THE CANADIAN HYDROFOIL PROGRAMME

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Summary

The history of the Canadian Hydrofoil Programme is outlined starting with the work by Alexander Graham Bell and F. W. "Casey" Baldwin in 1911 to 1920 at Baddeck, Nova Scotia, which culminated with the breaking of the then water speed record using the HD4. The work during World War II on Smoke Laying Craft for the Canadian Army is mentioned. The concept of Bell and Baldwin was developed after the war by the Defence Research Board at its Naval Research Establishment at Dartmouth, Nova Scotia. Three craft were built, the 8-ton *Massawippi*, the 17-ton *Bras D'Or*, and the 3-ton "RX" research craft. The design and performance of these craft are discussed.

The Naval Research Establishment, as a result of its programme, developed a concept for a 200-ton open-ocean hydrofoil ship. The concept was investigated by De Havilland Aircraft of Canada Limited and their design study conclusions and proposals were endorsed by the Royal Canadian Navy. De Havilland was given a contract in April, 1963, to design and construct a Development Prototype Hydrofoil Ship. This paper reviews the N.R.E. concept and the current R.C.N. development programme, including salient features of the F.H.E. 400 prototype ship design.

Highlights of some of the theoretical work and research in the development of the ship are outlined. Considerations in the design of the subcavitating and the superventilating foil sections are also reviewed.

I. Historical Review of Canadian Hydrofoil Research

Hydrofoil research in Canada has its origins in the work of Alexander Graham Bell and F. W. "Casey" Baldwin at Baddeck, Nova Scotia, during the period 1911–20. Mr. Philip L. Rhodes, the well-known naval architect of New York, also contributed to this work by his assistance in the closing phase of the experiments. Their research was a development of earlier work by Enrico Forlanni of Italy from 1898 to 1905 and was confined to surface-piercing "ladder" type foil systems.

Experiments by Bell and Baldwin culminated in the development of the "HD-4" hydrofoil. In 1919 this remarkable craft achieved a world water-speed record of 61·5 knots. Over 30 years were to elapse before this record was exceeded by another hydrofoil, the American Grumman XCH-4. The HD-4 was 60-ft. long, by 5 ft. 9 in. beam of the main hull, with an all-up weight of 11,000 lb. and was powered by two 350 hp Liberty aero-engines driving pusher airscrews. The foil sections were developed empirically by Baldwin and Rhodes. It was claimed that these produced a maximum lift/drag ratio of eight at 30 knots. This dropped to four at 60 knots, indicating that severe cavitation was occurring. See Ref. (1), (2), (3), and (4).

Regrettably, little work on this novel concept was conducted after 1920 in Canada until, in 1943, the National Research Council undertook the development of expendable smoke-laying hydrofoil craft for the Canadian Army. These were termed the "Comox" boats. Equipped with surface piercing foils, these craft were 20 ft. in length and were capable of operating at speeds up to 35 knots in wave heights of 6 to 9 ft.(5)

In 1947–49, a 45-ft hydrofoil craft powered by a Rolls-Royce "Merlin" aircraft engine of 1,200 hp was designed by Philip Rhodes, based on the HD-4 experimentation, for Cdr. D. M. Hodgson, R.C.N.R., of Montreal. The craft was to be used in an attempt to set a new water-speed record. At about this time, the Defence Research Board (D.R.B.) became interested in the potential naval applications of hydrofoils and the craft was built with some design modifications under D.R.B. direction. It was designated R-100 and named *Massawippi* after Lake Massawippi, Quebec, the site of its construction and first tests. The craft was then shipped to Halifax for further trials and in 1951 the responsibility for the project was transferred to the Naval Research Establishment (N.R.E.) of the Defence Research Board.

Early trials were conducted at all-up weights in the 8,000 to 10,000 lb. range. Good performance was achieved at speeds up to about 55 knots. However, it was considered that craft weight in relation to size was not representative of the length/weight ratios for operational naval roles then envisaged for hydrofoils. In consequence *Massawippi* was ballasted for an all-up weight of 12,000 lb. and instrumented for further tests. At this weight, the craft exhibited an instability in pitch associated with cavitation on the foils. It is interesting to note that a similar tendency to porpoise was evident in the HD-4 characteristics.

Concurrent with the R-100 trials, a contract was awarded to Saunders–Roe Limited of Cowes, Isle of Wight, England, for the design study of a 100-ton hydrofoil craft (designated R-102), for naval employment. The British Admiralty supported a series of model tests for this design study and the investigation of R-100 behaviour. The study concluded, however, that a craft of this size was not feasible within the limitations of power plants and structural materials, then available.

In consequence, a further design study contract was established with Saunders–Roe to design a craft (known as R-101), based upon existing materials and power plants. The study considered two versions of a craft of about 80 ft. in length, each having an all-up weight of 47 tons, but designed for diametrically opposed proportions of hullborne and foilborne time in their respective missions. One version was an "orthodox" craft, analagous to a "boat that flies," and intended for missions where hullborne operation would predominate, (about 80 per cent of mission time). The other version was an "unorthodox" craft, likened to "an aircraft that acts like a boat" and intended for missions where foilborne operation would predominate (about 80 per cent of the time).

It was decided in late 1953 to design and build an approximately 1/3 scale model of the "orthodox" version. This project was undertaken by Saunders-Roe and resulted in the delivery in mid-1957 of the 17½ ton, 59 ft. *Bras D'Or* or R-103. It was powered by two 1,500 hp Rolls-Royce "Griffin" aero-engines and designed for a top speed of 55 knots. Extensive trials in 1958 revealed several areas in which further tests and modifications were required.

During the work by Saunders-Roe on the R-101 study and the *Bras D'Or*, N.R.E. designed a new set of foils for the *Massawippi*. In 1956, *Massawippi* was tested with the new foils at an increased all-up weight of 16,800 lb. The craft performed well in all of these tests, including a single sea trial, without the porpoising associated with the original foils.

Foil systems of the R-101 designs and the *Bras D'Or*, including the set designed by N.R.E. for *Massawippi*, were of the "V" ladder type. This marked a significant departure from the earlier straight dihedral ladder type foils employed on the HD-4, the original foil system of *Massawippi* and in the R-102 design. In the later designs, a cavitation-delaying foil section was adopted. This was originally developed by Walchner during World War II(6) and is known as the "Walchner 'C' section."

In addition to the craft previously described, N.R.E. developed and constructed a small hydrofoil as a basic research vehicle, starting in 1954. Designated "Rx," it has a simple scow-like form, an all-up weight of approximately 6,000 lb. and is powered by a Chrysler "Imperial" marine gasoline engine up-rated to 335 hp. The foils are mounted on parallel rails along the gunwale to permit convenient alteration in their longitudinal position when required. Rx is fully instrumented to enable motions in the six degrees of freedom to be measured as well as thrust, torque, *rpm* and foil unit lift. It is being employed extensively in model tests of the F.H.E. 400 hydrofoil ship design as described in the later sections of this paper.

A central theme of hydrofoil research in Canada, as illustrated by the preceding review, is the concentration upon surface-piercing foil systems and their development by N.R.E. for application in relatively small craft capable of open-sea operations in the 45–60-knot speed range. It is against this background that considerations leading to the R.C.N. programme for an ocean-going hydrofoil ship are traced in the following section.

II. Concept for an Open-Ocean Hydrofoil Ship

1. Concept Originated by the Naval Research Establishment

A conclusion of studies in 1953 was that fixed, surface piercing hydrofoil craft in the 40–60 knot speed range would be limited in size to about 50 tons. However, by 1959, N.R.E. considered that this limitation was no longer applicable. Developments in the intervening years by the aircraft industry now offered the prospect of efficient light weight, high strength materials and structures and high power, light weight propulsion units essential to the feasibility of large hydrofoil craft. At about the same time, Grumman Aircraft Engineering Corporation also concluded that larger hydrofoils would be practicable and envisaged commercial craft in the 500–3,000 ton range.(7)

N.R.E. therefore investigated the requirements for the smallest, simplest, and most economical vehicle which could operate in the open ocean with acceptable seakeeping, comfort and reliability and achieve a high degree of effectiveness in anti-submarine or other appropriate naval roles. It concluded that a 200-ton ship with a surface piercing foil system and 50 to 60-knot speed capabilities would be highly effective in many open-ocean A.S.W. roles. Equally significant was the conclusion that the relatively low cost of the system would make it feasible as a "Small and Many" concept at a cost effectiveness superior to conventional surface forces.

Consideration of various craft configurations resulted in the form shown in Fig. 1. It will be noted that the foil system combines features of the Grunberg and the Bell–Baldwin systems employing a fixed, surface-piercing hoop main foil generating 90 per cent of the total lift and a "V" ladder bow or pitch stabilizing foil unit. The canard configuration of foils inherent in this system offers some decided advantages in craft intended for rough water operation. It avoids a long bow over-hang and permits fine lines forward, thus reducing wave impact loads. The canard configuration also promotes good internal and propulsion machinery arrangements, is well suited to towed sonar installations and can achieve good foilborne stability in following seas. Since it was anticipated that, in the roles envisaged, the craft would operate largely in the hullborne mode, displacement seakeeping qualities were considered of paramount importance.

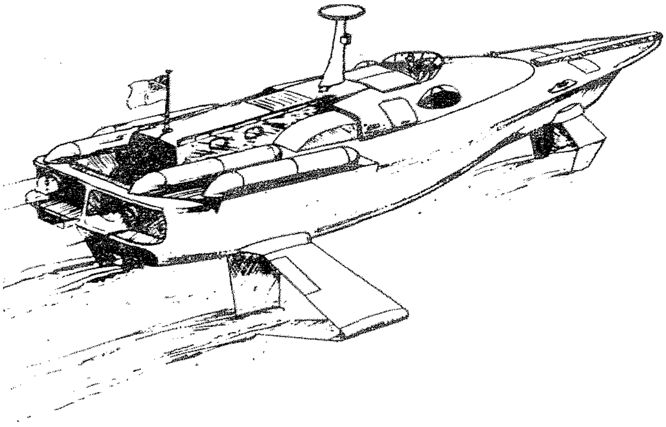


FIG. 1.—ARTIST'S IMPRESSION OF N.R.E. 200 TON DESIGN

The principal characteristics of the N.R.E. design were:—

Length overall	130 ft. (39·6 m.)
Beam of hull	28 ft. (8·5 m.)
Depth of hull	14 ft. (4·3 m.)
Span of main foils	64 ft. (19·5 m.)
Foil base length	81 ft. (24·7 m.)
Draught in displacement mode	23 ft. (7·0 m.)
Draught in foilborne mode	6 ft. (1·8 m.)
Foilborne power	16,000 hp
Displacement power	3,000 hp
Maximum foilborne speed in calm water	60 knots
Foilborne speed in SS5	50 knots
Normal cruise displacement mode	12 knots
Maximum speed displacement mode	18 knots

At a tripartite conference early 1960, a group of specialists from Britain and the United States reviewed the N.R.E. report. The conference concluded that the concept was feasible and warranted further study.

As such, the first objective is a prerequisite to the second and the latter will be fundamental to the consideration of any subsequent warship production programme.

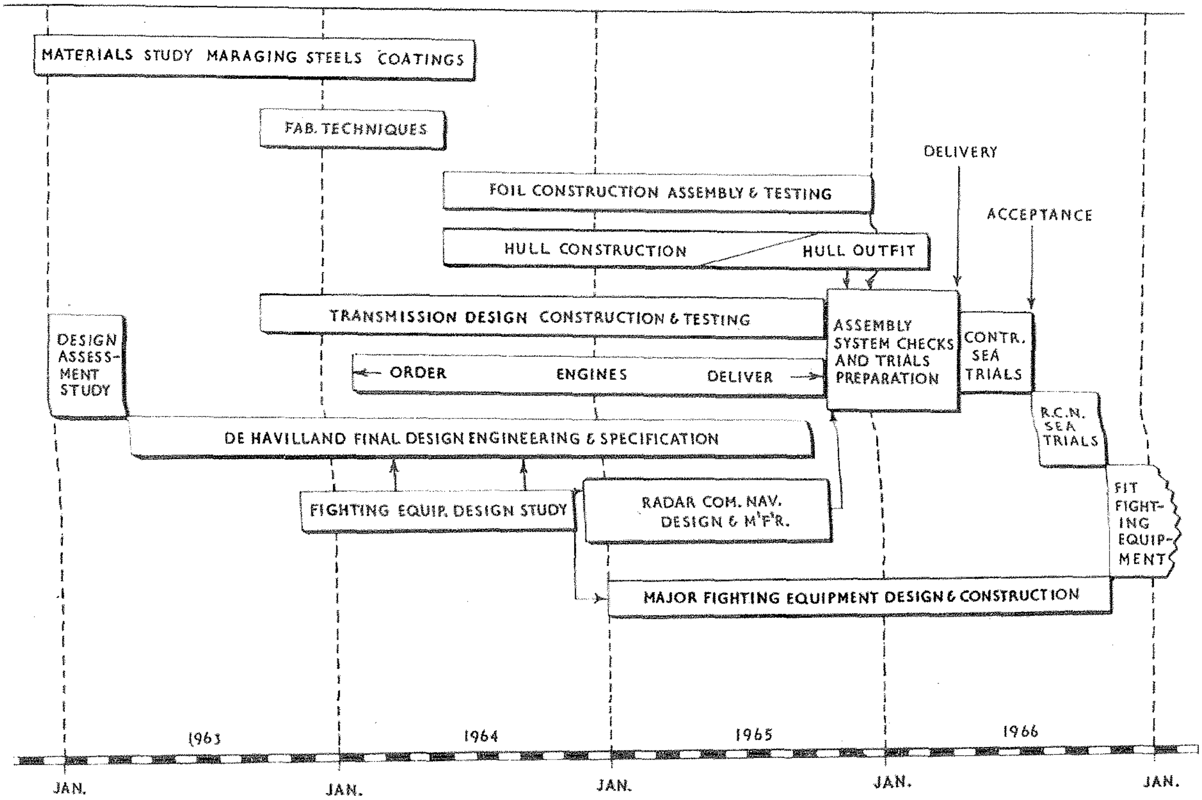


FIG. 2.—THE 400 HYDROFOIL PROGRAMME

Fig. 2 outlines the major components of the programme and their phasing. Prime contractor for the design and construction of the ship is De Havilland Aircraft Company of Canada Limited. Design and production of Fighting Equipment which includes the complex of navigation, detection, communication, armament, and tactical data sub-systems is under contract to Canadian Westinghouse. Construction and outfitting of the ship is being undertaken by Marine Industries Limited, Sorel, P.Q., on sub-contract to De Havilland. The ship programme is phased to accommodate the sequence of construction and outfitting at the shipyard for the earliest possible delivery date. Thus, design of some systems and manufacturing of others are proceeding concurrently in many instances. At this stage, the detailed design is well advanced in all areas. Foil system manufacture and hull construction are underway. The latter, as lead item, is due for completion in September, 1965. The schedule is a demanding one considering the attendant uncertainties of an extensive development programme and the reliance upon a large number of firms and agencies in the fulfilment of individual tasks. The P.E.R.T. (Programme Evaluation and Review Technique) method is being employed in the two prime contracts to assist in management of the project which is drawing upon a wide variety of support from research agencies and suppliers in Canada, Sweden, Britain, and the United States.

After launching, instrumented calm water and rough water trials will be conducted prior to the installation of Fighting equipment in late 1966 for operational evaluation in the anti-submarine role. The base of operations will be R.C.N. facilities at Halifax, Nova Scotia. Plans for shore support include the construction of a docking facility adapted to the special needs of the prototype ship. Preliminary studies have now been completed and design work is progressing on a facility which will embody a marine elevator type dock and meet the needs of other R.C.N. vessels as well. Construction is scheduled for completion in April, 1966.

2. F.H.E. 400—Prototype Ship—Design Basis

The design basis for the prototype ship established by the 1961–62 De Havilland studies of the N.R.E. concept has been closely adhered to. In its design development, apart from the specified aims for high speed and manœuvrability, emphasis has been placed upon the need for good seakeeping in foilborne and particularly hullborne operation.

An objective which is fundamental to the N.R.E. concept and its realization in the R.C.N. development programme, is to achieve the minimum size and cost of ship practicable for open-ocean operations in the A.S.W. role. Early parametric studies by De Havilland confirmed that about 200 tons was the optimum size for the requirement. A smaller ship would be deficient in range while a larger one would not yield a significant increase in payload because of the rising proportion of foil system weight with increasing size. On the other hand, seakeeping ability improves with size. These were important considerations in the final decision on form and size of the ship from standpoint of habitability and operational effectiveness in open-ocean employment, particularly for extended periods in the hullborne mode.

Accordingly a fundamental aim has been the achievement of the smallest practicable ship with hullborne seakeeping qualities equivalent to conventional warships of over ten times its size. This is made possible by a design of the hull complimentary to the non-retractable foil system. The latter is a natural ally which, through its extensive immersed area, exerts a powerful damping action on ship motions, particularly in roll.

A notable feature of the ship is its broad foilborne speed range capabilities compared to contemporaries employing submerged automatically controlled foil systems. This is due in part to the rapid low speed take-off provided by the surface-piercing foils and also because the fundamental design aim was to achieve the maximum speed, particularly in rough water. Detailed consideration of operational requirements have also been a heavy influence in the refinement of the overall design of the ship and its facilities. However, the generally sensitive interdependencies of speed, payload, range, size, and cost in a ship of this type have been a decisive factor in limiting deviations from the basic design.

The foil system of F.H.E. 400 has no direct precedent. As a key feature upon which the feasibility of the concept hinges, its design has been supported by a comprehensive programme of material research and hydrodynamic development, beyond that of the earlier Phase I and II studies.

A specific aim in the prototype design is to employ proven equipments where suitable and to restrict operational features to those essential to proof of feasibility. The general approach, however, has been to minimize the transitional development which would be necessary for a warship class.

3. Related International Designs

International developments in hydrofoil craft have been prolific and widely reported in recent years. These have marked a growing interest in commercial applications, exemplified by the *Denison* and the Supramar series of hydrofoils. None of these however have been designed for long-range open-ocean employment and are generally limited to operation in low sea states.

In the military sphere, the Canadian F.H.E. 400 programme is joined by the United States Navy PC(H) and AGE(H) projects described in a recent paper(9) by Mr. Ralph Lacey, Bureau of Ships. Of these three ships, only the A.G.E.H. and F.H.E. 400 have been specifically designed for ocean operations. The fundamental differences between the latter two as illustrated by Mr. Lacey's paper, lie in size, foil configuration, and end purpose. In contrast to the 320-ton experimental A.G.E.H. employing a "conventional" configuration of automatically controlled, submerged foils capable of retraction, the 200-ton F.H.E. 400 development prototype is based upon a "canard" disposition of surface-piercing, non-retractable foils with an overall design and outfit specifically oriented to an A.S.W. application. The pivotal point in the design of either ship is the type and configuration of foil system. While each has its own particular virtues and disadvantages, the choice of foil system for F.H.E. 400 was influenced by the requirement for good seakeeping qualities and a high degree of inherent simplicity, ruggedness, and reliability in the demanding environment of oceangoing naval operations. In many respects the development of hydrofoil craft and equipment are in their infancy. Contributions to the advancement of these developments, especially in the military sphere, are being made by the U.S.N. and R.C.N. programmes. A close identity of interests links these two projects and the attendant cooperation has been of great benefit in the progress towards allied goals.

4. F.H.E. 400 Design

Principal Features

The form and external features of the ship are shown in the views of Fig. 3. The general layout of main and lower decks, including Bridge and Operations room is illustrated by Fig. 4. These are in the course of mock-up development in a full-scale wooden replica of the hull and superstructure at De Havilland.

Leading particulars are summarized in Table I and do not differ substantially from those of the Phase II design proposal.

Hull Structure

The hull structure design involves some departure from normal practice. It caters for hull bending while foilborne, high bottom impact loads at take-off and foil attachment fittings.

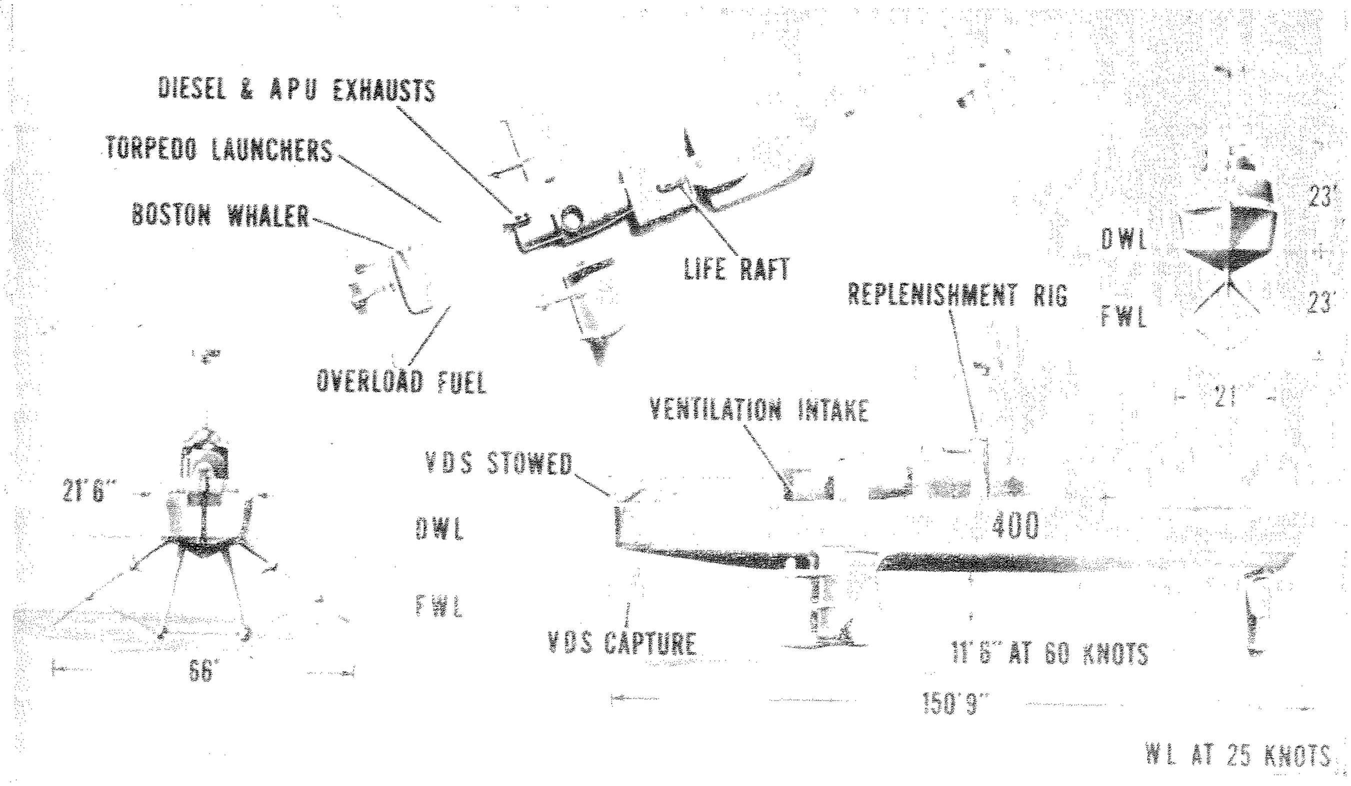


FIG. 3.—R.C.N. PROTOTYPE A.S.W. HYDROFOIL SHIP
Plan and profile views

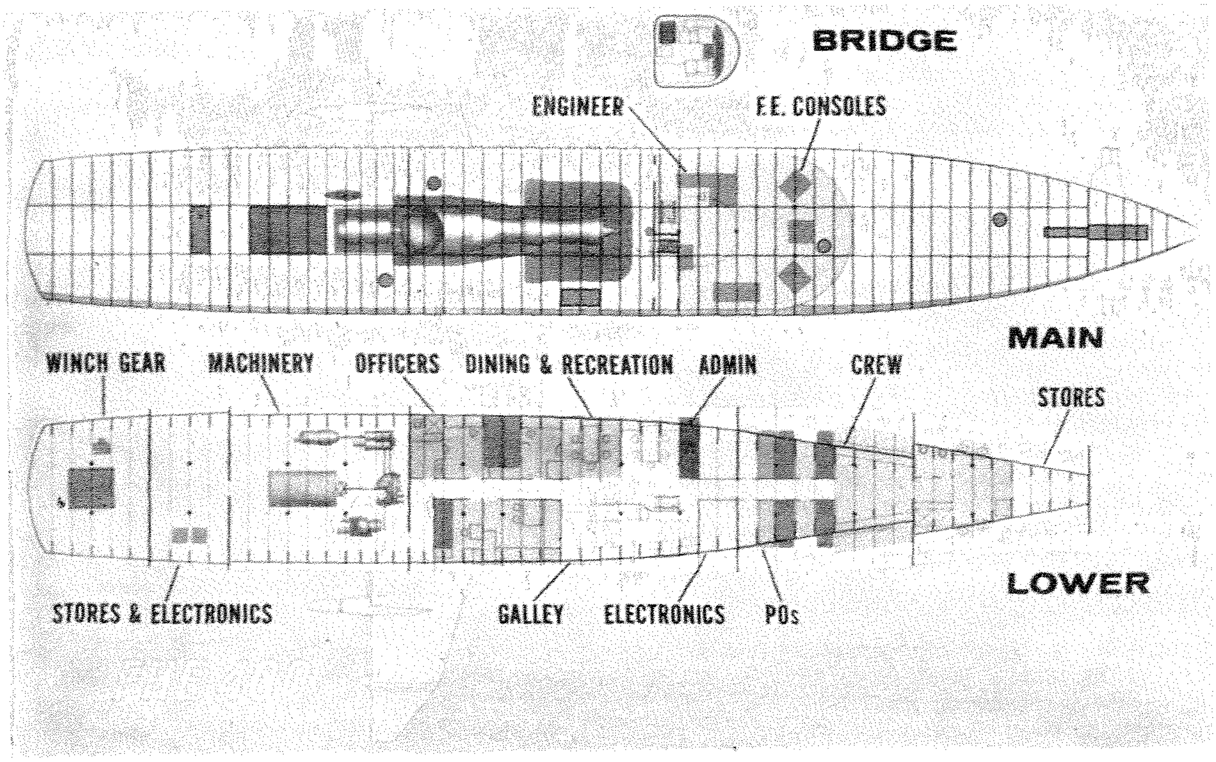


FIG. 4.—R.C.N. PROTOTYPE A.S.W. HYDROFOIL SHIP
Deck plans

TABLE I

PRINCIPAL PARAMETERS AND FEATURES– F.H.E. 400

Dimensions	
Length overall	151 ft. 5 in. (46·2 m.)
Length of waterline	146 ft. 6 in. (44·6 m.)
Beam of hull	21 ft. 6 in. (6·6 m.)
Foil base	90 ft. 0 in. (27·5 m.)
Bow foil span	22 ft. 6 in. (6·7 m.)
Main foil span	66 ft. o in. (20·1 m.)
Hull depth	15 ft. 0 in. (4·6 m.)
Keel clearance at 60 knots	11 ft. 6 in. (3·5 m.)
Draughts	
Hullborne draught	23 ft. 6 in. (7·2 m.)
Foilborne (60 knots) draught	7 ft. 6 in. (2·3 m.)
Displacement	about 200 tons
Main, Auxiliary, and Emergency Power Plants	
Foilborne gas turbine—(Pratt and Whitney FT4A-2)	22,000 shp cont.
Hullborne Diesel (Davy Paxman 16YJCM)	2,000 bhp cont.
Auxiliary gas turbine and hullborne boost) (Canadian Pratt and Whitney ST6A-53)	390 shp cont.
Emergency gas turbine (Airsearch GTCP85–291)	200 shp cont.
Propellers	
Foilborne—twin supercavitating props) (fixed pitch)	3 ft. 8 in. dia.
Hullborne—twin controllable pitch props	7 ft. 0 in. dia.

Hull and superstructure will be of all aluminium welded construction, fabricated from ALCAN D54S or equivalent plate and extrusions except for the foil attachments which are 7075(T73) aluminium forgings bolted to the welded structure. Extensive use has been made of large extrusions of combined stringers and plating.

The slender hull, designed for minimum resistance, is highly stressed. In consequence, structural joints must be carefully designed and marry up precisely.

The hull is being constructed in the inverted position on an erection bed. When completed, it will be rotated to an upright position for the erection of superstructure, outfitting of systems and attachment of foils.

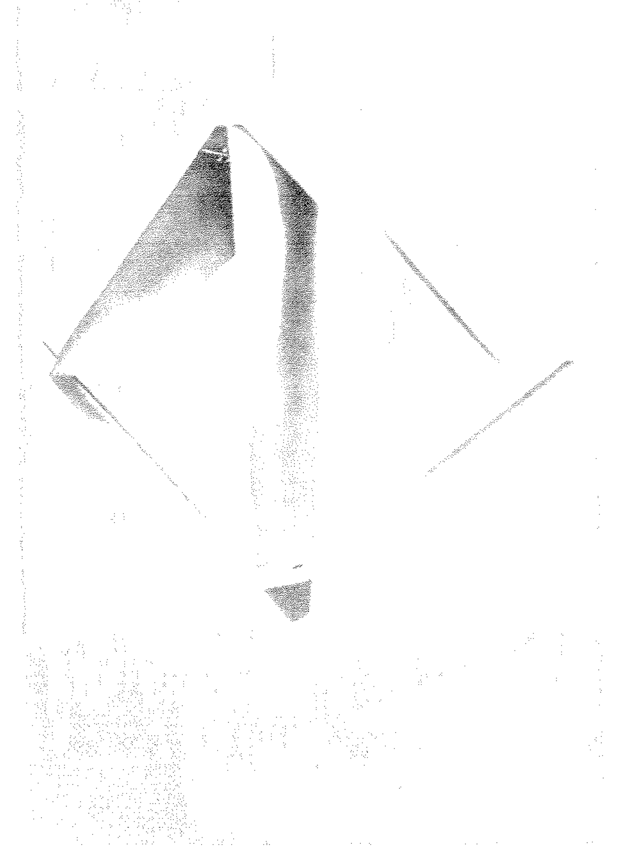
Foil System

The system consists of two surface piercing, non-retractable units, the bow foil supporting 10 per cent of the ship's weight with the remaining load on the main foil.

The bow foil (Fig. 5) is a supercavitating design for good response in a seaway and acts as a wave sensor to trim stabilize the ship when foilborne. The centre strut is coupled to a shaft which rotates about its axis for steering control at all but low harbour speeds when the use of the controllable pitch propellers is necessary. The shaft can also be raked fore and aft to adjust the pitch angle of the bow foil for hullborne or foilborne attitudes.

The main foil (Fig. 6) has elements with delayed cavitation sections and is an unusual combination of surface-piercing and submerged foils. The large anhedral foils provide reserve lift at the low take-off speeds. Anhedral tips are rotatable and can be manually or automatically controlled in incidence to ensure adequate roll stability at very low foilborne speeds. These can also be employed at higher foilborne speeds to decrease turning diameters in "coordinated" turns. Fences are fitted to the high-speed foils and struts to inhibit ventilation.

The foil system is constructed of welded 250 ksi maraging

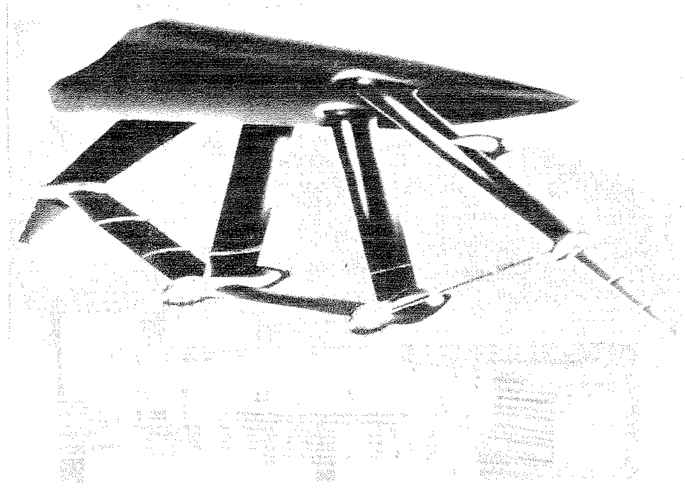


Supercavitating foil section

FIG. 5.—R.C.N. PROTOTYPE A.S.W. HYDROFOIL SHIP. BOW FOIL

steel of the 18 per cent nickel variety, to which a protective coating, being developed by De Havilland, will be applied. Foil elements are bolted to each other and to the hull. Leading edges of the foils are replaceable and made of INCO 718 stainless steel.

Although the hull and foil elements are relatively simple structures, an analysis by conventional means would be unreliable because of the multiple load paths. Matrix methods have therefore been adopted in critical areas such as the foil elements and main foil foundation.



Delayed cavitation foil section

FIG. 6.—R.C.N. prop R.C.N. PROTOTYPE SHIP. MAIN FOIL

Although the ship is relatively small, the foil system acts as a strong damper to hullborne motions. Model tests indicate that hullborne motions will be less severe than those of a destroyer escort.

Foilborne Propulsion System

The roughly ten to one difference in foilborne and hullborne power requirements dictate separate propulsion systems for economical performance.

The foilborne system is powered by the FT4A-2 turbo-shaft engine rated at 22,000 shp continuous duty and mounted in a protective cowling headed by an air intake abaft the operations room on the main deck. This arrangement minimizes noise and heat transfer to the living spaces of the ship and avoids large structural cut-outs in the highly stressed hull. Power is transmitted from a dual output gearbox abaft the engine via downshafts in the main foil struts to a pod mounted gearbox and supercavitating propeller at the foot of each strut.

The propellers are fixed pitch, three bladed and 44 inches in diameter. The design is currently under joint development by the National Physical Laboratory, England, and De Havilland, Canada. Over-running clutches in the pods automatically disengage the propeller during hullborne operations.

Both hullborne and foilborne transmissions are being designed and built by General Electric, Lynn, Massachusetts, under contract with De Havilland. Previous experience with the transmissions designed by G.E. for H.S. "Denison" and the AG(EH) will be a significant benefit to the F.H.E. 400 transmission development.

Hullborne Propulsion System

The hullborne system is powered by the 2,000 bhp Paxman 16YJCM diesel centred in the engine-room as shown by Fig. 4. Power is transmitted by a dual output gearbox and downshafts to an outboard gearbox and propeller at a pod on each anhedral foil. The propellers are 84 in. in diameter, three bladed, controllable in pitch and feathered to minimize wave impact loads during foilborne operations. These are being designed and built by KMW, Sweden.

Auxiliary Machinery and Systems

Engine-room. The engine-room shown on the lower deck plan of Fig. 4 contains the propulsion diesel and all auxiliary systems, including the 390 shp ST-6A auxiliary gas turbine and 200 shp Airesearch emergency gas turbine driving generators, hydraulic and salt water pumps. The auxiliary system is designed around a dual input auxiliary gearbox driven via clutches from either the diesel while hullborne or the ST-6A while foilborne. The gearbox is also capable of coupling the ST-6A to the displacement transmission for "boost" power with the diesel or by itself for emergency propulsion. The emergency gas turbine pack provides a secondary source of electric and hydraulic power, firefighting services and bleed air for main gas turbine starting. The engine-room is unmanned and controlled from the bridge and a machinery console in the operations room.

Sub-Systems

The hydraulic system operates bow foil steering and trim, anhedral tips, V.D.S. and anchor winches and various lubricating pumps.

The pneumatic system provides compressed air for gas turbine and diesel starting, torpedo launching, and other services.

Fresh water is supplied from two distillation units. Diesel-engine jacket water is the heat source for the units.

Electric power is generated at 115/200 volts, 400 cycle, 3 phase.

The ship is heated from an exhaust gas heater exchanger operating from the diesel or ST-6A turbine. Electrically driven air conditioning units are employed.

Firefighting services include a remote controlled CO_2 flooding system for the engine-room, fire hydrants on upper and lower decks, and a portable gas turbine powered emergency pump.

The fuel system is designed to accommodate any diesel or turbo fuel suitable for the four engines. JP5 will be the standard fuel in F.H.E. 400. Four tanks are incorporated below the lower deck.

The bow foil steering system includes features for manual or automatic control of heading, the latter operating from the ship's gyro compass.

Seamanship Outfit

Outfit plans include anchor and associated facilities on the quarterdeck, with a lightweight winch in the compartment below. Hydraulic powered bollards and other normal fittings for line handling are being provided. A 13½ ft. Boston Whaler with an 18-hp outboard motor will be carried as shown in Fig. 3.

Facilities for refuelling and replenishment at sea are being incorporated.

Variable Depth Sonar Winch and Handling Gear

Facilities for the streaming and recovery of a towed V.D.S. body are being developed based upon handling gear designed to recover over-the-stern. These are in the course of design. A representative installation is shown in Fig. 3.

Accommodation

Feasibility of the ship is dependent upon its habitability in open ocean operations. Environmental considerations have therefore heavily influenced accommodation design. Planning has been based on a crew of 4 officers and 16 men with provisions for operations in excess of two weeks at sea. This is subject to possible change when operating and maintenance tasks are more fully explored during the evaluation. Because of the uncertainties, an aim is flexibility of arrangement. The general arrangement which has now been mocked up is shown in Fig. 4.

The galley provides for storage, preparation, and cafeteria style serving of all food. Meals will largely consist of precooked and frozen foods, selected in portions on board according to the menu and served after rapid heating in a micro-wave oven. Conventional foods can be prepared when practicable. This approach has been dictated by weight, space, manpower, and foilborne motion considerations.

Bridge and Operations Rooms

A general arrangement of Bridge and Operations Room is shown in Fig. 4. The Bridge is confined to ship control and navigation functions and provides for two manned positions, a primary and secondary. The Operations Room is the centre for tactical control of the ship and its weapons system. A representative arrangement of manned consoles is shown. The engineers console is also fitted in this space. Systems engineering analysis techniques, including work study has been applied to the design of arrangements and definition of operator duties and qualifications.

5. Problem Areas

Some degree of uncertainty on the full attainment of objectives is inherent in any development programme, however well founded. The F.H.E. 400 prototype will in many respects be the product of recent research and developments. Herein, certain possible difficulties, which may emerge in evaluation, have been acknowledged and high-lighted as "key problem areas" in the project. These bear upon questions of operational as well as technical feasibility of the design and includes foil materials and coatings, supercavitating propeller design, seakeeping and noise influences on the habitability of the ship.

IV. *Research and Development Aspects*

1. Introduction

The F.H.E. 400 programme constitutes the development of a complete "weapon system" based upon a relatively unprecedented vehicle design, which compared to conventional warships, places stringent limitations on the size and weight of its elements, including systems and payload. This has necessitated some research and a considerable dependence upon development or adaptation of lightweight hardware. The latter is, unfortunately, a costly process, particularly for a single experimental ship. The foil system is, however, the focal point of development effort upon which the success of the entire programme depends. Theoretical studies and research have also played a considerable role in the work to ensure a sound foil system hydrodynamic, material and structural design. These encompass an extensive range of studies and tests over the past four years.

The scope of this paper permits only a brief review of the vehicle considerations. Highlights are grouped and summarized in the following sub-sections.

2. Hydrodynamics

In the process of developing a specific foil system for F.H.E. 400, it is considered that significant contributions have been made to the design of surface piercing hydrofoil craft. This applies particularly to the dynamic simulation of craft motion in a random seaway and in subcavitating foil design. Other contributions are also being made to the art of superventilating foil sections and supercavitating propeller design. Some considerable effort has also been applied to hydroelastic studies and tests on divergence and flutter clearance margins of the main and bow foil.

(a) Craft Motion in a Random Seaway

A fundamental aim of the N.R.E. concept was an all-weather craft capable of open-ocean performance. A major problem in the feasibility design studies was, however, the estimation of the degree of stability for foilborne operation in a random sea. Up to 1960, little work had been published on this subject. Accordingly, De Havilland, as previously noted, undertook the development of the equations of motion and a method of representing a random seaway for an analogue computer simulation of craft in six degrees of freedom. The initial simulation was in sinusoidal seas and results were correlated with model tests at N.P.L., London.

Subsequently, random seaway simulation was incorporated during the Phase II studies, and has since been extensively employed in the design development and proving of the foil system. The forthcoming phase of computer simulation studies will be applied to the anhedral tip and bow foil control systems to establish gains and stiffness requirements.

A comprehensive treatment of the theory of craft motion and the correlation of computer predictions with trials results is contained in the paper of Ref. (8) presented by Davis and Oates to the O.N.R. Symposium at Bergen, Norway, in August, 1964.

(b) Subcavitating Foil Design

The main foil design requirement is for cavitation free operation at 60 knots in calm water and for a wide angle of attack range at 50 knots in Sea State 5.

Design of a satisfactory non-cavitating foil involves the determination of the shape required to support a given pressure distribution. At infinite depth, this problem is identical to the airfoil, for which methods of computation already exist.

However, the free surface can cause significant effects on the pressure distribution at practical depth/chord ratios and Froude Numbers. Thus an extension of airfoil theory is necessary to account for the effect of the free surface.

Such a technique was developed for the F.H.E. 400 design programme using the method of singularities in which the lift is represented directly by vortices, and thickness by doublets. This work is described in Ref. (10).

Using this technique, hydrofoils can be designed to have a minimum cavitation number for a given thickness and lift, by specifying flat-topped types of pressure distributions. However, at off-design angles of incidence, these profiles have poor cavitation characteristics, since the additional lift due to change of incidence causes sharp (negative) pressure peaks near the leading edge. The objective therefore is to design a profile having as wide a cavitation free range as possible. This can be achieved by designing a profile which will have a positive pressure peak near the leading edge on both upper and lower surfaces at the design angle of attack. The negative pressure peak due to change of incidence will then "fill in" this part of the pressure diagram, leading to a flat-topped pressure distribution on one side at each extreme of the cavitation free incidence range.

(c) *Fully Ventilated Foil Design*

The environment and stability requirements for the bow foil favour the use of a fully ventilating foil section. However, it is difficult to design such a foil which would have satisfactory characteristics due to the wide range of angle of attack experienced in a seaway and the need for a section with good low speed resistance. In developing the foil section, it is first necessary to define the pressure face for normal supercavitating or fully ventilating operation. A Tulin–Burkart pressure face is used with a design C_L of $0 \cdot 1$ and a nominal operating C_L of $0 \cdot 2$, using the method outlined in Ref. (11).

For minimum resistance in the displacement mode, the foil should have an upper surface shape approaching that of a circular arc, the ordinates of which should have the minimum included angle compatible with structural requirements. In a seaway, however, very small relative angles of attack occur, and under such conditions, the flow will re-attach to the circular arc top surface, with a consequent large lift increment in the fully wetted condition, due to the camber of this type of foil. Since re-attachment leads to violent pitching motions, it is necessary to provide a spoiler on the upper surface, in the form of a "step" to prevent flow re-attachment over the rear portion of the foil during foilborne operations.

3. Materials Investigation

One of the major problems in the development of a surface-piercing hydrofoil craft of the F.H.E. 400 size is the limited selection of structural materials with the high strength/weight ratio and other properties required for an efficient and durable foil system.

As previously mentioned, De Havilland were assigned a contract to conduct a comprehensive investigation to determine the best materials and protective coatings available in the time scale for production of the F.H.E. 400 foil system. The Department of Mines and Technical Surveys was also engaged as a consultant.

A number of materials were investigated for various properties in tension, shear, fatigue, impact, weldability, and for resistance to normal corrosion and stress corrosion.

The results of these studies led to the selection of an 18 per cent nickel maraging steel with a 250,000 psi yield strength. An extensive series of tests were conducted. Fatigue characteristics were determined by random load tests using the load spectrum derived from the analog simulation of the ship.

The need for coatings to provide adequate protection of foils against corrosion was established. Investigations were conducted on a large variety of types for adhesion, water absorption, resistance to cavitation erosion and other critical properties. These have resulted in a concentration on two of the most promising, both of organic composition. Small scale tests of these coatings have been run in cavitation loops developed by De Havilland at speeds of 65 knots. Larger scale tests are in progress at Grumman Aircraft Engineering Corporation facilities. Qualitative trials on large underwater sections of two R.C.N. destroyers are being conducted. Arrangements have also been made for tests of these on the bow foil of the U.S.N. Hydrofoil PC(H).

The Department of Mines and Technical Surveys is investigating the proporties of the new 12 per cent nickel maraging steels (180 ksi yield) which appear to offer attractive advantages as a replacement for the 18 per cent material in any future foil manufacture. This is subject to determination of suitable fatigue properties and other qualities.

The necessity and feasibility of a cathodic protection system for the ship is also under investigation.

4. Habitability

In the final analysis, the feasibility and operational capabilities of the ship will be dependent upon the habitability of the ship and thus the efficiency of its crew. The nature of F.H.E. 400 and its envisaged operation presents some unusual environmental conditions, particularly while foilborne. Accordingly, considerable attention has been given to habitability aspects in the design of accommodation and operator facilities. Factors which have influenced these are ship motions, noise, and vibration, together with space, weight, manpower, and equipment limitations.

Extensive use has been made of "Method Study" in establishing requirements and the design of arrangements. Its applications by the R.C.N. are described by Ref. (12), including the study from which the F.H.E. 400 galley design was developed. Accommodation, Bridge and Operations room arrangements and management have also been defined by R.C.N. method studies. These have been of great assistance in charting requirements and designs which have, in most instances, little precedent in conventional warships. In keeping with the concept, every effort has been made to minimize operating and maintenance requirements, thus to achieve the smallest crew for efficient, "round-the-clock" operation at sea. While living accommodation is not cramped by submarine or M.T.B. standards, the limitations of layout and other criteria have required careful design of arrangements and the development or adaptation of lightweight, easily maintainable equipment and furnishings.

Measures to ensure adequate levels of comfort and efficiency while foilborne have received particular attention. Human thresholds of tolerance to ship motion are not well defined. While hullborne motions are predicted to be less severe than a destroyer escort, there is the uncertain effect of the stiff damping action of the foil system. Finally, there is the entirely different nature of foilborne motions and the difficulty of predicting crew reaction to these. While tests in Rx craft indicate that levels of acceleration should be acceptable, it should be noted that a surface piercing foil craft such as F.H.E. 400, is a semi-contouring or partial response system with less potential for smoothness of ride than an equivalent craft with submerged automatically controlled foils.

In the study of F.H.E. 400 environmental factors by the Canadian Forces Institute of Aviation Medicine, attention has focused upon foilborne motion considerations. Part of the investigative programme includes the study and test of sleeping and operator console arrangements under simulated foilborne motion conditions using "live subjects." A motion simulator platform which can reproduce foilborne motions in roll, heave, and pitch has been constructed for this purpose at the National Research Council laboratories in Ottawa. It is operated from magnetic tapes of the predicted random seaway motions of F.H.E. 400 derived from the De Havilland computer simulation.

Experimental mock-ups of crew bunks and operator control positions will be instrumented and tested to assess comfort and efficiency of arrangements, including modifications to their form or employment to minimize any adverse effects of foilborne motion. Trials are now underway on an experimental version of the bunk design concept developed by I.A.M.

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DISCUSSION

Mr. K. G. Evans, R.C.N.C. (*Member*): Less than a year ago I was fortunate in being able to visit both De Havillands at Toronto and also Marine Industries Limited at Sorel, and I came away impressed by the effort and the depth of study being devoted to this ambitious project.

The F.H.E. breaks new ground internationally by setting out from the start to be ocean-going. This, I would suggest, involves accepting two challenges: firstly, whether the craft can be made strong enough to ride out a storm it may inadvertently be caught in, and secondly, whether the crew will be resilient enough to stand up to the tough conditions. I have no doubt that the hydrodynamic problems can be solved, with some perseverance, but the strength of materials and of humans can set limits.

The F.H.E. 400 is some 10 ft. longer than the British coastal minesweeper, a craft able to make ocean passages and which is at this moment carrying out patrols which years ago would have been undertaken by destroyers. The C.M.S. is also of light materials and in storms slides down the waves like a raft. The fixed foils in the F.H.E. 400 will damp the motion, causing the hull to be hit and washed down with greater violence than the C.M.S., so are the authors satisfied that the hull will have enough strength in hand to take such treatment?

I agree with the authors that "human thresholds of tolerance to ship motion are not well defined." In the lively C.M.S., where a feeling of near-weightlessness may be experienced when pitching in heavy seas, reserve trawler skippers have owned up to being seasick for the first time in their lives. From this, I would suggest that personnel should not be exposed for prolonged periods to accelerations in excess of 0·3 g. An airsick jet pilot of course can cause a catastrophe. Some years ago a lot of attention was paid to this problem and one thing which came out of it was that both the acceleration itself and the first derivative of the acceleration are equally important parameters affecting motion sickness, a fact also known to lift designers. I can give the authors published references if they would find them of use. A hydrofoil can give a bumpy ride under certain conditions, and in fact the film conveyed this, and I would suggest that the human tolerance to these motions which could bring on sickness might be explored further, consulting the experimental evidence over here on aircraft and the C.M.S.

A further human strain is noise and I presume this will be great, although not so earsplitting that it cannot be overcome by earplugs, but I would hope that you do not have to issue these as well as pieces of rubber to put between the teeth to overcome the wash-board ride!

Incidentally, you have not shown any clear indications of the place taken up by the military assignment inside, and I expect it is true to say you have space in this craft but weight is at a premium, so I imagine although you have arranged fairly good accommodation you will probably in the long run be rather pinched for amenities; so a volunteer force, well paid, might have to be a solution. Do you accept that possibility?

One last point on the foils, which have to take tremendous loads in a most punishing environment, would it not be wise to assume that these will require frequent renewal? How is replacement of the foils undertaken and can this be accomplished without docking, which would not appear to be easy and a possible disadvantage of the fixed foil system?

In conclusion, I wish the F.H.E. 400 every success, and do the authors consider there is a commercial application? I am wondering whether it might be possible to see hydrofoils on the Canadian Great Lakes as well as those now plying the Black Sea.

Mr. A. K. Buckle, B.Sc. (*Associate-Member*): On page 101 the authors specifically state that the hull is intended to bend while foilborne. Most hydrofoils are subject to considerable deflections but this one seems to be particularly "bendy." Accepting this low inertia it would seem there is the possibility of two node vibration in otherwise quite reasonable sea states. What is the critical frequency of this hull?

The authors also state that the bottom impact pressures are high. I think most people know this but I would like to know what ultimate pressure values have been allowed for. They could not have been measured on this vessel yet but would the figure of 35–40 lb./sq. in. be reasonable, the same as on the bottom of the M.T.B.s? Judging by the films I have seen the R.C.N. do not seem to have done any measuring of impacts during the model testing experimental work.

Can the authors say whether, for the extruded shell and frames, the same extrusions were used as on the PC(H)1 or were they specially designed for this vessel, and if so is a constant shell thickness used or does it vary in thickness between the frames?

The bowfoil is directly under the bow and does not seem to be very strongly attached. If this hits driftwood what is the result? Some foils are made to break off, but if this one did it would go straight through the bottom of the boat just about where the crew accommodation is. If it does not break off troubles can also be pretty severe.

Could the authors give some indication of the speed-resistance curve for this boat? Has it a very high hump? Some hydrofoils have an excessive hump at take-off speed. From the film this does not appear to be the case here but if it is, could the authors say at what speed this occurs?

The gearing appears to be almost at deck level—is there anything against epicyclic gearing in the pods? The pods are an unusual shape, thinner in the middle than at the end. Would it not be liable to cause cavitation at non-optimum speeds as has happened on other craft and unfortunately broke down in way of the propeller roots and did the propellers no good at all.

Finally, could the authors give some information on the actual trials of the *Bras d'Or* to tie in with the model trials results quoted in the 1958 paper, in particular with regard to accelerations and impacts? Could they give scantlings of the *Bras d'Or*?

Mr. H. Lackenby, M.Sc. (*Member of Council*): One cannot fail to be impressed by the considerable effort put into this project by the Royal Canadian Navy for the development of a high-speed sea-going, hydrofoil craft for anti-submarine duties. Although the stimulus here is certainly a military one, the work described will also interest those concerned with the possible commercial development of such craft. In his presentation Mr. Milman mentioned that tens of millions of dollars had been spent on these developments over the years and from the commercial point of view one is tempted to ask whether a rough indication could be given of the development costs of the F.H.E. 400 since the project started in 1963.

I would like to raise a few points of detail. The hull is stated to be of welded aluminium construction fabricated from ALCAN D54S. It would be of interest if the authors would give information on the nature and mechanical properties of this material. In the United Kingdom the two aluminium alloys considered suitable for marine environments are those containing magnesium up to 42 per cent known as N8 and the magnesium silicide alloy known as H30 which is heat treated. It is also stated that the hull structure is highly stressed and information on the actual stress levels worked to would be helpful.

The items mentioned under "Problem Areas" are of special interest and not least of these appears to have been finding suitable materials for the foils. In this connection it is noted that a maraging steel of about 110 tons per square inch yield point has been used and here again an indication of the designed working stress would be of interest.

Finally, I would like to wish all success to the authors and their colleagues in this very interesting project and I look forward to hearing about the sea trials to be carried out next year. It is hoped that the results and experiences, at least the non-military aspects, can be made generally available.

Mr. C. Hook: One point is that the leading foil, the bowfoil, is spoken of as being supercavitated: I rather quarrel with that term because it is, strictly speaking, an aerated foil.

My other point is that it is mentioned that an emerging foil boat 20 ft. long was able to take waves 6 ft. to 9 ft. high. I think it is rather regrettable that we are using this somewhat rough method of talking about waves. I believe it would be an excellent idea if the Institution would take the lead in giving us perhaps a theoretical sine curve of a wave that we can properly specify and talk about, not only in terms of height but also in the ratio of height to length. It would be better to have a purely theoretical sine curve to talk about. Indeed, in my view, our need for a defined wave is as great as the engineers' need for a system of weights and measures.

Mr. M. N. Parker, B.Eng. (*Member*): The thing that impresses me most about this project is what has been achieved with a fixed foil system. For high performance craft for ocean going service we have usually tended to think in terms of fully submerged foils with incidence control. In this connection perhaps the authors could give us some indication of the standards they were aiming at in this project as regards ship motion response to waves. Were the naval requirements with which they were faced more or less stringent in this respect than would be required for a passenger-carrying vehicle? If satisfactory tolerance to waves can be achieved with a fixed foil system the simplicity of the arrangement will be much in its favour under sea going conditions. The same applies to the non-retractable foil system, but I would like to ask the authors how frequently they expect to have to dock the craft in order to do maintenance of one sort or another on the foils, even if it is only a matter of cleaning.

Finally, I would like to express my admiration of the way in which the programme of hydrodynamic work in connection with the development of the foil system has been conceived. As I understand the account of this programme given on the third page of the paper, the essential purpose of the model experiments at Ship Division was to determine and quantify the various coefficients in the equations of motion. These were then set up on an analogue computer and this was used to make the ship predictions. The purpose of the quarter scale model was to check the reliability of this method on the basis that if you could predict for the quarter scale you could also predict for the full scale. This seems to me to be the most efficient way to use model testing facilities and it is one to which we should perhaps give more attention in conventional ship work.

Mr. A. Silverleaf, B.Sc. (*Member of Council*): This paper forms a useful supplement to that presented a year ago by Mr. Lacey which was a much broader review of recent progress on hydrofoil ships and was naturally primarily concerned with developments in the United States. Although some may think it rather premature, the present paper provides an interesting account of Canadian effort. The world-wide development of foilcraft can be broadly divided into three stages. First, were the rather haphazard and unco-ordinated efforts of several notable pioneers, many of them enthusiastic and very able amateurs, including the Wright Brothers and Alexander Graham Bell. However, in spite of their work little real progress had been made by 1935, largely because of lack of support by any government, partly because the hydrofoil ship, unlike the aircraft, has to face competition from high speed surface transport. Thus, the story of the modern hydrofoil ship really begins about 30 years ago, when von Schertel in Germany and Grunberg in France independently produced quite different designs, both of which have shown themselves capable of considerable development, although sometimes with marked modifications. During the Second World War, the Germans made serious and intensive efforts to apply von Schertel's ideas to high speed patrol boats and tank transporters, while in Britain a much less ambitious attempt was made at Dumberton by a team led by the late Dr. Allan to adapt the Grunberg principle and produce a fast hydrofoil M.T.B. This limited British effort was not unseccessful, and speeds of over 50 knots were reached in trials on the Gare Loch, but the craft never became operational, and after the war the Admiralty lost interest in hydrofoil ships, thus ending British active interest for 20 years, though there are recent signs of a revival.

The third stage in the development of hydrofoil ships is their post-war story which itself has three separate parts. First, von Schertel's work was continued and led to the development of the commercial Supramar PT craft, of which over 70 of different sizes are now in operation in many countries, while there have been other types of craft developed for similar purposes with the same general characteristics. Then since about 1950 an independent, very ambitious and expensive development programme of more sophisticated types has been undertaken in the United States and Canada, principally for naval purposes. Lastly, the Soviet Union has built large fleets of commercial hydrofoil ships of rather unusual design, particularly for river passenger services. The introduction to the present paper shows that Canada has been concerned in all three stages of this development and is now much in the forefront, since F.H.E. 400 may well turn out to be a most remarkable craft of most advanced design.

As the authors know, Ship Division, N.P.L. has been fortunate to have the opportunity to work with the Canadian Government on hydrodynamic problems involved in the design of both R–103 and F.H.E. 400. Indeed, the experiments made in connection with the development and design of F.H.E. 400 represent perhaps the most comprehensive series of model experiments of this kind ever carried out, of which a full impression is not given in the paper. In addition to experiments to establish the force and pressure characteristics of the separate foil units, very impressive experiments were made on a complete skeleton of the craft to determine its motions in irregular as well as regular waves, and recently some most novel experiments have been made to study flutter characteristics. These form part of a co-ordinated triple effort, with design studies and analogue computer simulation being carried out by De Havilland in Toronto, sea trials with the RX craft by N.R.E. in Bedford Basin, and model experiments at N.P.L. in England. It would not be untrue to say that at one time or another each of three groups identified and then resolved what at first appeared to be almost insuperable problems. I am quite sure that without this co-ordinated and co-operative effort it is most unlikely that F.H.E. 400 would now be under construction.

One example of this co-operative attack is hinted at in the section of the paper which briefly discusses the design of fully ventilated foils where the authors rightly state that "since re-attachment leads to violent pitching motions . . . ." This might have been anticipated, but it was not clearly understood until experiments at N.P.L. had vividly demonstrated its importance; we at N.P.L. were then able to identify the cause of the trouble and our friends at De Havilland very ingeniously found a simple solution by providing "a spoiler on the upper surface in the form of a 'step' to prevent flow re-attachment . . . ." Indeed, this episode was a significant factor in changing the configuration of the bow foil unit, which is now as in Fig. 5 and differs from that seen in the film which the authors showed.

This paper has many lessons for us in Britain. I very much hope that the recent revival of interest in hydrofoil ships by several British industrial firms will lead to a renewed activity in this country. In spite of the recent success of hovercraft I feel sure that there are still many future roles which can be well filled by hydrofoil ships. Indeed, hovercraft and hydrofoil ships complement one another as much as they compete with each other, and I think it would be a mistake for us to overlook the potentialities of either. Already two hydrofoil services have been operated in British waters by foilcraft built abroad and this is a challenge which should not be ignored by British builders. If they take up this challenge—as I very much hope they will—then I am quite sure that many of the lessons learned by the Canadians in their development of hydrofoil ships will be of value to us.

Commander T. B. Wilson, Jr., M.Sc., U.S.N. (*Member*): I think that the authors should be congratulated on the presentation of this fine paper. Following the trend of the morning which seems to be to try to get the authors to provide additional information, I would like to ask if any of the details of the weight breakdown can be made available. In addition, following on the discussion of the design wave criteria, I would like to point out that if this hydrofoil is to be a patrol craft operating in the near shore environment, then the wave considered should be the shallow water wave (where the depth of the water is less than half the length of the wave) which has different characteristics than the deep water wave. It is well known that as the deep water moves into shallow water both the length of the wave and its period decrease—the law of the conservation of energy requires that the third parameter, the wave height increase and the wave encountered is of the order of a L/10 rather than a L/20 wave. Similarly the frequency of encounter changes as does the required clearance for slap free operation.

Mr. W. A. Crago, B.Sc. (*Member of Council*): When running in waves the field of operations of any high speed craft such as the A.S.W. hydrofoil ship can be conveniently deliniated on a graph where the axes are acceleration and frequency respectively. Operation at any specific point within this field would come about say as the result of running into a regular head sea with a particular frequency of encounter and sustaining in the process a cyclicly varying acceleration.

Human reaction to environments consisting of various levels of acceleration and frequency has been widely investigated in recent years and boundaries have been established beyond which physiological or subjective response becomes intolerable. However, most of this research has been associated with the passage of vehicles over rough ground or buffetting in aircraft or space vehicles. Attention has therefore been focussed on a frequency range higher than that which normally concerns the naval architect.

However, with a high speed craft such as the A.S.W. hydrofoil ship these high frequency ranges will, in fact, be traversed to a certain extent. Fig. 7 shows the frequency of encounter resulting from running in head seas of various lengths at each of three speeds. Also shown are some of the phenomena which have been noted at various acceleration levels. The highest frequencies result from a combination of the highest speed and the shortest waves and in these conditions the accelerations would presumably be low. At somewhat lower speeds however the accelerations, when taken in conjunction with the associated frequency could be significantly large from the crews' point of view even if negligible as far as the structure were concerned. Furthermore, at the lower frequencies there must of course be acceleration levels where seasickness occurs (although quantitative data on this aspect is difficult to obtain).

The importance of the foregoing considerations is emphasised by the authors' statement that the feasibility of the ship depends upon its habitability in open ocean conditions. This is particularly true when it is recalled that the crew will have to spend relatively long periods of time at sea. Thus human reaction to the environment could well be of critical importance and one would like to know that work has been done, first to specify the field of operation in terms analogous to acceleration and frequency, and second to determine human reaction to operating in the more unpleasant parts of it.

Finally, I trust that, with our appetites nicely whetted by this general description, members of the De Havilland team will be encouraged to let us have technically detailed accounts of specific aspects of their development, one which I believe may have far reaching effects on our profession.

Verbal Reply to Discussion

by Mr. Milman

Some of the detailed questions cannot be answered at this time, but replying first to Mr. Evans; one of the design criteria laid down right at the first was that the craft must be capable of surviving under any weather and sea conditions that can occur on the North Atlantic. This of course is in the hull-borne mode, hove-to if necessary, that we felt this condition would be met.

Several speakers have queried the capability of the crew to withstand the expected motions. This was recognized right from the start as a major problem and the Institute of Aviation Medicine, run by the Royal Canadian Air Force in Toronto, was consulted at a very early stage. They are now undergoing experiments at the National Research Council, using a hydraulically controlled shake table, the motions of which are fed from the results of the computer study. This table is some 6 ft. square and we will be able to mount on it a bunk, a console chair and other pieces of furniture to ensure that the crew can eat, sleep and operate under the conditions that we expect.

The question of the docking was also raised by Mr. Evans and other speakers. For the cleaning of the foils we intend to use skin divers. Regarding docking with non-retractable foils, this was from the start realized to be a problem but it was decided that for the prototype at least the added complication of bringing in retractable foils was undesirable because it would merely add more trouble, so R.C.N. faced up to the fact that they would have a craft with a large draught and some awkward extrusions to deal with. A special docking facility, using the synchro-lift mechanism, is being installed in Halifax harbour.

Mr. Buckle asked a number of very detailed questions, the answers to most of which I will leave to the written reply. The question of the strength of the hull as a whole has been looked into and the reason for the high strength levels was following normal aircraft procedure. The extrusions were specially made in the United States. The hull skin, which is some 80 thou., together with the stringers, are extruded in blanks.

Mr. Buckle asked what happens if the craft hits some driftwood. R-100 *Massawippi* actually hit a piece of driftwood. It was an old telegraph pole which was floating vertically just about waterlogged, and it was hit at a speed of 55 knots. The result was that the telegraph pole was cut three-quarters of the way through and split. The engineer, obeying standing orders, immediately cut the throttle and the vessel returned to the displacement mode, and an inspection found that there was no damage to the foils whatever.

I regret that for security reasons we are unable to supply any information on the trials. The question of the pods was raised. These odd-shaped pods were deliberately designed that way, in conjunction with Mr. Silverleaf, to minimize cavitation, following the "area-rule" method developed for aircraft.

I am afraid I am not able to give Mr. Lackenby any information about development cost. Regarding commercial results I agree that there could be several areas in which the commercial field could benefit. One is the research that was done on the maraging steel used for the foils, and the other is that since this steel does not have good corrosion-resisting properties we had to develop a plastic coating. The aluminium alloy being used is the standard naval marine aluminium that has been used on superstructures of destroyers for some years now.

I am sorry if I misled Mr. Hook. I endeavoured to call this section superventilated and not supercavitated. I fully agree with him also in connection with weight measuring, in the engineering field, being no more important than wave measuring is for us. We tend to use height as our measure of the sea wave and I agree it is not sufficient.

I wish to thank Mr. Parker for his comments regarding the computer. I would like to mention that we were using an analogue computer with four consoles and it was not big enough, but it was the biggest one we had.

Mr. Silverleaf's remarks on the most valuable work that his department did for us were extremely welcome and I would like to thank him for his efforts. I feel that this project would have got nowhere without the efforts of Mr. Silverleaf and his colleagues. The work they did for us cannot be measured.

For Commander Wilson we will endeavour to provide a weight breakdown. However this craft is not intended for coastal control; this is an open ocean craft for operating in the same areas as the A.G.E.(H.).

In reply to Mr. Crago I agree the acceleration frequency is below 1 g, and again this is the reason for employing the shake table.

In reply to Mr. du Cane the question of the prevention of intake of water into the gas turbine has of course been investigated and extensive model studies have been done in the wind tunnel by Pratt and Whitney. We feel we will in fact be able to keep the water out. Pratt and Whitney are, of course, providing the gas turbine.

Regarding the interference of the bow foil on sonar, we are using a variable depth sonar so I feel there is no problem there.

Written Reply to Discussion

The authors would like to express their appreciation for the interest which has been shown in this paper and to those gentlemen who have contributed to the discussion.

In reply to Mr. Evans, as noted in the verbal reply, the criteria for the designing of the craft was that the vessel must be capable of surviving under any weather and sea conditions. Model tests have shown that this craft should be able to ride out a storm as well as a vessel some ten times its displacement. Regarding the capability of the crew to withstand the motions of hydrofoil craft, this problem, as noted in the paper, received early consideration by the various authorities concerned and the Institute of Aviation Medicine run by the Royal Canadian Air Force have been consulted regarding this problem from the start. The experiments are now under way at the National Research Council, using a hydraulically controlled shake table, the motions of which are fed to the results of the computer study for comparison. The shake table motions are fed from a tape of the De Havilland computer simulation, and the experiments are then studied by the Institute of Aviation Medicine to determine the effects of motion on individuals in hydrofoil environment.

However, it may have been of interest to note that the subjective opinion of the trial crew of the RX craft, which had very rudimentary seating and which did not, because of its shape, completely model the impacts of the waves, were that the ride felt like "driving on a hard-sprung truck along a rough country road." While it is felt that this would not be conducive to efficient operation for any length of time, it is felt that by suitable seating and by the better ship-shape hull of the F.H.E. 400, these motions would be drastically reduced and could be kept to within acceptable limits. Further, regarding the motion of the craft in waves while in the hull-borne mode, it has been shown by tests that the craft, due to the damping action of the foils, in fact rides to the waves and hence has less impact from waves breaking over the hull.

The question of noise has been looked into and it is hoped by the use of suitable insulating materials that it will be kept to a minimum. Regarding the use of volunteers for the crew, all candidates were interviewed before final selection and will undergo periods of shore training before joining the ship. There were ample volunteers in the first instance.

In answer to Mr. A. K. Buckle, the question of the deflection to the hull in the foilborne mode has been under extensive study and it is felt that, by using aircraft type construction, the strength of the deflections of the hull are kept to a minimum. The natural frequency of hull bending is about 6 cycles per second when foilborne. Seaway frequencies of encounter are about 0·02 to 1 cycle per second with dominant frequencies and energy at about 0 to 3 cycles per second. Therefore, we do not expect any resonant coupling between hull bending and seaway motions.

The bottom impact pressures could be high but it is felt that, with the high dead-rise of 25 deg. these are being kept to a minimum and thus could be considerably less than that of an M.T.B. which has a much flatter dead-rise and, in fact, a figure of some 52 lb. per square inch has been taken for design purposes. As far as the use of shell and frames extrusions, these were not the same as on the PCH and were specially designed for this vessel. The stringers were designed to be extruded integrally with the shell and a special die was developed by the Aluminum Company of America for this purpose, the shell being extruded in planks containing some three stringers.

Regarding the problem of hitting of driftwood, etc., this has been recognized and the effect of the R-100 *Massawippi* hitting a piece of driftwood was described in the verbal reply. It is felt that, under normal conditions in the mid-Atlantic where the craft expects to be flying, the incidence of hitting such driftwood would be extremely low. It is regretted that the speed-resistance curve for this vessel cannot be given, however it can be noted that, for surface-piercing foils, the high take-off hump does not appear as in the case for fully-submerged foils. It can be said that the take-off is approximately 18 to 20 knots.

There is some gearing at deck level, together with gearing in the pods forming a Z-type drive. The pods were designed to reduce cavitation, using streamline contouring similar to that developed for supersonic aircraft, based on the work of Drs. Kucheman and Weber of R.A.E. We regret that no information can be given of the *Bras d'Or* trials nor the scantlings of the *Bras d'Or*.

In reply to Mr. Lackenby, the following points are noted. D54S is basically an aluminium/magnesium alloy which is non-heat treatable. Tensile strength is 42,000 lb./in.^{2} and yield strength 21,000 lb./in.^{2} Composition is as follows:—

Copper	0·10
Iron	0·40
Magnesium	4·0–4·9
Manganese	0·5–1·0
Silicon	0·2
Chromium	0·05–0·25

Normal hull stresses are about 6,000 p.s.i. and designed proof stress of 20,000 lb. per sq. in. Maraging steel about 20 to 25 tons per sq. in. working stress.

As mentioned in the verbal reply to the discussion the efforts of Mr. A. Silverleaf and his colleagues in the National Physical Laboratory were indispensable to the F.H.E. 400 programme and without their assistance and advice, together with the testing facilities, we would not have been able to achieve the results that have been given in this paper. Mr. Silverleaf's contribution, therefore, is greatly appreciated and his remarks have added a valuable contribution to the paper. The authors would concur that this method of use of small scale models, analogue computer studies and self-propelled larger models have produced information which could not have been obtained in any other way.

In reply to the contribution of Mr. W. A. Crago I would draw attention to the earlier remarks in reply to Mr. Evans about the importance of actual research into the capability of a human being to withstand various accelerations and motions which could be expected in a craft of this type. It is also shown that, in most cases, the accelerations are of a frequency sufficiently low that they are, in fact, approximately one cycle a second and that therefore some of the more objectionable phenomena are not felt.

As mentioned in the verbal reply to the contribution by Mr. Du Cane: the prevention of salt water getting into main gear turbine was recognized to be a problem from the start, and the work on this problem by the organization which Mr. Du Cane represents was extensively studied by the R.C.N. In fact, a plenum chamber is used and appears on Fig. 3 under what is labelled "Liferaft." Extensive wind tunnel tests were done by Pratt & Whitney Aircraft Limited to design this chamber and it is hoped that little, if any, water or spray will penetrate into the turbine itself.

Regarding the interference from the bow foil, on the sonar, as mentioned in the verbal reply, a variable depth sonar is to be used and therefore it is felt that the greater interference will be obtained from the supercavitating screws rather than the bow foil. The authors would like to thank Mr. M. C. Eames, who was responsible for the original concept of the F.H.E. 400, in clearing up some possible errors in the paper and adding a summary of the background to the concept. In conclusion the authors would like to thank the Institution for the opportunity to present this paper and to the Canadian Department of National Defence for permission to present it.