning from all-day joint operations and tests with a U.S. Coast Guard Cutter. A high ranking Coast Guard official was on board the Cutter, and since the trials themselves during the day had not required anything spectacular in terms of speed and maneuverability on the part of the PHM, the Commanding Officer of PHM decided to show the Coast Guard Cutter personnel and the Admiral what a PHM could really do! Several "figure eights" were executed as the PHM circled the Cutter while it steamed back to her Key West pier. The response of the PHM to the helmsman's rapid movement of the helm was truly remarkable and is not easily forgotten by anyone lucky enough to experience such a ride. One could almost see that the "Coasties" at the rail of the cutter wishing that they had joined the Navy instead, and had been assigned to PHMRON TWO! It is understandable also that the cutter declined to race PHM back to the outer marker at the entrance to the Key West channel. No contest!

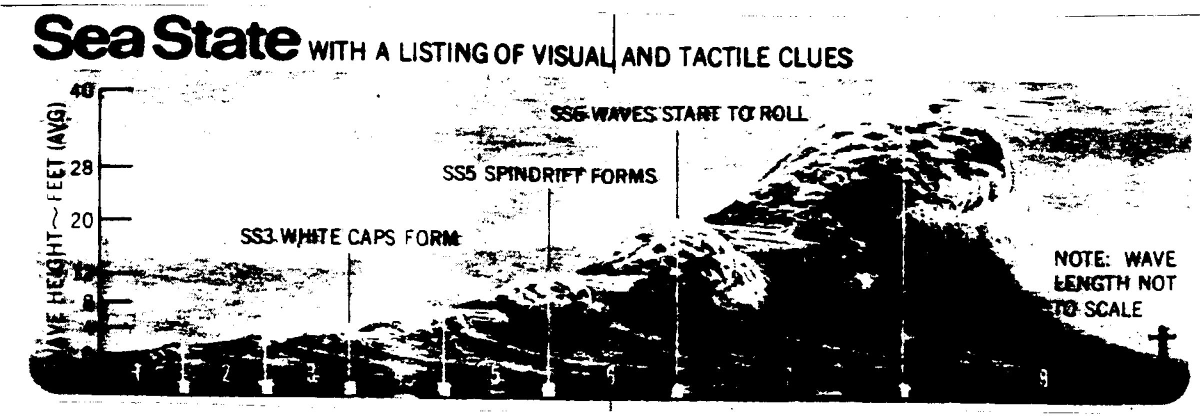
Ride Comfort - Along with these advantages of speed and maneuverability comes another "goodie", namely a comfortable ride. A hydrofoil with a fully-submerged foil system is the smoothest ship on the sea, producing far less motion in response to waves than ships many times larger. Much data has been collected on this subject which shows that hydrofoils provide a superior ride at high speed with pitch and roll motions much less than larger conventional ships, as illustrated here. It has been widely reported that (also shown here) hydrofoils of the fully-submerged type (with their automatic control systems) have relatively less motion than comparable hydrofoils of the surface-piercing type.



Comparison of Ship Motions

Interestingly a relatively comfortable ride is obtained from such a hydrofoil even when it is hullborne at very moderate speeds. This is because the foils and struts act as large dampers to the motion that would be imparted to the hull by large waves. The author had an opportunity to experience this fact first hand during a one-week series of trials on a PHM. The ship was on a mission south from Key West, through the Yucatan Channel and on to Guantanamo Bay, Cuba in consort with a support ship, the USS NEWPORT (LST 1179). Don Rieg, the author, and another Navy test engineer were carrying out tests to determine the best foil flap settings while under tow from the LST. The objective was to establish a towing procedure to minimize drag from the PHM on the tow ship. During the several days of trials we spent the daylight hours on the PHM collecting data, while from late afternoon each day the three of us were transferred back to USS NEWPORT where sleeping quarters were provided.

During these trials some fairly rough water was experienced which made transfer back and forth each day between the PHM and NEWPORT rather risky. However, it was an excellent opportunity to compare the motions of two very different ships! The LST is 522 feet long, 70 feet in beam and has a displacement of 8,450 tons. Believe it or not, the 235 ton PHM had much better motions, was very comfortable, and provided a good test platform on which to work, observe instruments, and take data. While, on the contrary, back on the LST the roll motions were not very kindly.



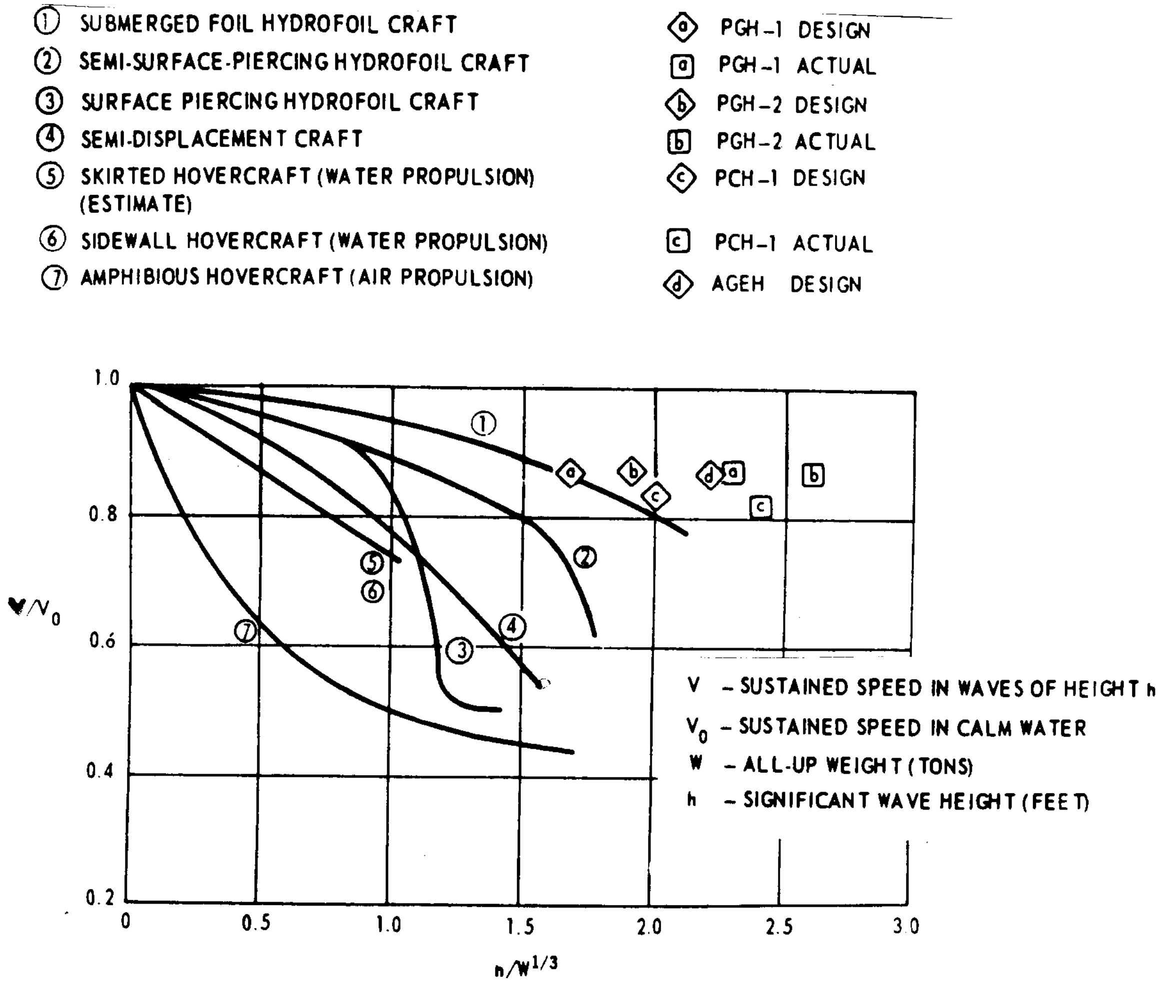
SEA STATE DESCRIPTION

SS1 Smooth Sea -	Ripples, no foam. Wind: Light air,1-4 Knots Beaufort 1. Not Felt On Face.
SS2 Slight Sea -	Small Wavelets, No Foam. Wind: Light To Gentle Breeze; 4-10 Knots. Beaufort 2-3. Felt On Face, Light Flags Flying.
SS3 Moderate Sea -	Large Wavelets, Crests Begin To Break. Wind: Gentle To Moderate Breeze; 7-15 Knots. Beaufort 3-4. Light Flags Extended.
SS4 Rough Sea -	Moderate Waves, Many White Caps, Some Spray. Wind: Moderate To Strong Breeze; 14-27 Knots. Beaufort 4-6. Wind Whisles In The Rigging.
SS5 Very Rough -	Seas Heap Up, With Spindrift and Foam Streaks. Wind: moderate To Fresh Gale; 27-40 Knots. Beaufort 6-8; Walking Resistance High.
SS6 High Sea -	Seas Begin To Roll, Dense Streaks Of Foam And Much Spray. Wind: Strong Gale, 40-48 Knots. Beaufort 9. Loose Gear And Canvas May Part.
SS7 Very High Sea -	Very High Waves With Overhanging Crests. Seas Appear White As Foam Scuds In Very Dense Streaks; Visibility Reduced. Wind: Whole Gale, 48-55 Knots. Beaufort 10.
SS8 Mountainous Sea -	Extremely High Rolling Breaking Waves. Sea Covered With Foam; Very Poor Visibility. Wind: Storm, 55-65 Knots. Beaufort 11.

Sea State Guide Chart

Sea State Degradation - It is well known that ships slow down when the seas get rough. They do this for two reasons. First, it takes more power and hence more fuel is burned to travel a given distance, and second, the ride gets rough especially when the hull begins to slam as large waves impact the rapidly descending bow. This process of slowing down, for whatever reason, is known as Sea State Degradation. A hydrofoil, on the other hand, rides above the waves. The automatic control system maintains the hull and its occupants straight and level, so it does not have to slow down until it gets really rough and extremely large waves are encountered. Larger hydrofoils with fully submerged foils and sufficiently long struts can delay the effect of waves to a much greater degree than smaller hydrofoils, particularly those with surface-piercing foils.

We have referred to Sea State several times, so now is the time to give the reader some feel for what a Sea State is all about. The illustration on the previous page showing waves pictorially and a verbal description explains the concept of Sea State. Hence when one refers to a Sea State 5, for instance, 10 to 15 foot waves can be experienced.



Speed Degradation of Various Craft

Shown on the previous page is a chart of speed ratio plotted against Sea State for several types of craft. The chart indicates that as the sea builds up and wave height, h, increases, the ship can only travel at a fraction of its calm water maximum speed. The horizontal scale of this plot[37] is non-dimensionalized and designed to take account of ship size. For example a 250 ton ship (like PHM) in 10 foot waves would have a $h/W^{1/3}$ value of about 1.58. This corresponds to a V/V_o value of 0.90 for the line designated "1" on the plot. Actually, since this plot was made, PHM data indicates that the V/V_o value is closer to 0.95.

From this plot we can see that a comparably sized semi-displacement hull, line "4", for example, can travel at only a little more than one-half its calm-water speed when in waves with a significant wave height of 10 feet. This condition corresponds to a Sea State 5, previously described as a "very rough" wave condition. Even large monohull ships of several thousand tons slow down when the weather gets very rough.

HYDROFOIL DESIGN METHODS

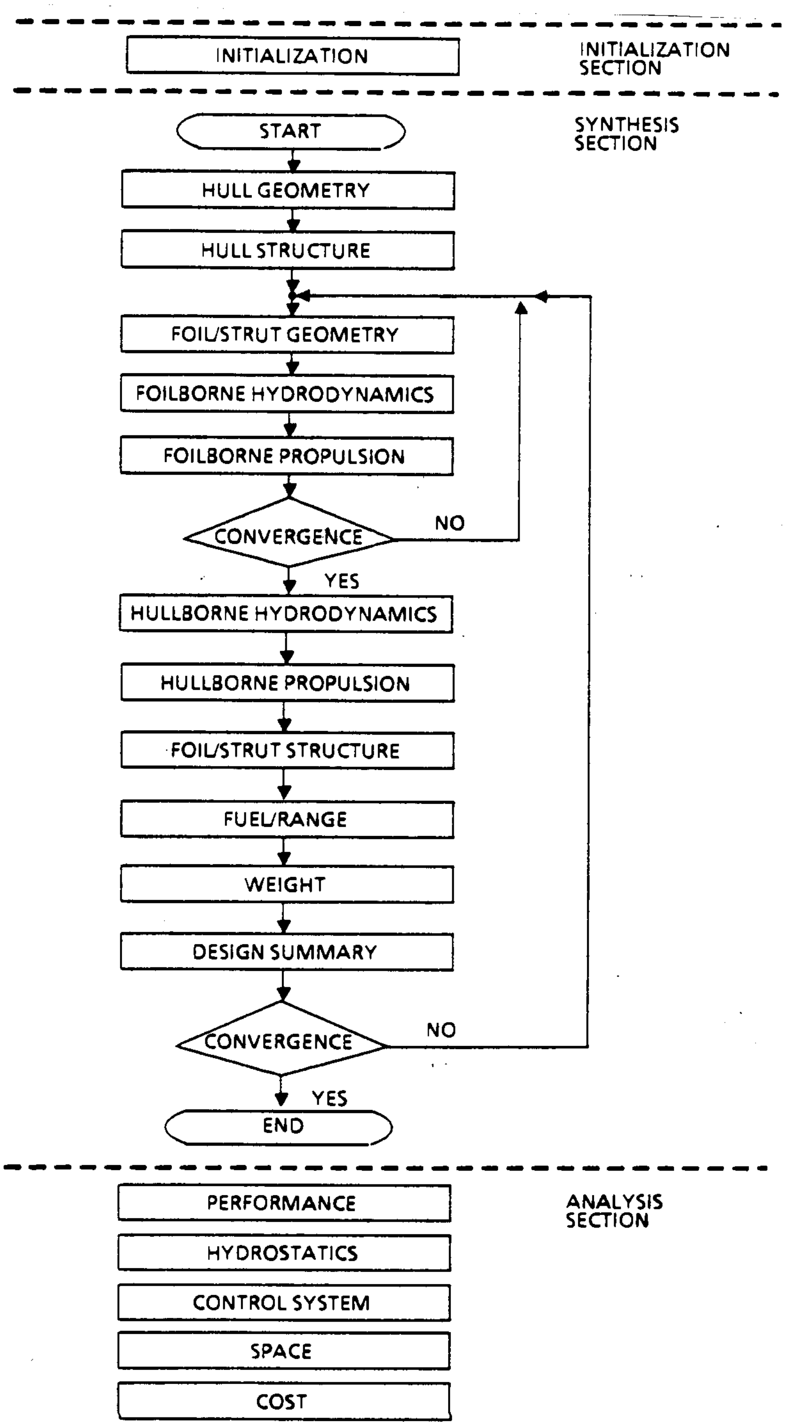
One might ask: How does one design a hydrofoil? Well, "it ain't easy". Commercial hydrofoil manufacturers each have their own methods based on their experience which may have involved a lot of "cut and try" attempts. The details of these methods are closely guarded, and hence not usually available to everyone. However, much has been published which provides the basic theory of the hydrofoil.[38]

The U.S. Navy has developed a very elaborate design tool which is very useful in exploring hydrofoil designs. The computer program allows the user to examine a variety of designs to meet certain requirements of speed, range, and payload relatively quickly, and determine the sensitivity of certain physical parameter changes on the overall design, such as total weight and cost. This capability grew out of a computer program called HANDE (Hydrofoil ANalysis and DEsign)[39] developed by Boeing Marine Systems under U.S. Navy contract.

King and Devine explain that the use of the HANDE engineering system closely parallels the classical process of ship design. The design begins with a set of mission requirements that the ship is to accomplish. For example, this includes such items as speed, range, mission endurance, payload, and crew size. Existing design data are employed in an iterative sequence to derive the hydrofoil design in a fashion that it frequently described as a "design spiral". In this manner the initial design starts on the outside of the spiral, is modified as the various elements of the design impact on each other, and closes at the center of the spiral on a design that meets all of the requirements. It is essential to realize that, although the computerized design tool automates many of the more arduous tasks in designing a hydrofoil, the critical engineering decisions that heavily impact on the design are still left to the individual designer. For instance, HANDE does not decide whether to employ waterjet or propeller propulsion, and if a propeller is selected by the designer, what kind of propeller to use. Such decisions are in the hands of the hydrofoil designer. However, he has the opportunity to quickly vary the design by incorporating waterjets in one design, and propeller propulsion in another. When both are computed to the same requirements, he can then make a comparison to determine the superior approach.

The synthesis-type computational programs within HANDE are shown in the accompanying diagram. One can readily see that the procedure is divided into a series of modules within "initialization", "synthesis", and "analysis". The various loops and convergence points amongst the synthesis modules are indicated.

The "HANDE" computational design tool was used for many of the hydrofoil designs that are described in the Chapter on "What's Next?".



HANDE Computational Modules

CHAPTER 8

HYDROFOILS AROUND THE WORLD

In the last several chapters we have been reading about U.S. Navy hydrofoils, why and how hydrofoils fly - but what about the commercial applications of hydrofoils and the use of hydrofoils in the rest of the world?

Hydrofoils in regular commercial service date from the mid-1950s, and by 1990 well over 550 hydrofoils were operating in the free world and many more than this in the Soviet Union. Commercial hydrofoils have been built in at least fifteen different countries and have varied in passenger capacity from about 40 to over 300. These craft have been used to carry high priority freight as well as passengers, as offshore crew and work boats, and for fisheries patrol. According to Fast Ferry International, by mid 1989 there were about 170 companies operating hydrofoils in passenger service, and the number appears to be rapidly growing, particularly in Japan.[40]

Then too, military applications of hydrofoils can be found in other parts of the world, such as Israel, Italy, Japan and of course the Soviet Union. The numbers of hydrofoils in the Soviet Union far outstrip those in use throughout the rest of the world.

RODRIQUEZ HYDROFOILS - MAJOR SUCCESSES

Several European shipyards have produced hydrofoil craft for the commercial market. The major Western European manufacturers include: Gustoverft of the Netherlands; Westermoen of Norway; Vosper Thornycroft of Great Britain; and Rodriquez of Italy. They have all based their designs generally upon General Croco's principles and Baron Von Schertel's designs with some modifications.[18]

There will probably be little argument however, that the most successful commercial hydrofoils designed and built in the free world are those produced by Rodriquez Centieri Navali of Messina, Italy. So, we have gone full circle from our earlier observations that the hydrofoil really started in Italy!

The basis for the Rodriquez success is adherence to some fundamental principles. These include: the hydrofoil must fulfill the customer's needs; must be reliable and meet the required specifications; have adequate support from advertising to product service; and most importantly, must be economically acceptable from the various cost aspects.

The Rodriquez Hydrofoil Series (RHS) including the latest RHS 200 passenger ferry design has been described in Chapter 5. The relatively large numbers of these craft and the wide distribution of them throughout the world has been impressive. Accumulated seat capacity of Rodriquez-built hydrofoils has steadily grown starting in the year 1956 to over 16,000 in 1990. The types of service that these hydrofoils provide range from "commuter service" which utilizes waterways to shortcut longer road or rail service or avoid congestion, to "rapid passenger service" where the speed and comfort of hydrofoils are preferred to conventional ferries, particularly on the longer routes. Under these circumstances, the distances covered by these routes vary extensively; from as short as about **3** miles (like Rio de Janiero to Niteroi in Brazil) to as much as 180 miles (Palermo to Naples). For the Rio to Niteroi service there is a continuous chain of passenger traffic, with a few minutes interval for embarking and unloading passengers before resuming the **7-**minute trip. On the other hand the Naples to Palermo hydrofoil service offers passengers a daily trip of 5 hours against a **13-** hour train trip or a full night sailing by ship.[18]

RHS-160 Rodriquez Hydrofoil

The RHS-160 shown above has been one of the most popular and successful hydrofoils with a passenger capacity of about 160 to 200. The RHS line of hydrofoils have all been diesel powered and the designers have followed the philosophy that 35 knots is fast enough! Rodriquez has observed that whenever higher hydrofoil design speeds are set, the costs of the craft and their operation tend to threaten the economic viability of the venture. A speed of 35 knots has therefore been adhered to as an acceptable value for sea transportation on short/medium distances, and for Rodriquez, represents the economic answer for fast water transportation, especially when cost of fuel is a large factor in determining operational costs.

RHS-200 SUPERJUMBO Hydrofoil

As long ago as 1982 it was estimated that, by that time, European commercial hydrofoils had already carried more than 260 million passengers and had logged in excess of 60- million sea miles.[18] This was indeed impressive for the first 25 years of these operations. But even more impressive is the fact that in 1981 alone, these hydrofoils transported 9,810,681 passengers for a distance of 2,474,960 sea miles. The ten years subsequent to this have shown considerable growth.

BOEING JETFOIL - HIGH SPEED WITH COMFORT

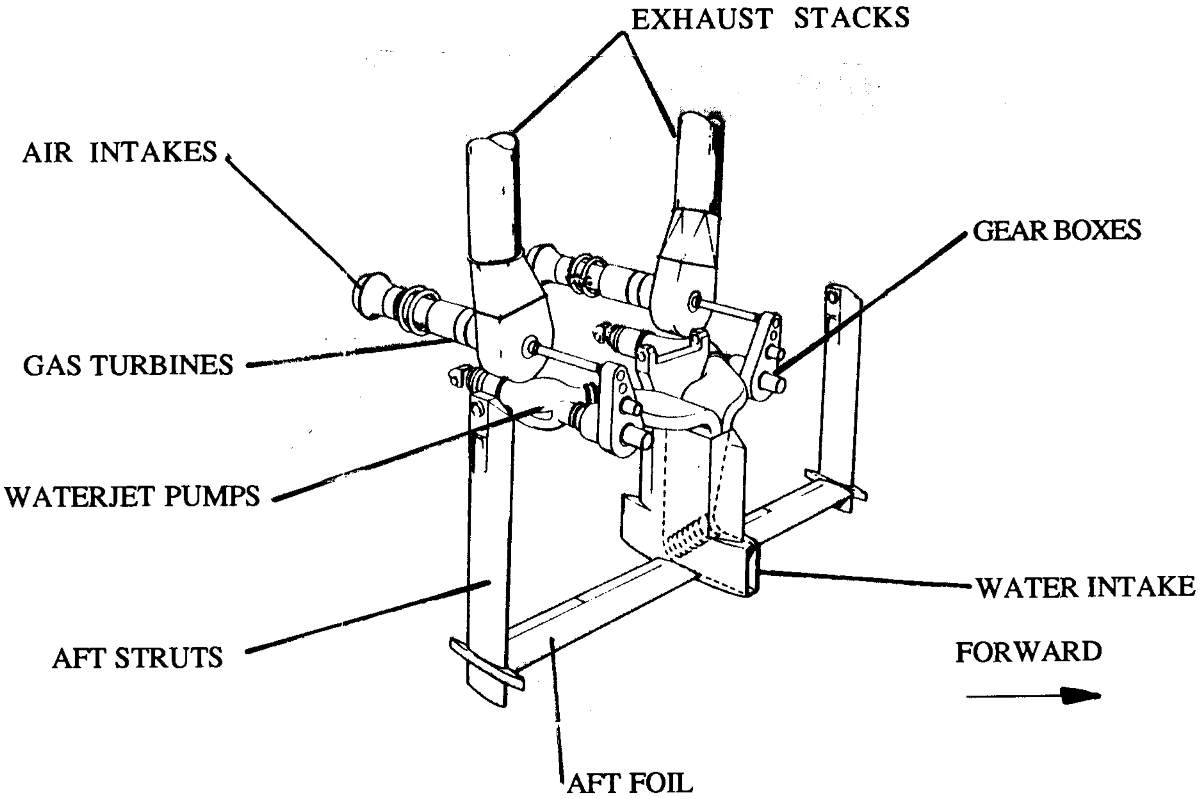
There is no argument that the Boeing JETFOIL is the world's most technologically advanced commercial hydrofoil. Unlike the Rodriquez philosophy, the Boeing approach was to achieve a much higher speed and the highest possible level of ride comfort in sea conditions that existed on the world's major open water routes. With the technology available to Boeing through its aircraft experience and that gained from U.S. Navy hydrofoil developments, it was natural to exploit fully-submerged foils, automatic control systems, and waterjet propulsion. The result was the JETFOIL with a cruise speed of 45 knots in heavy seas, and a high speed, rough water ride quality unmatched by any other high speed commercial marine vehicle.

Boeing JETFOIL

Keel-laying of the first **JETFOIL** took place at the Company's Renton, Washington plant on 19 January 1973 and the craft was launched about a year later on 29 March 1974. Several variants of the 125- ton **JETFOIL** Model

929 have been produced to meet customer requirements, but they have all been generally similar to the "Flying Princess II" pictured here. The 90 foot hull is a deep-vee type with a hard chine and has seating arrangements for 224 to over 300 passengers. The foil system is a canard arrangement with a single tee-strut forward and a three-strut full-span foil aft. For retraction, to reduce draft when required, the forward foil is swung upward into the slot in the bow of the hull. The aft foils likewise swing aft to provide a draft of only 5.5 feet.

JETFOIL has twin Detroit Diesel Allison gas turbine engines, each producing about 3700 horsepower and driving Rockwell Rocketdyne waterjets.[41,42] The waterjet pump flow rate is about 24,000 gallons per minute. The craft does not have a separate hullborne propulsion system like those of the Navy hydrofoils that were described earlier. This is because hullborne operation constitutes a very small percentage of the craft's time underway. JETFOIL is designed to be foilborne almost 100% of the time.



JETFOIL Propulsion System[41]

The foilborne propulsion system can be operated at reduced power when the hydrofoil is operating hullborne even with the the foils retracted. Water is taken in at the bottom of the aft center strut and ducted up through an opening in the keel to each of the pumps located in the hull. The pumps discharge through nozzles on the underside of the hull. For ship control when operating hullborne and maneuvering in and around a pier, hydraulically operated vectoring and reversing buckets are installed downstream of the nozzles. These are used in conjunction with a bow thruster which is installed forward on the hull to provide side forces in docking operations.

As in all hydrofoils with fully submerged foils, JETFOIL has an automatic control system. This system provides for continuous control of the craft by sensing its motions and position by gyros, accelerometers and height sensors. Resulting signals are combined with selected manual commands and are converted in the control computer to provide deflection of the foil flap surfaces through electro-hydraulic actuators. JETFOIL banks into all turns, blends the proper amount of steering and banking to produce a fully coordinated, comfortable turn.

Approximately 28 JETFOILs were built by Boeing and marketed throughout the world. The first operational JETFOIL service was started on 25 April 1975 by Far East Hydrofoil Company of Hong Kong. In the United States, first service began about that same time with delivery of a total of three JETFOILs to Pacific Sea Transportation Ltd for inter-island services in Hawaii. As long ago as 1984, there were about five operators utilizing these $10 million hydrofoils on their high speed passenger ferry routes. At that time the 23 hydrofoils in the various fleets had chalked up an impressive figure: total passenger miles of over one billion.[19] The most experienced operator of the craft is Far East Hydrofoil Company with its fleet of 12 JETFOILs used on the 36 mile route between Hong Kong and Macau. Other JETFOIL operations were carried out in Venezuela, across the English Channel, and in the Canary Islands. By 1987 the total JETFOIL passenger ferry fleet had accumulated well over 2 billion passenger miles.

Orders for JETFOIL tapered off in the 1984 to 1986 time frame, and although the program was given a boost with a military variant ordered by the Republic of Indonesia, the Boeing Company decided to discontinue JETFOIL production in 1987. Instead, a license agreement with Kawasaki Heavy Industries was established covering production of the craft in Japan and marketing in Asia and the Pacific regions. In the same year Kawasaki refitted two JETFOILs earlier built by Boeing in Seattle. These craft are owned by Jet Line in Japan and are operated on routes across the Sato Island Sea. In 1989 Kawasaki delivered its first "built-from-scratch" JETFOIL, TSUBASA, to a passenger ferry operator in Japan who had previously utilized three of these hydrofoils. The market for high speed passenger ferry craft promises to be very lucrative in and around the Japanese Islands and Pacific region. Kawasaki appears to be filling the need with a "high-tech" hydrofoil.

Kawasaki-Built JETFOIL, "JET 7"

As Boeing has stated in their JETFOIL data sheets: "There's no other ride on earth quite like it", and the Asiatic market appears to agree.

JETFOIL VARIANT-HMS SPEEDY

All of Boeing's JETFOILs were not destined for passenger ferry service. In 1979 the 14th ship in the production line was diverted to the Royal Navy of Great Britain. They purchased the hydrofoil "HMS SPEEDY" as a demonstration vehicle to investigate it technically and evaluate several operational roles. Although there are obvious differences in the superstructure between JETFOIL and SPEEDY, the fundamental elements of the craft in terms of propulsion system, foils and automatic control system are essentially the same. However, there is a small exception. Separate hullborne propulsion engines consisting of two GM Detroit Diesels were installed to drive directly into the foilborne propulsion gearboxes and in turn drive the waterjets. This provided more economical, low speed, hullborne operations.

Fisheries Protection was the major role in which SPEEDY was evaluated. Operating extensively around the British Isles and in the North Sea, the ship was exposed to a complete spectrum of the sea environment. Seas as high as State 7 (waves can be as high as 25 feet) were experienced which of course forced SPEEDY into the hullborne mode. She maintained headway, good control and survived the ordeal with no damage to equipment or personnel.

HMS SPEEDY

During other rough water evaluations, SPEEDY was compared side-by-side with Britain's ISLAND and TON Class patrol boats, and it was concluded that the foilborne SPEEDY was more comfortable than the much larger conventional boats. It should be noted that these ships were about 1000 and 425 tons respectively. However, SPEEDY's endurance was found to be limiting in that the 10 hours of foilborne time was not sufficient for patrols in the more remote parts of the fisheries enforcement zones. The ISLAND class ship has a much higher endurance of 7,000 nautical miles at 15 knots. On the other hand, the hydrofoil's higher speed of 45 knots gave her considerable greater annual "census taking" ability and quicker reaction to intelligence and hence the arrest of offenders who would escape or appear innocent by the time the conventional patrol boats could have arrived on the scene.

At the completion of the evaluation it was concluded[44] that "SPEEDY cannot be regarded as a direct alternative to fishery protection vessels, since there are some requirements that she cannot meet (primarily range and towing ability). However, a hydrofoil could have a useful role as part of a "mixed force." Since SPEEDY could not substitute directly for the conventional ship's role, and finance precluded her from joining the Fishery Protection Squadron without a compensating reduction in its normal strength, it was reluctantly decided to decommission SPEEDY in April 1982 and offer her for sale. Subsequently she was purchased in 1986 by Far East Hydrofoils for conversion to a passenger ferry and integration into their fleet of other JETFOILs.

It must be said that an evaluation or comparison, which such evaluations inevitably become, are somewhat unfair - something like comparing apples and oranges. The vast differences in range and towing capability between the ISLAND Class and SPEEDY were bound to produce the Royal Navy eventual negative "evaluation" in the Fisheries Protection role. Apparently there was no way to accept the tradeoffs of high speed and excellent motion characteristics for SPEEDY's lack of range and towing capability.

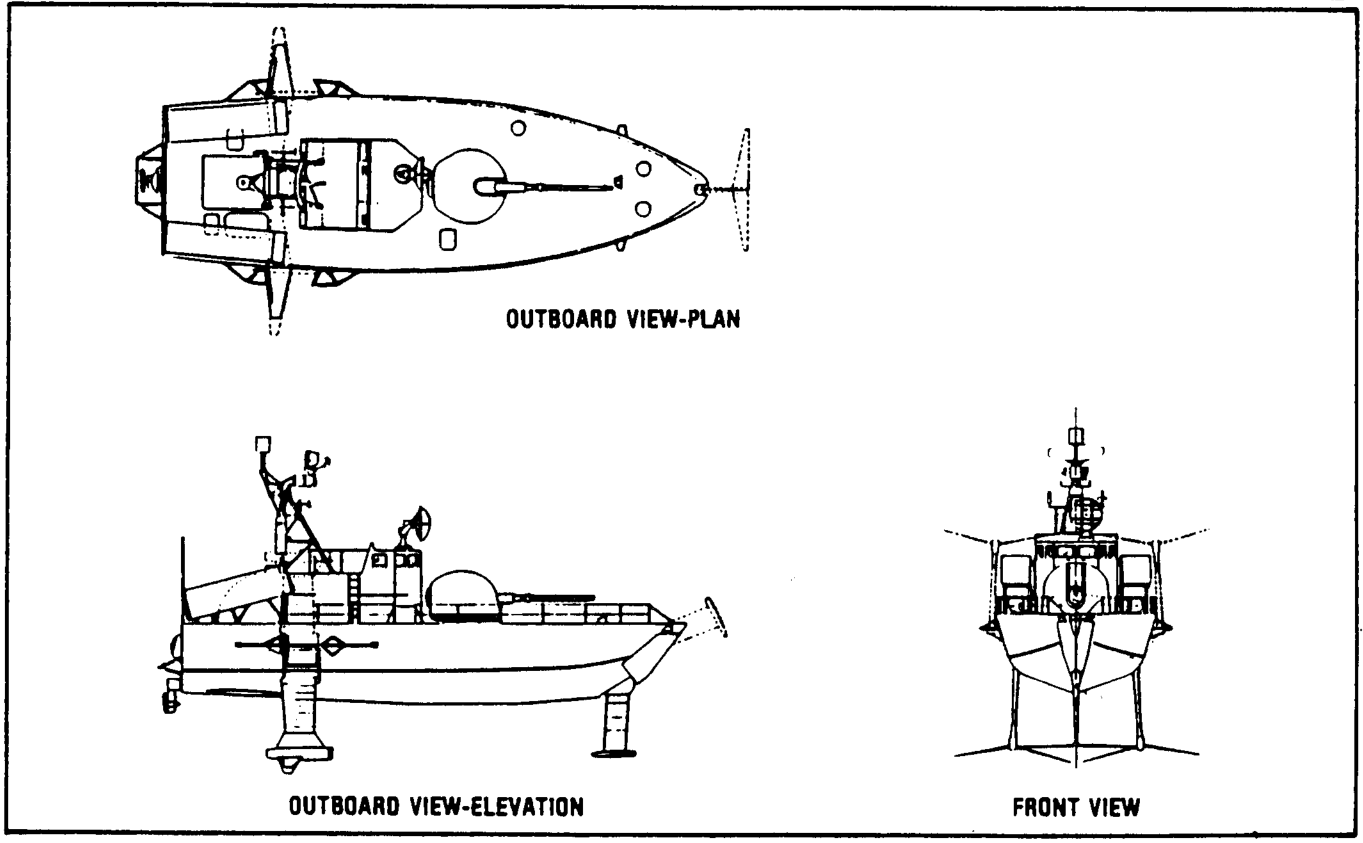
ITALIAN NAVY HYDROFOILS

It has been said that the NIBBIO Class of hydrofoils of the Italian Navy is the grandchild of TUCUMCARI. This can be understood when one traces the successful evolution of its design from TUCUMCARI through its predecessor, SPARVIERO.[45]

In October of 1970 Alinavi, S.p.A. was awarded a contract by the Italian Navy for the design and construction of the P420 SPARVIERO Class hydrofoil missile craft. Alinavi had been formed in 1964 to develop, manufacture and market military and commercial advanced marine systems, particularly in the European and Mediterranean areas. The company was jointly owned by The Boeing Company (60%), Finmeccania (30%), and Carlo Rodriquez (10%). Under the terms of a Boeing-Alinavi licensing agreement, Alinavi had access to Boeing technology for fully-submerged-foil hydrofoil craft. Hence the SPARVIERO - TUCUMCARI connection.

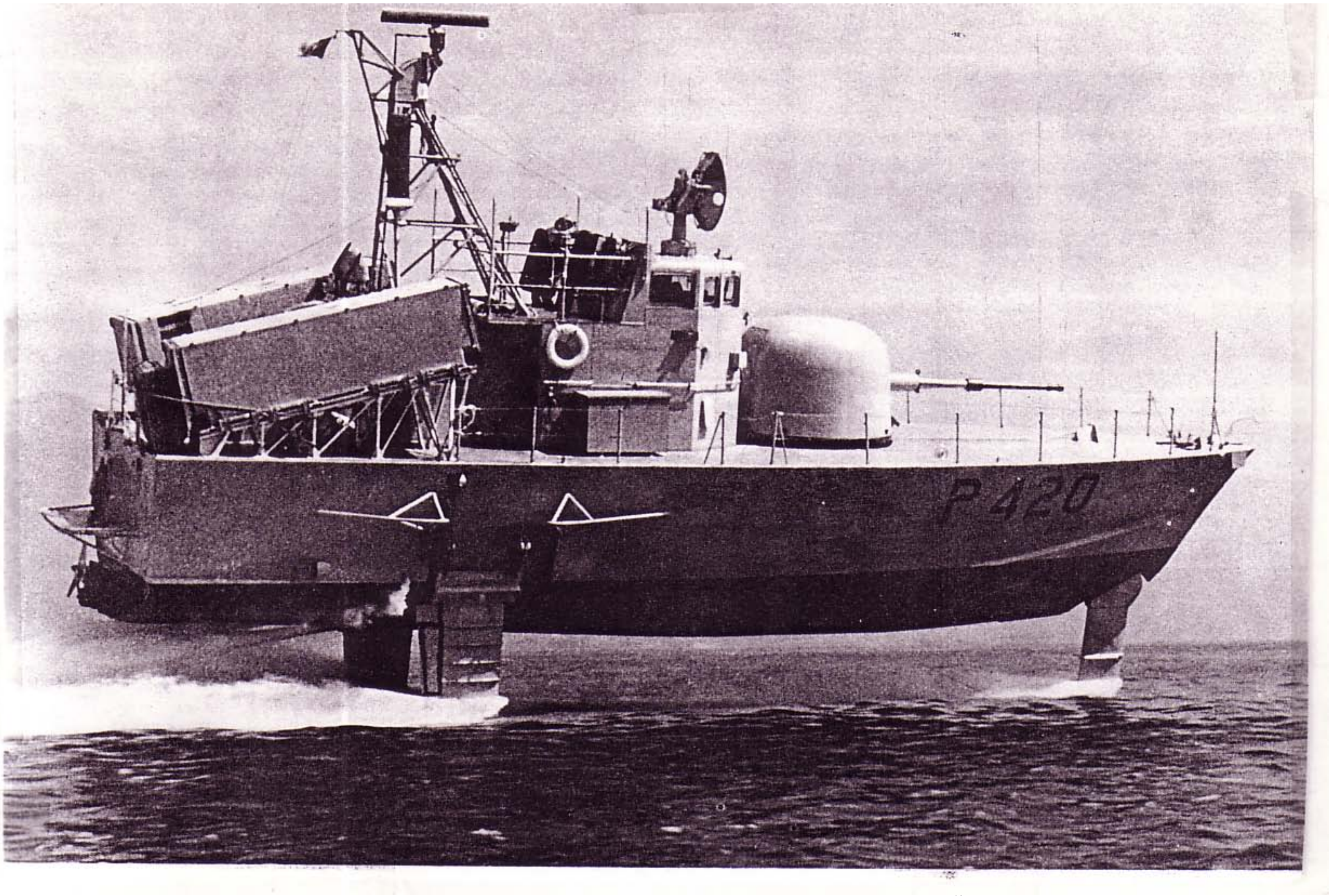
Whereas TUCUMCARI was a patrol boat carrying a crew of 13, the Italian boats were to be designed as fast-attack craft for very short duration missions with minimum "hotel" services. Thus a crew of only 10 was required. Because of the mission requirements, emphasis was placed on heavier weapons than those on TUCUMCARI. SPARVIERO's OTOMAT missiles and a 76mm OTO Melara gun dominated the deck of this relatively small, 60-ton craft. You may remember that this is the same gun that was incorporated on the 235-ton PHM. Although the craft retained the foilborne propulsion system, foil system, and automatic controls of TUCUMCARI, extensive rearrangement of the hull was required. The hull was wider, the internal layout to accommodate the larger Combat Operations Center and electronics equipment was completely different.

Named SWORDFISH, this 60-ton fast attack hydrofoil was delivered to the Italian Navy in July 1974. Although designed primarily as a "day-boat", it could stay out up to 5 days if foilborne operations were restricted and remained hullborne for most of the voyage.



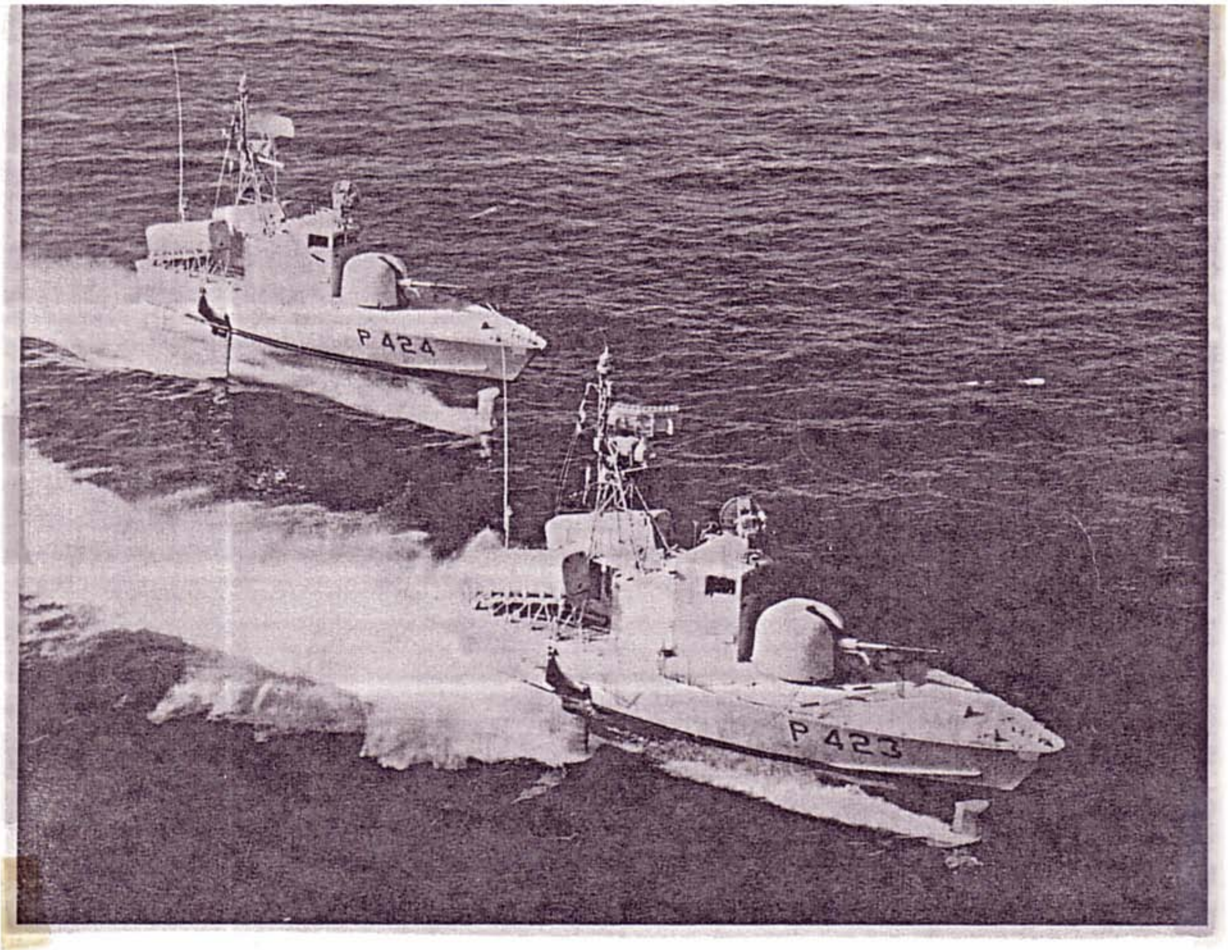
Drawing of Italian Navy SPARVIERO Hydrofoil

To obtain this hullborne capability in such a small boat, another difference from TUCUMCARI was evident, namely a hullborne propulsor utilizing a propeller outdrive instead of a waterjet on the transom centerline. With this 360 degree fully rotatable outdrive, the designers of SPARVIERO were able to eliminate the bow thruster used on the PGH-2.



SPARVIERO Class Hydrofoil, SWORDFISH

The NIBBIO Class of Italian Navy hydrofoils followed closely behind SWORDFISH with relatively minor, but important changes. These centered around the rather interesting and innovative use of distilled water injection in the gas turbine engine. The result was a 600 horsepower increase in maximum engine power. The ship can carry up to about 1,100 pounds of water which is sufficient for up to one hour of higher power operation. This additional power provided such advantages as takeoff in very rough seas, takeoff in very warm air, takeoff with very high weight such as a fuel overload, and probably most important, an increase in maximum speed from 48 knots to 50 knots in battle conditions. An additional 3,300 pounds of fuel, plus the 1,100 pounds of injection water, could be carried as a fuel overload. A total of seven SPARVIERO/NIBBIO hydrofoils were built for the Italian Navy up until 1990. The other ships in the Class were: Falcone, Astore, Grifone, Gheppio, and Condor. They were all commissioned in the 1981 to 1983 time frame.



NIBBIO- Class Hydrofoils, GRIFONE and ASTORE

The TUCUMCARI heritage did not end with the Italian Navy. The Japanese Defence Agency, after considering a larger alternative hydrofoil, in 1989 included three SPARVIERO-Class hydrofoil missile boats for its Maritime Self Defence Force in its FY90 Defense budget. These hydrofoils, to be built under license in Japan, will retain the OTO Melara 76mm gun, but will replace the SPARVIERO's missiles with the Mitsubishi SSM-1B, a derivative of the Ground Self- Defence Force's land-based missile.

SHIMRIT - A GRUMMAN/ISRAELI COLLABORATION

In 1977, the Israeli Government contracted with Grumman Aerospace Corporation to design and build the first of a series of hydrofoils based on the U.S. Navy FLAGSTAFF (PGH-1) described in an earlier chapter. However, its full load weight was increased from 69 tons to about 105 tons. The agreement was for Grumman to build the No. 1 ship, then provide the Israelis with foil systems, control systems, and propulsion components so they could build additional ships in their country. The Israeli Navy anticipated that with the employment of appropriate tactics and techniques, this high performance hydrofoil would provide a substantial improvement in fast striking power against the conventional hullborne vessels of its adversaries.[46] As one can see from the illustration of this hydrofoil, the radome, which almost overpowers the superstructure, is indicative of the "high tech" nature of the ship.

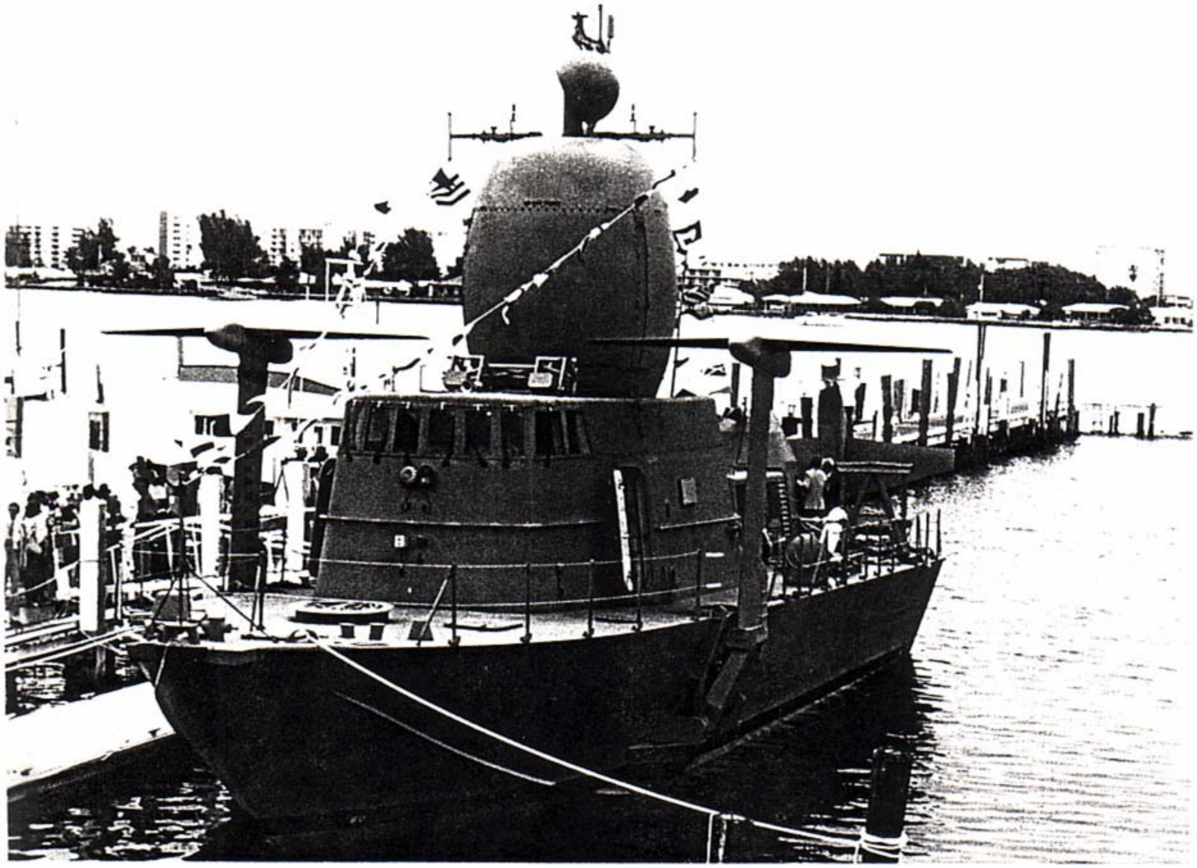
The first ship of the series, SHIMRIT (Guardian) was actually built in Lantana, Florida at Lantana Boatyard, Inc, rather than at Grumman's plant in Bethpage, Long Island where the engineering base was located. Grumman therefore had a real challenge: design, build and test an essentially new hydrofoil with 1,500 miles between engineering and construction, and another 8,000 miles from the customer and their second construction base.

Grumman-Israeli SHIMRIT

After launch of SHIMRIT in May 1981, a series of sea trials in the Atlantic and equipment tests were performed with approximately 550 operational hours accumulated at the time of acceptance by and delivery to the Israel Navy.[47] The first Israeli-built hydrofoil, LIVNIK (Heron), followed about 18 months behind the lead ship. Launched during the latter half of 1982, it was identical to the U.S.-built craft. A third ship, SNAPRIT was completed by the

Israeli Shipyards Ltd. in Haifa in the first half of 1985. The original plan to build a total of 12 hydrofoils of this class has been dropped.

The hull of SHIMRIT is about 11 feet longer and 2 1/2 feet greater in beam than FLAGSTAFF. 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 a larger gun, an enlarged forward deckhouse with provisions for the large radome, and accommodations for a 13-man crew.



SHIMRIT Dockside at Lantana Boatyard

The overall general foil and propulsion arrangement is the same as FLAGSTAFF with two foils/struts forward and a single aft foil/strut. Foilborne propulsion is provided by a four-bladed controllable-pitch propeller driven by a four-gearbox main transmission system. Hullborne propulsion is different from the many described earlier on other hydrofoils. It consists of two hydraulically-powered sterndrives mounted on port and starboard lower outboard sections of the transom. In the extended position, the lower leg of the unit protrudes below the bottom of the hull, rotating inboard 90 degrees to its retracted position behind the transom for foilborne flight.

Due primarily to the hydraulic sterndrives, SHIMRIT is equipped with perhaps one of the largest hydraulic systems 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 control, aft strut steering, main engine start, various pumps, transmission brake/clutch, and forward deck gun positioning. Hydraulic fluid at 3,000 psi is provided by seven pumps, each with a capacity of 64 gallons per minute.

SHIMRIT is designed with an advanced hybrid (digital/analog) fly-by-wire automatic control system (ACS). Craft motions and position relative to the calm-water surface are sensed and the information processed by a digital computer. This in turn generates foil commands which (via a digital to analog interface) are transmitted to the servo amplifier unit and the servo actuators. The ACS craft attitude and motion inputs include height above the water surface from two French TRT radar altimeters in the bow, vertical acceleration from an accelerometer, heading from a gyro, roll and pitch attitude from dual redundant vertical gyros, and roll, pitch and yaw rate from rate gyros. Signals from these sensors are supplied to the ACS computer which compares them with desired parameters and automatically commands the required foil incidence and aft strut turning angles.

These advanced features, combined with a 5,400 horsepower Allison 501-KF marine gas turbine engine, give SHIMRIT a maximum intermittent speed of 52 knots, a most economical speed of 42 knots, and hullborne propulsion speed of 9.5 kts. With a fuel load of 16 to 21 tonnes, the ship has a foilborne range of about 750 to 1,150 nautical miles.[48]

Armament on this small ship, like that of SPARVIERO, is indeed impressive. SHIMRIT carries four HARPOON missiles in two pairs of launchers mounted aft, and two Israeli Aircraft Industries GABRIEL Mk III ship-to-ship missiles immediately just forward of them. Anti-ship missile and aircraft defense is provided by a twin 30mm EMERLEC remote-controlled cannon on the foredeck. Chaff launchers are mounted on the deckhouse roof. The large radome contains a powerful search radar antenna.[48]

One of the most interesting and advanced systems on SHIMRIT is the Engineering Monitoring and Control System (EMCS) which is warranted because of the complexity and sophistication of her systems. Without an EMCS, about half of the crew would be assigned to systems operation, monitoring and control duties, whereas with it, a single Engineering Officer is able to do the same job. The EMCS is an integrated, distributed microprocessor based system, designed to provide reliable single point management of SHIMRIT's propulsion, hydraulic, electrical, and support systems; this amounts to twenty-two parameters in all.

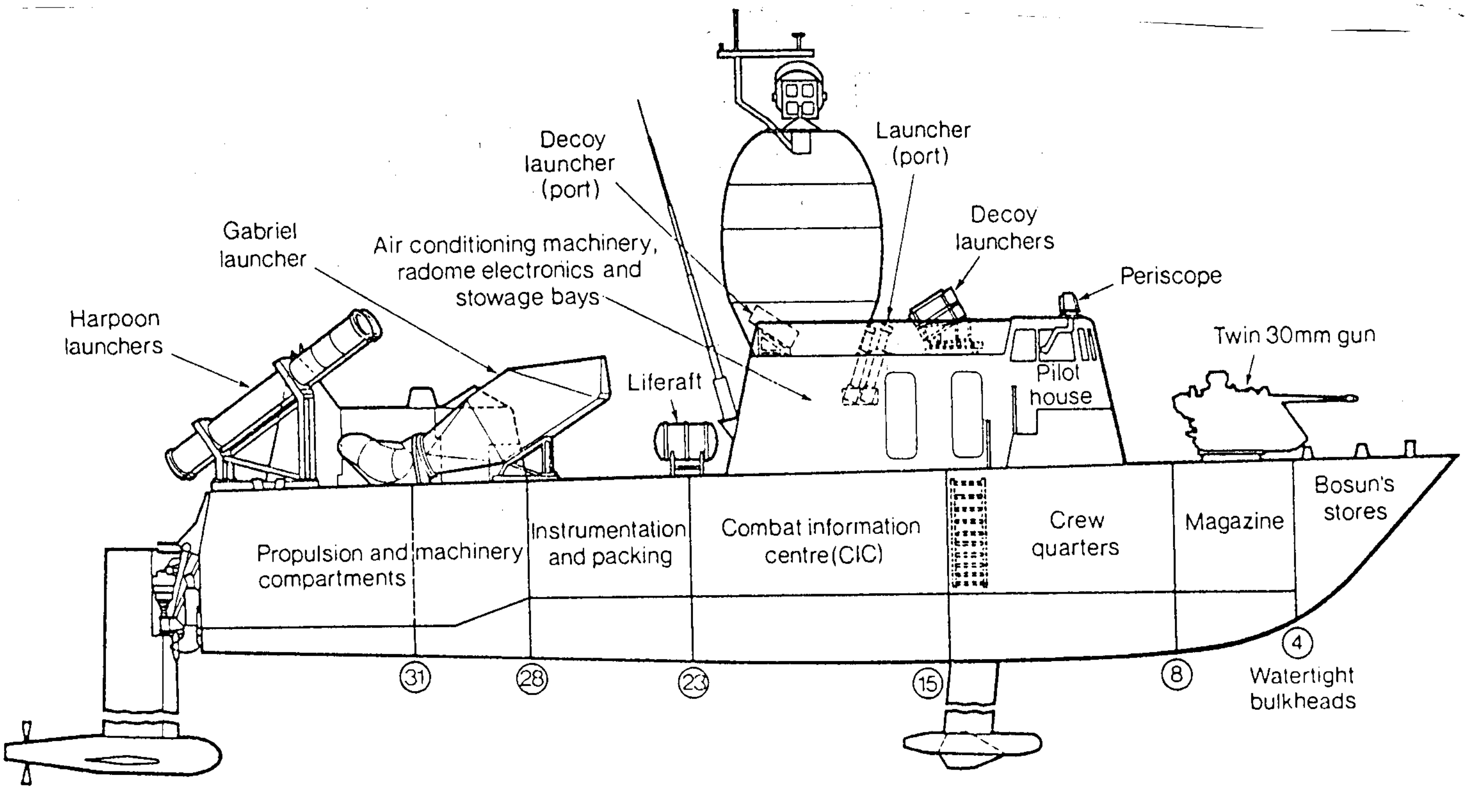


Illustration of SHIMRIT General Arrangement Profile[46]

Overall, SHIMRIT demonstrated a high level of reliability throughout the trials program. Very few failures of significance or of critical components were experienced. The large majority of hardware failures were with components such as valves, sensors, etc. which were designed and built as "commercial quality". A great deal of time was required to develop and refine the complex systems aboard the ship. Frauenberger reported that as these various tasks were completed and corrections incorporated, the operational readiness and performance of SHIMRIT improved to provide the basis for concluding that she was truly an outstanding military hydrofoil.[47]

SOVIETS COVER THEIR RIVERS AND LAKES WITH HYDROFOILS

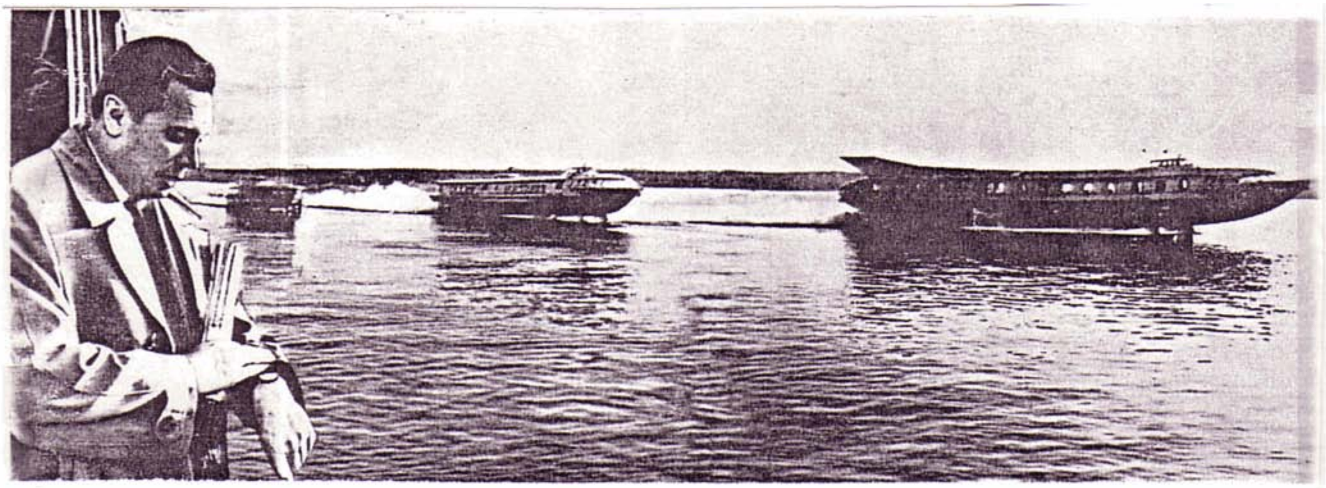
By contrast with the U.S. and the rest of the west, there are several thousand hydrofoils operating in the Soviet Union on a commercial basis on the many rivers, canals and lakes of that vast country. This may be more understandable when one realizes that there are 150,000 rivers and 250,000 lakes along with relatively few automobiles and many bad roads in the Soviet Union. Janes "Surface Skimmers"[17] and later editions of the same publication, entitled: "High Speed Marine Craft and Air Cushion Vehicles"[48], provides an impressive account of Soviet hydrofoil craft. As we will see, Soviet commercial hydrofoils are generally surface-piercing or shallow-submerged hydrofoils with diesel engines, and have top speeds about 32 to 40 knots. However, on the military side, at least five military-type hydrofoils of up to about 400 tons with speeds of up to about 55 knots have been built which employ fully-submerged foils and gas turbine engines.

Baron von Schertel described how the fundamental hydrofoil knowledge in the Soviet Union came from Germany.[6]

> "Immediately after World War II, the Russians established a design office in the Sachsenburg Shipyard, Dessau-Rosslau, where the German military hydrofoils had been built. They engaged the 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 of hydrofoils was elaborated on and reported to Russia. The surface effect for controlling foil submergence came to the knowledge of the Soviet engineers by the experimental work of the first person who used it--Wankel. The next step for the design office was to design and construct a 57-ton Torpedo hydrofoil vessel projected for 55 knots and powered by two Mercedes Diesel engines of 1,000 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 the Western European hydrofoils had already been offering scheduled passenger service. The Soviet boats are powered more recently by diesel engines and gas turbines. The Russian diesels are mostly overloaded, and very susceptible to problems. In recognition of this weakness, an arrangement was made with MTU of Germany for delivery of diesel engines. Many types of hydrofoils were built in Russia according to a modified Schertel-Sachsenberg system."

According to Reference 17, Krasnoye Sormovo in Gorki is one of the oldest established shipyards in the Soviet Union. In addition to building displacement craft of many kinds for the Soviet River Fleet, the yard constructs the world's widest variety of passenger hydrofoils. Many of these are equipped with the so-called Alexeyev shallow-draft submerged- foil system developed by Dr. R.Y. Alexeyev starting near the end of 1945. The system was specifically designed for operation on smooth, but open and shallow rivers and canals. The basic principle underlying Alexeyev's foil system is the immersion depth effect (or surface- effect based on Wankel's earlier work, according to von Schertel) for stabilizing foil immersion in calm water by the use of small lift coefficients.

The Alexeyev system consists of two main horizontal foil surfaces, one forward and one aft, with little or no dihedral, each carrying about one half the weight of the craft. A submerged foil loses lift gradually as it approaches the water surface from a submergence of about one chord length. The effect prevents the submerged foil from rising completely to the surface. A planing sub-foil of small aspect ratio is used as a means of providing take-off assistance and preventing the hydrofoil from settling back to the displacement mode. The planing sub-foils are located in the vicinity of the forward struts arranged so that when they are touching the water surface, the main foils are submerged approximately to a depth of one chord. The system was first tested on a small launch powered by a 77 hp converted automobile engine.



Designer Alexeyev and Three of His Hydrofoils on the Volga[49]

By 1957, the Gorki Yard launched the first Soviet hydrofoil passenger ferry, RAKETA, employing this foil design. Shown above is a picture of Dr. Alexeyev observing three of his hydrofoils (SPUTNIK, METEOR AND RAKETA) taken in 1961.

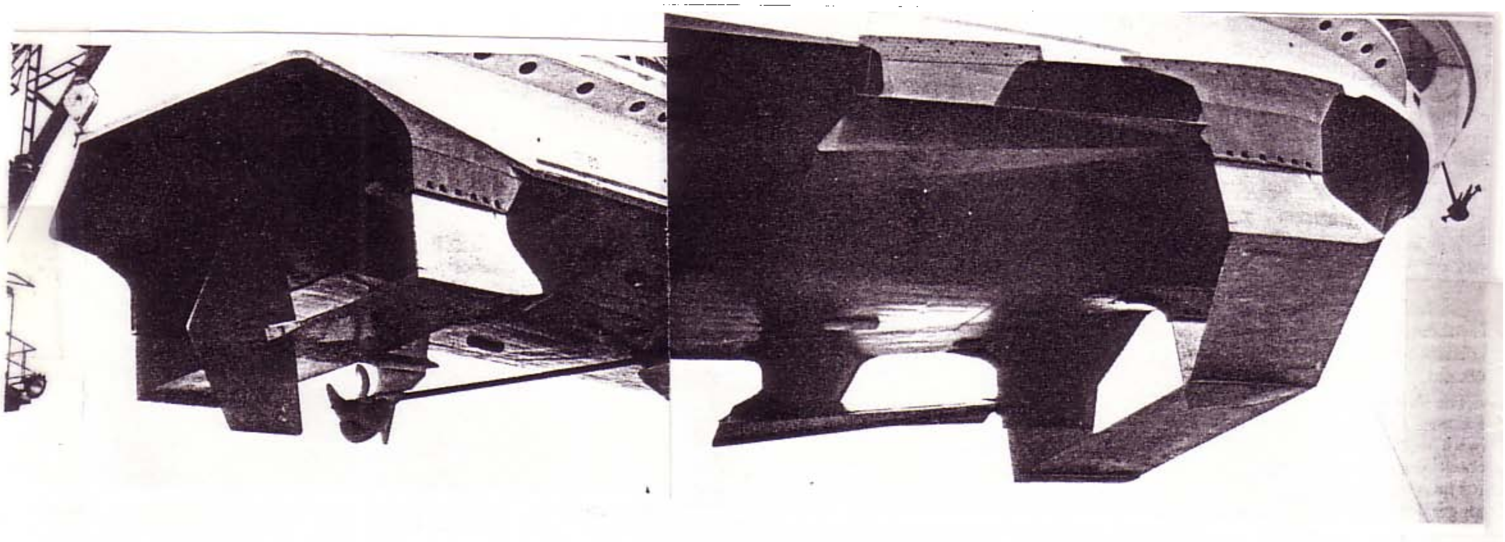


Illustration of the Alexeyev Foil System on RAKETA[48]

The Gorki Yard also cooperated with the Leningrad Water Transport Institute in the development of hydrofoil craft with fully-submerged V-type and trapeze-type surface piercing foils of the Schertel-Sachsenberg system. The first craft in the Soviet union employing the latter type foil was the STRELA hydrofoil. To support the Soviet hydrofoil activity, a design office for hydrofoils was established in Gorki where, by the early 1980s, there were 1,000 people employed and more than 20 different craft were developed! As early as the mid-to-late 1960s, at least 45 hydrofoil services were being operated in Russia and approximately 3,000,000 passengers carried in one year.

RAKETA

The prototype RAKETA, employing the Alexeyev foil system, was launched in 1957. Several hundred of these craft were built over the ensuing years and operated on the major rivers of the USSR. In spite of its early design and launching in 1957, RAKETA can be dubbed one of the most successful Soviet commercial passenger hydrofoils. Even as far back as 1973, before the first PHM was launched, there were more than 300 RAKETAs in service on the rivers and lakes in the Soviet Union, including 66 in service alone, with the Volga United River Shipping Agency.

[redacted]

A Version of RAKETA on the Rhine in Germany

Many variants of RAKETA were produced, including the "T" model which was the standard export model. This 88- foot, 27-ton hydrofoil was powered by a single Soviet M-401A 12-cylinder, V-type, supercharged diesel engine with a normal service power output of 900 hp. The craft's speed at this service power is about 32 knots, and can operate in waves with a maximum wave height of about 2 ft. 8 in. The passenger capacity has ranged widely, from as few as 58 and 64 seated, to as many as 100 passengers (58 seated) on high density, short-range commuter routes. Most of the exported RAKETA's have seen service in Romania, Hungary, Finland, Czechoslovakia, Yugoslavia, Austria, Bulgaria, the United Kingdom, and the Federal Republic of Germany.

Production of RAKETA was halted in the late 1970s, and the shipyards previously involved in their construction are building other hydrofoil designs including VOSKHOD, described later.

STRELA

Designed and built in Leningrad, the 92-passenger STRELA (Arrow) was launched at the end of 1961 and intended for service across the Black Sea. It saw regular passenger service between Odessa and Batumi. In June 1962 STRELA was put in service between Yalta and Sevastapol, where it cut the normal ferry service of 6.5 hours one way to 1.5 hours. Later on operations between Leningrad and Tallinn, with a speed of about 40 knots, it covered the trip in four hours which was 90 minutes faster than the express train between these two ports.

Only two craft of this type have been built. The second **STRELA** was completed in October 1965, and at that time held the world's record for a long-distance journey by hydrofoil. The trip from Yalta to Leningrad, a distance of 2,735 miles, was completed in 100 hours of operational time.[1]

Prototype STRELA off Yalta Coast[48]

The 46-ton **STRELA** had two 970-hp 12-cylinder V-type M-50 F3 Soviet diesel engines driving twin propellers. The craft has trapeze type surface-piercing bow foils with a horizontal center section between the main struts, and can operate in Sea State 4.

SPUTNIK

The maiden voyage of this other "SPUTNIK", a passenger-carrying hydrofoil, took place as early as 1961. This was about the time that HIGH POINT was being designed. This relatively large (for it's time) 100-ton hydrofoil carried 300 passengers between Gorki on the Volga River and Moscow (a distance of about 560 miles) in about 14 hours.

SPUTNIK was built for service on inland waters only which, in the Soviet Union, include some large bodies of water such as the Caspian Sea and Lake Baikal. The craft employs the Alexeyev foil system and is reported to have an average cruising speed of about 43.5 knots. Power is supplied by four 850 hp Soviet M-50 V-type diesel engines, each driving its own propeller shaft. The craft has a length of 157 feet and an overall beam of 29.5 feet. The hull was made of an all-welded aluminum magnesium alloy and the superstructure made extensive use of plastic materials. The all-welded hull construction technique facilitated prefabrication of sections at the Sormovo shipyard and elsewhere. The sections were sent to other yards in the USSR for assembly, one of which was at Batumi on the Caspian Sea.

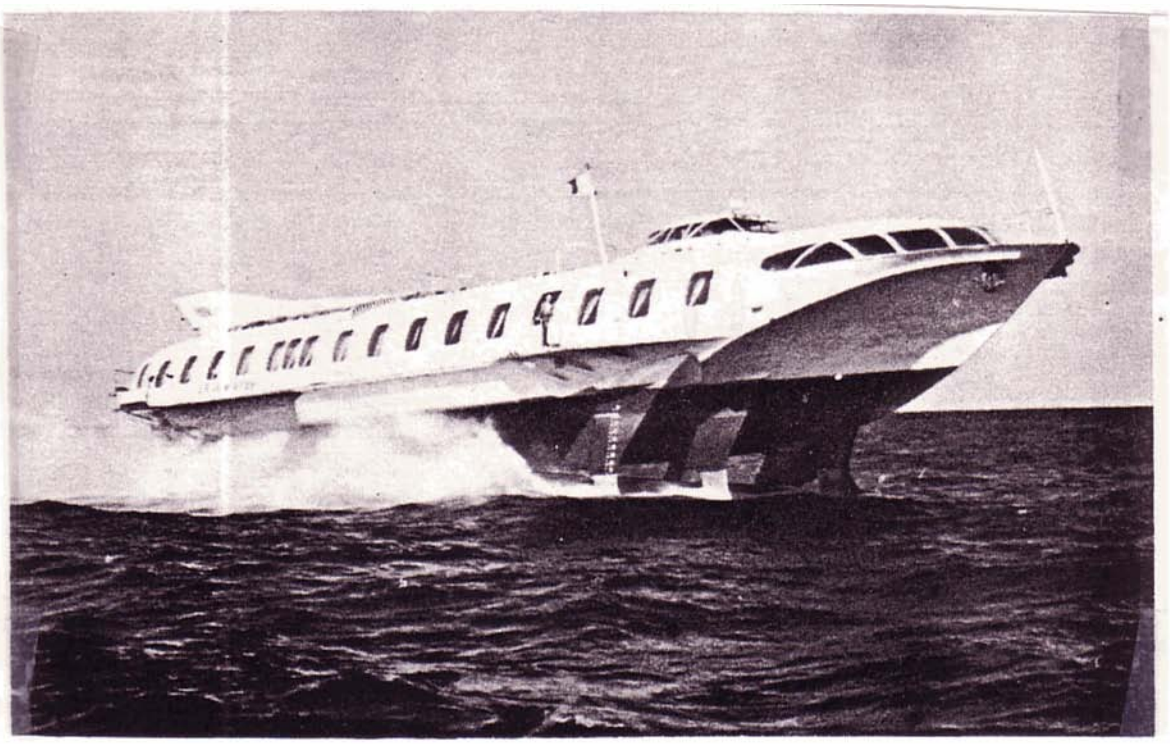
Soviet Passenger Hydrofoil SPUTNIK

Passenger accommodations ranged from 260 to as high as 368. The latter capacity for short, high frequency services, was achieved by installing padded benches in the aft compartments instead of the usual adjustable aircraft-type seats. One can see from the picture that the forward saloon of SPUTNIK was completely glassed in and provided an excellent view for the passengers.

VIKHR

A sea-going version of SPUTNIK, called VIKHR (Whirlwind) was launched only a year after its predecessor in 1962. Described as a "coastal liner", it was designed to operate on a year-round basis on inshore services on the Black Sea up to 31 miles from the coast. This passenger hydrofoil saw service on the Odessa to Herson route, a distance of about 100 miles.

The Soviets introduced an innovation on VIKHIR, namely about a 30° sweep back on the forward foils, which introduces a certain amount of stability augmentation for operations in larger waves than normally experienced by SPUTNIK. Power was increased to 1200 hp from each of the four M 50-F3 diesel engines to account for the greater weight of 117 tons and a higher speed of 43 knots.



VIKHIR

METEOR

The early 1960s saw a lot of hydrofoil activity in the Soviet Union, for it was then that Dr. Alexeyev's METEOR made its maiden voyage from Gorki to Moscow in the summer of 1960. This 54.3- ton hydrofoil, having a length of about 112 feet and overall beam of 31 feet, carried a crew of 5 and 116 passengers. Later versions of METEOR were operated in Bulgaria, Yugoslavia, Hungary, and Poland.

The METEOR's Alexeyev foil system has already been described, but Reference 17 mentions an interesting aspect of Soviet practicality, namely that "foil incidence could be adjusted when necessary by the insertion of wedges between the flanges and the foils when the vessel was in dock". This was not a very sophisticated foil control system, but it was apparently good enough at that time.

Two supercharged 12-cylinder Soviet M-50 diesel engines having a normal service power output of 1,000 hp each provided the METEOR with a speed of 35 knots. It is interesting to note that the guaranteed overhaul life of the engines was 1,000 hours. Each engine drove its own five-bladed propeller through a reversing clutch on an inclined shaft. Take-off time for foilborne flight was from 120 to 140 seconds and took place within a distance of 25 to 28 boat lengths.

METEOR Operating in Leningrad[48]

KOMETA

Derived from the METEOR hydrofoil, the KOMETA was the first seagoing commercial hydrofoil to be built in the Soviet Union. The prototype KOMETA seated 100 passengers and made its maiden voyage on the Black Sea in the summer of 1961. It was then employed on various routes on an experimental basis while obtaining experience which led to various modifications before the hydrofoil was put into series production. They were built mainly at Gorki and Poti, one of the yards at the Eastern end of the Black Sea, and designed to operate on coastal routes up to about 50 miles from ports of refuge under moderate climate conditions.

Operators of KOMETA hydrofoils outside of the Soviet Union include the countries of Yugoslavia, Cuba, Italy, Morocco, Romania, Poland, Turkey, Greece, Iran, Bulgaria, and the German Democratic Republic. Export orders to these and other countries totalled 52 by early 1978.

The main difference between KOMETA and its forerunner, METEOR, is a completely revised foil system necessitated by the requirement to operate in relatively rough water. The craft employs a surface-piercing trapeze-type bow foil with an auxiliary "stabilizer" foil located above it to improve pitch stability. In addition to the aft surface-piercing foil there is another auxiliary foil located amidship near the longitudinal center of gravity to assist take-off. It can operate foilborne in waves up to 5 ft. 7 in. high and travel hullborne in waves up to about 11 ft. 10in.

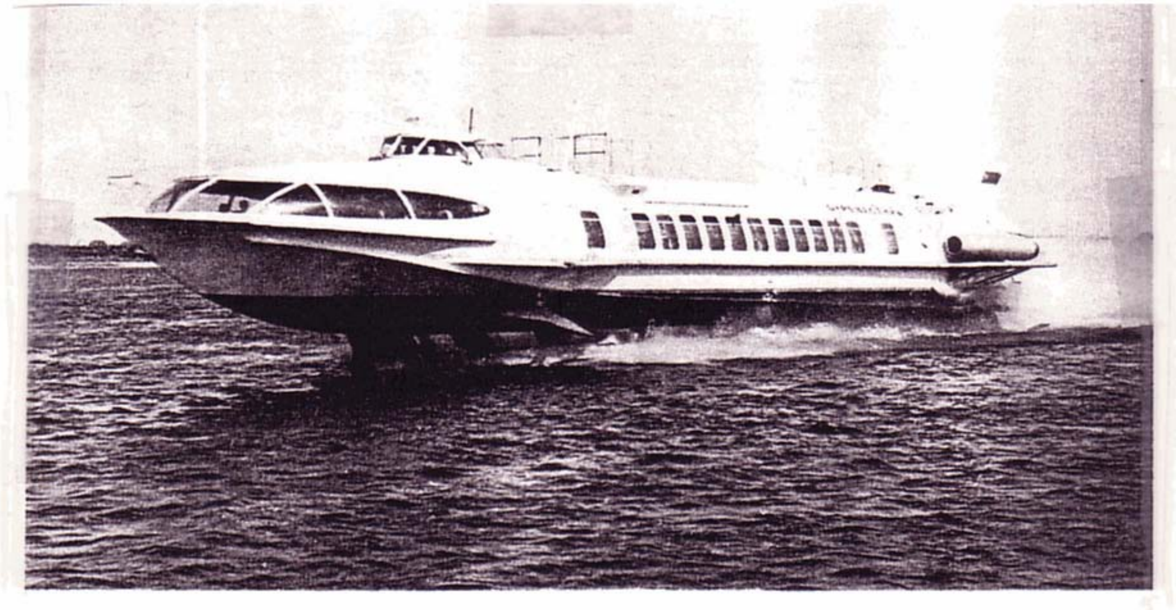
KOMETA Seen Leaving Napoli

Power to propel the 60-ton KOMETA at 32 knots is provided by two Soviet M-401A supercharged, V-type diesel engines, each with a service output of 1,000 hp. A maximum intermittent speed can be attained in calm water by running the engines at 1,100 hp. Each engine drives a propeller through a reversing gear and an inclined shaft. Later models of KOMETA have their engines located aft and incorporate a V-drive instead of the long inclined shaft. In this arrangement the engine output shaft faces forward driving into a V-type gearbox which reverses the direction of the output shaft to accept an inclined propeller shaft. An illustration of such a V-drive arrangement can be seen in the the inboard view of VOSKHOD, described later. The relocation of the engine room aft results in a reduction of noise in the passenger cabins.

BUREVESTNIK

The prototype 130- passenger BUREVESTNIK was the first gas turbine driven commercial hydrofoil to be designed in the Soviet Union for series production. Launched in April of 1964, it had two 2,700 hp marinized aircraft gas turbines driving two, two-stage waterjets. The foil system was of the Alexeyev type with two main foils and a stabilizer foil at midships, all built of titanium alloy. The 67-ton vessel had a length of 142 feet, a beam of 19.5 feet, and a width across its foils of about 24 ft..

During 1986 BUREVESTNIK underwent extensive trials and modifications including operations on the Gorki-Kuibyshev route, a distance of about 435 miles. However, it is understood that this 67-ton hydrofoil never went into production.



BUREVESTNIK Prototype During Trials[17]

TYPHOON

The fast ferry TYPHOON, carrying between 98 to 105 passengers, was the first production hydrofoil to be built in the Soviet Union having gas turbines and a fully-submerged foil system with automatic controls. The prototype was constructed in Leningrad and launched in December 1969. It was placed in passenger service during 1972 to 1973 to technically assess the design under commercial operating conditions. In 1975 it was reported that the hydrofoil was to be produced at a shipyard on the Baltic where it was part of the ship building program from 1976 to 1980.

With a length of about 103 ft and displacement of 65 tons, TYPHOON had a service speed of about 42 knots in calm water and 38 knots in sea state 4. This loss of speed of only 10% in waves of 6 to 7 feet was made possible by the fully-submerged foil system rather than the earlier surface-piercing designs. As can be seen in the illustration, the foils were of the conventional, or airplane configuration with about 77% of the lift produced by the set of foils just forward of midships. They are supported by four vertical struts; the two outboard struts are **supported by auxiliary** fins which provide additional stability during takeoff. The aft foil has two vertical struts, each of which has a rudder built into their trailing edge.

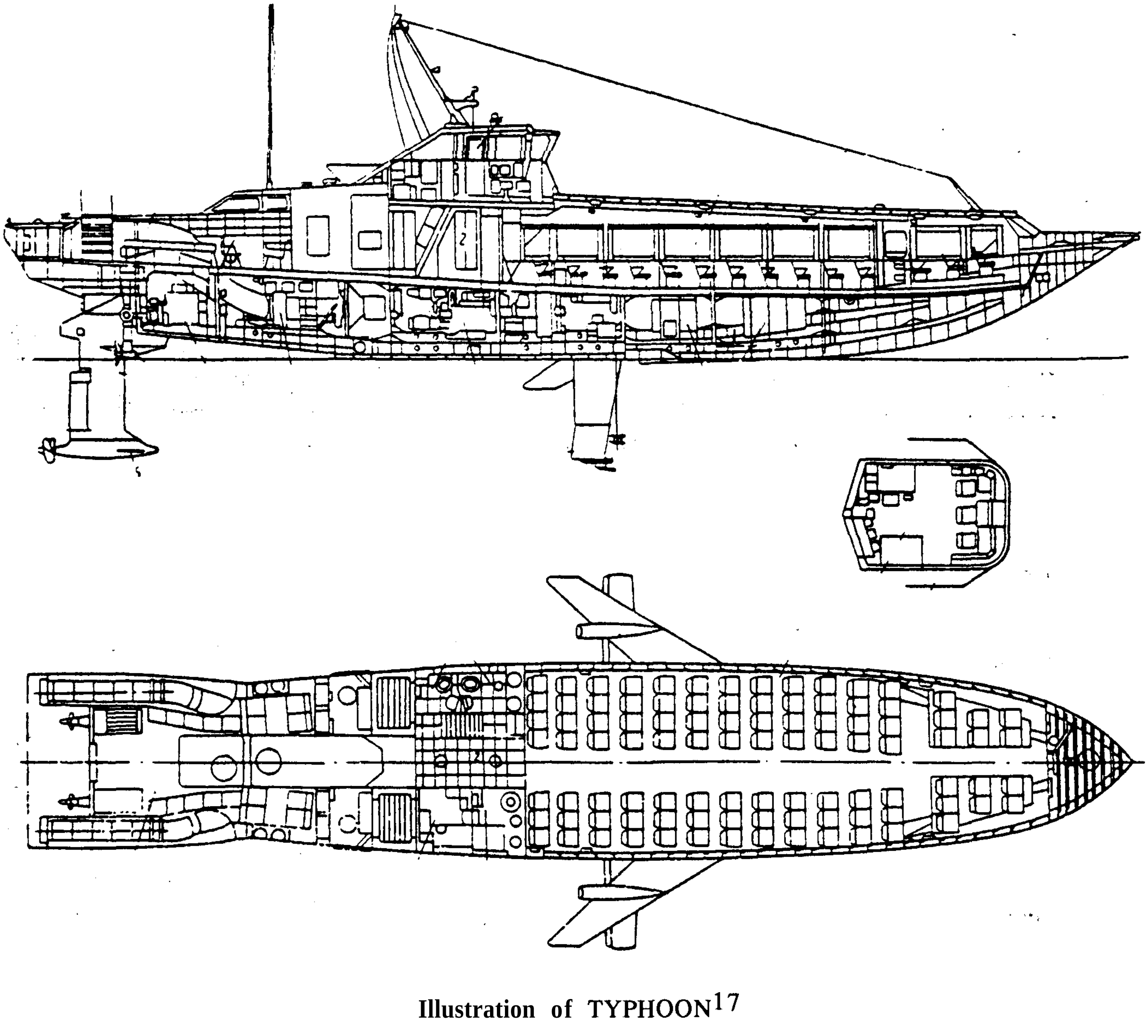


Illustration of TYPHOON[17]

Foilborne power is provided by two Ivchenko marine gas turbines having a rating of 1,750 hp each. Power from these engines is transmitted to two propellers via Z-drives located at the transom and through two vertical shafts within each of the two aft struts. The pod at the lower end of each strut contains the lower gearbox, shaft, 2 ft. 3in, 3-bladed propeller, and aft foil controls.

It is interesting to contrast this design with the U.S. Navy PGH-1 FLAGSTAFF, described in Chapter 4. This hydrofoil, designed and built by Grumman Aerospace about the same time as TYPHOON, had about the same displacement, but carried the same foilborne power in one gas turbine rather than two, had one propeller instead of two, one aft strut rather than two, and two forward struts rather than four. FLAGSTAFF understandably achieved a much higher speed.

VOSKHOD

The engineering experience gained from the RAKETA, METEOR and KOMETA hydrofoils was put to good use on the VOSKHOD series of relatively small, 28-ton passenger craft. VOSKHOD-2 was to retain RAKETA's general foilborne operating characteristics along with maximum use of standard mechanical, electrical and other components that were proven to be satisfactory on RAKETA.

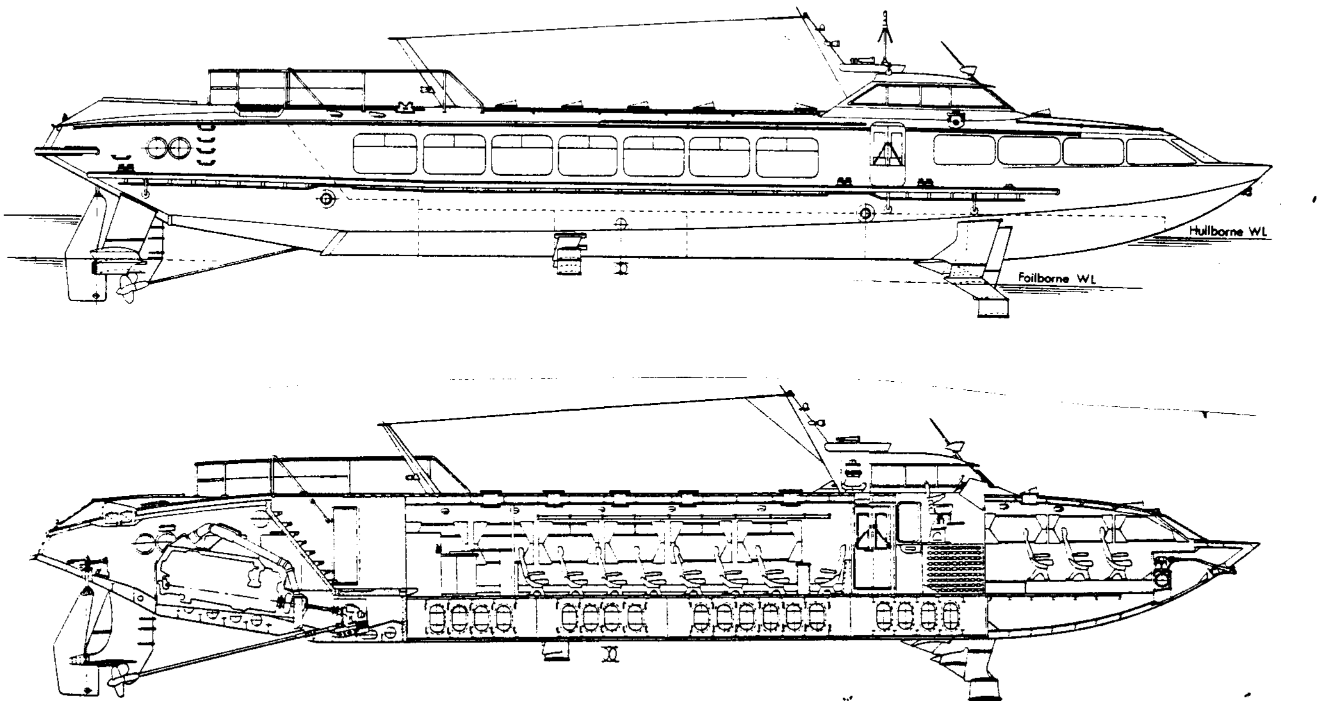


Illustration of VOSKHOD-2[17]

The design improvements on VOSKHOD-2 consisted of employment of a Vee-drive transmission, placing the propeller further below the hull which resulted in greater hull-to-water clearance. This also reduced hydrodynamic drag under certain aft load conditions. Apparently RAKETA had a tendency to drag its stern in the water under heavy loads aft. A variety of improvements were made to accommodate passenger boarding, additional passenger capacity from 64 to 71 was provided, and generous soundproofing for greater passenger comfort was installed. Also, it should be noted that one of the four crew is a "barman". Provision was also made for the future replacement of the VOSKHOD-2 single 1,000 hp M-401A 12 cylinder, supercharged diesel engine with one having a power rating of 2,000 shp.

VOSKHOD's foil system, like so many of the Soviet shallow submerged designs, had a bow foil with a pitch stability sub-foil immediately behind, one aft foil, plus a midship foil to facilitate takeoff. The stern fully submerged foil has two side struts and is supported in the center by the aft propeller shaft support bracket as can be seen in the above illustration.

The VOSKHOD series of passenger craft have a length of 90 feet, a beam of 20 feet, and a payload capacity of about 6 tons. Its speed with the 1,000 hp diesel was about 37 knots in calm water. At the time that the design was started it was planned that a number of versions be available to suit local requirements. As mentioned above, one was to have a more powerful diesel engine. Another version of this craft, VOSKHOD-3, was to be provided with a gas turbine power source.

KOLKHIDA

The KOLKHIDA hydrofoil was designed to replace the aging 1961 KOMETA fast passenger ferry. Two versions of the craft are available; one for domestic service in the Soviet Union, another intended for export. The keel of the first craft was laid in May of 1980 and has since then entered into series *production with foreign operators in Yugoslavia, Italy and Greece.*

KOLKHIDA is faster than KOMETA, seats more passengers, uses less fuel, and can operate foilborne in rougher water. Major physical differences are the introduction of an automatic foil control system, the use of new materials in the hull structure, and an improved cabin layout to accommodate more passengers. The foil configuration is similar to KOMETA, however, the engine room was placed aft as in VOSKHOD (using a V-drive transmission), to reduce the noise level in the cabin, but overall dimensions are the same as KOMETA. Power is supplied by two MTU 12V 396 TC82 supercharged 12-cylinder V-type marine diesel engines with a maximum rating of 1,430 hp which results in a cruising speed of 34 knots in calm water. This is apparently the first

Soviet hydrofoil to use modern West German-built light-weight diesel engines!

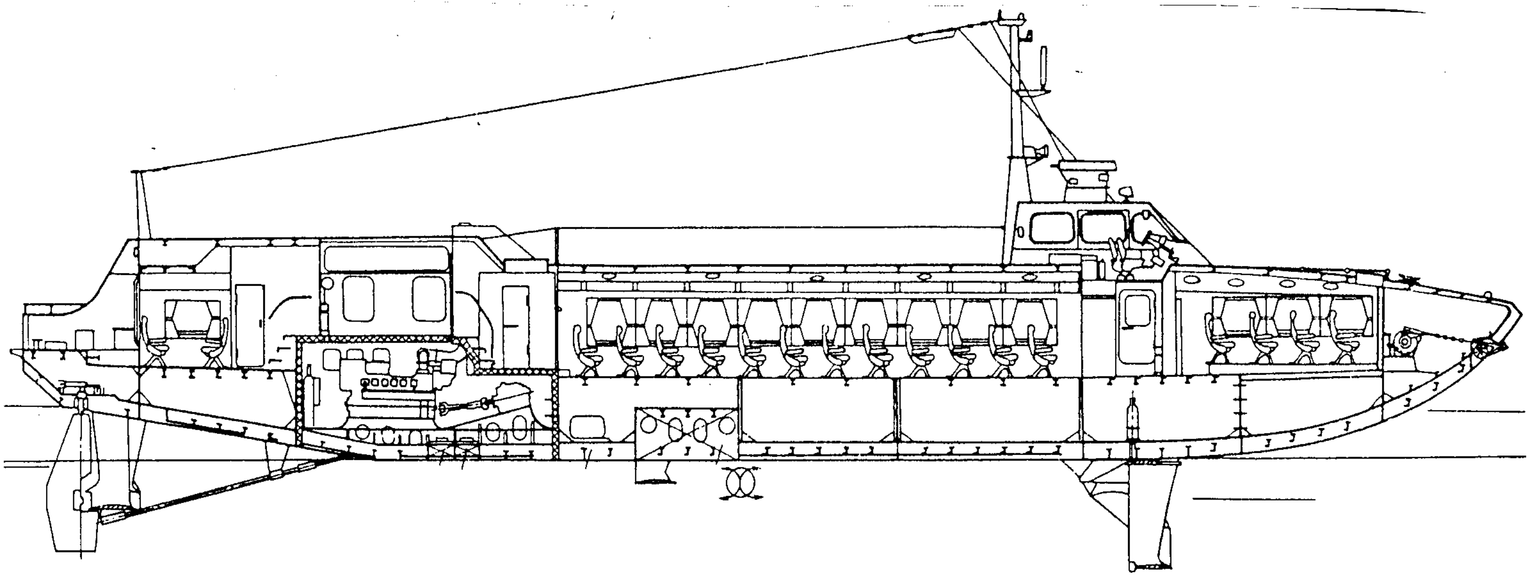
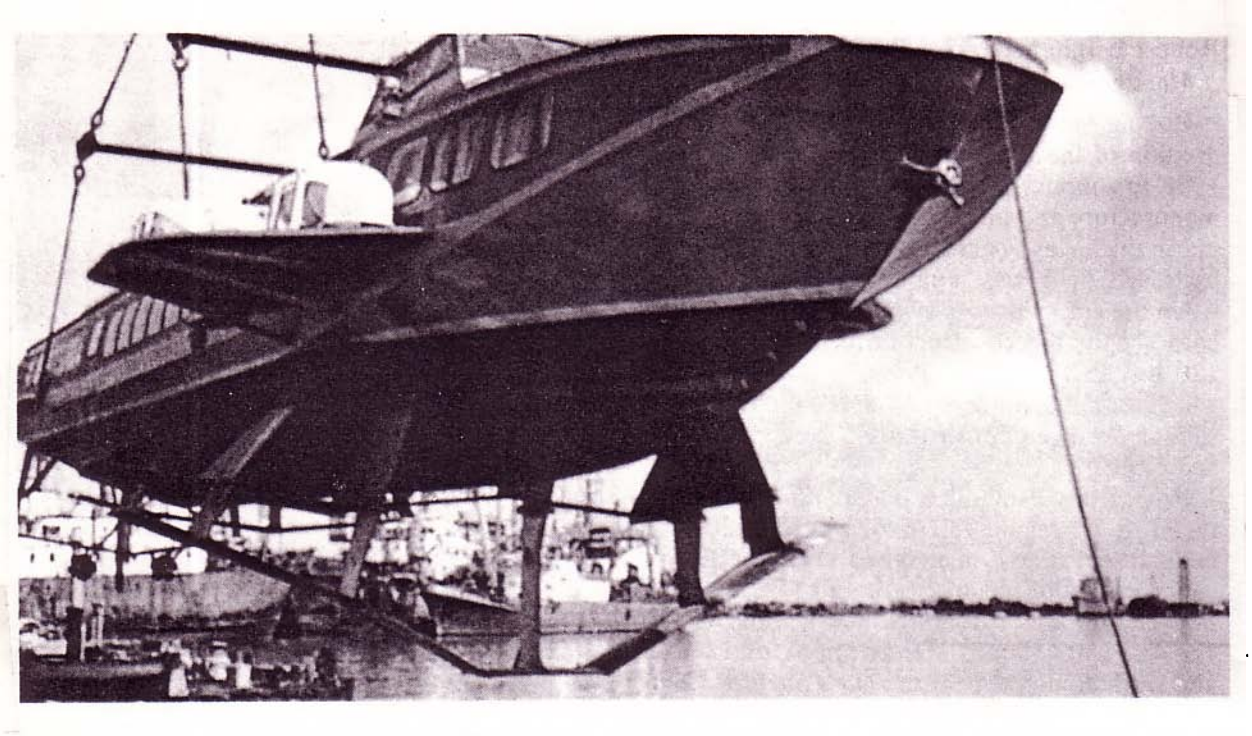


Illustration of KOLKHIDA[48]



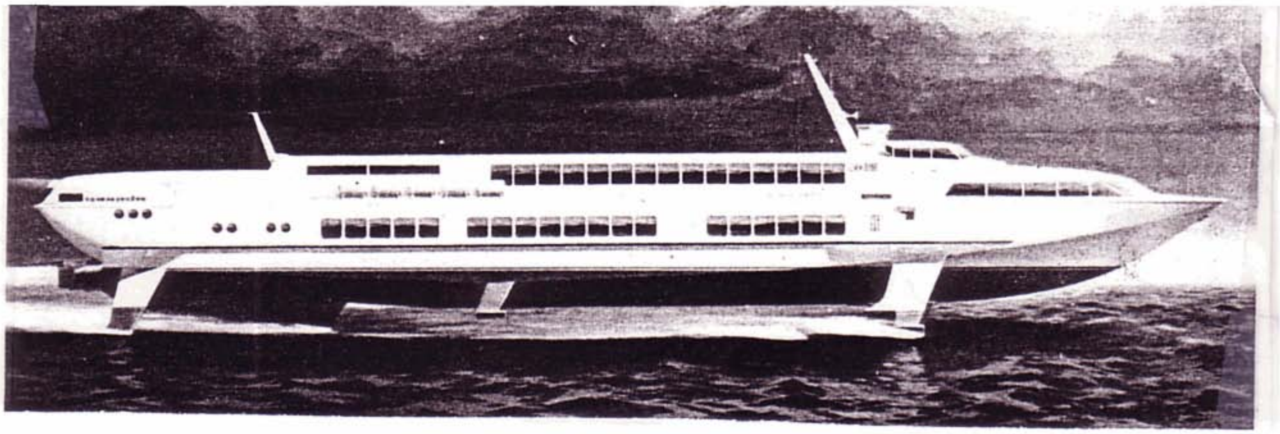
KOLKHIDA Showing Bow and Stern Foils[48]

CYCLONE

This most recent Soviet commercial passenger hydrofoil is an enlarged, double-deck derivative of KOMETA. CYCLONE seats 250 persons and its two 5,000-hp gas turbines driving two waterjets make it the most powerful commercial hydrofoil in the East. It is reported to have a maximum speed of 45 to 50 knots and a cruising speed of 42 knots.

The 140-ton CYCLONE has an overall length of almost 164 feet and a width across its foils of 43.5 ft. The surface-piercing foil system is of the conventional configuration consisting of two main foils, one at the bow and one at the stern with a midship foil to assist take-off, and a pitch stability sub-foil immediately aft of the bow foil. A sonic/electronic automatic control system provides inputs to the various flaps to control the craft and improve ride quality. This is a far cry from the earlier, simple, brute force method of controlling lift by inserting wedges between flanges of the foil/strut system at dockside!

Here again it is interesting to contrast CYCLONE with its U.S. counterpart, the Boeing JETFOIL. Although the latter carries the same or more passengers, it is much smaller in length and displacement, has less power installed, has a higher cruise speed, and can operate comfortably in rough water. However, the author is not familiar with either the acquisition or operating cost differences.



Soviet Passenger Hydrofoil, CYCLONE[48]

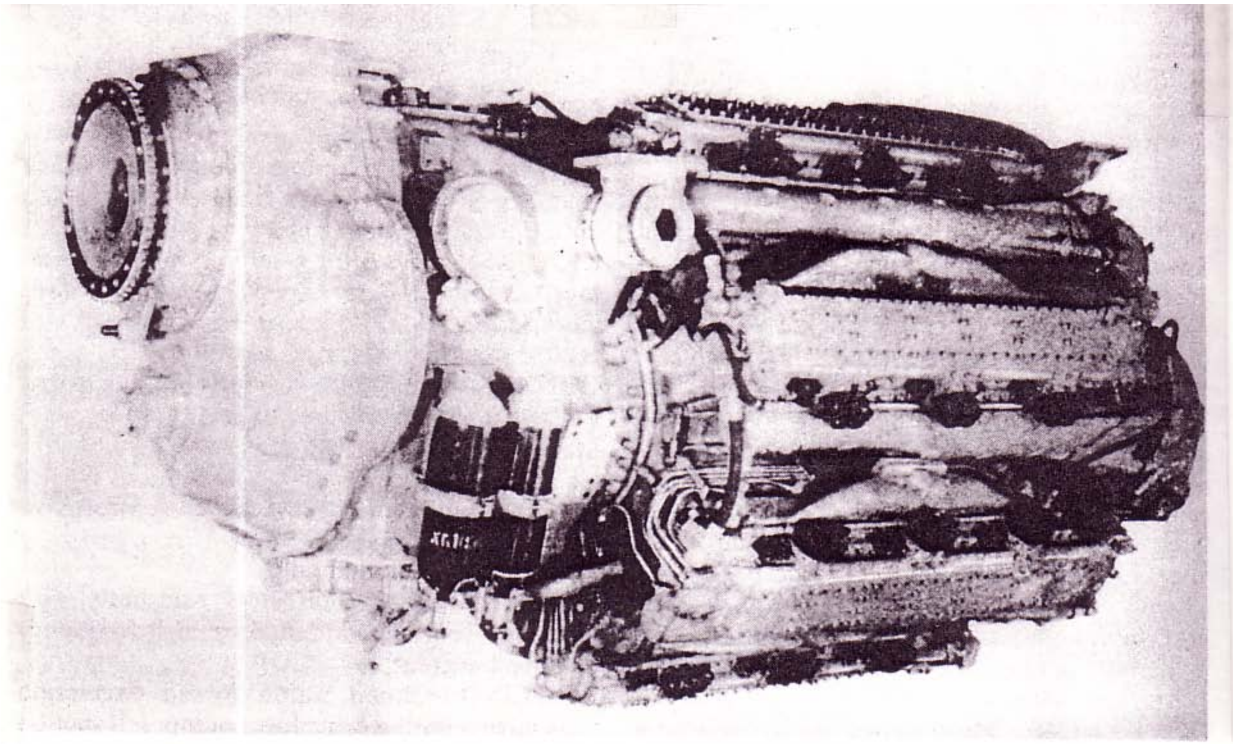
Turning now to the Soviet military hydrofoils, we will see that they have many high technology features compared to their commercial counterparts. They are then more comparable to the U.S. Navy hydrofoils described in earlier chapters in certain respects.

PCHELA

An early Soviet military hydrofoil was the PCHELA (BEE) derived from the commercial craft, STRELA. Although 25 of these craft were built between 1968 and 1972 for service with the KGB on frontier patrol duties in the Baltic and Black Seas, Janes[48] reports that only four remained in service by the late 1980s.

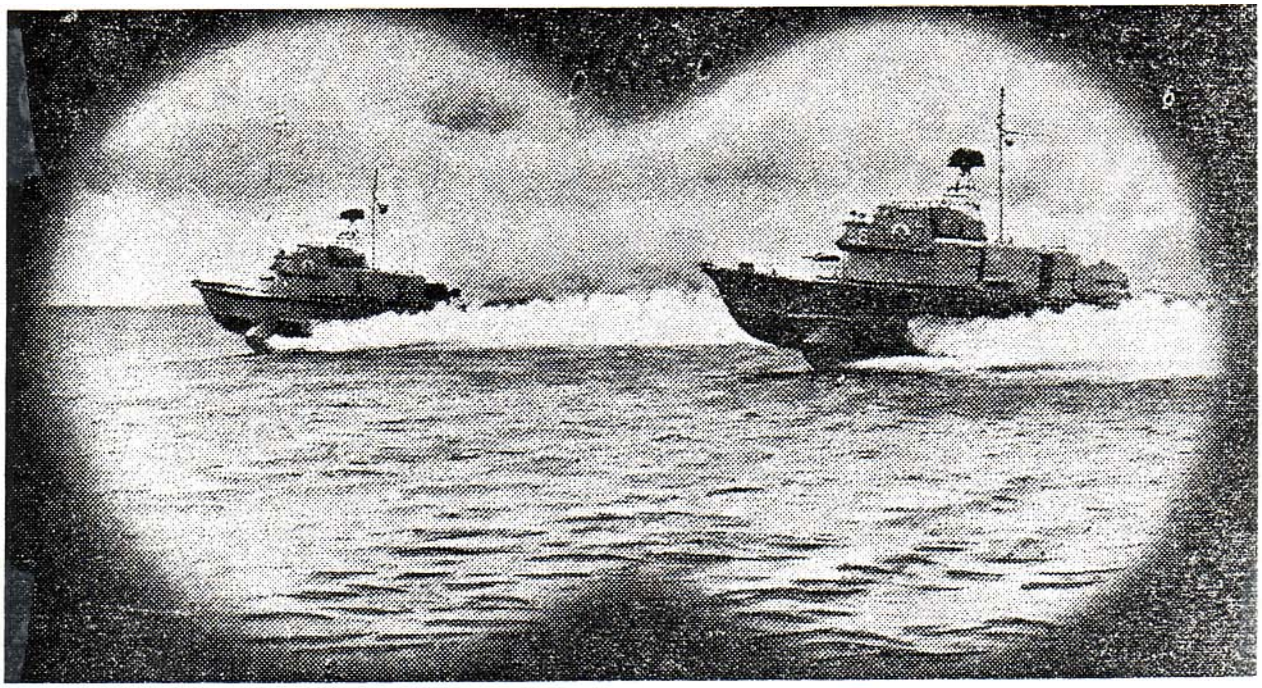
Much more powerful and carrying a greater payload than STRELA, this hydrofoil had a full load weight of 75 tons, and its single 4,000 hp M-503 diesel engine drove it at a maximum speed of 42 knots. The M-503 is a multi-cylinder radial-type engine which was introduced on the OSA missile attack craft in the late 1950s. The illustration shows the engine with its 42 cylinders in seven cylinder blocks of six cylinders each.

Armament consisted of two twin 23mm anti-aircraft mounts with remote optical director, and two to four depth charges. The craft was equipped with surface search and navigation radar along with a dipping-type sonar.



M-503 Soviet Radial Diesel Engine[48]

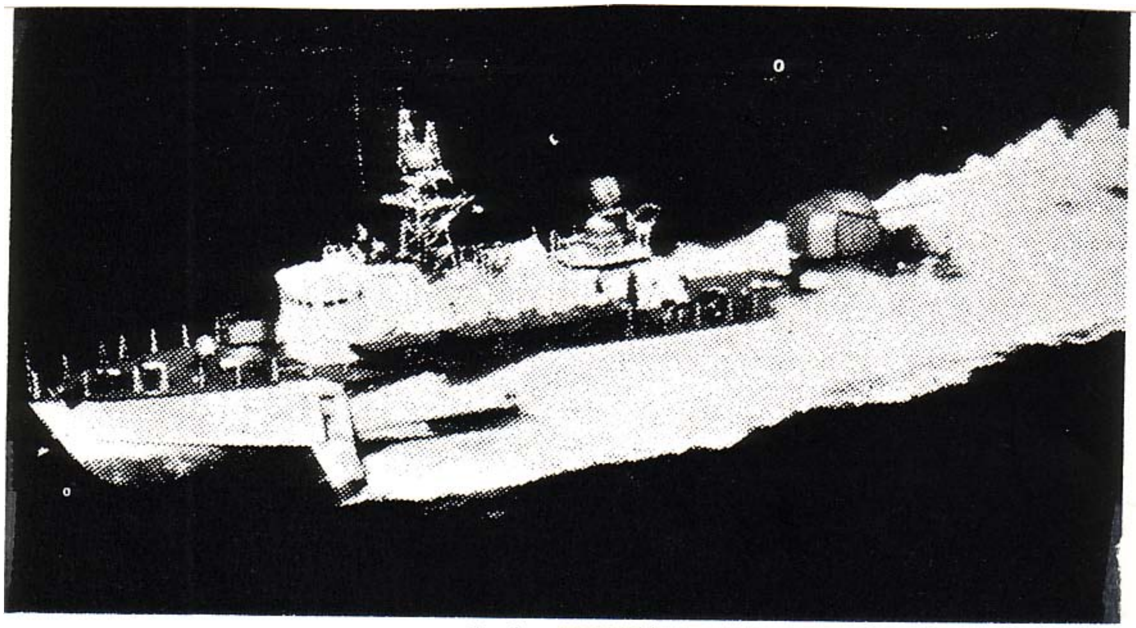
Since it was a derivative of STRELA, it employed an identical foil system of the surface-piercing trapeze type as can be vaguely seen in the picture. Apparently the photographer could not get too close to the ships and had to resort to taking the picture through binoculars.



Two PCHELA Soviet Military Hydrofoils[17]

TURYA

The Soviet TURYA, shown here, is known as a "tail dragger". It has a forward surface-piercing trapeze foil set back about 1/3 from the bow. There is no aft foil. When the craft comes up to a speed of 24 to 28 knots, the forward mounted foil raises the bow of the hull clear of the water, but the stern is left to drag in the waves. Later versions of the ship were equipped with semi-retractable foils permitting the overall beam to be reduced, thus enabling it to be taken alongside conventional berthing facilities without damaging the foil tips.



Soviet TURYA

This hydrofoil was based on the well-proven Soviet 39.3 meter OSA missile-firing fast patrol boat hull using welded steel construction. The hydrofoils described have used light-weight aluminum for hull construction. In addition to improving the maximum speed of its forerunner, the foils reduced the craft's wave impact response and provided an improvement in its performance as a weapon carrier. The TURYA has three very high performance Soviet M-504 radial-type diesel engines at 5,000 hp! Each of these drive a variable- pitch propeller through an inclined shaft. Reportedly, this gives the 250-ton TURYA a top speed of 40 to 45 knots. The M-504 radial diesel is a derivative of the M-503 in that it has two more banks of cylinders for a total of 56! The engine has a length of about 14 feet and a width and height of about 5.3 feet. Its power- to- weight ratio is reported to be 3.17 pounds per hp, which is much lower than conventional light-weight diesel engines. One observation is in order however, and that is it must be very difficult to work on when installed in a vessel. Getting to the cylinders on the bottom of the engine must be a job every Soviet sailor must abhor. This is probably why radial-type diesel engines have not been popular in the West.

The first of the TURYA Class was launched in 1972, about two years before launching of the U.S Navy PHM-1 (PEGASUS). In contrast to the limited number of 6 PHMs built, about 30 TURYA hydrofoils were placed in service; eight of which were supplied to the Cuban Navy.[48] It would be interesting to know what the acquisition cost difference was of these hydrofoil ships which were somewhat comparable except for ride quality in rough water.

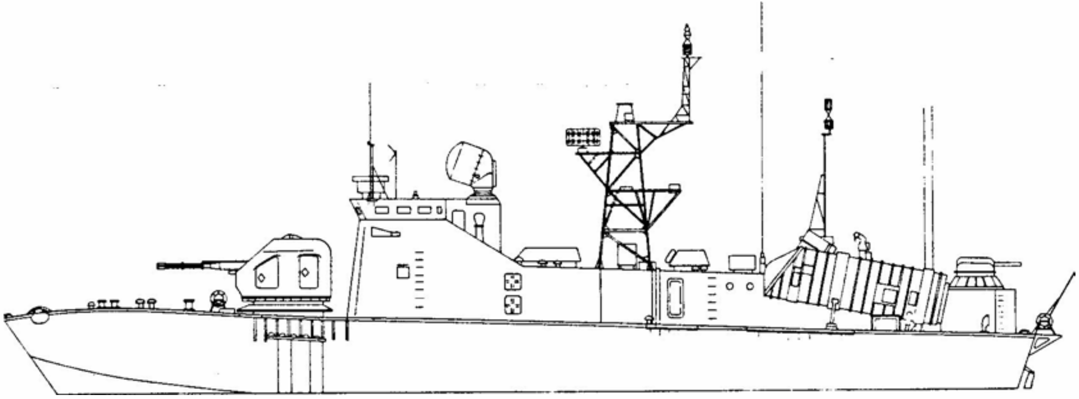
TURYA's armament consists of one twin 57 mm dual- purpose gun with radar control and one optical director. It has one twin 25mm anti-aircraft mount, a light anti-aircraft missile launcher, and four anti-submarine or anti-ship torpedoes. TURYA also carries navigation radar and a dipping sonar.

MATKA

Also described as a missile-equipped fast- strike hydrofoil, the 260- ton MATKA with a crew of 33 was designed to replace the Soviet OSA fast patrol boat. As such it was also based on this craft's 39.3 meter steel hull and has many of the characteristics of TURYA, including its "tail-dragging" feature.

The prototype was launched in 1977 and series production began in the Spring of 1978. In the late 1980s, at least eight were in service. Although the hull, powerplant, and foil system were the same as TURYA, the armament complement was much more formidable. The latter included two surface-to-surface missiles, one 76mm dual-purpose cannon, one six-barrelled Gatling-type 30mm cannon, and one mount for a light anti-aircraft missile launcher.

The ship also carried two 16-tube chaff launchers along with an electronic countermeasures suite.

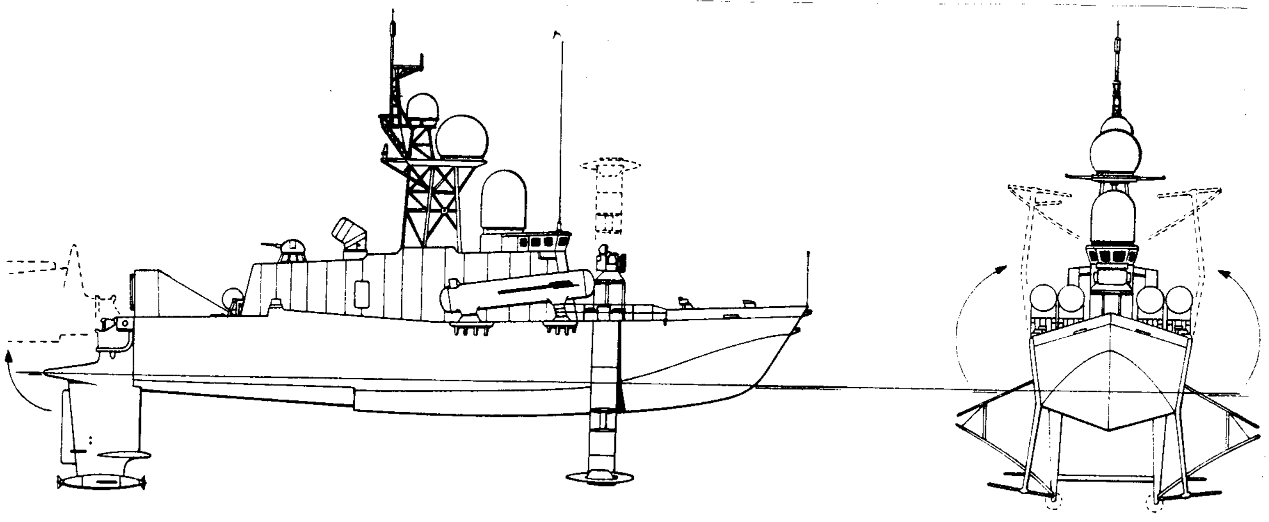


Outboard Profile of MATKA[48]

MATKA with Bow Supported by Forward Foil[48]

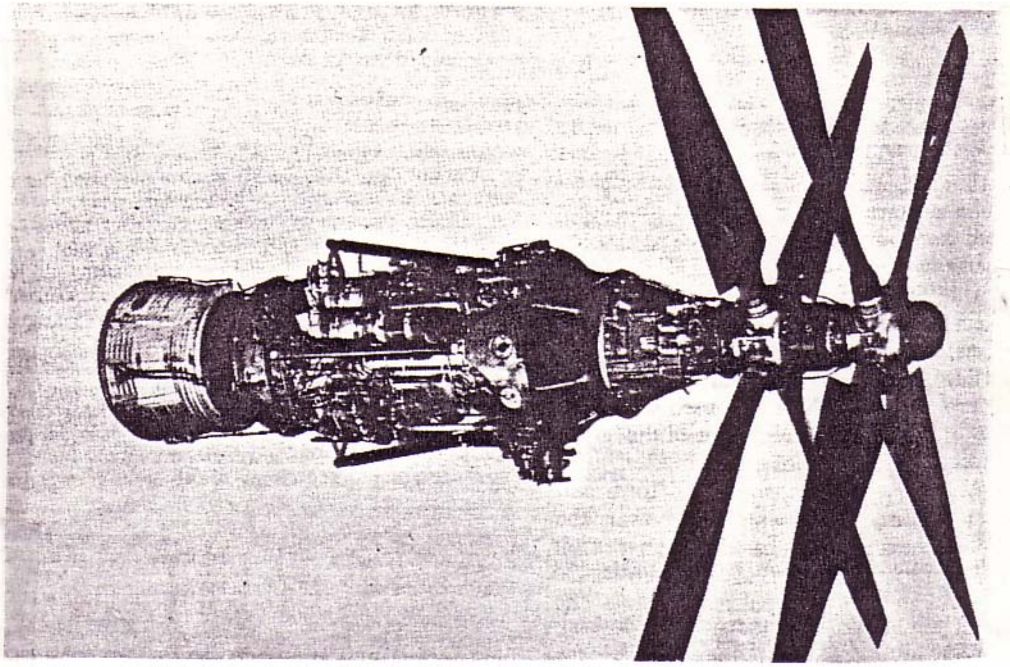
SARANCHA

Designed and built in Leningrad, the SARANCHA (NATO Code Name) is a true hydrofoil with a surface-piercing foil system forward and a fully-submerged configuration aft. The bow foil is a split V surface–piercing type (see illustration on p. 185) which carries about 60% of the lift and the single fully-submerged foil aft carries the remaining 40%. The rear foil is supported by two vertical struts, each of which carries a propeller on each end of the propulsion pod at the lower end of the strut. Note that this foilborne propulsion Z-drive is similar in configuration to that of the U.S. Navy PCH-1 HIGH POINT designed in 1960.



Soviet Fast Attack Hydrofoil, SARANCHA[48]

SARANCHA has two Soviet NK-12MV 12,000 to 15,000 hp marinized gas turbines installed to provide a maximum speed of greater than 50 knots! The engine illustrated here is configured to power the Soviet AIST amphibious assault Air Cushion Vehicle. It is reported to be the world's most powerful turboprop engine.[48]



Soviet NK-12MV Gas Turbine Engine[48]

At 330 tons (about the same full load weight of PLAINVIEW), SARANCHA was the largest operational naval hydrofoil at the time. As can be seen from the description of PLAINVIEW in a previous chapter, it also had a foilborne powerplant of about 30,000 hp, but transmitted its power to the water through two supercavitating propellers.

The 147 ft SARANCHA had a beam across the foils in the extended position of 75.5 ft. From the illustration one can see that the retraction arrangement is similar to that of FLAGSTAFF and PLAINVIEW. Foil control was obtained through an electronic autostabilization system. A point of contrast with U.S. hydrofoil designs, however, is the utilization of rudders on the trailing edges of the aft struts of SARANCHA to improve its maneuverability. The rudders are probably used because of the large surface-piercing foil system forward which makes it more difficult to roll into a turn and accomplish a coordinated maneuver, particularly at high speed.

Soviet Navy operational testing of SARANCHA began in the eastern Baltic in mid-1977. Armament on the ship consisted of four SS-N-9 anti-ship missiles on lightweight launchers amidship, one twin SA-N-4 surface-to-air missile launcher with 15 to 20 missiles on the forward deck and one 30mm Gatling-type rapid fire anti-aircraft cannon aft. Each of these was of course accompanied by its fire control radar along with navigation radar and an electronic countermeasures (ECM) suite.

BABOCHKA

The BABOCHKA (Butterfly) at 400 tons, with three Soviet NK-12MV marinized aircraft gas turbine engines rated at 12,000 to 15,000 hp each, and an impressive array of armaments is indeed the world's largest and most powerful operational hydrofoil "warship". Like SARANCHA, it has surface-piercing foils forward, fully- submerged foils aft, and according to Janes[48], this hydrofoil has a maximum speed of 50+ knots. It is not certain how the propeller drive train is configured with three foilborne engines, but it may be safe to say that the aft foil/strut/propulsion arrangement is similar to and derived from SARANCHA except that there are three aft struts rather than only two.

Although relatively little is known about the internal design details of BABOCHKA, some armament is evident and impressive for a 400 ton ship. This consists of two six-barrelled 30mm Gatling-action guns for anti-aircraft defense, and eight 40cm torpedoes in two quadruple mounts immediately ahead of the superstructure between the deckhouse and the forward 30mm mount. In addition there are undoubtedly missiles, the nature of which is not widely known in the West.

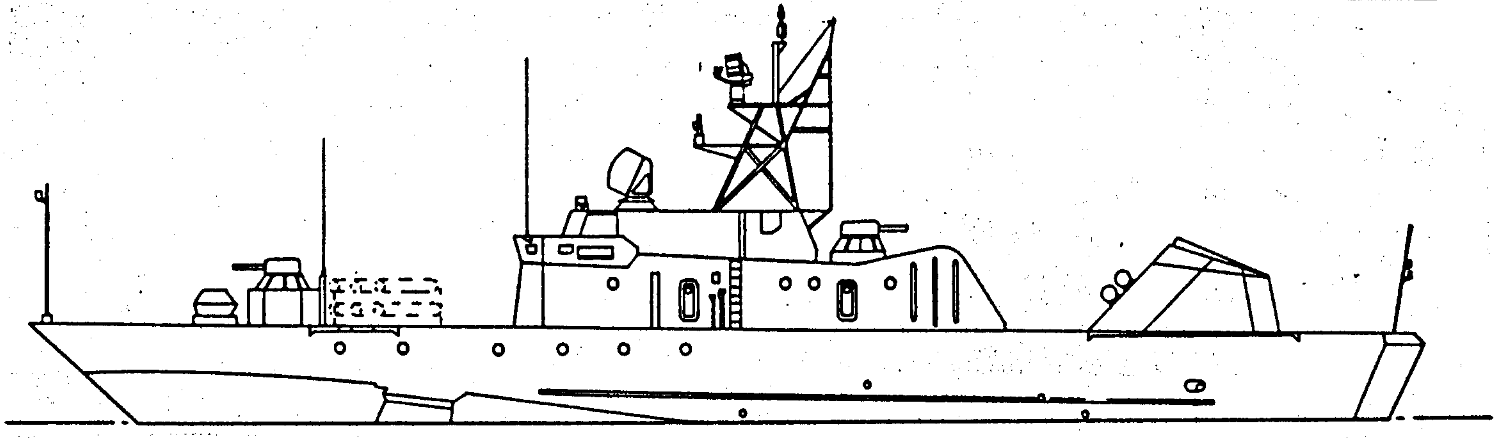
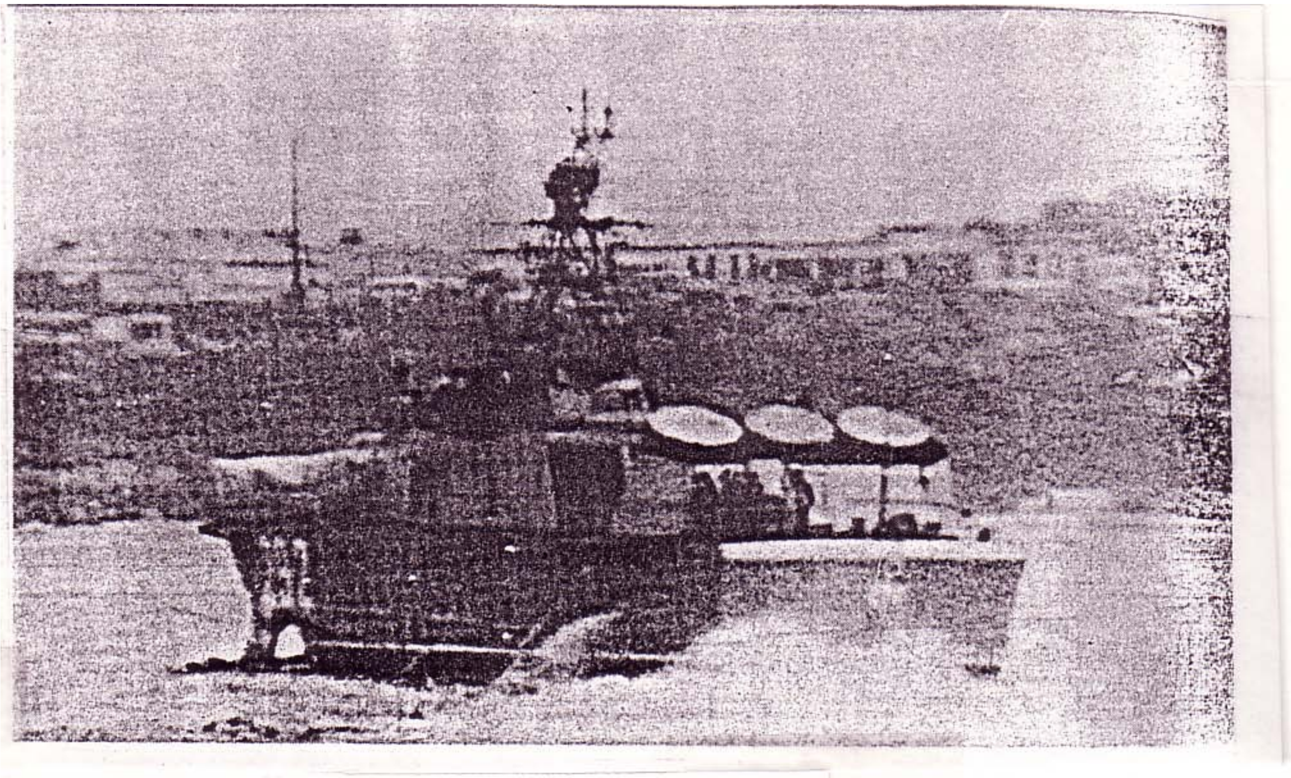


Illustration of the World's Largest Hydrofoil, BABOCHKA[48]



Stern View of BABOCHKA[48]

References have been made to U.S. Navy hydrofoils several times in describing the Soviet Navy hydrofoils. The table below summarizes some of the pertinent characteristics of USS PEGASUS and somewhat comparable Soviet Navy hydrofoils.

	PEGASUS	TURYA	MATKA	SARANCHA	BABOCHKA
LENGTH	133 FT.	129 FT.	129 FT.	148 FT.	164 FT.
BEAM	28 FT.	27 FT	28 FT.	33 FT.	28 FT.
DISPLACEMENT	231 T.	250 T.	215 T.	280 T.	400 T.
GUNS	76 mm	TWIN 57mm TWIN 25mm	76mm 30mm	30mm	30mm (2)
TORPEDOES	0	4	0	0	8
MISSILES	8 HARPOONS	0	2 SS-N-2C	4 SS-N-9 2 SA-N-4	?
SPEED	40+KNOTS	42 KNOTS	40 KNOTS	45 KNOTS	50-55 KNOTS
CREW	23	30	33	35	45

Comparison of USS PEGASUS and Soviet Navy Hydrofoils[50]

WHY NOT HYDROFOILS IN THE U. S. A.???

Hydrofoils have not proliferated the rivers, lakes, and coastal areas of the United States. The reason for this is not obvious to the average observer. On the contrary, from what has been said about hydrofoils, it would be easier to understand why the use of hydrofoils should be more prevalent in the U.S. After all, we're the high-tech society, right?

The explanation is not simple, and there may be conflicting opinions on the subject. However, central to the explanation are three general points which collectively shed some light on the problem. One point is that Americans are enamored with their automobiles. Taking a hydrofoil from point A to point B means one has to park his car at point A. Then what do you do when you get to point B? "Where's my car?" Is there a bus, or train or plane at point B to take me where I really want to go, and will the cost be acceptable? If I'm left high and dry at point B, I'm not going to leave my car at point A and "take any ole hydrofoil anyplace!"

Another point. Hydrofoil design and construction of any significance in the United States has been just about 100% sponsored by the U.S Navy, and as we have seen, the hardware has been very high-tech in character - meaning complex and expensive - compared to the European and Soviet hydrofoils that have been described. As a result, if a potential passenger ferry operator was to operate U.S.-built hydrofoils of this ilk, he would have to pass a relatively high seat-mile cost onto his passengers. A market analysis would probably show that not many customers would pay the high price of such sophisticated travel. Government subsidy could bring the price down to acceptable levels, but in the environment of the 1990s, the chances of lobbying for such an arrangement are small.

One may ask, well why not purchase a European-built, simple, low-cost hydrofoil and operate it on the host of potential routes all over the U.S.? After all, like the Soviet Union, the U.S. has many rivers and lakes plus thousands of miles of coastal areas. Now enters the "Jones Act" - a law that states in simple language: foreign built boats and ships are not permitted to he used for public transport between two domestic points within the United States. This act prevails in spite of the fact that it is certainly not consistent with the import of millions of cars, trucks, buses and airplanes that are used domestically!

So under the current law, a firm would have to build a "low-tech", low-cost hydrofoil in the U.S. and operate it on a route that makes sense, be part of an integrated transportation system at both ends of the hydrofoil route, and draw sufficient passengers to make an acceptable profit. As yet, all of this has not occurred successfully for a significant length of time in the United States.

A high-speed waterborne transportation study[51] was performed in the 1983 to 1984 time frame for the Department of Transportation. These seven volumes of information on high-speed marine vehicle passenger travel elaborates most eloquently on this subject and is highly recommended to anyone wanting to pursue this subject in detail.

A breakthrough in this situation in the United States may come about as a result of a recent development. It is understood that Kawasaki, as was mentioned, is licensed to build JETFOILs in Japan, is pursuing the prospect of having JETFOILs built by an American firm for use on passenger ferry routes in the United States. This development, although ironical for Boeing, would be interesting to see come to fruition.

CHAPTER 9

WHAT'S NEXT?

It is regrettable to say that since development, production, and deployment of the PHM, JETFOIL, and SHIMRIT hydrofoils, advancement of hydrofoil technology in the United States, and particularly the U.S. Navy, from the mid-1980s has been restricted to essentially "paper studies". The desire on the part of hydrofoil technologists for more research and development to reduce cost and improve performance has not been shared by those decision makers having control of research and development funding. Priorities have been placed elsewhere, but the hydrofoil community has had an opportunity from time to time to provide conceptual studies, feasibility designs of hydrofoils to suit a variety of purposes and missions. Within the constraints of national security, this chapter will describe some of these endeavors. But first let's talk a little bit about a dilemma facing U.S. Navy decision makers when it comes to "small" ships.

THE PLANING CRAFT VS HYDROFOIL DILEMMA

Whether it be a navy or a commercial ship operator, the choice between a hydrofoil versus a planing hull is somewhat like a choice between apples and oranges. Comparisons galore have been made and will probably continue to be made ad infinitum. The U. S. Navy spent $10 Million on a comparison of a host of Advanced Vehicles in the late 1970s. Also, in the late 1980s hydrofoils, planing hulls, and surface effect ships (SES) were compared for a given high performance requirement. When the price tag got too high, the requirement was changed to be less stringent so that less expensive, relatively low performance planing-type boats could do the "job". The question as to what is the appropriate "job", or requirement, is always a tough one to get decision makers to agree on and stick to when the price tag rises.

In the early 1950s, Gabrielli and von Karman (of California Institute of Technology fame) wrote a paper on "What Price Speed".[52] It is a classic and has been updated from time to time as the size and speeds of the broad scope of "vehicles" from million-ton tankers to supersonic aircraft have entered the picture. There is no way to beat nature on this one! Speed costs money! One might also say that comfort, or ride quality, as the technologist would put it, costs money. The hydrofoil, with a fully-submerged foil system, offers both speed and comfort in a small ship, and every cost analysis that has been done will give the same result: higher cost than an "equivalent" planing craft. "Equivalent" being in its ability to carry a crew and payload from point A to point B. On the other hand, a monohull or planing hull will never offer the rough water speed and ride quality of an equivalent hydrofoil.

The question then resolves itself as to whether or not the decision maker (naval or commercial) sitting in a comfortable, plush-chaired office, is willing to pay the price of getting a hydrofoil from point A to point B faster and in a manner so that the crew can perform its tasks aboard ship more proficiently, and successfully complete the mission at a high level of morale. If he ignores the latter factors and opts to "save money", play it safe, and make certain there are no chances of failure on "his watch", he will <u>not</u> select a hydrofoil, but rather compromise the sailor's ability to do his job with a monohull or planing hull.

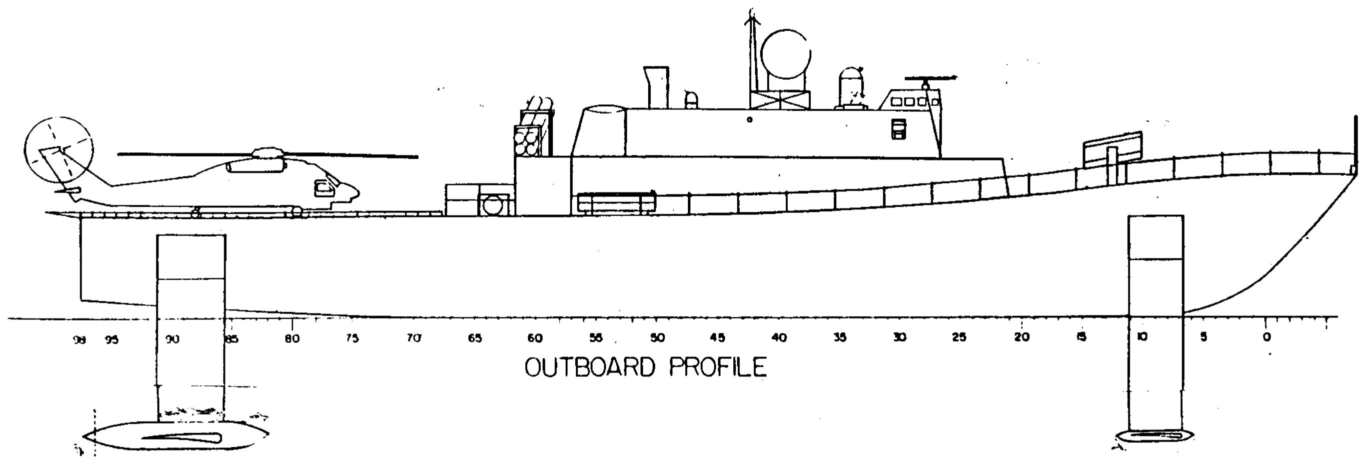
NEXT GENERATION U.S. NAVY HYDROFOILS

In spite of the above, a host of "paper" hydrofoils have been studied as potential designs for the future U.S. Navy hydrofoils. These have consisted of ships in the size category of from 300 to 2,400 tons. Several of these hydrofoils, such as the PHM Growth and the PHM Hybrid Hydrofoil, based on the PHM were described in Chapter 6. The reader should be aware that the list of "paper" hydrofoils described below is in no way complete, but those shown do represent the breadth of work that has been accomplished in this area.

CORVETTE ESCORT

The Corvette Escort hydrofoil design shown here is about 615 tons, is 196 feet long, has a maximum beam at the deck of about 39 feet, and a beam across the foils of 47.5 ft.. A unique feature of the ship is its propulsion and ship service power arrangement which makes it possible to meet the stringent requirements that were established. A normal-conducting electric transmission system is used instead of a gear and shaft arrangement. A single LM 2500 gas turbine engine drives two different sized electric generators. One of them, the larger, is connected electrically to two electric motors in the two propulsion pods at the bottom of the aft struts. The other generator provides electric service power for the entire ship.

This U.S. Navy Corvette Escort hydrofoil design features a retractable, fully submerged Pi-type foil/strut system both forward and aft. Incorporation of an electric drive system mentioned above provides arrangement flexibility, thereby enabling a relatively large unobstructed aft deck for accommodation of a LAMPS III helicopter.



Corvette Escort Hydrofoil

Mission equipment planned for the Corvette Escort hydrofoil includes: LAMPS III helicopter with reloading and refueling capability, high speed Depressor Towed Array System (DTAS) for detection, classification and tracking of targets, Expendable Reliable Acoustic Path Sonobuoy (ERAPS) for detection, classification and localization of submarines, sonobuoys, free-floating line arrays, Advanced Light Weight Torpedoes (ALWT), missiles, and electronic warfare equipment.

Although several propulsion system alternatives were explored during the early design work, the final selection consisted of a combined gas turbine or gas turbine (COGOG) using an LM2500 or TF40 combined propulsion and ship service system. The LM2500 drives a 16 megawatt (Mw) normal conducting liquid-cooled generator and a 0.4 Mw alternator. The 16 Mw generator, in turn, is connected to two 8 Mw liquid-cooled normal conducting motors located in pods at the aft foil/strut intersections. A planetary gearbox in each pod drives controllable pitch propellers for either hullborne or foilborne operation. A TF40 gas turbine drives a 4 Mw generator and a 0.4 Mw alternator. With the 4 Mw generator connected to the propulsion motors, a hullborne speed of about 15 knots is estimated. The 0.4 Mw alternators are connected to the ship's service system. An auxiliary power unit is provided for docking and maneuvering at speeds up to 8 knots and consists of a 510 hp P&W ST6J-70 gas turbine with outdrive. It was found that this total system maximized usable fuel and hence resulted in relatively large fuel margins and range compared to alternative designs.

The foil/strut system was of HY 130 steel construction. Several forward strut steering approaches were considered consisting of rotating struts, strut trailing edge flaps, circulation control, and ventilation control. This area has been identified as one in which R&D is required to resolve the steering problem on forward "Pi"-type foil systems.

DEVELOPMENTAL BIG HYDROFOIL

During the 1970s, several U.S. Navy designs for hydrofoils of about 750 tons were studied for a trans-oceanic mission. These were referred to as the DBH, Developmental Big Hydrofoil; also dubbed the "Damn Big Hydrofoil".

The study concluded that such hydrofoils could be constructed to meet specified performance criteria. Mission roles for which the DBH was designed include Anti-Submarine Warfare (ASW), Surface Warfare (SUW), and limited Anti-Air Warfare (AAW) for self defense as primary; shore bombardment, coastal patrol and surveillance and electronic warfare were secondary roles.

Developmental Big Hydrofoil

Two LM2500 gas turbines power the ship in the foilborne mode. They drive through a right-angle transmission which permits both single and dual engine operation of both supercavitating pusher propellers. A unique feature of this design is an arrangement which allows the struts to retract about the input shaft axis without a disconnect coupling and permits propellers rotating in opposite directions. Hullborne propulsion is provided by two smaller gas turbine engines rated at 2,500 horsepower. Each one drives a controllable-reversible- pitch (CPR) propeller through reduction gears and a retractable outdrive.

The hull of the DBH is of a conventional planing form with a canard-configured strut/foil system. The ship has an overall length of 173 ft. and a maximum beam of 45 ft. With the foils retracted, the navigational draft is about 10 ft., whereas with the foils down, the hullborne draft of DBH is 39 ft. This contrasts with only 12 ft. of draft when the ship is foilborne.

A dynamic lift of 717 tons is provided by the foil system; the load is distributed 33% on the forward foil, 67% on the aft foil which has a span of 85.5 feet. The forward foil/strut system is an inverted "T" which retracts forward into the bow and the aft system is an inverted "Pi", retracting over the stern in the same manner as PHM. As in all hydrofoils with a fully-submerged foil system, an automatic control system is incorporated in DBH similar to that on the PHM.

A combat subsystem was selected to provide a "representative" assortment of weapons, surveillance and combat and control equipments for escort type vessels. The combat subsystem consists of: a MK 16 launcher (mounted aft), ASROC, HARPOON missiles, chaff dispensers, torpedo tubes, torpedoes, OTO Malara 76mm cannon (mounted forward), 20mm Close-In Weapon System, and associated fire control systems.

GRUMMAN HYD-2

In the late 1970s a major U.S. Navy study was undertaken to investigate a wide variety of advanced naval vehicles. Of the several hydrofoils studied, one was a design by the Grumman Aerospace Corporation - the HYD-2 shown here.[53] It was 2400 tons, 365 ft. long, had a 116 ft. aft foil span, and the aft deck was equipped with a helicopter hangar and landing pad. Its foilborne propulsion system used two Pratt and Whitney FT-9 gas turbines with a power output of 43,000 hp each!

The 2,400- ton hydrofoil ship is capable of achieving a maximum foilborne speed of 53.1 knots in calm water.[53] In sea state 6, the speed is projected to be reduced only a small amount to 51.6 knots. The maximum foilborne range in calm water is 2,950 nm at 45 knots. The foilborne propulsion system drives two controllable- pitch propellers through a combined transmission arrangement. Hullborne propulsion is provided by one General Electric LM500 gas turbine driving two identical propellers through the combined transmission arrangement. Maximum hullborne calm water speed is about 26 knots using one FT-9 or 15 knots with the LM500. The hullborne engine is rated at 4,650 horsepower continuous. Electric plant prime movers are three Lycoming TF-35 gas turbines rated at 2,800 horsepower each.

Grumman 2400 Ton HYD-2 Hydrofoil[53]

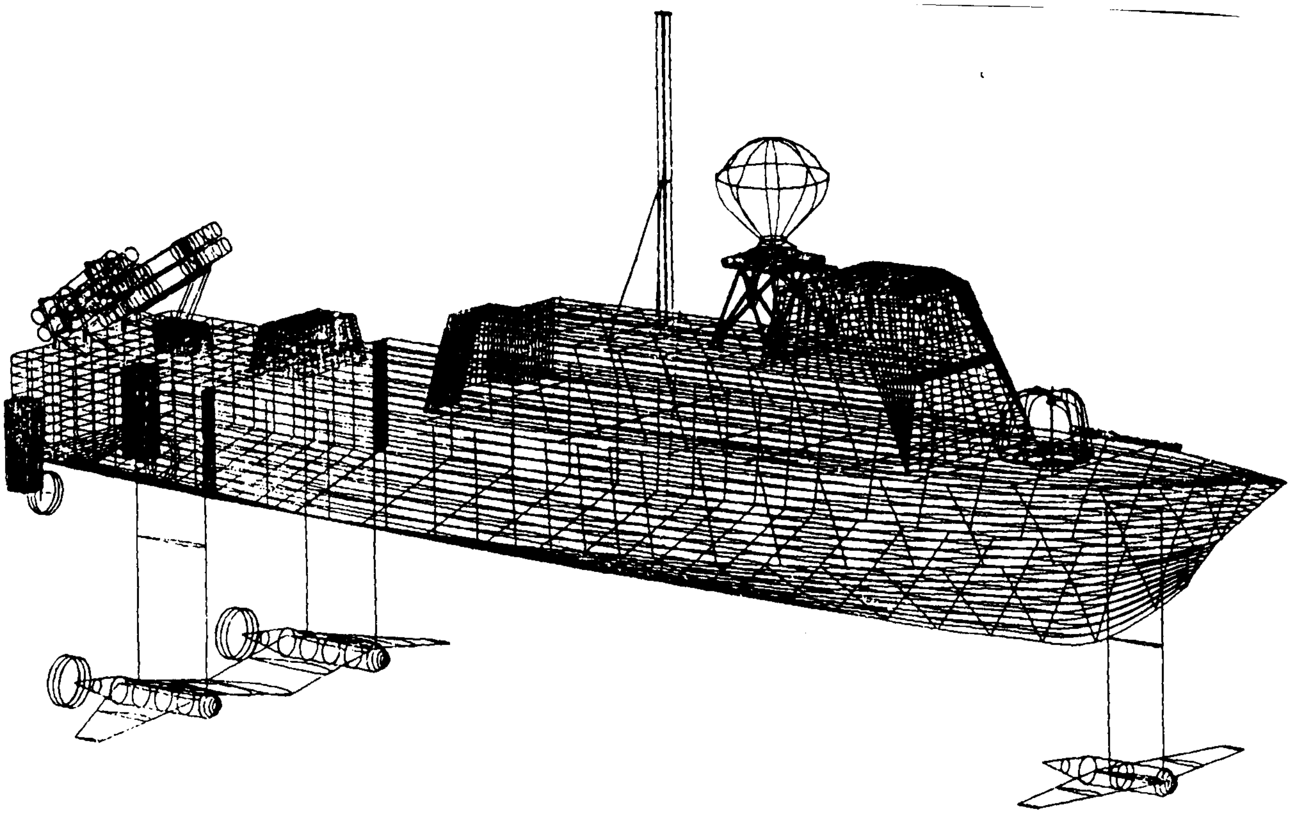
The foil system selected for the MK 63 consists of two inverted "Pi" assemblies. The aft foil system supports 60% of the craft weight; the forward system, 40%. The aft assembly consists of a foil, two struts, two pods, housing the flap control mechanism and the power transmission, and two propellers located at the aft end of the pods. The two struts are mounted on either side of the hull; the system retracts in the aft direction. The forward system is similar but with smaller pods. A third pod is located at the forward foil root chord housing the foil folding mechanisms, and steering trunnions are located above the keel line for the steerable struts. All struts have NACA 16 series sections and constant chord over their length.

This vessel was designed to accommodate a variety of combat systems for various missions. The primary Anti-Aircraft Warfare (AAW) suite includes: advanced radar and fire control systems, multimode missiles, advanced vertical launching system, and advanced self-defense missiles with launchers. For the Surface Warfare (SUW) suite, HARPOON missiles are added. For the

Anti-Submarine Warfare (ASW) suite the following items are added: various towed sonar arrays, MK 48 improved torpedoes, Advanced Lightweight Torpedoes (ALWT), and LAMPS MK III helicopter and associated equipment.

PCM

Two U.S. Navy hydrofoil design studies performed in the latter part of the 1980s includes the PCM, a patrol missile-carrying combatant, and a NATO hydrofoil. The PCM hydrofoil design illustrated here was intended to supplement the PHMs currently in the U.S. Fleet. Several variants of PCM were explored each to have a greater range than the PHM and some were to carry a more capable combat system. The entire Navy study also considered conventional monohull ships and Surface Effect Ships (SES).



PCM Hydrofoil

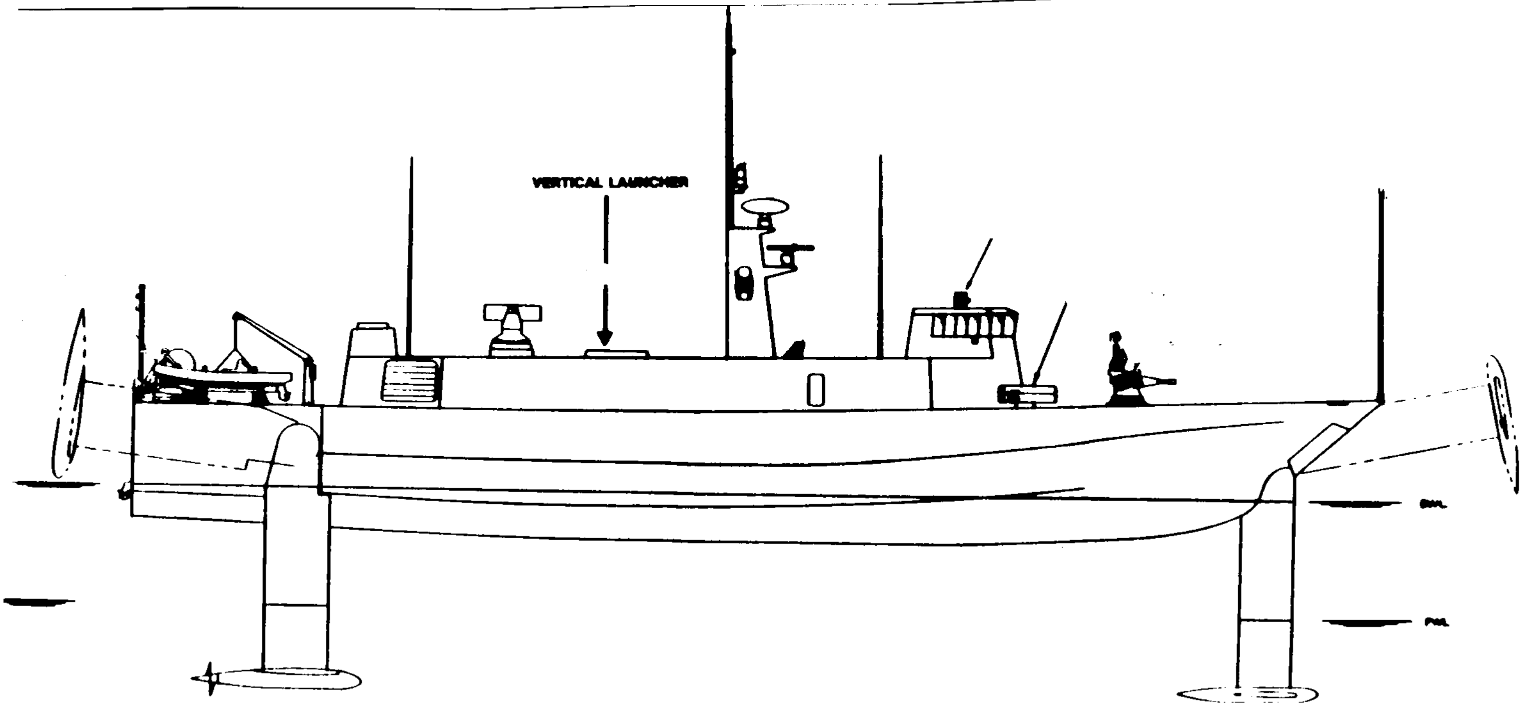
The PCM hydrofoil version illustrated above is about a 500 ton ship, and was much smaller than either the monohull or the SES projected to satisfy the same requirements. Power for foilborne operation would be one LM2500 gas turbine engine (as on the PHM except that the full power level of the engine would be utilized) but driving two propellers through a series of reduction gear boxes instead of the current PHM's waterjet. A separate propulsion system consisting of two diesel engines with retractable propellers would be used for hullborne operations.

Main foil span of the 147 ft. PCM was to be about 61.5 ft. with a hullborne draft of **28** ft. with the foils extended and only about **8.3** ft. with foils retracted. Instead of the 17-4PH stainless steel on PHM, the PCM was designed to use a different material, namely HY-130 steel. Although this steel requires a coating, it was anticipated that some of the problems with PHM foil material could be avoided. It should be noted that in spite of the fact that PHM foils were not originally anticipated to require a coating, the Navy finally decided to paint the 17-4PH stainless steel to reduce foil maintenance costs.

The PCM crew was to consist of 4 officers, 1 Chief Petty Officer, and **24** enlisted personnel. This was only a small increase in the crew members carried by the PHM. This version of the PCM carried about the same combat system, but with technical improvements and weight savings. Several other variants of PCM were explored with more extensive combat systems.

FUTURE HYDROFOILS FOR NATO?

A hydrofoil study that was performed by the U.S. Navy for a NATO mission resulted in a ship in many respects similar to the PCM hydrofoil described above. It is somewhat larger however at 780 tons, is 196 feet long, has a greater range, more elaborate weapon system and a larger crew. Because of the NATO connection, two British Rolls Royce Spey gas turbine engines were selected at a rating of 15,000 hp each. The engines were interconnected to drive two propellers at the bottom of the aft struts through a series of gear boxes.

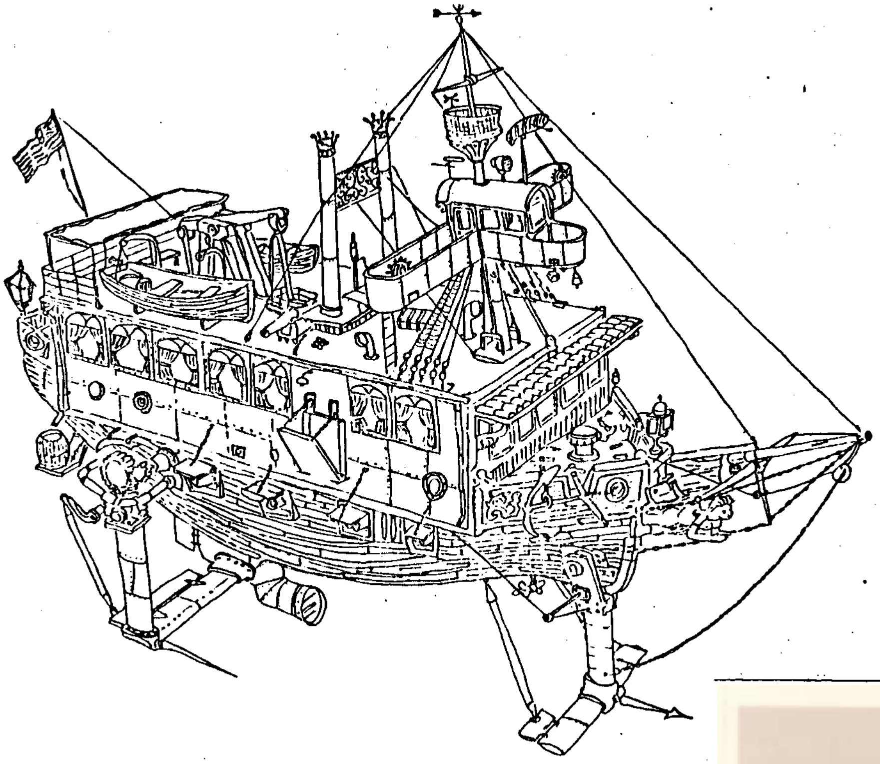


Future NATO Hydrofoil?

No definitive NATO advanced naval vehicle was ever produced as a result of this particular study. However, several NATO countries during the late 1980s and early 1990s were either studying or actually building several Surface Effect Ships (SES). Although most of the NATO countries will agree that the advantages of hydrofoils lie in their high speed, good seakeeping and good maneuverability in all but the worst sea conditions, the general perception of hydrofoils is that they are endurance limited and have used aircraft-type high-technology leading to high procurement and life-cycle costs.

To many of us in the hydrofoil technical community the "high cost" of a fully-submerged hydrofoil design is something that need not be a weight on our shoulders we have to suffer with forever! There are ways of reducing costs, particularly in the foil system, subsystem components and hull production methods. One may recall that only four Research and Development hydrofoils plus six PHM hydrofoils were built for the U.S. Navy. Although they provided an excellent technical base for future hydrofoil designs, applying inflationary factors to their costs to arrive at the cost of future hydrofoils, may be completely misleading-and discouraging. Alternate technical approaches, such as the PHM Hybrid Hydrofoil described in Chapter 6, combined with shipyard construction techniques are anticipated to result in "more hydrofoil" for less cost.

It remains to be seen how successful or acceptable medium size SES craft will be in an open ocean, North Sea, Baltic environment. Also will the estimated construction and operating costs be consistent with those actually experienced? We have seen that large hydrofoils are predicted to have acceptable range and endurance while retaining their unique advantages of high speed in rough water, excellent seakeeping, and superior maneuverability. It will be interesting to see if NATO countries are forced to go full circle: PHM hydrofoil to SES and back to a hydrofoil to satisfy their real requirements.



YE OLDE HYDROFOILE

Yes, it is no doubt true that the hydrofoil community has come a long way since Forlanini, Alexander Graham Bell, von Schertel and the unknown artist that concocted "YE OLDE HYDROFOILE" shown here.

Is the technology in hand to design and build the hydrofoil shown below? Probably not. But who knows what the next century will bring if the young hydrofoilers of today, and particularly those of tomorrow are given a chance to apply the everchanging technological improvements available to them?

Futuristic Hydrofoil Concept

EPILOGUE

As we look to the future, there are several quotations that those who would stand on the shoulders of the "Hydrofoilers of the Past" should remember and give serious consideration:

> THE GREAT ENEMY OF TRUTH IS VERY OFTEN NOT THE LIE - DELIBERATE, CONTRIVED AND DISHONEST, BUT THE MYTH - PERSISTENT, PERSUASIVE AND UNREALISTIC. TOO OFTEN WE HOLD FAST TO THE CLICHES OF OUR FOREBEARERS. WE SUBJECT ALL FACTS TO A PREFABRICATED SET OF INTERPRETATIONS. WE ENJOY THE COMFORT OF OPINION WITHOUT THE DISCOMFORT OF THOUGHT.
>
> John F. Kennedy

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"A MAN'S REACH SHOULD EXCEED HIS GRASP, OR
WHAT'S A HEAVEN FOR?"

Robert Browning

FURTHER READING

Parkin, J.H., "Bell and Baldwin; Their Development of Aerodromes and Hydrodromes at Baddeck, Nova Scotia." University of Toronto Press, 1964.

Nutting, W.W., "The HD-4, a 70-Miler With Remarkable Possibilities." Reprinted Smithsonian Institution Report for 1919, Pub. 2595, Government Printing Office, 1921.

von Schertel, H., "Experiences of a Pioneer Hydrofoil Designer", Talk presented to the AIAA Advanced Marine Vehicles Conference, Annapolis, Md., July 1972.

Barbour, Alex, "Reconstruction of the HD-4 Hydrofoil, 1976-1979." Parks Canada, Atlantic Region, Draft Report EA-PC-82-15, July 1982.

Buermann, T.M., Leehey, LCDR P. (USN), and Stillwell, CDR J.J. (USN), "An Appraisal of Hydrofoil Supported Craft." Paper Presented at SNAME Meeting, New York, NY, 12-13 November 1953.

Oakley, O.H., "Hydrofoils-A State of the Art Summary." Proceedings of the Institute of Aeronautical Sciences, National Meeting on Hydrofoils and Air Cushion Vehicles, 17-18 September 1962.

Lacey, R.E., "A Progress Report on Hydrofoil Ships." Quarterly Transactions, Royal Institution of Naval Architects, Vol. 107, No. 1, January 1965.

Gunston, Bill, "Hydrofoils & Hovercraft, New Vehicles for Sea and Land." Doubleday Science Series, Doubleday & Co., Inc., Garden City, NY, 1970.

Eames, M. C. and Jones, E.A., "HMCS BRAS D'OR-An Open Ocean Hydrofoil Ship." Transactions Royal Institute of Naval Architects, Vol. 113, 1971.

Jeffry, N.E. and Eames, M.C., "Canadian Advances in Surface-Piercing Hydrofoils." SNAME Journal of Hydronautics, Vol. 7. No. 2, April 1973.

Eames, M.C. and Drummond, T.G., "HMCS BRAS D'OR-Sea Trials and Future Prospects", Transactions Royal Institute of Naval Architects, Vol. 115, 1973.

Lynch, T. G., "The Flying 400." Nimbus Publishing Ltd., Halifax, Nova Scotia, Canada, 1983, ISBN 0-920852-22-X.

Hoerner, Dr. S.F., "Five-Ton Autopilot-Stabilized Hydrofoil Research Craft-Hydrodynamic Tests and Analysis." Gibbs & Cox, New York, NY, Report to Office of Naval Research, November 1958.

Browne, R., "Running with SEA LEGS." Gibbs & Cox, New York, NY, Trip Report, September 1958.

"Study of Hydrofoil Sea Craft." Report PB 161759, Office of Technical Services, U.S. Department of Commerce, Prepared by Grumman Aircraft Engineering Corporation, 3 October 1958.

Godwin, R.P. and Higgins, J.A., "The Maritime Administration Hydrofoil Program." Paper Presented at Hydrofoil Transportation Conference Sponsored by University of California at Lake Arrowhead, CA, 17 April 1961.

Wennagel, G.J., "Characteristics of the U.S. Maritime Administration Hydrofoil Test Vehicle." Paper Presented at SAE National Aeronautics Meeting, 1961.

Sullivan, E.K. and Higgins, J.A., "Test and Trials of the HS DENISON." Published by the Maritime Administration, circa 1962.

Bovee, E.C., "Design and Construction of the PC(H) Hydrofoil Patrol Craft." Paper Presented to Northwest Section Meeting, SNAME, Seattle WA, 5-6 October 1963.

Stevens, D.L., Jr., "The Bureau of Ships Hydrofoil Craft FRESH-I." Paper Presented to Chesapeake Section, SNAME, 26 February 1964.

Petrie, D.M., "Operational and Developmental Experience on the U.S. Navy Hydrofoil HIGH POINT." AIAA Journal of Aircraft, Vol. 3, No. 1, January-February 1966.

Ellsworth, W.M., "The U.S. Navy Hydrofoil Development Program-A Status Report." AIAA Paper 67-351, Presented at AIAA/SNAME Advanced Marine Vehicles Meeting, Norfolk, VA, 22-24 May 1967.

Vogt, James E., "Automatic Control of the Hydrofoil Gunboat, TUCUMCARI," AIAA 2nd Advanced Marine Vehicle and Propulsion Meeting, AIAA Paper No. 69-729, 1969.

Stark, D.R., "The PHM Automatic Control System", SAE National Aerospace Engineering and Manufacturing Meeting, San Diego, CA, Oct. 1974.

Johnston, R.J. and W.C. O'Niell, "The Development of Automatic Control Systems for Hydrofoil Craft", International Hovercraft, Hydrofoil and Advanced Transit Systems Conference, Brighton, England, May 1974.

Puckett, L., "HICANS-Navigation for High Speed Ships." Journal of Institute of Navigation, Vol. 30, No. 2.

Irvine, J.E. and Williams, R.E., "Operational Evaluation of the Hydrofoil Concept for U.S. Coast Guard Missions, Phase III Report of Operations with USCG HIGH POINT (WMEH-1)." U.S. Coast Guard Report CG-D-192-75, July 1975.

Ehrmon, P.L. and Williams, R.E., "Operational Evaluations of the Hydrofoil Concept for U.S. Coast Guard Missions-Executive Summary", U.S. Coast Guard Report CG-D-14-76, December 1975.

Dogan, P.P., Gamber, F.S. and Decanto, F.T., "Hydrofoil Universal Digital Autopilot (HUDAP), Phase I Final Report." Charles Stark Draper Lab, Mass. Inst. of Tech., Report 745, January 1973.

Gamber, F.S. and Medetrios, A., "Hydrofoil Universal Digital Autopilot (HUDAP), Phase II Final Report." Charles Stark Draper Laboratory, Massachusetts Institute of Technology, Report 817, May 1974.

Duff, Karl M., "The NATO Patrol Missile Hydrofoil (PHM)", AIAA Paper No. 72-596, AIAA/SNAME/USN Advanced Marine Vehicles Meeting, Annapolis, MD, July 17-19, 1972.

King, John W., "The PHM-The NATO and U.S. Requirements", AIAA Paper No. 83-0614, AIAA/SNAME/ASNE 7th Marine Systems Conference, New Orleans, February 23-25,1983.

Patch, David A., "Operational Utilization of the Patrol Hydrofoil Missile (PHM)", First International Hydrofoil Society Conference, Ingonish Beach, Nova Scotia, Canada, July 27-30,1982.

Rieg, Donald F., and King, James H., "Technical Evaluation of the RHS-200 for High Speed Ferry Application and U.S. Coast Guard Missions", David Taylor Research Center Report No. DTNSRDC/SDD-83/10, December 1983.

REFERENCES

---

1. Hayward, L., "The History of Hydrofoils", Hovering Craft and Hydrofoils, Vol. 4, No. 8 (May 1965) - Vol. 6, No. 6 (Feb 1967).

2. Arseneau, Dr. D.F.,"Bell's Work in Baddeck", Paper dated January 7, 1982, Presented at 1982 Annual Meeting of the Association for the Advancement of Science, Washington, D. C.

3. Roos, A.E., "The Artifact as Historic Document: A. G. Bell's and F. W. Baldwin's Hydrofoil Boat", Parks Canada Research Bulletin No. 153, March 1981.

4. Johnston, R.J., "Historical Perspective", Hydrofoil Lecture Day, Massachusetts Institute of Technology Professional Summer, July 8, 1975.

5. Johnston, R.J., "History of U.S. Involvement in Developing the Hydrofoil", Paper Presented at 1st International Hydrofoil Society Conference, Ingonish Beach, Nova Scotia, Canada, July 27-30, 1982.

6. Von Schertel, Baron Hans, "European Development of Hydrofoil Craft Technology", Paper Presented at the 1st International Hydrofoil Society Conference, Ingonish Beach, Nova Scotia, Canada, July 27-30, 1982.

7. Ellsworth, W.M., "Twenty Foilborne Years - The U.S. Navy Hydrofoil HIGH POINT, PCH-I", David Taylor Research Center, 1987.

8. Eames, M.C., "A Review of Hydrofoil Development in Canada", Paper Presented at 1st International Hydrofoil Society Conference, Ingonish Beach, Nova Scotia, Canada, July 27-30, 1982.

9. Baker, G.G., "Design of Hydrofoil Boats with Particular Reference to Optimum Conditions for Operating in Waves", Baker Manufacturing Co., Engineering Report No. 248, July 29, 1960.

10. Alexander, Alan F., etal, "Hydrofoil Sailing", Juanita Kalerghi, 51 Welbeck Street, London, 1972.

11. Carl, W.P. Jr., and R.R. Gilruth, "Development of a 53-Foot Hydrofoil Vehicle", John H. Carl & Sons Report for Office of Naval Research, September 1954.

12. Browne, R., "Running With SEA LEGS", Gibbs & Cox, New York, N. Y., Trip Report, September 1958.

13. Myers, G.R., "Observations and Comments on Hydrofoils", Paper Presented at the Society of Naval Architects and Marine Engineers Spring Meeting, Seattle, WA., May 13-14, 1965.

14. Jones, E.A., "RX Craft, a Manned Model of the RCN Hydrofoil Ship BRAS d'OR", Journal of Hydronautics, Vol. 1, No. 1, July 1967.

15. Williams, R.E. and P.L. Ehrman, "Operational Evaluation of the Hydrofoil Concept for U.S. Coast Guard Missions-Executive Summary", Report No. CG-D-14-76, D. O. T., Dec 1975.

16. Johnston, R.J. and W.C. O'Neill, "A Ship Whose Time Has Come--And Gone", AIAA/SNAME Advanced Marine Vehicles Conference, Baltimore, MD, October 2 - 4, 1979.

17. Janes, "Surface Skimmers - Hovercraft and Hydrofoils", Edited by Roy McLeavy, 1978, 1980, and 1982.

18. Rodriquez, Leopoldo, and Di Blasi, Dino, "Current Status and Future Prospects for European Commercial Hydrofoils", Paper Presented at 1st International Hydrofoil Society Conference, Ingonish Beach, Nova Scotia, Canada, 27-30 July 1982.

19. Modern Ships and Craft, Special Edition of the Naval Engineers Journal, February 1985.

20. King, John W., "The PHM - The NATO and U.S. Requirements", AIAA Paper No. 83-0614 AIAA/SNAME/ASNE 7th Marine Systems Conference, New Orleans, Louisiana, February 23, 1983.

21. Olling, D.S., and R.G. Merritt, "Patrol Combatant Missile Hydrofoil-Design Development and Production - A Brief History", High Speed Surface Craft, January-February 1981.

22. Duff, Karl M., "Still The Master Of The Sea", Vantage Press, Inc, New York, N.Y.

23. Duff, Karl M., H. Schmidt, and M.R. Terry, "The NATO PHM Ship and Weapons Systems Technical Evaluation Program", AIAA Paper 76-848, AIAA/SNAME Advanced Naval Vehicles Conference, Arlington, VA, Sept 20-22, 1976.

24. Maier, Anton, "Trans-Oceanic Deployment/Fleet Exercise Experience", Hydrofoil Support Applied Technology, Inc., HY-311-062, 9 September 1985.

25. Chapin, Stephen, "The History of the PHM", Proceedings, September 1986, page 80.

26. Survey of Selected Grounding Incidents, "Case Number Forty Three".

27. Smith, R.H., "The PHM In Missions Of Regional Defense", Naval Reserve Association, May 1987.

28. Horn, Captain Frank, USN, "PHM Squadron Two Operational Experience", AIAA/SNAME/ASNE 7th Marine Systems Conference, New Orleans, Louisiana, February 1983.

29. Klinkenberger, F. J., "PHM's Show Their Capabilities", Surface Warfare, May/June 1983.

30. PHM Operational Notebook, Hydrofoil Office, David Taylor Research Center, April 1989.

31. Berns, Thomas H., "Some Tactical Considerations", Proceedings, Seotember 1986, p 84.

32. Boeing Document D312-80946-2, "Improved and Enlarged Variants of the PHM-3 Series Patrol Combatant Missile Hydrofoil", 31 October 1983.

33. Merritt, R.G. and R.L. Herechkowitz, "Variations on a Single Theme: Future Configurations and Growth of the Patrol Hydrofoil Combatant (PHM)", AIAA Paper 76-854, AIAA/SNAME Advanced Marine Vehicles Conference, Arlington, Virginia (September 20-22, 1976)

34. Coates, J.T.S., R.G. Merritt and T.C. Weaton, "Why PHM? Further Studies on Roles and Missions", AIAA Paper 78-729, AIAA/SNAME Advanced Marine Vehicles Conference, San Diego, California (April 17-19, 1978)

35. Meyer, John R., "HYBRID HYDROFOIL-A Concept Whose Time Has Come", Intersociety Advanced Marine Vehicles Conference, Paper No. 89-1450, Washington, D.C., June 1989.

36. Schab, H.W., "Life History of USS PLAINVIEW (AGEH-1) Hydrofoil Power Transmission Systems", DTNSRDC Report No. 80/109, December 1980.

37. Silverleaf, A. and F.G.R. Cook, "A Comparison of Some Features of High Speed Marine Craft", Royal Institution of Naval Architects, March 26, 1969.

38. Crew, P.R., "The Hydrofoil Boat; Its History and Future Prospects", Quarterly Transactions, The Institution of Naval Architects, Vol. 100, No. 4, October 1958.

39. King, James H. and M. Devine, "HANDE-A Computer-Aided Design Approach for Hydrofoil Ships", Naval Engineer's Journal, April 1981.

40. Fast Ferry Directory 1989, Fast Ferry International, September 1989.

41. Shultz, W.M., "Boeing JETFOIL Model 929-100", AIAA Paper No. 74-308, AIAA/SNAME Advanced Marine Vehicles Conference, San Diego, CA, February 25-27, 1974.

42. Shultz, W.M., "Current Status And Future Prospects United States Commercial Hydrofoils", Paper Presented at 1st International Hydrofoil Society Conference, Ingonish Beach, Nova Scotia, Canada, 27-30 July 1982.

43. "Boeing Marine Systems Confident About JETFOIL Prospects", Article in High Speed Surface Craft, February 1984.

44. "Evaluation of the Boeing JETFOIL SPEEDY in the Fishery Protection Role", Article in Combat Craft, p. 158, July 1983.

45. King, James H., "The Evolution of the NIBBIO Class Hydrofoil From TUCUMCARI", Paper Presented at 1st International Hydrofoil Society Conference, Ingonish Beach, Nova Scotia, Canada, 27-30 July 1982.

46. "Grumman M161 - Israel's Combat Hydrofoil", Defense Attache, pp 11-21, No. 5, 1981.

47. Frauenberger, H.C., "SHIMRIT Mark II Hydrofoil For The Israeli Navy", Paper Presented at 1st International Hydrofoil Society Conference, Ingonish Beach, Nova Scotia, Canada, 27-30 July 1982.

48. Janes High Speed Marine Craft and Air Cushion Vehicles, Janes Publishing Co. Ltd., 1987 and 1989.

49. Hovering Craft and Hydrofoil, Vol. 1, No. 3, p.8, December 1961.

50. Surface Warfare, May/June 1983.

51. "Study of High Speed Waterborne Transportation Services Worldwide", Urban Mass Trans. Agency, UMTA-IT-32-0001-84-3, August 1984, Seven Vols., NTIS #PB 85129906/U.

52. Gabrielli, G. and Theodore von Karman, "What Price Speed?", Mechanical Engineering, Vol. 72, October 1950.

53. Pieroth, C., "Grumman Design M163, a 2400 Metric Ton Air Capable Hydrofoil Ship", AIAA Paper 78-749, AIAA /SNAME Advanced Marine Vehicles Conference, San Diego, CA, April 17-19, 1978.

APPENDIX A

HYDROFOIL SKETCHES AND DATA

This Appendix contains illustrations, outline drawings, sketches, and tabulated data for several of the hydrofoils described in the main portion of the book that may be of interest to the reader.

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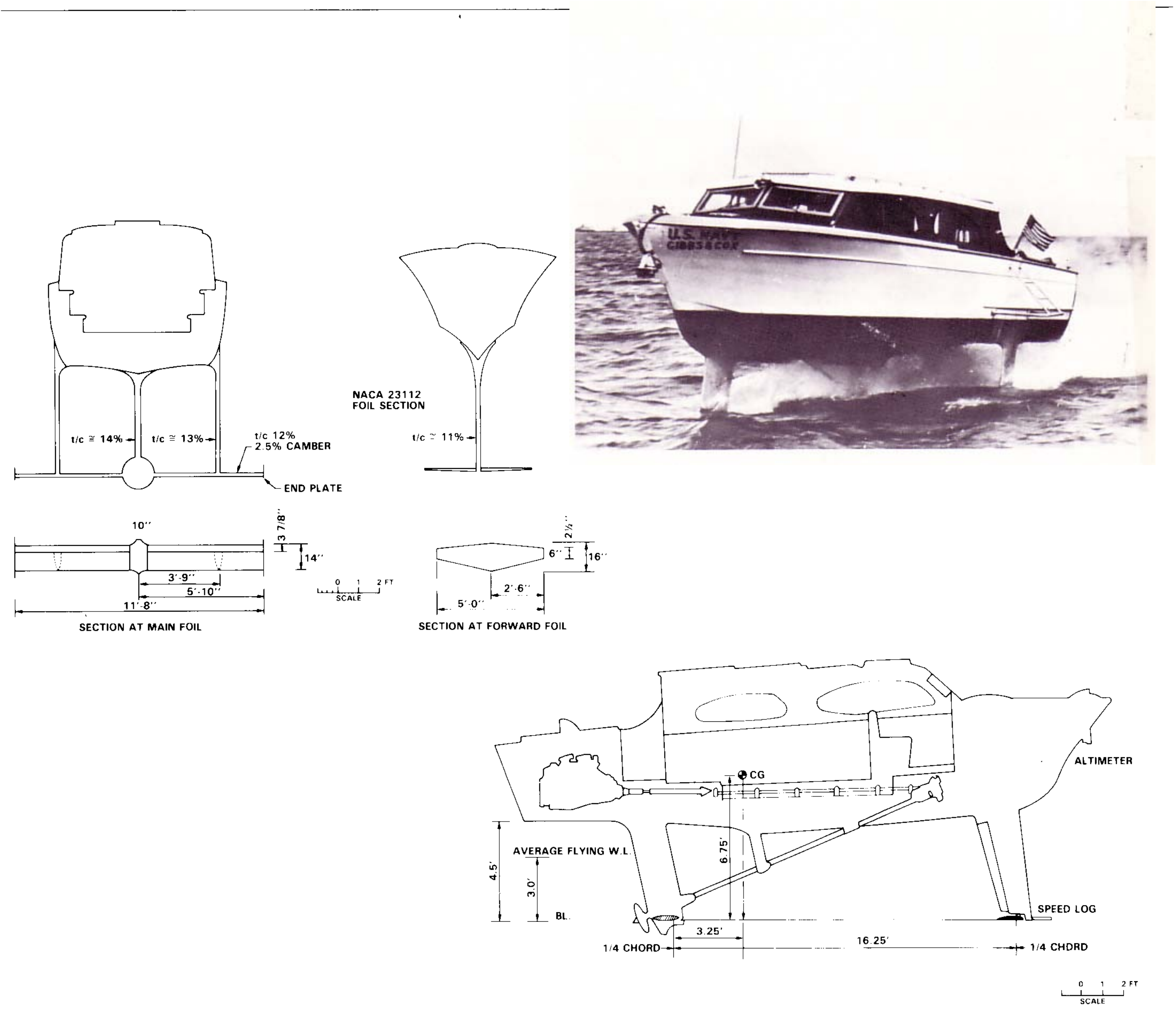
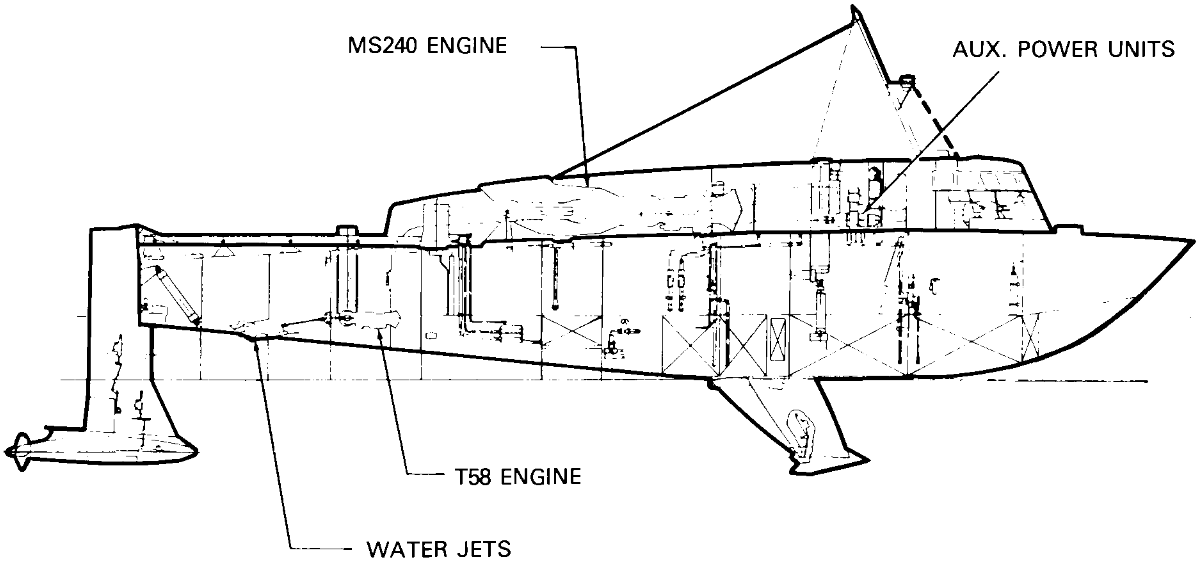
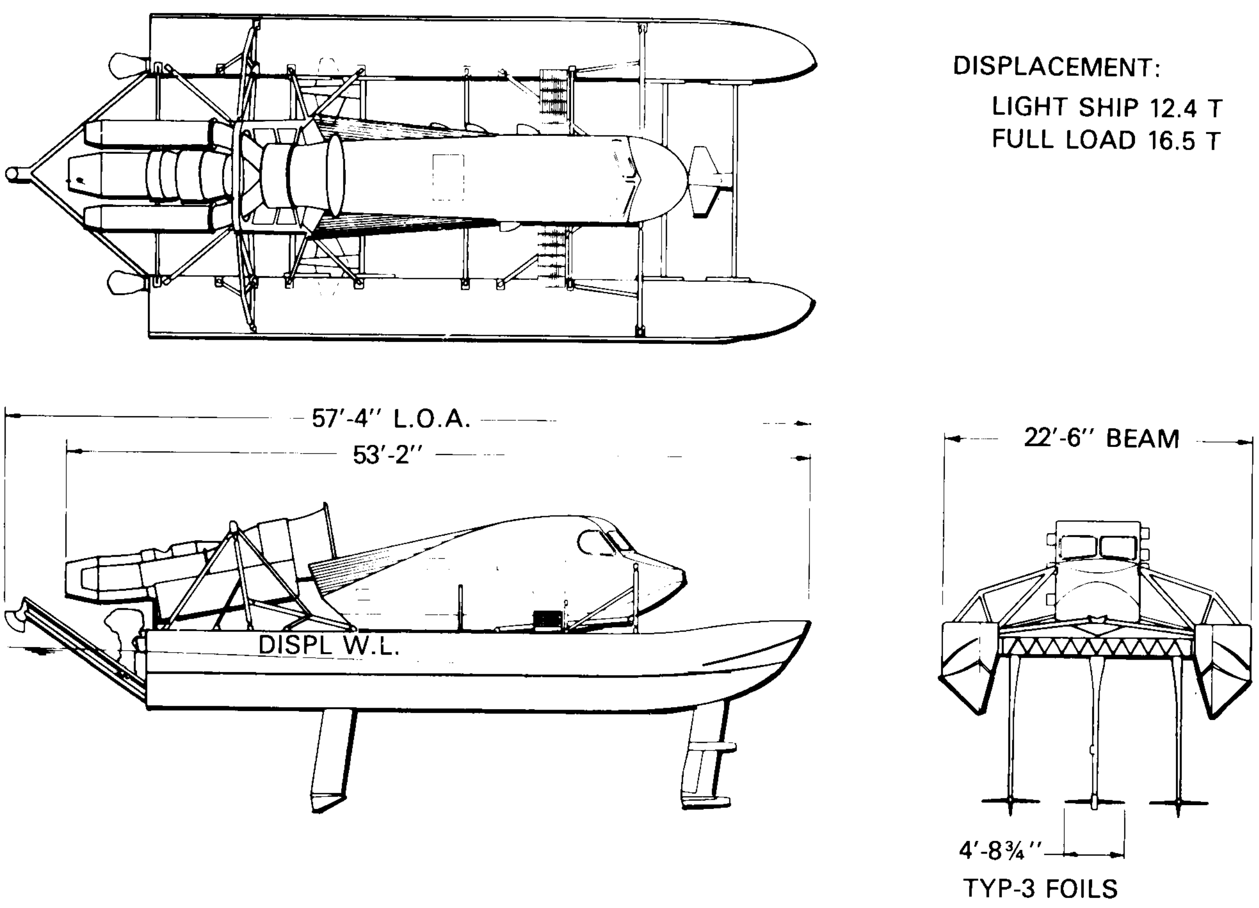


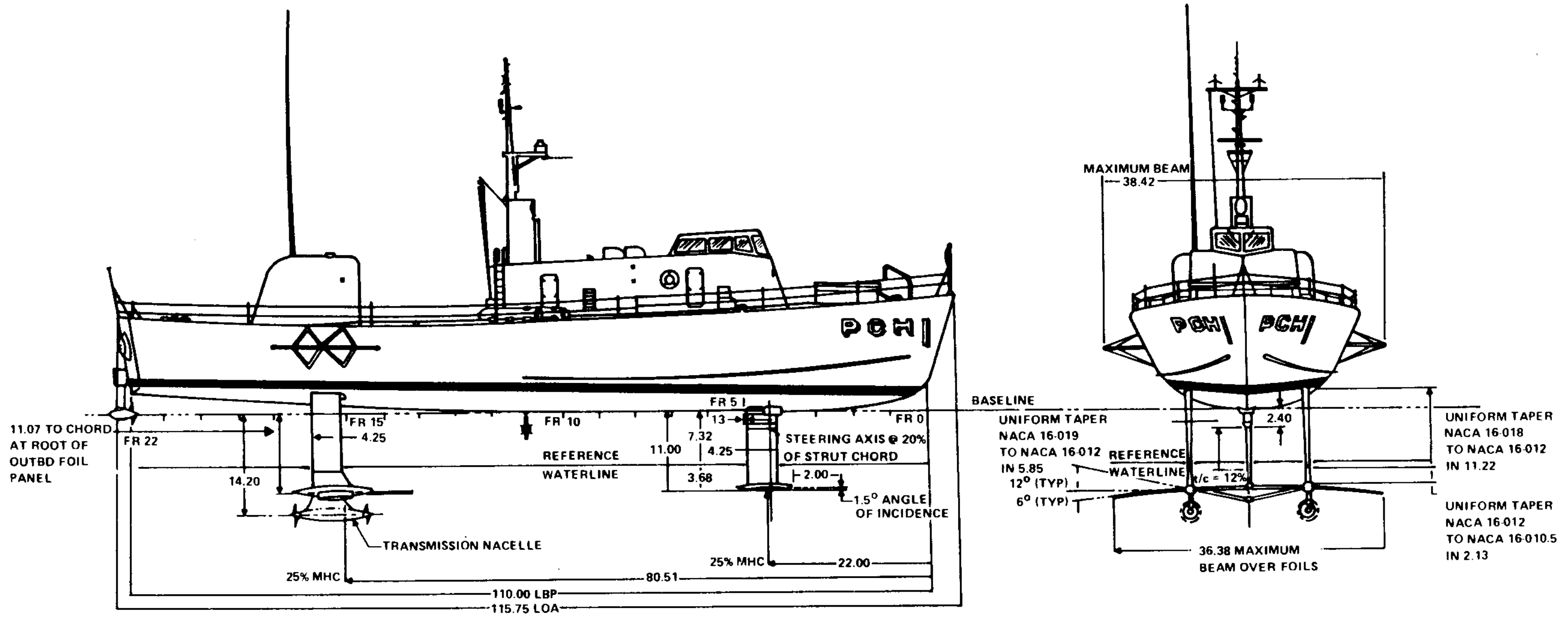
SEA LEGS - Hydrofoil Test Craft Particulars[7]

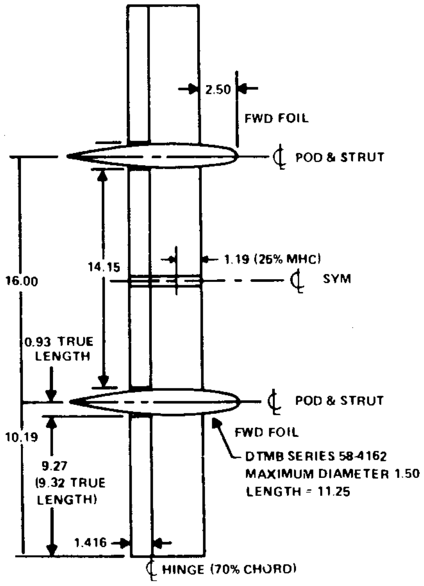


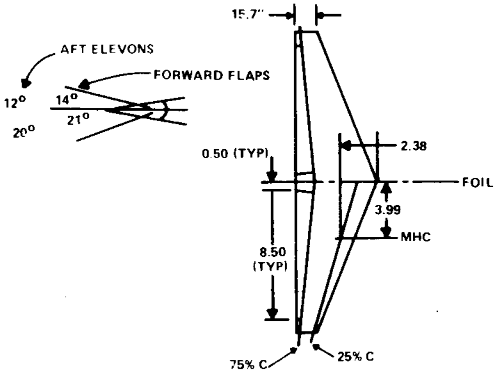
HS DENISON - Machinery and Systems[7]



FRESH-1 - Principal Dimensions in Canard Configuration[7]







AFT FOIL

W/S	1060 lbs/ft^2
S	172.85 ft^2
Æ	7.65
b	36.38 ft
C_R	4.75 ft
C_T	4.75 ft
λ	0.00
MHC	4.75 ft
t/c	0.09
SWEEP $^c/_4$	0°
DIHEDRAL ANGLE	6° OUTBOARD - 12° INBOARD
% TOTAL FOIL AREA	72.48
TOTAL FLAP AREA	46.29 ft^2
FLAP CHORD / FOIL CHORD	0.3
SECTION	NACA 16-309

FORWARD FOIL

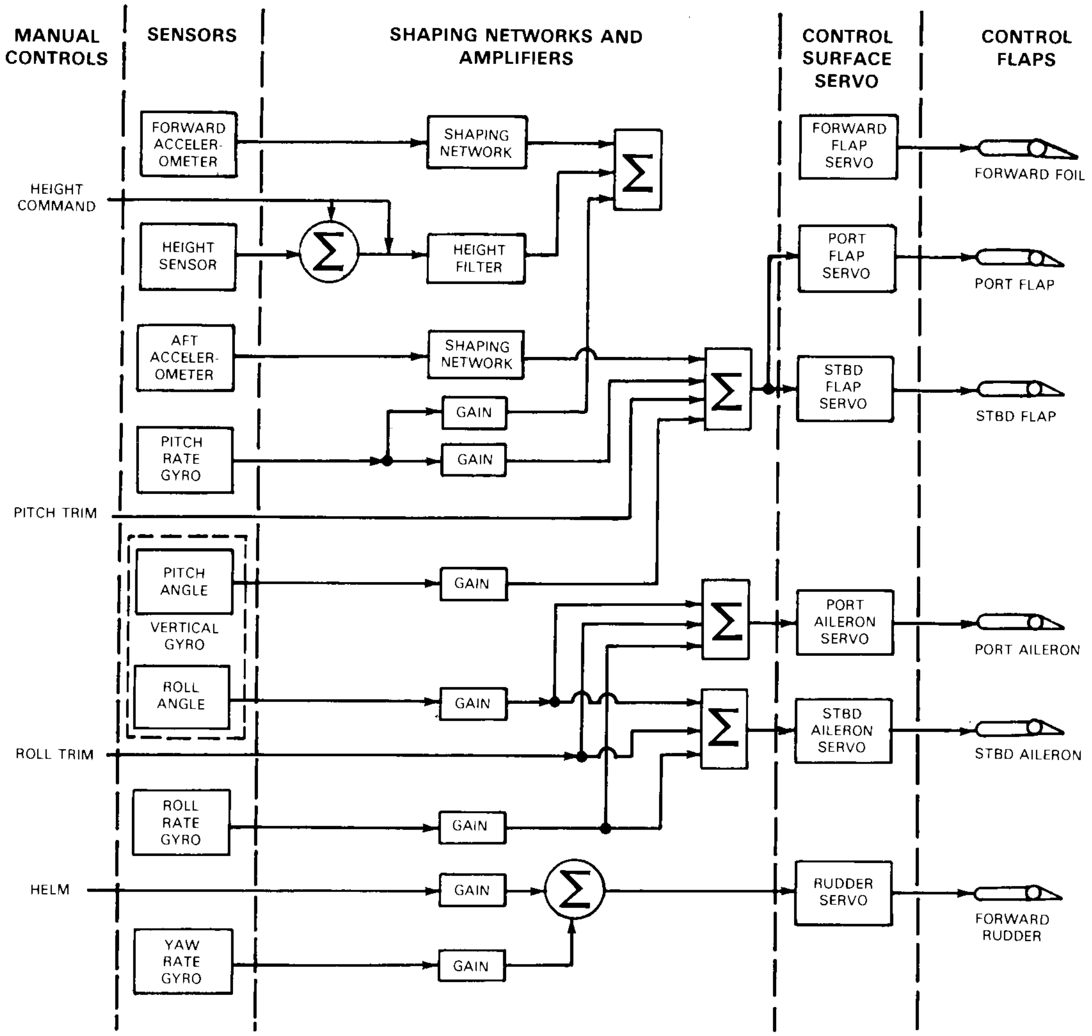
W/S	1370 lb/ft^2
S	65.63 ft^2
Æ	6.1
b	20.0 ft
C_R	5.25 ft
C_T	1.31 ft
λ	0.25
MHC	3.68 ft
t/c	0.09
SWEEP $^c/_4$	15°
DIHEDRAL ANGLE	0°
% TOTAL FOIL AREA	27.52
TOTAL FLAP AREA	6.416 ft^2
FLAP CHORD / FOIL CHORD	0.25
SECTION	NACA 16-309

NOTE:

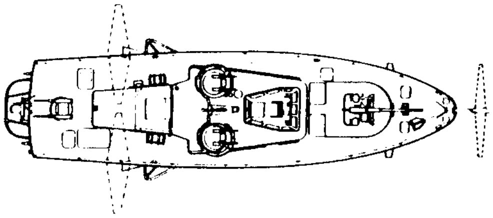
ALL DIMENSIONS ARE IN FEET (EXCEPT AS NOTED)

FWD STRUT ROTATES ± 10°

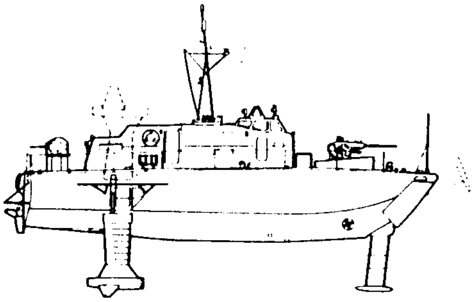
HIGH POINT - MOD-1 Geometric Characteristics[7]

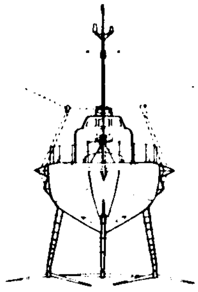


Schematic and Block Diagram of PCH Autopilot[7]



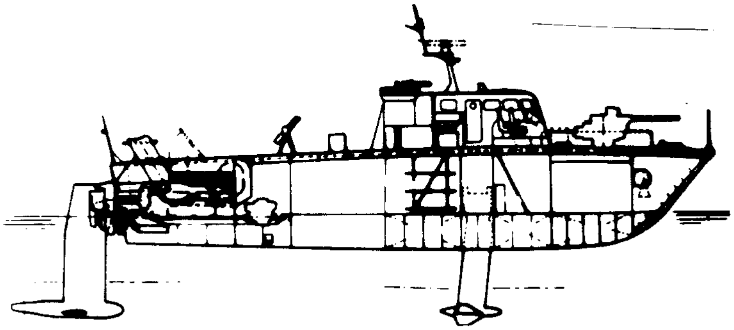
FULL LOAD DISPLACEMENT 57.4 Long Tons
LOA = 71.8 Ft. LBP = 65.8 Ft.
LBP 65.9 Ft.
BEAM = MAX. = 35.3 Ft (foil extended)
DWL. = 17.0 Ft
DRAFT: FOILS EXTENDED 13.9 Ft
FOILS RETRACTED 4.5 Ft
FUEL: JP-5 or DIESEL OIL Wt 11.05 LT
(3,537 gals)
CONFIGURATION: CANARD
FOIL LOADING DISTRIBUTION: fwd = 31% aft = 69%
MANNING: 13 (1 officer & 12 enlisted)
TOTAL SHIP STRUCTURAL DENSITY = 11.9 lbs/ft^3

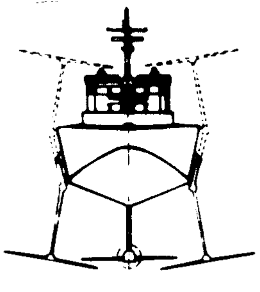




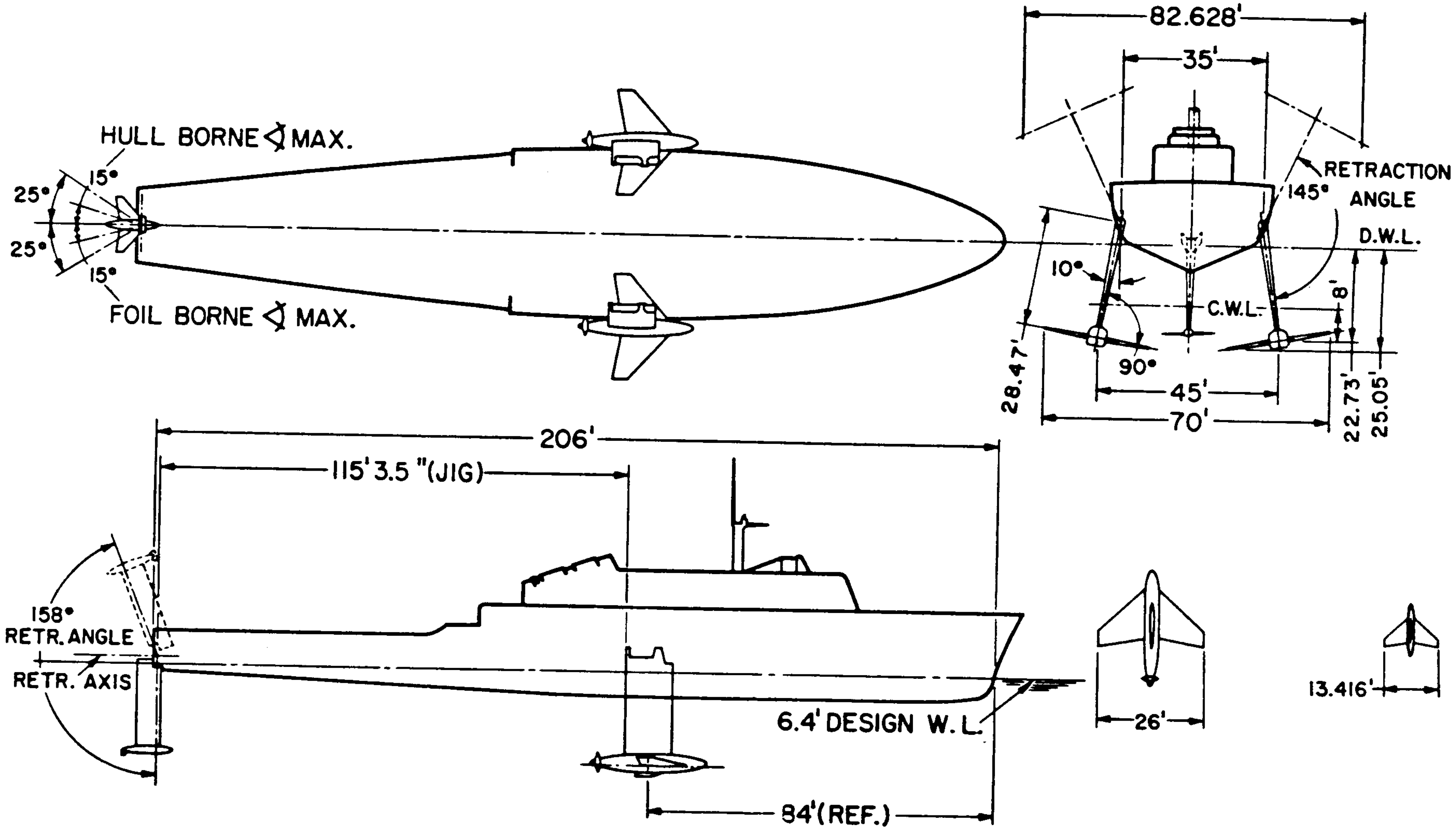
TUCUMCARI Particulars

FULL LOAD DISPLACEMENT = 68.59 Long Tons
LOA = 74.0 Ft.
LBP = 66.67 Ft.
BEAM: MAX. = 37.08 Ft (foil extended)
DWL. = 18.20 Ft
DRAFT: FOILS RETRACTED = 4.20 Ft
FOILS EXTENDED = 13.50 Ft
FUEL: DIESEL OIL OR JP-5. Wt = 8.98 LT (2,962 gals)
FOIL LOADING DISTRIBUTION: aft = 30% fwd = 70%
CONFIGURATION: AIRPLANE (CONVENTIONAL)
MANNING: 13 (1 officer & 12 enlisted)
TOTAL SHIP STRUCTURAL DENSITY = 13.0 lbs/ft^3

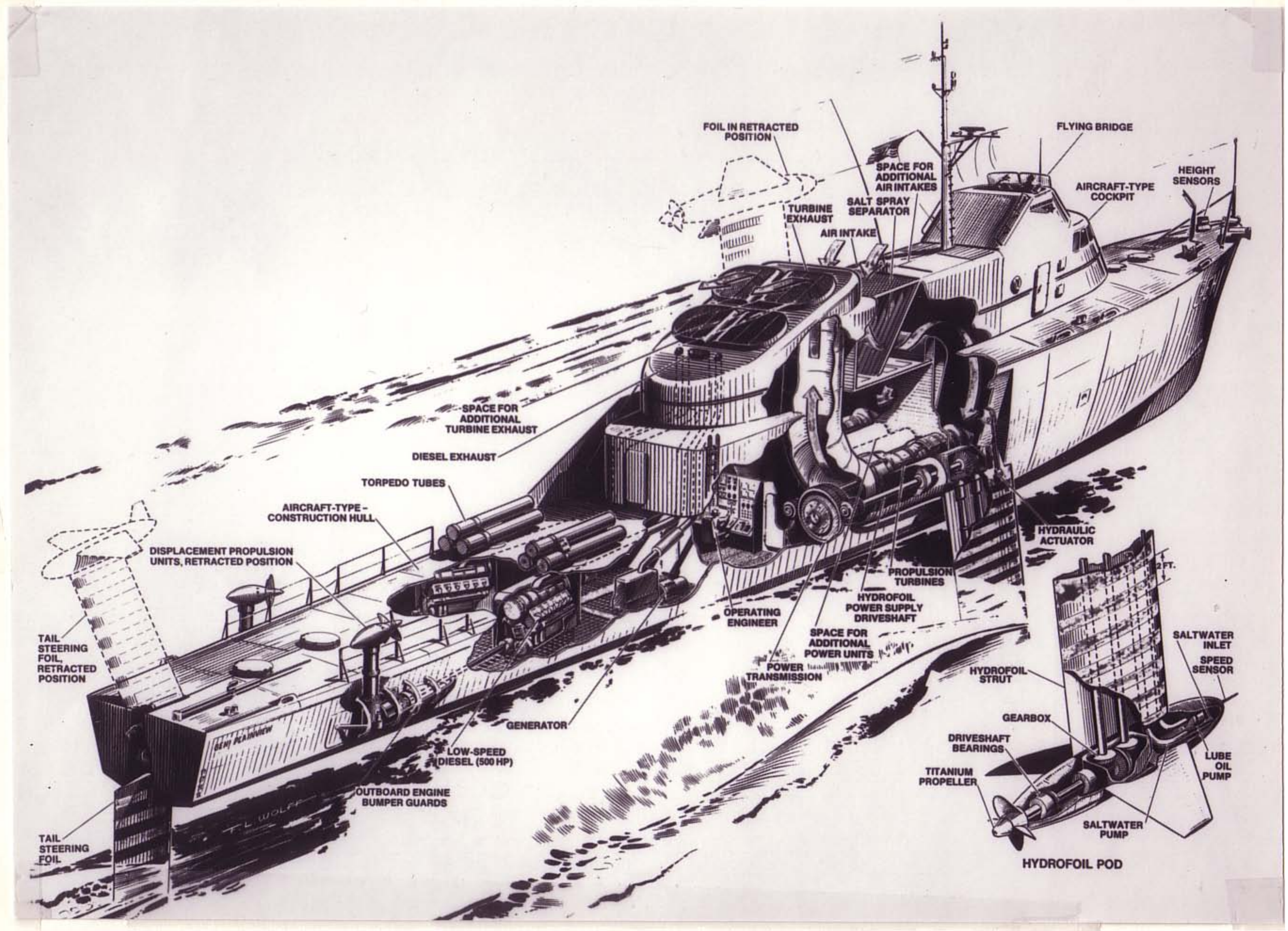




FLAGSTAFF Particulars

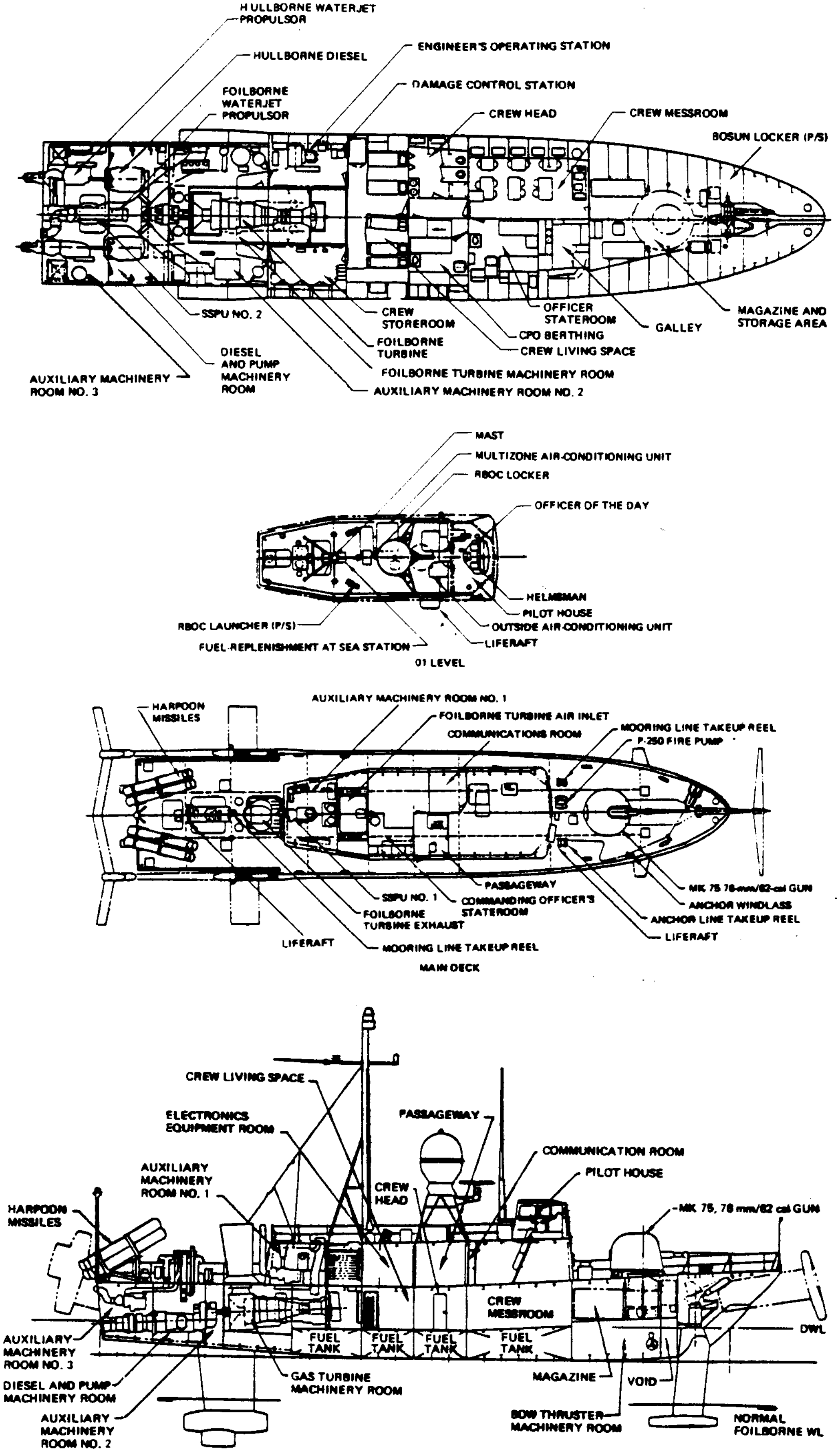


PLAINVIEW - Principal Dimensions



Courtesy Popular Mechanics

Cutaway View of PLAINVIEW

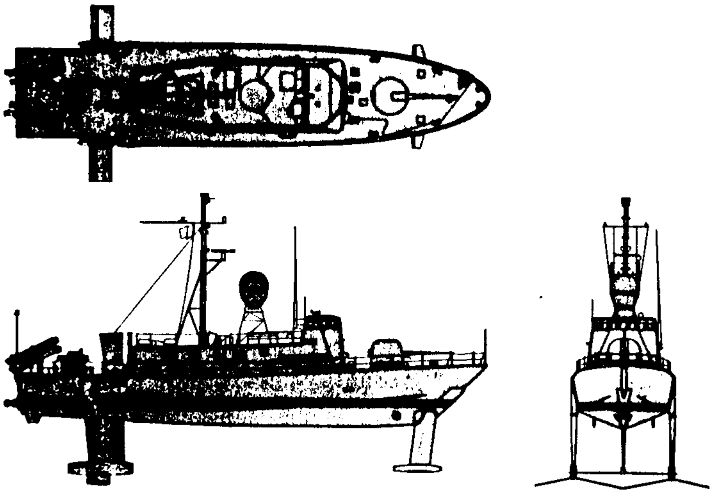


PHM Deck Plan and Inboard Profile[19]

PHM

PRINCIPAL DIMENSIONS

Overall hull length, foils down	40.5 meters
Overall length, foils up	44.7 meters
Hull length, waterline	36.0 meters
Aft foil span	14.5 meters
Hull beam	8.6 meters
Hullborne draft, foils down	7.1 meters
Hullborne draft, foils up	1.9 meters
Displacement	241.3 metric tons



PATROL COMBATANT MISSILE (HYDROFOIL) HIGHLY RESPONSIVE, ALL-WEATHER CAPABILITY

- Foilborne operation 95% of time in all seas
- Low-motion environment

ARMAMENT	(1) 76-mm/62 cal. Oto Melara Gun (2) Surface-to-surface missile canister launchers (2) 4.4-in RBOC launchers
AMMUNITION	(400) 76-mm rounds (8) Surface-to-surface missiles (24) Chaff cartridges Small arms, ammunition and pyrotechnics
COUNTERMEASURES	Rapid blooming off-board chaff ESM equipment
FIRE CONTROL	Gun fire-control system Surface-to-surface missile ship command launch control set
FOILBORNE PROPULSION	(1) G.E. LM 2500 gas turbine engine (17000 hp) (1) Aerojet Liquid Rocket Company waterjet propulsion
HULLBORNE PROPULSION	(2) Motoren-und Turbinen-Union (MTU) MB8V331TC81 diesel engines (1630 hp total) (2) Aerojet Liquid Rocket Company waterjet propulsors with nozzle steering and reverser assemblies
ELECTRICAL	(2) AiResearch ME831-800 gas turbine engines, each driving 1 generator rated at 200 kW (250 KVA), 400 Hz, 450V, three phase
FUEL	Diesel oil per MIL-F-16884 (NATO F-76) or JP-5 per MIL-T-5624 (NATO F-44)
HULL	Welded 5456 aluminum
FOILS AND STRUTS	Welded 17-4PH corrosion-resistant steel
ACCOMMODATIONS	24 berths
COMPLEMENT	23 officers and enlisted men
PROVISIONS	5 days

PHM - Summary of Characteristics

CHARACTERISTICS OF U. S. NAVY HYDROFOILS

	PCH-1	AGEH-1	PGH-1	PGH-2	PHM-1
Full Load Displacement (Tons)	126	320	69	58	231
LOA (Ft.)	115	212	74	72	146
Max. Beam (Ft.)	32	40	21.5	19.5	27.6
Draft (Ft.)					
Foils Up	8.6	6.3	4.3	4.4	6.0
Foils Down	19.8	25	13	13	22
Speed (KTS)					
Hullborne	12	13	9	9	11
Foilborne	High*	High*	High*	High*	High*
Foil Configuration	CANARD	AIRPLANE	AIRPLANE	CANARD	CANARD
Max. Cont. HP.	6200	28000	3200	3200	18000
Gas Turbine	PROTEUS(2)	LM1500(2)	TYNE	PROTEUS	LM2500
Propulsor	PROPELLER	PROPELLER	PROPELLER	WATERJET	WATERJET

*Greater than 40 knots.

Comparison of Characteristics of U.S. Navy Hydrofoils

FOIL GEOMETRY (SWBS 567.3A&F)	PLAINVIEW		PEGASUS		HIGH POINT - O		HIGHPOINT - 1		DENISON		FLAGSTAFF		TUCUMCARI		* FRESH - 1	
	FWD	AFT	FWD	AFT	FWD	AFT	FWD	AFT	FWD	* AFT	FWD	AFT	FWD	AFT	FWD	AFT
FOIL SECTION (NACA)	* *		16-206.5		16-309		16-309		16-(.004)		16-(.27)(.077)		16-306		CAMBERED PARABOLIC	
S AREA (FT²)	225.0	59.9	141.0	302.5	65.6	149.6	65.6	149.6	–	49.4	70.0	35.0	36.0	79.0	7.65	15.3
Æ ASPECT RATIO	3.0	3.0	5.5	5.7	6.1	6.6	6.1	7.65	N/A	2.23	5.5	5.5	7.3	7.3	3.0	3.0
b FOIL SPAN (FT)	26.0	13.4	27.9	47.6	20.0	31.5	20.0	31.5	18.6	10.5	13.9	13.9	16.2	16.9	4.73	4.73
C_R ROOT CHORD (FT)	13.31	6.86	7.77	6.35	5.25	4.75	5.25	4.75	---	6.83	3.88	3.88	3.61	3.78	2.43	2.43
C_T TIP CHORD (FT)	3.99	2.06	2.33	6.35	1.31	4.75	1.31	4.75	—	2.58	1.16	1.16	.83	.87	.81	.81
λ TAPER RATIO	.30	.30	.30	1.0	.25	1.0	.25	1.0	—	.38	.30	.30	.23	.23	.30	.30
t/c THICKNESS RATIO	.08	.08	.065	.065	.09	.09	.09	.09	—	.04	.077	.077	.06	.06	.10	.10
Λc/4 SWEEP ANGLE OF QUARTER CHORD (°)	35.2°	35.2°	11°	0°	15°	0°	15°	0°	—	?	11.72°	11.72°	9.74°	6°	17.1°	17.1°
Γ DIHEDRAL ANGLE (°)	0°	0°	0°	12°	0°	0°	0°	12° INBD 6° OUTBD	—	0°	0°	0°	0°	13°	0°	0°
F_S FLAP AREA (total) (FT²)	N/A	N/A	35.31	61.61	14.04	33.70	14.04	33.70	N/A	N/A	N/A	N/A	15.12	52.56	2.46	4.92
L/A LOADING (lbs/FT²)	1,434	1,196	1,340	1,080	1,140	1,140	1,436	1,195	?	?	1,492	1,248	1,184	1,135	1,600	1,600
FOIL WEIGHT (lbs)	17,690	2,314	7,377	15,364	3,264	4,139	4,005	8,141	13,920	1,476	2,200	960	1,873	4,631	277	562
% OF WEIGHT DISTRIBUTION	90 %	10%	34.6 %	65.4 %	30.2%	69.8 %	34.5 %	65.5 %	85%	15%	70 %	30 %	31 %	69 %	33.3 %	66.7%
MATERIAL	HY-80, HY-100 STEEL		17-4PH STEEL		HY-80, HY-100 STEEL		HY-80, HY130 STEEL		4130-STEEL/6061-AL.		6061-T652 ALUM.		17-4PH STEEL		17-4PH STEEL	
CONFIGURATION	AIRPLANE		CANARD		CANARD		CANARD		AIRPLANE		AIRPLANE		CANARD		AIRPLANE OR CANARD	

* In the Canard Configuration.

* DENISON AFT FOIL IS FULLY SUBMERGED

* * AFT- 16(.425)(.08)
FWD- 16(.39)(.08

Summary of Foil Geometry Data

	PCH-1 HIGHPOINT		AGEH-1	PGH-1	PGH-2
	MOD 0	MOD 1	PLAINVIEW	FLAGSTAFF	TUCUMCARI
SENSORS					
Pitch	Vertical Gyro	Vertical Gyro	Vertical Gyro	Vertical Gyro	Vertical Gyro
Roll	Vertical Gyro	Vertical Gyro	Vertical Gyro	Vertical Gyro	Vertical Gyro
Height	Sonic	Sonic/Radar	Sonic	Radar	Sonic
Heave Acceleration	Servoed Accel.	Servoed Accel.	Servoed Accel.	Servoed Accel.	Servoed Accel.
Roll Rate	Rate Gyro	Electronically Derived from Roll Angle	Rate Gyro	Rate Gyro	Electronically Derived from Roll Angle
Pitch Rate	Rate Gyro	Electronically Derived from Pitch Angle	Rate Gyro	Rate Gyro	Electronically Derived from Pitch Angle
Yaw Rate	Rate Gyro	Rate Gyro	Rate Gyro	Rate Gyro	Rate Gyro
FORCE PRODUCERS					
Lift	Trailing Edge Flaps	Trailing Edge Flaps	Pivoted Foils	Pivoted Foils	Trailing Edge Flaps
Rudder	Trailing Edge Flap plus Spade Rudder	Pivoted Forward Strut	Pivoted Rear Strut	Pivoted Rear Strut	Pivoted Forward Strut
COMPUTERS	Analog Solid State Electronic Plug-in Modules	Analog Solid State Electronic Cord-Wood Construction Plug-in Modules	Analog Solid State Electronic Plug-in Modules	Analog Solid State Electronic Plug-in Modules	Analog Solid State Electronic. Hard Wire Wrapped in Place Modules
ACTUATION	3000 psi Hydraulics pump redundancy with decreased capability	3000 psi Hydraulics pump redundancy with decreased capability	3000 psi Hydraulics 100% redundant system with tandem actuators	3000 psi Hydraulics pump redundancy with decreased capability	3000 psi Hydraulics pump redundancy with decreased capability
MANUFACTURER	Boeing	Boeing	Grumman	Grumman	Boeing

U.S. Navy Hydrofoil Control System Components

Characterisitcs	PCH-1 (Mod 1) (HIGH POINT)	AGEH-1 (PLAINVIEW)	PGH-1 (FLAGSTAFF)	PGH-2 (TUCUMCARI)	PHM-1 (PEGASUS)	DENISON	Canadian FHE 400 (Bras D'or)
Foilborne Propulsion	Two Gas Turbines RR Proteus	Two Gas Turbines GE LM-1500	One Gas Turbine RR Tyne	One Gas Turbine RR Proteus	One Gas Turbine GE LM-2500	One Gas Turbine GE LM-1500	One Gas Turbine P&W FT4A-2
Continuous Rating	3,600 SHP (each) @ 5,000 RPM	14,000 BHP (each) @ 5,000 RPM	3,600 SHP @ 14,500 RPM	3,200 SHP @ 1,545 RPM	16,000 BHP @ 3,000 RPM	14,000 BHP @ 5,500 RPM	22,000 SHP @ 3,600 RPM
Thrust Producer	Four 5-bladed, counter-rotating, fixed pitch, subcavitating propellers DIA 32.4" RPM 1484 One tractor and one pusher prop on each pod.	Two 4-bladed, fixed pitch, super-cavitating propellers DIA 62.4" RPM 1345	One 3-bladed, variable pitch, super-cavitating propeller DIA 45" RPM 1115	One double suction, centrifugal flow water-jet, Byron-Jackson, DVDS Impeller DIA 28" RPM 1350	One axial flow, 2 stage, water-jet. Aerojet AJW-18800-1 Inducer DIA 44.4" RPM 690 Impeller DIA 30" RPM 1570	One 3-bladed, fixed pitch, super-cavitating propeller. DIA 40" RPM 2250	Two 3-bladed, variable pitch, super-cavitating propellers DIA 48" RPM 2000
Transmission	Engine mtd. planetary reduction gear. Subsequent reduction via upper and lower single mesh, spiral bevel gears. Lower gear splits power to fwd & aft props. **Vertically retractable struts.**	Hull mtd. helical reduction gear (w/ idler), dual mesh spiral bevel upper and lower gears. Retractable struts.	Hull mtd. reduction gear transmits power to single mesh bevel gearbox at top of retractable & steerable tail strut. Pod contains spiral gear and planetary reduction gear.	Direct drive, eng. mounted planetary reduction gear.	Double helical reduction gear w/ coaxial output shafts.	Double helical reduction gearbox in hull, dual mesh right angle spiral bevel gearbox at top of retractable & ste- steerable strut and in pod.	Hull mtd double helical step-up gear splits power to each strut via dual mesh, spiral bevel gearbox es. Pod contains bevel gear and compound star epicyclic. Fixed struts.

Propulsion Systems For U.S, Navy and Canadian Hydrofoils

APPENDIX B

GLOSSARY OF HYDROFOIL TERMS

Abaft - Astern of, towards the stern; at the rear of.

Abeam - Position of another craft or object at side or 90 degrees to the longitudinal axis of the vessel.

Airplane Foil Arrangement - A foil system in which the main foil assembly is located forward of the vehicle's center of gravity and whose foil area (lifting surface) represents the major portion (65% or more) of the total foil lifting area. The remaining area is given to a smaller foil located aft of the center of gravity.

Amidships - Anything midway between stem and stern of a hull, frequently abbreviated to midships meaning rudder or helm in mid-position.

Air Stabilized Foil - A lifting foil utilizing the controlled ventilation of air to modulate lift for purposes of achieving craft stability and control.

Anhedral Foil - A foil whose intersection with its strut forms an angle greater than 90 degrees, such as PHM aft foils.

Angle of Attack - Angle between the mean chord line of the foil and the direction of local water flow.

Angle of Incidence - The angle between the mean chord line of a foil and the longitudinal axis of the ship.

Aspect Ratio - The value obtained by dividing foil span by foil average chord length. The transverse direction of the ship.

Athwartship - The distance across the hull from one side of the ship to the other.

Base- Ventilated Foil - One with an air-filled or ventilated wake downstream from the foil. Air is fed continuously to the upper surface of the foil un-wetting the surface and preventing the formation of critical areas of low pressure.

Beam - A measurement across a hull at a given point.

Beaufort - Wind- force scale developed by Royal Navy Admiral Sir Francis Beaufort in 1850 but still in use today to standardize the wind forces (not velocities) needed to maneuver an English ship of the line with a given set of sails. See Chapter 7.

Bow Thruster - Propeller or water jet used to provide side force forward of the center of gravity of the craft to assist in maneuvering. Thrust vector can be varied.

Breguet Range - The approximate range of a craft based upon the average values of propulsion efficiency, specific fuel consumption, the ratio of initial to final gross weight, and assuming a constant lift to drag ratio; named after L. Breguet, who first suggested the simplified formula applied to airplanes.

Broach - The unwetting of a foil with resultant loss of lift due to the foil coming near to or penetrating the air-water interface.

Broach to - To swing sideways in following seas; usually dangerous.

Camber - The convex curve on the surface of a deck or a foil.

Canard Foil Arrangement - A foil system in which the main foil assembly is located aft of the vehicle's center of gravity and whose foil area (lifting surface) represents the major portion (65% or more) of the total foil lifting area. The remaining area is given to a smaller foil located well forward of the center of gravity.

Cavitation - Formation and collapse of vapor bubbles caused by the decrease in pressure from flow over a cambered surface (foil, strut, rudder, or propeller).

Cavity - A gas or vapor-filled "bubble" attached to and covering all or part of the suction side of a surface in liquid flow.

Chine, Hard - Angular intersection of the side and bottom of a craft's hull, as opposed to a round bilge, which is sometimes called a "soft" chine.

Chord - Foil or strut dimension from leading edge to trailing edge generally in the direction of normal flow.

Continuous Foil - A main foil system in which the foil area is one continuous section as opposed to being split in the center.

Contouring - The motion of a craft when tending to follow the surface wave profile rather than tending to travel horizontally over the waves.

Conventional Foil Arrangement - Same as airplane arrangement.

Cresting - The condition of foilborne operation of a hydrofoil caused by contact of the lower part of a hull and keel with the crests of the larger waves. The contact is brief and does not prevent the craft from remaining foilborne. Also called furrowing.

Dihedral Foil - A foil whose intersection with its strut forms an angle less than 90 degrees.

Displacement - Weight of the water displaced by a floating vessel. On a hydrofoil with a retractable foil system, its displacement is recorded with the foils up.

Draft - Depth between water surface and deepest part of the ship. In the case of a hydrofoil with foils down, it is measured to the bottom-most part of the foils or pods.

Drag - The force tending to impede the motion of the ship. On a hydrofoil the hydrodynamic resistance is contributed by wave-making, friction, and induced drag components. At higher speeds, aerodynamic drag from the hull and superstructure can be of significance.

Drag Coefficient - A value C_D, which when multiplied by $1/2\rho A V^2$ yields Drag. Here ρ is density of the fluid, A is the planform area, and V is velocity.

Efficiency - Ratio of useful work performed (ie thrust times relative velocity through air or water) to total input power.

Fences - Small fins placed on surface-piercing struts or foils to prevent ventilation air from migrating down a strut or along a foil. The fences are attached to the strut or foil so as to be parallel to the direction of the fluid flow.

Flap Control - A method of controlling the lift of a submerged hydrofoil system by varying the angle of trailing edge flaps on the foils.

Flying Height - The flying height is the distance between the keel and the mean water surface while foilborne. This provides a measure of actual keel clearance.

Foil - Lifting surface designed to support all or part of the weight of a waterborne craft at an appropriate forward speed.

Foilborne - A hydrofoil craft is said to be foilborne when the hull is raised completely out of the water and wholly supported by lift from its foil system.

Foil Broaching - Sudden breaking of the water surface by a foil or part of a foil, resulting in a loss of lift due to air flowing over the foil's upper surface.

Foil Depth - The distance between the foil and the mean water surface while foilborne.

Freeboard - Depth of the exposed or free side of a hull between the water level and the freeboard deck.

Fully Cavitating - Refers to the formation of a gaseous cavity in the liquid flow past a body, e.g., a foil, and which terminates downstream behind the body.

FWL - Foilborne water line.

Fully- Submerged Foil System - See Submerged Foil System.

Head Sea - A sea approaching from the direction steered.

Heave - The vertical motion of the center of gravity of a ship in response to waves.

Heel - To incline or list in a transverse direction while under way. Also lower end of mast or derrick.

Hullborne - Operating condition of a hydrofoil craft or ACV in which the weight of the craft is supported by the displacement of its hull.

Hump - The hump or peak formed on the graph of resistance against speed for planing craft, hydrofoils, or ACVs, due primarily to maximum wave-making drag of the hull and induced drag of the foils.

Hump Speed - Speed at which the hump occurs.

Hump Drag - The drag at Hump Speed.

Incidence Control - The method of controlling the lift of a submerged hydrofoil system by varying the angle of incidence of the foil or foils.

Ladder Foils - A hydrofoil system consisting of several small parallel foils such that as speed is increased fewer foils are required to support the craft. The remaining foils are then above the water surface and contribute no hydrodynamic drag.

Lift Coefficient - A value C_L, which when multiplied by $1/2\rho AV^2$ yields Lift. Here ρ is density of the fluid, A is the planform area, and V is velocity.

Metacenter - The point of intersection of the vertical through the center of buoyancy of a ship in the position of equilibrium, with the vertical through the new center of buoyancy when the ship is slightly inclined, the displacement remaining constant.

Orbital Motion - Orbital or circular motion of water particles forming waves. Circular motion decreases in radius with increasing depth.Peculiar sequence of motion causes illusion of wave translation. In reality, water moves very little in translation. Circular directions re: up at wave front, forward at crest, down at wave back, and back at trough.

Pi Foil - **A** foil system consisting of a continuous foil connected to the main hull by two vertical struts, the entire assembly thus resembling an inverted Greek letter π.

Pitch - Rotation or oscillation of hull about transverse axis in a seaway. Also angle of propeller blades.

Pitch Angle - Angle that a ship adopts in the pitch direction relative to the horizontal datum

Pitch Pole - The motion of a boat which, through the force of a breaking sea, is turned stern over bow, or vice versa.

Planing - Operating mode of a high-speed craft in which most of the vehicle weight is supported by hydrodynamic lift rather than by static buoyant forces and which is characterized by a clean flow separation at transom and chine.

Platforming - An operating mode of a hydrofoil craft in which the center of gravity of the craft is constrained to travel in straight and level flight with the hull clear of the waves, rather than conforming to the wave profile.

Roll - Oscillation or rotation of a hull perpendicular to the longitudinal axis.

Roll Attitude - Angle of roll that a ship adopts relative to a longitudinal datum.

Seakeeping - General term describing the performance, controllability, and dynamic response of a vessel in a seaway.

Seakindliness - Quality of a craft/ship behavior in waves characterized by easy motions (i.e., low accelerations), dry decks, absence of propeller racing and slamming, and easy steering.

Seaworthiness - Condition of a vessel being fit for a sea voyage, i.e., able to stand heavy weather in safety.

Sea State - A scale of sea conditions classified from state 1 (smooth) to state 8 (percipitous) according to the wind duration, fetch and velocity, also wave length, period and velocity. See Chapter 7.

Significant Wave Height - Average height of the largest 1/3 well formed and defined waves.

Slamming - Violent impact between sea waves and a portion of a craft's hull, resulting in large plating loads due to the large relative velocity. This can occur subsequent to a forward foil broach.

Split Foil - A main foil system with the foil area divided into two, either to facilitate retraction, or to permit the location of the control surfaces well outboard, where foil control and large roll correcting moments can be applied for small changes in lift.

Strut - Streamlined, column-like appendage or support for foils or components of water propulsion systems.

Subcavitating Foil - A general classification given to foils similar in section-shape to subsonic airplane wings. These foils are designed to operate effectively (high lift-to-drag ratio) in fully wetted, non-cavitating flow conditions.

Submerged- Foil System - A foil system employing totally submerged lifting surfaces. The depth of submergence is controlled by mechanical, electronic, or pneumatic systems which alter the angle of incidence of the foils or flaps attached to them to provide stability and control. Also fully-submerged foil system.

Supercavitating Foils - A general classification given to foils designed to operate efficiently at high speeds while fully cavitated. Since at very high speeds foils cannot avoid cavitation, sections are designed to induce the onset of cavitation from the leading edge and cause the cavities to proceed downstream and beyond the trailing edge before collapsing. Lift and drag of these foils is determined by the shapes of the leading edge and undersurface.

Superventilating Flow - Cavitating flow, with cavity, artificially vented to the atmosphere or a source of pressurized air.

Superstructure - Any structure extending above the upper or main deck of a ship.

Surface-Piercing Foil System - **A** foil system in which the lifting surfaces that are partly submerged at foilborne speed. The system is stabilized by the varying submerged foil area. The lift produced is proportional to the submerged foil area and square of the speed.

Surge - Oscillatory motion of a ship in the longitudinal direction.

Tactical Diameter - Distance from the position when the helm was put over to the position when the ship has turned through 180 degrees.

Take Off - The transition from hullborne operation to foilborne operation.

Tandem Foil Arrangement - A foil system in which the area of the forward foil(s) is between *35%* to *65%* of the total foil area.

Taxi - Hydrofoil craft operations with struts down and main engine running but craft not foilborne. Examples are: proceeding at reduced speed in restricted channels to or from berth; operating above design sea states to maintain heading and reduce rolling; and, to reduce radar signature by lowering craft to displacement mode.

Thickness-to-Chord Ratio - Maximum thickness of a foil or strut section in relation to its chord.

Thrust - The impulsion or push exerted by a propeller or **waterjet** in driving a ship.

Transcavitating Foils - Foils designed to have no abrupt changes of loading as they pass from the fully wetted flow region through partial cavitation to the fully cavitating flow region at high craft speeds. Also called transiting foil.

Transom - Last transverse frame of ship's structure forming stern board.

Trim - Difference between drafts forward and aft in displacement vessel. On a hydrofoil, it is the hull attitude relative to line of flight when foilborne.

Ventilation - Process by which a ventilated flow is formed and maintained. "Natural Ventilation" exists when a continuous or intermittent flow of air is created by means of the flow itself, as from the free surface in the case of a surface- piercing, ventilated strut. "Forced ventilation" exists when the air is continuously supplied into the cavity by auxiliary means such as a pump.

Waterjet - A water propulsion system consisting of an inlet, a duct, and an exit nozzle, or combination thereof, with a pump located in the duct for transferring energy from a prime mover to the fluid. The system is used for propelling low-speed craft where low draft is required and for propelling high-speed craft as an alternative to a mechanical transmission and propeller system.

Wave Height - The distance from the trough to the crest of the wave, equal to double the amplitude, and measured perpendicular to the direction of advance.

Wave Length - The horizontal distance between successive wave crests or the distance traveled by a wave during the time interval of one complete cycle.

Yaw - The motion of a ship as the bow and stern move from side to side in opposite directions (motion about the ship's vertical axis).

Yaw Angle - Rotation or oscillation of a ship about the vertical axis.

Z-Drive - Drive system employed on a hydrofoil to transmit power from the engine in the hull to propellers through horizontal shafts leading to a bevel gear, then via vertical shafts and second bevel gear to the horizontal propeller shaft, thus forming a "Z" shape. See Chapter 7.

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SHIPS THAT FLY

BY

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