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SURVEY OF HYDROFOIL MATERIALS

By
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MATERIALS LABORATORY

RESEARCH AND DEVELOPMENT REPORT

November 1969

Report **3067**

Report 3067

Survey of Hydrofoil Materials

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ABSTRACT

A survey has been made of the materials used in hydrofoil craft for the purpose of ascertaining the current state of the art and indicating directions for further material development. The U. S. Navy's HIGHPOINT (PCH- 1), PLAINVIEW (AGEH-1), FLAG-STAFF (PGH- 1), TUCUMCARI (PGH- 2), and H. S. DENISON as well as the Royal Canadian Navy's Bras d'Or (FHE-400) have been examined to determine the material-selection criteria used in construction of the major subsystems. The hull and superstructure, struts and foils, and propulsion systems for each craft were studied. The materials employed, the reasoning behind their employment, and the record of their performance (when available) are discussed. Recommendations for future hydrofoil development are made.

ADMINISTRATIVE INFORMATION

This report was prepared under Work Unit 1-107-116, Task Area 54606, Task 1703, on Hydrofoil Craft Development -Materials, and constitutes Milestone 3 in October 1968 Program Summary.

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INTRODUCTION

Since the late 1940's the U.S. Navy has been involved in developmental research in the field of high-speed hydrofoil craft. This effort, as documented by Oakley,[18] Lacey,[12] and Ellsworth,[3] has progressed in two stages. Prior to 1960, the feasibility and design criteria of such craft were established. Beginning in 1960, the effort was expanded to include broader research, as well as the design and construction of several craft. One important aspect of the performance of hydrofoil craft is the performance of the materials used in hull, strtus and foils, and machinery. These applications require combinations of material properties that are often quite unique. Consequently, the materials used have at times been the critical element in advancing the hydrofoil craft art. This report surveys the materials used in the Navy's major hydrofoil craft, as well as two others on which information is available, for the purpose of indicating where further material development should be carried out. The craft studied include the U.S. Navy's HIGHPOINT (PCH- 1), PLAINVIEW (AGEH-1), H. S. DENISON, FLAGSTAFF (PGH-I), and TUCUMCARI (PGH-2), as well as the Canadian Bras d'Or (FHE-400). The sources of information are various reports and technical papers listed in Appendix A. Because many pieces of information are listed in more than one of these documents, specific sources will not, in general, be cite&for descriptive information on the craft.

U.S. NAVY HYDROFOIL DEVELOPMENT PROGRAM

The U.S. Navy Hydrofoil Development Program is directed toward the development of reliable craft with various high-speed mission capabilities as well as toward the generation of design criteria.3 It is managed for the Naval Ships Systems Command by the Naval Ship Research and Development Center, Carderock, Maryland. On-the-scene management of craft evaluation is carried out by the Hydrofoil Special Trials Unit (HYSTU) based at Bremerton, Washington. Technical assistance on materials and machinery is provided by the Naval Ship Research and Development Laboratory, Annapolis. (The latter two organizations are part of the Center.)

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[18] Superscripts refer to similarly numbered entries in the Bibliography.

As a result of the decision to broaden the Navy Hydrofoil Development Program, funds were allotted in 1960 for the design and construction of a 110-ton hydrofoil patrol boat, the PCH-1 (Figure 1). This craft, constructed by the Boeing Company, is 115.7 feet in length with a maximum beam of 33.3 feet. Its foil system consists of a canard configuration (main foil aft, small foil forward) of fully submerged, partially retractable struts and foils. It is powered in the foilborne mode by two Bristol Proteus gas turbines. Power is transferred through a zee-drive transmission down through the two struts of the rear foil to propellers at both ends of the two pods. The PCH-1 is designed to travel in excess of 40 knots in fulfilling its patrol craft capability. This craft, delivered to the Navy in August 1963, was meant to be an advanced design craft eventually destined for Fleet use. However, difficulties prior to delivery and during the initial testing program led to a complete refurbishing and repair program from September 1964 to June 1966. Among the difficulties needing correction was poor performance of foil and strut coatings which resulted in corrosion and erosion damage to certain areas of these assemblies. In the repair program, a number of different coatings were applied to critical areas in an effort to determine the best coating for this application. Further testing, including extended runs in high sea states, led to a decision to proceed with plans for the extensive modification (Mod 1) of the craft to raise its performance level. Until such time as this major step takes place, the PCH-1 Mod 0 will continue to undergo testing and evaluation.

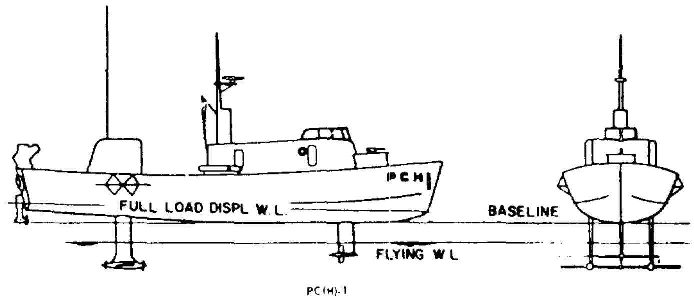


Figure 1
PCH-. 1

In 1960 the U.S. Maritime Administration entered into a contract with an affiliate of the Grumman Aircraft Engineering Corporation for the design, construction, testing, and demonstration of a hydrofoil seacraft vehicle.4 This vehicle, the H.S. DENISON (Figure 2), was funded jointly by the Maritime Administration and about 70 industrial companies. This craft is 104.6 feet in length and has a beam of 23 feet. It is propelled by a single water propeller mounted on the rear pod. Power is supplied by a General Electric gas turbine and is transferred by a zee-drive transmission. Tbe foil system consists of a conventional configuration (main foils forward, small foil aft) of two fully retractable, surface-piercing forward foils and a fully retractable, fully submerged aft foil. After completion of construction, the DENISON underwent testing and evaluation from June 1962 until September 1963. From then until February 1964, the craft was employed i.n an industry demonstration program. The DENISON was used in Navy service after this demonstration program, but adequate records of material performance or details of the service have not been located. The Hydrofoil Special Trials Unit acquired the DENISON in January 1968 and is presently storing it while potential testing applications are explored.

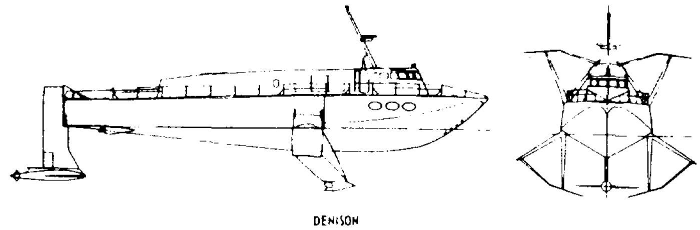


Figure 2
DENISON

The 320-ton, 212-foot AGEH-1 (Figure 3) is the world's longest hydrofoil craft. Funds for its design and construction were authorized in Fiscal Year 1962, and the guidance design was completed by Grumman in May 1963. In June 1963 a contract for detailed design and construction was awarded to Lockheed Shipbuilding and Construction Company. Delivery to the Hydrofoil Special Trials Unit was made on 1 March 1969. The AGEH-1 was designed as an experimental craft to test the feasibility of the application of the hydrofoil design and technology to a craft of this size. During construction it was outfitted with strain gages in the struts, foils, and hull, as well as accelerometers, velocity transducers, and other measuring and monitoring equipment. The foil system of this craft consists of fully submerged, fully retractable foils and struts in the conventional arrangement. Propulsion power is supplied by two General Electric gas turbine engines, each of which drives a water propeller, mounted on each main foil pod, through a zee-drive transmission. The AGEH-1 is designed to "fly" in excess of 50 knots.

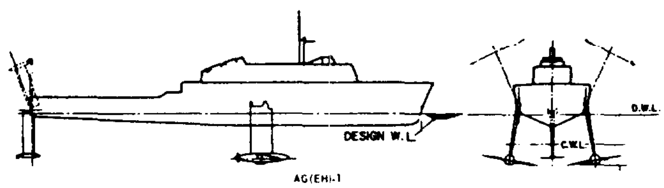
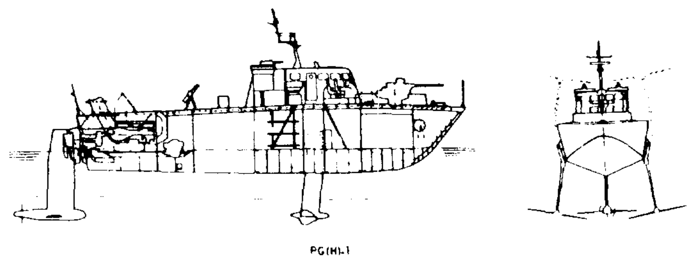


Figure 3
AGEH- 1

Early in 1965 the final characteristics for a high-speed hydrofoil gunboat were approved. In July of that year, requests for proposals were sent to seven contractors. Boeing and Grumman, who generated the only responses, were each awarded a contract for a single craft. These contracts were awarded in April 1966. Both of these craft were somewhat similar in design and were considered within the state of the art (using only proven technology). The Grumman craft, PGH- 1, (Item (a), Figure 4) has fully submerged, fully retractable foils in a conventional configuration. Propulsion is provided by a Rolls Royce Tyne gas turbine which powers a single propeller in the aft pod through a zee-drive transmission. The Boing PGH-2 (Figure 4) has a canard arrangement of fully submerged, fully retractable foils. This craft is driven by a Bristol Proteus gas turbine which powers a water-jet propulsion system.

Item (a) - PGH- 1



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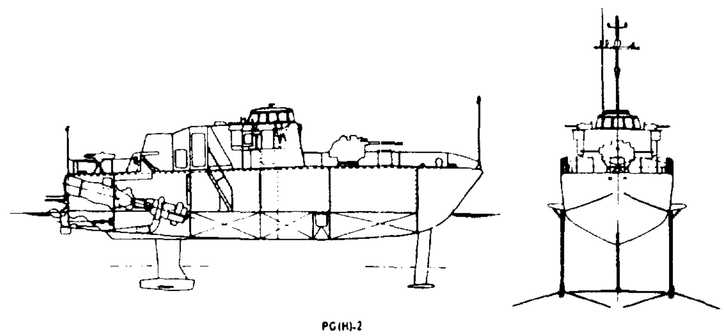

Figure 4
PGH- 1 and PGH- 2

CANADIAN PROGRAM

The Naval Research Establishment of the Canadian Defense Research Board has sponsored theoretical studies and experimental programs in the field of military hydrofoils for the past 20 years.13 This work has progressed at essentially the same pace as that of the U.S. Navy, although there are major differences between programs. In early 1963 after completion and evaluation on a design study, the Canadians proceeded on the design, construction, and development of a prototype antisubmarine warfare hydrofoil craft designated FHE-400 (Figure 5). This craft is 151.5 feet in length a:nd displaces approximately 200 tons. Its foil configuration is a considerable departure from those of the U.S. Navy in that it consists of nonretractable, surface-piercing foils in a canard arrangement. The FHE-400 is included in this report be-

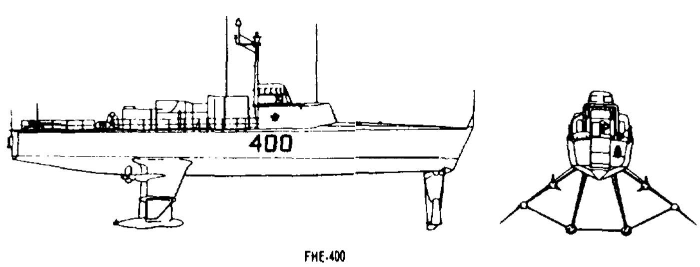

Figure 5
FHE-400

cause the record of performance of this advanced design craft should be of great benefit to the U.S. Navy effort.

SCOPE OF REPORT

Table 1 presents the characteristics of the craft considered in this study. It can be seen that, in considering the five U.S. Navy hydrofoils and the FHE-400, the spectrum of size, performance, mission, foil configuration, and arrangement as well as propulsion systems will be covered.

The major subsystems which can be defined as material dependent are the hull and superstructure, the struts and foils, and the propulsion system. In these subsystems, the selection of materials in conjunction with structural design is considered critical. Each of the subsystems will be examined in terms of the materials selected by the designers and, in the case of PCH-1 and DENISON, in terms of the performance of those materials in the craft. Performance of materials in the other craft must await accumulation of enough service for meaningful experience to be acquired.

HULL AND SUPERSTRUCTURE1

MATERIALS USED

In examining the materials used in hydrofoil hulls and superstructures, it should be noted that there still remain differences of opinion as to the optimum hull design. This is reflected in the variety of configurations which have been used. Generally, however, the major considerations in hull design have been weight fraction, impact load reliability, and hullborne stability. The materials selection criteria were then based on satisfying these design requirements while providing good sea-water corrosion resistance and good fabricability.

The alloys used in the hull and superstructure of the various craft are presented in Table 2. The 5000 series aluminum alloys were used quite extensively. These alloys fulfill the design requirements while providing adequate weld strength and generally good resistance to sea-water corrosion. Sheet and plate (5456) of various tempers were used in all craft except the FHE-400. Sheet, plate, and extrusions were used for deck, side, and bottom plating, frames, girders , and watertight bulkheads. In the FHE-400, Alcan D54S, which is similar to 5086, was used for these applications. The 6061 alloy was used in the form of sheet and formed longitudinals in the PGH-2 and in sheet form in the FHE-400. In the former, the deckhouse shell, bulkheads, and platform decks are of 6061-T6, while in the latter, turbine intakes and several internal structures are of this alloy. It is to be noted that mechanical fasteners were used with 6061. The FHE-400 utilized 7075 forgings for large internal fittings. Welding was used predominantly with the 5456 alloy except in the DENISON where the hull plating was riveted. In the PGH-1, 5456 -H343 riveted plate and sheet were used for the bow and superstructure skin.

Table I
Hvdrofoil Craft Characteristics

	Design and Construction	Foil Configuration	Foil Arrangement	Length (overall) feet	Beam Extreme Foils Down feet	Full-Load Hull-borne Draft Foils Up feet	Full-Load Hull-borne Draft Foils Down feet	Full-Load Displacement long tons	Maximum Hullborne Speed knots	Maximum Foilborne Speed knots
PCH-1	Boeing	Fully Sub-merged	Canard	115.7	33.0	6.5	17.0	120	12	40+
AGEH-1	Grumman Lockheed	Fully Sub-merged	Conventional	212	37.7	6.4	25.0	320	15	50+
DENISON	Grumman	Forward, Surface-Piercing Aft, Fully Sub-merged	Conventional	104.6	23.0	6.25	15.4	95	10.4	50+
PGH-1	Grumman	Fully Sub-merged	Conventional	74.5	21.5	4.25	13.5	57	7+	40+
PGH-2	Boeing	Fully Sub-merged	Canard	71.8	19.5	4.5	13.9	58	7+	40+
FHE -400	De Havilland	Surface-Piercing	Canard	151.5			23.5	200	18	50+

Table 2
Hull and Superstructure Materials

Craft	Aluminum Alloy	Form
PCH-1	5456-H321 5456-H311 6061-T6	Plate Extrusion Plate, Shapes
AGEH-1	5456-H321, i-1323, H343 5456-H311	Sheet, Plate Extrusion
DENISON	5456-H321 5456-H311	Plate Extrusion
PGH-1	5456-H321, H 3 4 3 5456-H311	Sheet, Plate Extruded Plate
PGH-2	5456-H321 5456-H311 6061-T6	Sheet, Plate Extrusion Sheet, Forms
FHE-400	Alcan D54-S 6061-T6 7075	Sheet, Plate, Extrusions Plate Forging, Thick Plate

Table 3 is a presentation of typical mechanical properties of the materials used in the hulls and superstructures of the six hydrofoil craft.

Table 3
Typical Mechanical Properties of Hull and Superstructure Alloys

Alloy	Tensile Strength ksi	Yield-Strength 0.2% offset ksi	Elongation % in 2 in. *	Elastic Modulus psi x 106	Source
5456-H311	47	33	18	10.3	(1),(2)
5456-H321	51	37	16	10.3	(1),(2)
5086-H32	42	30	12	10.3	(1),(2)
6061-T6	45	40	12	10.0	(1),(2)
7075-T6	83	73	11	10.4	(1),(2)

'Van Horn, Kent R. (ed.), "Properties, Physical Metallurgy and Phase Diagrams,* Aluminum, Vol. I, American Society for Metals, 1967

[2]Alcoa Aluminum Handbook, 196 7
ksi-thousand pounds per square inch.

*Abbreviations used in this text are from the GPO Style Manual, 1967, unless otherwise noted.

GENERAL COMMENTS

All of the craft use some type of corrosion protection system for the hull in addition to paint systems. The PCH-1 employs sacrificial zinc anodes. The DENISON and PGH-1 hulls are protected with a sprayed zinc coating. The AGEH-1 and PGH-2 are equipped with impressed current cathodic protection systems, which are understood not to be in operation at this time. It can be said that service experience with the 5000 series of aluminum alloys has generally been good. However, within the last 18 months, exfoliation corrosion was found to ‘be occurring in the bilges of several of the U.S. Navy’s small aluminum craft as well. as in PCH- 1, AGEH-1, and PGH-2. This type of corrosion occurred exclusively in the 5456-H321 plate material and is thought to be due to the alignment of the Mg-Al precipitate within the matrix. This promotes rapid pianar corrosion , which when repeated on successive layers, produces exfoliation (Figure 6). The major suppliers have now produced the alloy in tempers that are expected to be free of the aligned precipitate. It is anticipated that with these alloys, the exfoliation will be eliminated.

It can be concluded that, for the five U.S. Navy craft and the FHE-400, the materials available meet the design requirements of the hull and superstructure. However, if service experience indicates that these criteria must be upgraded, there are materials potentially available to meet these needs. For instance, titanium alloys and glass-reinforced plastics might be used. Furthermore, even though the present materials generally meet the current standards when clearly superior materials exist, use of them could be expected to upgrade craft performance. A particular area of interest should be lightweight composite materials for the decks and superstructure.

STRUTS AND FOILS

The material situation for struts and foils is quite different from that for hulls and superstructures. For the latter, the requirements have been quite similar to those for highspeed hullborne craft, and the materials selections have also been similar. The struts and foils, on the other hand, present a new combination of requirements, and this situation is reflected in the variety of material choices by the designers of the different craft as shown in Table 4.

Figure 6

Exfoliation Corrosion of 5456-H321 Aluminum-Alloy Hull Plate
Which Occurred in Bilge of Navy Boat

Table 4

Strut and Foil Materials

Craft	Alloy	Form	Application
PCH-1	HY-80 Steel	Sheet, Plate	Struts, Foils
AGEH- 1	HY-80 Steel HY- 100 Steel	Sheet, Plate Sheet, Plate	Strut, Foil Foil, Skin
DENISON	AISI 4130 Steel AL5456-H321 AL7079-T611	Sheet, Plate Plate Forging	Forward Strust and Foils Aft Pod Skin Aft Foil
PGH- 1	HY-80 Steel AISI 4130 Steel 4330 Modified Steel Type 316 Corrosion Resistant Steel AL7075-T73	Sheet, Plate Plate Casting Sheet Forging	Struts Struts Support Fittings Main Foil Pods Strut Leading Edges Foils
PGH- 2	17-4PH-H950 17-4PH-H950	Sheet, Plate Wrought	Struts Foils
FHE-400	18Ni Maraging Steel 250 CVM 18Ni Maraging Steel 250 CVM	Sheet, Plate Forging	Struts, Foils Internal Fittings
	Inconel 718	Forging	Strut and Foil Leading Edges

The properties listed below have all been identified as significant in the selection of materials for the struts and foils:

- Strength and ductility
- Density
- Elastic modulus
- Fracture toughness
- Fatigue resistance
- Corrosion resistance
- Cavitation-erosion resistance
- Fabricability
- cost

The variety of materials used indicates the different designers' views of the relative importance of these properties in their particular design. The choices made and the performance obtained, where available, are discussed below for each of the craft.

PCH- 1

The PCII- 1 exhibits a canard configuration with 70% of the load carried on the aft foil. Both forward and aft foils are submerged at all times, but the struts retract into trunks in order to reduce the hullborne draft. The forward and aft struts, foils, and pods are constructed completely of HY-80 steel. Fioriti, Vasta, and Starr[5] noted that HY-80 is a proven reliable and weldable structural steel of 80 ksi minimum yield. It was also noted that this steel in its unprotected condition is not corrosion resistant and is subject to severe erosion and cavitation damage. Hy-80, typical of carbon and low alloy steels in this respect, exhibits a very low corrosion-fatigue limit. It has also a relatively low ratio of yield strength to weight. It was employed, however, because at the time of the design and construction, no stronger material was thought to provide an equal structural reliability in the fabricated condition and because it was expected that corrosion and cavitation erosion could be controlled by coatings. The struts, foils, and pods were coated initially with neoprene. This coating was almost completely torn loose or removed in the first 2 hours of foilborne operation.[16] The neoprene was then replaced by an anticorrosion vinyl system. However, the system displayed relatively poor general wear characteristics and did not prevent cavitation and corrosion damage on the struts and propeller pods. In order to protect these areas from damage caused by vortices in the wake of the propeller tips and forward foil tips, Stellite 6B plates were attached in areas impinged by these wakes. Attachment problems, among other reasons, proved the plates to be unreliable. Following this effort, various types of elastomeric, neoprene, and natural rubber coating systems were applied to particular areas of the struts, foils, and pods. The neoprene systems used included both liquid application and sheet types. Some contained antifouling ingredients. Further high-speed testing will be required to fully evaluate these systems, although information to date indicates a continued coating problem.

Because of the problems with coatings on the HY-SO steel, an investigation was undertaken during the Mod 1 planning stages to determine a better material to be used for the struts and foils.[20] Four alloys - 17-4PH stainless steel, Inconel 7 18, Ti- 6Al-4V, and Ti-6Al-2Cb- 1Ta-0.8Mo - were subjected to detailed analysis following the preliminary screening process. The selection criteria were mechanical and physical properties, corrosion characteristics, fabrication parameters, and cost considerations. It was particularly desirable that the material have strength enough to permit reducing the foil section thickness significantly, to reduce cavitation erosion. The material selected for the strut and foil system was 17-4PH. The titanium alloy, 6Al-4V, was eliminated in view of the highly sophisticated processing techniques and the low toughness of weldments, which could impose very severe demands on nondestructive testing for detection of critical flaws (of very small size). The Ti-6Al-2Cb-1Ta-0.8Mo alloy was eliminated due to the fact that its yield strength was considered to be too low to permit its use in the Mod 1 design. At the time, it was also noted that fabrication experience was lacking. Inconel 718 was eliminated because of inadequate information concerning fracture toughness of welds in heavy gages as well as lack of information concerning fabrication and nondestructive testing procedures. The choice of 17-4PH was made in the belief that pitting and crevice corrosion could be eliminated by the application of a cathodic protection system. (Since the time of this decision, Vreeland[26] has deter mined that a cathodic potential, to a satarated calomel electrode, between -600 and -750 millivolts must be maintained to protect the higher strength levels, while -600 to -1300 millivolts may be suitable for the lower strength levels.) It was also felt that the marginal fracture toughness would be improved by advanced mill practices and that a limited structural development effort would improve fabricability.

AGEH- 1

In the AGEH-1 craft, a conventional foil configuration is employed with approximately 90% of the weight on the two forward foils and the remaining 10% on the single aft foil. All struts and foils are fully retractable, reflecting the decision on the part of the program coordinators to abandon the wet retraction arrangement. The original Grumman design of the AGEH-1 called for all of the struts and the main foils and pods to be constructed mainly from AISI 4130 steel of a minimum yield strength of 150 ksi. The aft foil was to be made of solid Aluminum Alloy 5456 H-31 1, with the pod made of welded aluminum framework covered with a mechanically fastened aluminum skin. However, during the final design and construction phases, the decision was made to change the materials used. The final construction of all struts and foils was of a combination of HY-80 and HY-100 steel.. These materials were chosen because they were thought to satisfy the structural requirements, specifications, and guidance drawings and yet were workable with the tools and techniques available. A polyurethane coating has been applied to all of the strut, foil, and pod surfaces. It is interesting to note here that, as in the case of PCH-1, fabricability and structural reliability took precedence over other considerations in materials selection.

DENISON

The foil system of the DENISON consists of two forward surface-piercing, fully retractable hydrofoils which support about 85% of the ship's weight, an.d a fully submerged, fully retractable aft foil supporting the remaining 15%. It was noted by Grumann[4] that four materials were considered for the foils and struts: AISI 4130 steel, IN-80 steel, 17-4PH stainless steel, and an aluminum alloy. The comparison of these materials was on the basis of cost, physical and mechanical properties, weldability, weight, fatigue, and manufacturing experience with the material. The 17-4PH alloy was eliminated because of cost and also because of some experience with intergranular cracking of castings and extrusions in one of the Grumman experimental craft. The AISI 4130 alloy, quenched and tempered to a minimum yield strength of 150 ksi, possesses an advantage in strength-to-weight ratio over HY-80. It was finally decided that the forward foils and struts and the aft strut would be constructed of AISI 4130 steel because of the fact that Grumman had quite extensive fabrication experience with this alloy. The fact that weight savings could be accrued only cemented that decision. These assemblies were of fabricated and welded steel beams, ribs, and skin. The forward foil and strut elements were joined through forged internal fittings of 7079-T611 aluminum. The aft foil was a one-piece solid 7079-T611 aluminum forging. The propeller pod construction used welded 4130 steel for the framework, covered with riveted 5456-H321 aluminum sheet. All of the struts and foil surfaces were covered with a polyurethane coating. These coatings had to be repaired frequently, especially on the high- speed hydrofoil sections. [4] However, because of the full retractability of the foils, these repairs were made before severe corrosion damage occurred. This repatching of the coating was found to be the only structural repair necessary in preserving structural reliability.

PGH- 1

The PGH-1, designed and constructed by Grumann, reflects the experience gained with the DENISON, the commercial craft DOLPHIN, and to some extent in designing the AGEH- 1. It exhibits a conventional configuration with 70% of the weight on the forward main foils and 30% on the aft foil. All struts and foils are fully retractable. The construction of the struts was from a combination of HY-80, cast AISI 4330, and AISI 4130 alloy steels. [21] HY-80 was used for nearly all strut components which required welding. This includes the upper main strut fittings, the aft strut yoke fitting, the aft strut ribs, and some of the beams. AISI 4130 steel, plate quenched and tempered to a minimum tensile strength of 125 ksi, was used in the strut areas where no welding is required. Modified AISI 4330 steel castings were used for lower support fittings on the main struts as well as for the aft pod. Type 316 corrosion-resistant steel was used for the main foil pods and the leading edges of the struts. The foils were constructed of forged Aluminum Alloy 7075-T73. The strut and foil surfaces were coated with a polyurethane compound, Metallox-l l-X-2. It is interesting to note that Grumman has employed the same types of materials with progressive refinements in the three craft it has designed for the program. The long-term performance of PGH-1 will test the soundness of the Grumman approach to strut and foil material selection and application.

PGH-2

The Boeing PGH-2 exhibits a canard configuration with 30% of the weight on the forward foil and 70% on the aft foils. Once again, the foils are fully retractable. The requisites for strut and foil material for this craft were high strength, low weight, corrosion resistance in seawater, good fatigue characteristics, high fracture toughness, high elastic modulus, good fabricability to close tolerance, and low cost.24 In striving to meet as many of these requirements as possible, Boeing selected li-4PH stainless steel for all struts and foils. The struts were fabricated by welding followed by solution treating and aging to the H950 condition. The foils are solid, machined 17-4PH sections. All struts and foils are intended to be protected by an impressed current cathodic protection system.

FHE-400

The FHE-400 provides a departure from the arrangement of the U.S. Navy craft. Its foil system consists of a canard configuration of nonretractable, surface-piercing foils. This choice was based on the belief that a system of this type would offer the advantages of simplicity, reliability, and somewhat lower cost. An 18% nickel maraging steel was chosen for the struts and foils.[15] The sheet and plate were supplied in the 250 ksi yield strength grade and the large forgings in the 200 ksi yield strength grade. This alloy was chosen because maximum load stresses greater than 100 ksi are present in the foil system. When considered in terms of probelms of heat treatment and fabrication, as well as fatigue life and corrosion resistance, 18% nickel maraging steel emerged as the optimum choice. The leading edges of the struts and foils are fitted with replaceable sections o.f Inconel 718, a nickel-base alloy. All of the strut and foil elements were coated internally with zinc silicide and externally with neoprene. A system of sacrificial anodes will be used instead of an impressed current cathoid protection system to protect the steel with its susceptibility to hydrogen embrittlement is determined. It is intended to employ an impressed current cathodic protection system in the future. The results of the future testing program for this craft will be quite beneficial from the standpoints of materials selection and evaluation as well as the feasibility of the design.

DISCUSSION AND GENERAL COMMENTS

The characteristics of an ideal material for hydrofoil application were discussed in 1963 by Fioriti, Vasta, and Starr.[5] These are:

- Size - availability in sheet and plate up to 1 inch thick and up to 120 inches wide.

- Strength - 0.2% offset yield strength over 100 ksi. Lower strength is allowable if the ratio of yield strength to -weight (psi/lb per ft^3) is over 300.

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Table 5
Typical Mechanical Properties of Alloys Used in Strut and Foil Application

Alloy	Tensile strength ksi	Yield Strength (0.2% offset) ksi	Elongation % in 2 in.	Modulus of Elasticity psi x 10^6	Endurance Limit, ksi: Smooth Air 10^7 Cycles	Smooth Air 10^8 Cycles	Smooth Salt Water 10^7 Cycles	Smooth Salt Water 10^8 Cycles	References
HY-80	100	85	25	29	44	40	14	9	(2),(3)
HY-100	120	105	24	29	68	66	18	12	(3)
18Ni Maraging 200 Grade	210	206	13	26.5	105	100			(4)
18Ni Maraging 250 Grade	260	255	10	28.5	105	100			(4)
17-4PH H900(1)	190	170	10	29	90	80			(5)
Al5456 H321	51	37	16	10	22	20	5	2.5	(6),(7)
Al7079 T6	78	68	14	10	20	15	5	2.5	(6),(7)

[1] The actual temper used on PGH-2 is H950 which exhibits mechanical properties similar to those of H900

[2] "Tensile Properties of Eight Structural Steels," United States Steel Technical Rept, 1 Jan 1968.

[3] Gross, M. R., and E. J. Czyryca, "Effect of Notches and Seawater Corrosion on the Flexural Properties of Steel for Hydrospace Vehicles," Naval Engineers Journal, Dec 1967.

[4] Vanadium-Alloys Steel Co. specifications, 1966.

[5] Aerospace Structural Metals Handbook, Vol. I, Mar 1965.

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[7] "Fatigue and Notch Bend Properties of High Strength Aluminum Alloys," USN Engineering Experiment Station Rept 910163C, July 1962.

Early in the design phases of the program, the family of titanium alloys was ruled out because of cost and the lack of knowledge of fabricability. Over the last 10 years the cost has fallen, and many of the fabrication problems have been solved, However, the cost and difficulty of fabrication of titanium alloys, along with their low yield strength and modulus of elasticity in comparison with steel alloys, continue to be factors in rejection. Ti-6Al-2Cb-1Ta-0.8Mo was considered as a candidate material for the struts and foils of PCH Mod 1.20 This alloy, with 100 ksi yield strength, was judged to be superior to 17-4PH in corrosion resistance and strength-to-weight ratio. Ti-6-2-1-0.8 was rejected because, to meet the necessary design strength level and stiffness requirements, the size of the strut and foil would have to be unacceptably increased.

From the facts presented, it can be seen that the materials used to date for struts and foils are far from ideal for these applications. Other promising materials have not been employed for reasons such as cost or lack of confidence due to limited service experience. Many of the objections to these materials have been overcome by later information, and it appears now that the performance of struts and foils could be upgraded by the use of these materials.

The information on potential strut and foil materials is not complete, however, either on a laboratory or service experience basis. More laboratory data are needed on a number of titanium and high-strength nickel-base alloys, as well as on 17-4PH stainless steel. The potential of metallic matrix composites needs to be examined. It should be noted that a start has been made on both composite materials (in the form of a paper study) and titanium and nickel alloys (in the form of laboratory scale experimentation on particular alloys).

Better cavitation-erosion protection coatings are needed, and as concepts for improving coatings arise, they should be investigated as an adjunct to the materials studies.

The validity of assumptions as to material performance requirements must be verified by full-scale service evaluation of new materials and by interpretation of service experience with the current hydrofoil craft. This evaluation is perhaps the most urgent requirement for advancing the state of the art of strut and foil materials.

PROPULSION SYSTEM

The propulsion system is the last major subsystem to be considered. This subsystem consists of an engine, transmission, and thrust producer for both the hullborne and foilborne modes. Table 6 presents the characteristics of the propulsion systems of the six hydrofoil craft considered. All of the craft are powered in the foilborne mode by gas turbine <engines, and with the exception of the DENISON, are powered by diesel engines in the hullborne mode.

Table 6. Propulsion Systems Characteristics

	Displacement Mode Engine(s)	Displacement Mode Propulsion	Foilborne Mode Engine(s)	Foilborne Mode Propulsion
PCH-1	Packard Diesel	Retractable Water Propeller	Bristol Proteus Gas Turbine (two)	Zee Drive Transmission Water Propeller
AGEH-1	Curtis-Wright Model 12V-142 Diesel (two)	Retractable Water Propellers (two)	GE Model 240 Turbo-Shaft Engine (two)	Zee Drive Transmission Water Propeller
DENISON	Gems 240 (LM 1500) Gas Turbine	Water Jet	GE T58 Gas Turbine	Zee Drive Transmission Water Propeller
PGH-1	Detroit Diesel 6V-53 (two)	Water Jet	Rolls Royce Tyne Mx 621 Gas Turbine	Zee Drive Transmission Water Propeller
PGH-2	Detroit Diesel 6V-53	Water Jet	Bristol Proteus Gas Turbine	Byron Jackson Water Jet
FHE-400	Paxmann 16Y JCM Diesel	Water Propeller	Pratt & Whitney FT4-A2 Gas Turbine	Zee Drive Transmission Water Propeller

There are two types of thrust producers which are considered workable for both modes - the water propeller and the water jet. At high speeds, propeller cavitation occurs, causing erosion of the propeller material. Also, highly loaded propellers have failed by fatigue or stress corrosion. In the DENISON, Type 420 stainless steel propellers of supercavitating design showed severe erosion damage when operated over 60 hours, and in case experienced a corrosion fatigue failure after 4 hours of operation.[19] These problems are eliminated by employing a supercavitating propeller built up of forged Ti-6A1-4V alloy. This propeller was credited with providing excellent service. As a result of this experience, the AGEH- 1 has been equipped with forged titanium propellers. It should also be noted that a cast Ti-6A1-4V propeller failed after a few hours' use on the PCH-1. However, this failure was attributed to a casting fault[2] which led to stress-corrosion craking. Fatigue was also noted in the failure. A replacement for this propeller is being machined, and future testing is planned.

Interest in high-speed propulsion efficiency has led to the investigation of the water-jet propulsion system. Basically, the system consists of a water inlet, a pump, and an above-surface water-jet exhaust. I-t has been shown that, at moderate speeds, this type of propulsion system can nearly match the efficiency of the water propeller. However, this labratory has received evidence that pitting and cavitation in the pump and ducting of water-jet systems in other types of craft may be a problem. At this time, the PGH-2 is the only craft employing this type of system for foilborne propulsion. The experience with this craft should greatly advance the state of the art of the water-jet system.

Critical propulsion subsystem materials that have been identified include propeller alloys, water-jet ducting, and pump impellers. Work is needed to define the properties of cast titanium alloys to allow reliable propeller design with these materials. Performance of the water-jet system on PGH-2 should 'be followed closely in anticipation of a need for material improvement.

SUMMARY

The examination of materials used in recent hydrofoil craft shows:

- Hull materials used have given generally adequate performance. Performance demands and material used are similar to those on more conventional high-speed craft. Hence, similar results have been obtained.

- Foils and struts have been made of a variety of materials, with or without protective coating systems. Where performance information is available, it indicates that the application requires combinations of properties that are difficult to achieve, and that complete success in material selection has not been reached. Data are lacking, however, on sorne of the more interesting material selections because the craft involved have not been in service for long.

• Hydrofoil service puts severe demands; on propellers. Information on the best material for propellers is still incomplete.

It is important to continue monitoring of performance of materials in the various hydrofoil craft. This is especially important in the case of struts and foils, since they represent a new application of materials and very little service data are available to verify the assumptions being made as to the ideal material properties.

RECOMMENDATIONS

The following material recommendations are made:

- Continue close monitoring of performance of materials in hydrofoil craft to identify problem areas or superior performance.

- Investigate the usefulness of high-strength titanium and nickel-base alloys as strut and foil materials.

- Investigate the potential applicability of high modulus composite materials for strut and foil applications.

- Define physical, mechanical, and corrosion property requirements to allow optimum material selection and establish fabrication techniques for these materials to meet the design requirements of hydrofoil propellers.

- Keep abreast of new developments in materials of high-strength/weight ratio with a view to using them for hulls and superstructures where there might be a significant performance improvement.

- In conjuction with the above recommendations, plan and conduct necessary material development programs.

Appendix A

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NSRDC (Code L42)
DDC (20)

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA. R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Ship Research and Development Laboratory, Annapolis, Maryland 2 1402	2a. REPORT SECURITY CLASSIFICATION Unclassified
	2b. GROUP

3. REPORT TITLE
Survey of Hydrofoil Materials

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Research and Development Report

5. AUTHOR(S) (First name, middle initial, last name)
John P. Gudas

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
November 1969	29	27

8a. CONTRACT OR GRANT NO	9a. ORIGINATOR'S REPORT NUMBER(S) 3067
b. PROJECT NO. Task Area S4606 Task 1703 c. Work Unit 1 -107-116 d.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) MATLAB 284

10. DISTRIBUTION STATEMENT
Each transmittal of this document outside the agencies of the U. S. Government must have prior approval of Commanding Officer, Naval Ship Research and Development Laboratory, Annapolis, Maryland 21402

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	NSRDC (Code OH50)

13. ABSTRACT

A survey has been made of the materials used in hydrofoil craft for the purpose of ascertaining the current state of the art and indicating directions for further material development. The U. S. Navy's HIGHPOINT (PCH-1), PLAINVIEW (AGEH-1), FLAGSTAFF (PGH-1), TUCUMCARI (PGH-2). and H. S. DENISON as well as the Royal Canadian Navy's Bras d'Or (FHE-400) have been examined to determine the material-selection criteria used in construction of the major subsystems. The hull and superstructure, struts and foils, and propulsion systems for each craft were studied. The materials employed, the reasoning behind their employment, and the record of their performance (when available) are discussed. Recommendations for future hydrofoil development are made.

(Author)

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S/N 0101-807-6801

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