THE FEASIBILITY OF HYDROFOIL CRAFT

IN THE INDIAN ENVIRONMENT

"A dream is a ship of fancy that carries us

miles away but a hydrofoil is a measure of progress that has come at last to stay."

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INTRODUCTION

1. The word unconventional conjures up in ones mind various things, from long hair and a bohemian lifestyle to avant-grade architecture. But what, if anything, does it imply when applied to the maritime scene? The conventional in this environment may be construed as merchant vessels plying serenely for trade, warships going about their business, submarines, perhaps, engaged in their mysterious tasks and aircraft flying about in execution of their chores. Conversely, the unconventional would can note the family of surface skimmers like hovercraft, hydrofoils, SWATH ships, ram wing craft and the like or by a stretch of imagination; mammoth submarine bulk tankers [if these could become a reality].

2. In the same way that the super tankers, at their inception, may have been thought of as unconventional, but are now quite commonplace, similarly, a number of innovations like the helicopter, have gone the same way. In the case of surface skimmers, however, the state of the art is still sufficiently novel and exclusive, to a few, for these craft to be called unconventional, within the meaning of the term as specified in the Oxford English Dictionary.

3. The hydrofoil has been conceived through a marriage of the aerospace and marine technologies [1]At the present moment this craft as well as the other such innovation - the hovercraft - have a bright future in numerous applications in the military and civilian fields.[2]

4. The maritime environment today is fraught with a high threat factor where large warships are a definite liability. Aircraft carriers, for instance, require protective screens of escort ships, which are out of proportion to the cost effectiveness of the Task Force. Even so, some justification for carrier task forces can be found if one is to argue, for the preservation of a global stake, like the USA and more recently the USSR are doing. For smaller developing nations with

a regional stake this argument is a fallacy. What is required by them are small ships and craft with a sufficient punch, that brooks no mischief. It is for this reason that today, small fast craft, armed with immense firepower, are cheaper by the dozen.

5. A stage has been reached, when an edge in this high threat environment, can be obtained only by him who exploits the one capability which gives a significant advantage – speed. For conventional displacement craft the speed barrier of 35 knots or so cannot be economically crossed. This barrier needs to be crossed, however, for the advantage, to accrue. The rapidly blooming skimmer technology has not only enabled this speed barrier to be broken, but sights are now set, on the attainment of a hitherto inconceivable speed at sea – 100 knots.

Statement of the Problem

6. It is the aim of this paper to examine the feasibility of adapting the hydrofoil craft to the Indian environment. The aspects studied would be the need for such a craft and the capability of a nation like ours to imbibe the emerging technology and put it to practical use. The associated effectiveness of the craft, cost and otherwise, as against conventional displacement vessels like frigates, for the roles envisaged, would also be examined.

Justification for the Study

7. India is a nation, as yet, developing, which can ill afford the exorbitant cost of defence in general, and warship production in particular, but which nonetheless has an important role to play in the region. To give credibility to this status it is imperative, that the Indian Navy has a credibility at sea. With our Research and Development [R & D] and industrial infrastructure it is more than possible for us to adapt to the basic skimmer technology required for hydrofoil craft, and use its advantages to achieve, in some measure, this credibility. Additionally, hydrofoil technology is sufficiently widely dispersed for its acquisition, to be possible, from more than one source.

8. Through the application of this technology it is possible to convert the fast patrol boats [FPB], in the inventory from merely fast craft to craft with immensely improved capabilities. The OSAs, for instance, if given a shot in the arm with this technology, could be transformed, into well-nigh unbeatable adversaries, at sea.

Scope

9. For the study, accurate figures of the cost or time required to design a modified diesel, for the hydrofoil craft; have not been readily available. However, the annual costs for running such craft, the cost for modifying existing assembly lines and developing designs, have been extrapolated from information, regarding similar projects, carried out elsewhere, allowing for factors such as inflation, existing know-how and the possibility of collaboration with foreign firms in the field.

Definition of Terms

10. Understanding the principles of hydrofoil operation requires knowledge of some specialized terms. These have been placed in the glossary at *Appendix A*.

Preview

11. The study will examine the hydrofoil craft under the following headings:

[a] History of Military Hydrofoils.
[b] Principle of Operation.
[c] Military hydrofoils – their roles and advantages over other craft.
[d] Current state of the Art and Futuristic Projections.
[e] Do we need the hydrofoil.
[f] The possible options.
[g] The Financial Burden.

Sources of Data

12. The source matter available in the College Library, on which this study is primarily based are the monthly editions of Hovercraft and Hydrofoils, the annual publications of Jane's Surface Skimmers and data available on ship building in India. The Bibliography has been placed at *Appendix B*.

HISTORY AND DEVELOPMENT OF NAVAL HYDROFOILS

Pre World War II

13. No discussion on the pioneering design and development efforts, in the field of hydrofoils, can begin without a mention of Baron Hans Von Schertel. In the period, from 1927 to 1936, he designed eight experimental boats, despite the negative attitude and discouraging prejudice, against the concept, of the conservative ship owners of the old school, in the Germany of that day. He was however, convinced of the feasibility of the idea, of flying on foils in the water, to reduce drag and thus attain extremely high speeds, whilst improving sea

worthiness. This steadfastness and some financial help from the pragmatic management of the Rhine Shipping Company enabled him to demonstrate his seventh experimental boat to Professor Kampf of the Hamburg Experimental Institute.

14. Professor Kampf was so taken up by the concept, that with help from the Institute, Baron Von Schertel, proved the utility of this craft, when he did a trip, in his eighth boat, on the Rhine, from Mainz to Koln and back, a total distance of 370 kilometer in unfavorable weather conditions. This first success induced Herr Gothard Sachsenberg to form with him the Schertel-Sachsenberg Syndicate, in October, 1936, which granted a license to the Gebrunder-Schsenberg Shipyard, in Germany. This Shipyard subsequently produced a 17-ton minelayer [VS-6] and other hydrofoil craft for the German Navy.

15. In the meanwhile Professor Tietjens, in the United States had tested a one-seater hydrofoil craft using a monoplane configuration, for which he filed a patent in 1934. The Vertens Shipyard in Germany obtained a license from him, in 1940, and also constructed a 17-ton minelayer. The problem of maintaining flight in a seaway was not sufficiently solved, however, and the craft crashed several times due to foil broaching. Although the boat was considerably faster than the Gebsuder-Sachsenberg VS-6, its turning ability and longitudinal stability were not satisfactory. The Tietjens concept never came into prominence and development was eventually stopped.

16. Two other personalities who bear mention as pioneers, in the field of hydrofoil technology, were Grunberg who had migrated from Paris to USA in 1939 and Christopher Hook, an American. Both of them were instrumental in developing the fully submerged foil system and the associated control system.

Wartime Development

17. Construction of the first vessel for the German Navy was started in June 1940 and completed in 1941 at the Gebruder-Sachsemberg Shipyard at Dessau-Rosslau. This hydrofoil craft, called the VS-6, was equipped with a vee-foil system in a tandem configuration. The craft attained a speed of 47 knots on two 1,500 h.p. diesel engines, each running its own propeller.

18. A month after starting construction of the VS-6, a series of six smaller craft was started. The propulsion system of the last of these is interesting as an attempt was made to avoid the use of long propeller shafts and their brackets by employing a double bevel gear or a "Z" drive, for the first time. This craft was less thoroughly tested than the VS-6, as the Russian Army occupied Dessau-Rossiau just after completion of the craft.

19. The wartime hydrofoil craft which deserves the most attention was the

80-ton VS-8. Just as the speed of the VS-6 was unchallenged for a number of years the VS-8 remained the largest craft for over two decades. It was initially designed as a 70-ton fast transporter working on two super charged 2,500 h.p. Mercedes-Benz diesels. The craft was designed to carry tanks from Sicily to North Africa. For this purpose, the after quarter of the VS-8 could be flooded, so that a pontoon raft with a 20-ton Army tank could float in. After unloading the tank and withdrawal of the raft, the ballast water was pumped out and the craft could take off. Due to the supply of normal 1,830 h.p. diesels and weight additions during construction, the craft could attain only 37 knots in six-foot waves as against the designed 45 knots. The dimensions and performance of the VS-8 were as follows:

[a]	Length overall	105 ft.
[b]	Beam over deck	25 ft. 6 ins.
[c]	Width over front foil	33 ft. 8 ins.
[d]	Draught hull borne	14 ft.
[e]	Draught foil borne	6 ft. 6¾ ins.
[f]	Displacement	80 tons.
[g]	Relative Payload	33%
[h]	Power	2 x 1,830 h.p. diesels
[i]	Max speed	40 knots
[j]	Material	hull: aluminum foil: steel.

20. Another major wartime construction was the 46 ton, VS-10, torpedo boat which was designed to use four 1,500 h.p. diesel engines and be capable of 60 knots. The outcome of this venture was unknown as a day before the scheduled launching of the boat, it was completely destroyed in an air raid. Another fast hydrofoil to be tested was a single seat 30-ton torpedo boat. During tests in the lakes of Berlin this craft had attained 52 knots. Tests stopped at the end of the war and were not completed.

21. Concluding the line of wartime boats one particularly unusual craft was the four-ton Pioneer workboat built for the German army's Pioneer Corporations. The requirement was for the boat to be able to beach. This was achieved by providing the forward hull of the craft with floats with the forward foil between the floats. The rear, foil was attached to the transom by struts. As the craft approached the beach the foils were retracted and the craft settled onto the floats maintaining a constant draught of two feet six inches. With the foils fully retracted the craft could run ashore bow on and remain steady on the floats for unloading or loading.

Post World War Proliferation

22. *Switzerland*: Baron Von Schertel moved for good to Switzerland in 1952,

for the foundation of Supramer AG,[3]a concern which today produces one of the widest range of hydrofoil craft. He took with him all the scientific works; results of tests and trials carried out before and during the war, as well as construction plans of various hydrofoil craft built during the war, in other words the technical know-how of two decades. These form the basis on which Supramer craft are built today. Baron Schertel is presently one of the directors of Supramar AG.

23. *Soviet Union*: The Soviets received their first knowledge of hydrofoil technology from studying the craft which fell into their hands, when the Russian army occupied Dessau-Rosslau. [4] This was a 6.3-ton coastal surveillance hydrofoil in which the Z-drive had been used for the first time. This Schertel-Sachsemberg vessel formed the basis, for the Soviet passenger craft Myr and Strela and the military version of the Strela, called the Pchela, which are in widespread use today, in the USSR. The Russians subsequently developed their own semi-submerged foil system, for their boats operating in relatively calm shallow rivers.

24. *Italy*: In 1953 one of the principals of the Leopold Rodriquez Shipyard, in Italy, obtained a construction license from Supramar AG. The Rodriquez Yard which had earlier been a repair yard for locomotives and railway carriages was transformed into a keel of the first Supramar designed, 32-ton vessel, was laid in 1955. The yard subsequently expanded on its own and is now one of the leading hydrofoil manufacturers. In 1974-75 the name of the yard was changed to Cantiere Naval Techniques.

25. *United States*: Apart from an examination of the possibility of constructing foil borne landing craft interest in naval hydrofoils, generally, was not displayed in the United States, till after the Second World War. After some preliminary comparative tests, the Department of the Navy, decided to abandon the surface piercing foil system and employ fully submerged foils. This was, possibly, due to the influence of Grunberg and Christopher Hook in this field. The fully submerged foil was, however, found to be inherently unstable. To achieve stability an automatic control system was necessary to vary the lift of the foils according to their submergence. Grunberg did toy with the idea of developing an autopilot based on sensing accelerometers on the principle, enunciated by Nicolai Miniovsky. This principle is the foundation, on which all modern autopilots used in aircraft, inertial platforms and spacecraft, are based [5] . The practical application of this principle was hampered, however, by the lack of precision engineering and complex electronic control mechanisms in those days. He thereafter, devised the Grunberg system, which though of simple design and a high drag and gave a rough uncomfortable performance in waves. Subsequently the Gibbs and Cox design and an autopilot developed at the Massachusetts Institute of Technology were tested. In 1959, test runs were carried out on a DUKN amphibian when the vehicle was also to attain 35 knots when equipped with fully submerged controlled foils and a gas turbine. In 1961 the programme was expanded to include a design of a LVHX-2 [Landing Vehicle Hydrofoil] which also attained 35 Knots with a 1,000 h.p. gas turbine and fully submerged foils. In 1960 super caviating foils were tested for the first time, on a 50 feet amphibious experimental craft, constructed by Grumann, called Sea Wings.

26. *Canada*: In early 1961 De Havilland Aircraft of Canada, was contracted by the Department of Defence, to construct the FHE 400, to establish the feasibility of an ocean going ASW hydrofoil. The first foil borne trails took place in April 1969. The craft was a super caviating steerable bow foil and sub caviating main foil in a canard configuration. The main foil is a combination of the fully submerged and surface piercing foil types and has a unique design made for excellent sea keeping qualities. The FHE 400 has been commissioned into the Canadian Navy as the Bras d' Or.

PRINCIPLE OF OPERATION

27. The concept of the hydrofoil craft was born from the need to break the speed barrier, caused in the case of displacement vessels, due to the drag caused by wave resistance. Sheer increase in power did not provide the answer as it was realized that after a certain stage, normally reached at speeds of approximately 22 to 24 knots, an inordinately high increase of power was required to generate even a marginal increase in speed. Thus the speed of displacement vessels is restricted to about 30 knots for larger vessels and about 35 knots for small patrol craft.

28. The use of a foil section to gain lift had been demonstrated, by the Wright brothers, at the turn of the century. It was not long before the aerofoil spawned the hydrofoil concept, designed to overcome the speed barrier. A significant aspect of this -concept is that since water has a density 815 times that of air the same lift as an aeroplane wing, is obtained for only 1/815 of the corresponding wing or foil area; for a given speed.

29. *Construction*: The hydrofoil craft is essentially a lightweight hull similar to that developed for FPBs i.e., it is a hard chine hull section. The hull is supported on foils which are mounted on struts forward and aft. With the increase in speed the foils generate lift until at the take-off speed the entire hull rises out of the water. The percentage of hull weight supported by the forward or aft foil, when the craft is flying, depends on the configuration. There are three types of foils employed currently namely the surface piercing or vee foil, the fully submerged foils and the shallow draught submerged foil invented by the Russians, for their craft plying in calm shallow river. All the foils can be made retractable, to decrease the hull borne draught. Among these the fully submerged foils being inherently unstable require an automatic control system and is the most expensive to install.

30. *Propulsion System*: There are two methods by which hydrofoil craft are propelled. Firstly by propellers which are mounted on shafts inclined between 10° to 15° to ensure submergence of the propellers when the craft is flying and secondly by water jets. In some craft there are separate propulsion system for

hull borne and foil borne operation to increase the endurance of the craft and provide an emergency "get home" capability. In either case, whichever method of propulsion is used the main engines can be either gas turbines or diesel. Examples of the various types of propulsion systems are available in craft currently in operation such as:

[a] High Point: This is a hydrofoil craft built by Boeing Aerospace Company for the US Navy. The foil borne propulsion is provided by two gas turbines coupled to a pair of contra-rotating super caviating five bladed propellers whilst the hull borne propulsion is provided by a single diesel driving a propeller.

[b] Flagstaff : This hydrofoil gun boat built by Grumann Aerospace Corporation is an example where a single gas turbine with a controllable pitch propeller provides foil borne propulsion and two diesels driving one feet four and half inch wide water jets, equipped with ± 35 degree steering and reversing nozzles, provide hull borne propulsion.

[c] Swordfish: This is a missile equipped hydrofoil craft built for the Italian Navy, which uses a single gas turbine driven water jet for foil borne and single diesel with propeller or hill borne propulsion.

[d] Soviet Hydrofoils: These craft seem to favour diesel engines for both foil borne and hull borne propulsion possibly due to the economy of operation.

31. *Comparative Study*: Despite the major drawback of low efficiency of water jet propulsion it has specific advantages over conventional propellers namely:

[a] It allows speeds in excess of 50 knots as beyond this speed the drag of appendages like propellers hubs and brackets is too high.

[b] Besides the ship auxiliary and lubricating machinery, it does not require any additional units as everything is already integrated in the system. Water jet propulsion systems normally require a bow thruster to enable control at slow speeds.

32. *Operation*: For take off the foil depth is set [in case of fully submerged foils only] and the throttles are advanced. As speed increases the hull clears the water. Landing is accomplished by reducing the throttle setting. Speed diminishes from 45 knots to 15 knots in as little as 30 seconds. There is a height command lever provided in some craft to make emergency landings. In this case since the foils are not retracted a minimum depth of five fathoms is required.

THE ROLES AND ADVANTAGES OF NAVEL HYDROFOILS OVER CONVENTIONAL WARSHIPS

33. Although military hydrofoils had been built during World War II, it is only recently that they have found acceptance, among NATO nations, as instruments of naval warfare – some 30 years after they had first proved their feasibility. Unlike the NATO nations, the Warsaw Pact countries were quick to recognize the suitability of hydrofoils for military roles and have been employing them on surveillance and other roles for many years [6][6].

Advantages and Adaptability

34. If the world fuel shortage is taken into consideration, as well as, the pollution problems which strangle today's economy and life, the hydrofoil is tailor made to overcome these difficulties. A hydrofoil files clean and requires only 50 per cent of the power of a displacement vessel of comparable size, for a given speed. The advanced military hydrofoil is superior to conventional warships, due to its superior speed, which can be maintained even in a seaway and due to better sea keeping ability. In fact, hydrofoils do not need to be large [multi-thousand ton size] to provide an all weather capability, which is in stark contrast to conventional warships.

35. Various comparative studies have been undertaken to ascertain the validity of better sea keeping qualities in a hydrofoil as follows:

[a] A study conducted by Boeing, for the Royal Navy and presented before the Royal Institute of Naval Architects, showed that the Boeing Jet foil [a 110 ton craft with fully submerged foils controlled by a sonic control system] was capable of operation in the North Sea 96 per cent of the year [at speeds greater than 38 knots] [7][7]. This corresponds to wave heights of four meters [see state 6].

[b] In November 1977, a study undertaken by the Cantiere Naval Technica [Italy] showed a far lesser roll and pitch in a surface piercing foil craft in sea

state 6 compared to a conventional ship at 20 knots in sea state 5.

[c] An all weather; high speed, smooth ride capability is illustrated in the graph opposite which was obtained as a result of a study, conducted by another leading Italian hydrofoil manufacturer; the Cantiere Navli Riunitis [CNR]; the makers of the "Sparviero Swordfish" missile hydrofoil, for the Italian Navy.

36. It is doubtless that larger warships due to their greater size and lesser maneuverability, are targets rather more vulnerable to tactical offensive weapons, like missiles. They are also more attractive both in terms of value and prestige. Therefore, employment of even a modern frigate, like the Leander, in a high threat environment is too hazardous, to be cost effective. Another consideration is the crew size of larger ships. This is quite a remarkable factor because of the high level of specific and qualified training required, for personnel to run the complex and sophisticated modern equipment.

37. All these considerations, of course to the advantage of the small ship, normally find compensation, in the employment limitations, which they have to face in rough sea conditions. The hydrofoil craft has overcome this handicap, and guarantees to a small craft the ability to put to sea in safety, have good platform stability, high speed and maneuverability and an all weather capability. It has been conclusively proved that the speed advantage passes from a hovercraft to a hydrofoil craft beyond sea state 3 and to conventional craft beyond sea state 6.[8]

38. When considering hydrofoil craft in general, and naval hydrofoils in particular, it is easy to get an impression that these are highly specialized vessels. This idea promotes the belief that they need to be supported by highly specialized workshops, specially trained and highly skilled technicians and extensive logistics. As a result, the idea develops that exceptional costs are involved, not to mention the high technical risk.

39. Any modern equipped FPB yard, however, would also be able to construct and support naval hydrofoils if a certain design philosophy is respected. When operational and maintenance requirements of a modern FPB are compared with those of a naval hydrofoil, it will be seen that the problems involved are identical Garden Reach Shipbuilders and Engineers [GRSE], Calcutta which has hitherto constructed FPBs for the Indian Navy could therefore be ideally suited for the purpose.

40. The lightweight form of construction, developed for hydrofoils, is in

demand, increasingly, for a modern FPB's. However, as the weight of marine engines is reduced,
so the need for this lightweight construction for naval hydrofoils is decreased. This enables the project engineer to specify heavier materials and use less expensive approaches, with lesser demands for a high level of metallurgical engineering. The marked similarity between well proven FPBs and hydrofoils currently operational is evident from the table below. Another thing brought out vividly in the table, is the power required, for the same speed, for a FPB [MT 250] and as hydrofoil [MZ 50G] of comparable displacement.

	FPBs				Hydrofoils		
	SA'AR	**OSA**	**MT 250**	**MT 504**	**FHE 400**	**TURYA**	**PEGASUS**
Max Displacement	240	210	250	250	212	190	235
Max Power [h.p]	13,500	12,000	25,000	14,000	22,000	13,000	--
Max continuous Speed [knots]	30	27	53	53	50	40	40
Max dash Speed [knots]	40	35	60	60	60	--	45
SSM	Gabriel	Styz	MM 38	MM 38	ASW Version	ASW Version	Harpoon
Guns	3x40 mm.	2x2.30mm.	1x76 mm.	1x76 mm.	--	1x1.5 mm. 1x2.25 mm.	1x76 mm.
Torpedoes	2 tubes	--	--	--	Yes	Yes	--

41. Today the makers of marine engines are capable of offering systems which enable the project engineer to install the required engine power within the weight and space limitations. Also, compared to conventional FPB, the increase in total weight when adding the foils, can be limited to a few percent, by using lightweight metals. As far as the basic design of the naval hydrofoil is concerned the hulls of numerous existing FPB's could be readily equipped with foils.

42. As a consequence, to the preceding examination, of the advantages and adaptability of the hydrofoil craft and concept, the naval hydrofoil can be viewed in an entirely different light. It is not for instance, such a sophisticated and expensive proposition as to be unacceptable. Another significant factor is that naval hydrofoils can be integrated with a force of conventional warships without difficulty and will contribute appreciably to its fighting capability.

Roles

43. The military missions that can be undertaken by hydrofoil craft are:

[a] Anti-ship strike.
[b] Decoy, picket duties
[c] Surveillance, interdiction, mine laying
[d] Screening coastal convoys
[e] Recce, clandestine operations
[f] Medical evacuation
[g] Amphibious operations
[h] ASW.

44. A hydrofoil craft equipped for the anti-ship strike role, with missiles and small caliber guns, would be able to undertake all except the last two roles and would be the most suitable configuration for a test craft, for purposes of evaluation.

CURRENT STATE OF THE ART AND FUTURISTIC PROJECTIONS

Operational and Projected Naval Hydrofoils

45. *The United States*: The US Navy has become the forerunner in the development of hydrofoil craft. Today, it has a number of such craft, which are suitable for open sea operation. These have all been primarily designed by the aerospace industry, particularly Boeing and Grunmann. Fully submerged foils are used exclusively, which are controlled by autopilots. The ability of these craft to maintain speed in high sea states has been proven. The first vessel called the "High point was a 120 ton craft designed for 45 knots and could operate in severe seas. Subsequently, the Flagstaff, the Super Flagstaff and the Tuenmcari were built, the former and latter of which were tested in surveillance operations during Operation Market Time, in Vietnam, for several months. Presently, the 230 on patrol missile hydrofoil craft, the Pegasus [PHM-1] is under extensive trials, for examining all aspects of operation. This has been designed to meet specific NATO requirements, the primary emphasis being on ship performance including a mission time of five days at sea, with substantial hull borne time. The PHM has during trials come up with various problems. A brief look at them would enable the state of the art to be more fully appreciated. The major problem areas identified after some 9,000 hours of underway time [more than 7,500 hours foil borne] were as follows:

[a] Sea Water System: There was a difficulty encountered in the operation of the auxiliary seawater pumps, when landing after foil borne operation. The pump motor was improved to withstand salt water and this resulted in a substantial reduction in failure rates.

[b] Piping System: The PHM uses glass fiber reinforced piping systems which suffered from leaky joints caused by faulty manufacture. After the factory made joints were repaired on board with more refined techniques a dramatic reduction in leak rate occurred.

[c] Height Sensor: The acoustic height sensor suffered from spurious returns, which signaled the automatic control system that the craft was flying too high and the ship would inadvertently, land. This occurrence was associated with operations in high sea states or large swells. Transmitter receiver gams and gating relationships were changed, water traps and drains were added at the transducer face and structural deflectors for secondary reflected signals were added. Thereafter, the vessel operated repeatedly in sea state 5 without any recurrence of the problem. A radar height sensor has been tested as a potential alternative.

[d] Hydraulic System: The PHM hydraulic pumps and system have a high noise level which is, presently, being treated to achieve reduction.

[e] Frequency Converters: Faulty parts and workmanship produced high failure rates in the frequency converters which were later rectified.

[f] Main Propulsion Gearbox: The main propulsion gearbox life needs to be improved as this was the greatest contributor to ship down time.

It will be noticed that most of these problems do not relate to the hydrofoil concept but to everyday aspects found on other FPB's as well. It is, therefore, possible to achieve trouble free service from a craft with the correct engineering techniques and expertise, of the type available, even in India.

46. *Swiss Hydrofoils*: Supramar AG designed a test craft for weapon systems, called the KTS 160, in the late sixties. It had a hybrid configuration consisting of surface piercing bow foils retracted sideways and a fully submerged retractable foil after. The hull was of plywood sheathed in glass reinforced plastic. Presently, a design concept for a patrol missile hydrofoil, MT 250G, capable of all weather operation exists. This craft uses an air stabilized fully submerged foil system in a

canard configuration.

47. *Italy*: A 64-ton missile-carrying hydrofoil has been built by the Cantiere Alnarc Shipyard. This craft uses auto controlled, fully submerged foils, in a canard configuration and uses water jet propulsion. For such a small craft it is surprisingly well equipped. The craft has two exocet launchers, one twin 76 mm. Oto Melara; IFF, search and navigation radar; HF SSB radio and an up-to-date combat information center. It is designed for a continuous speed of 45 knots in sea State 3 and 40 knots in sea State 4 with an endurance of five days. The Italians have also designed heavier missile carrying hydrofoils, namely, the 84-ton Maifus 300 and the 1127-ton Maifus 600, both with a speed of 37 knots and a range of 500 nautical miles. Both these craft use diesel engines with controllable pitch propellers.

48. *USSR*: The Russians have, in addition, to a series of craft for passenger ferry, a 46 ton, 35 knot craft, for the KGB frontier police, carrying depth charges and machine guns. The latest hydrofoil to enter service in the Soviet Navy is the Turya class. This craft is based on an OSA hull, equipped with are fixed surface piercing foil, set back approximately a third of its length from the bow. At 20 to 23 knots in relatively calm conditions the foil system generates sufficient lift to raise the greater part of the hull clear of the water, providing a 'sprint speed' of 45 knots. In addition to improving the maximum speed, the foil reduces the vessels wave impact response thus enhancing its performance as a weapon platform. The craft has a pocket size VDS aft with four 24-inch single AS torpedo tubes, as well as, 57 mm. and 25 mm. twin gun mounts. A missile-carrying version of this craft is also likely to go into production [9]. The craft is powered by three 4,330 h.p. diesels. The Soviets are also constructing an extremely formidable 300-ton craft with a hybrid foil system carrying the latest SSMs and SAM's. The craft is designed to do 55 knots.

49. *Canada*: One remarkably advanced concept, is the 200 ton HMCS Bras d'or [FHE 400] in the Canadian Navy designed for ASW operations in the open ocean. The surface piercing non-retractable foil system differs considerably from the usual configuration. It has a steerable bow foil carrying 10 per cent of the weight. The main rear foil uses sub caviating sections and is fully submerged. During trials wave heights of 25 feet were successfully negotiated. A calm water speed of 63 knots has been achieved by the craft, on one 22,000 h.p. gas turbine. A speed of 40 knots in 15 feet waves was also possible. Other models are now under development.

Futuristic Projections

50. Before an attempt is made to anticipate, the probable size, speed and character, of the next generation of naval hydrofoils, it must be accepted that

today, no such craft has been commissioned and engaged, in war actions. The comparatively short introduction of some craft, in Vietnam, do not lead to any far reaching conclusions. For any meaningful weapon package and more important, endurance, a displacement of 200 to 300 tons is required. Since the demand for firepower, in future, is likely to increase, so will the size of these craft.

51. Although the US Navy has decided to adopt fully submerged foils it should not be taken for granted that future naval hydrofoils will adopt this system indefinitely. The vee-foil offers the advantage of a higher potential for remaining foil borne in a seaway, a wider range of foil borne speeds and a less sophisticated solution combined with higher reliability. Another solution is the new partly revealed Supramar system which largely combines the advantages of the two systems.

52. *The DEH*: The US Advanced Naval Vehicles Concept and Evaluation Study has concluded, based on a design study carried out by Boeing that the present state of the art permits the construction of a 1,300 ton Destroyer Escort Hydrofoil [DEH], with endurance to cross the Atlantic foil borne, without refueling. The design study revealed that the craft would have a foil borne range of 2,500 to 3,700 nautical miles at 50 knots. There exists a general opinion, that the hydrofoil does not lend itself to exploitation, into the domain of a full blown open ocean escort, with all the attendant implications of long endurance, self maintenance and integration into existing logistic systems. In the opinion of the study, the often discussed 'size barrier' ascribed to the hydrofoil has not been adequately challenged, in the context of a real design based on contemporary data. The DEH is designed to have a far greater speed and wave height capability in a seaway, as illustrated in Figure 1 and 2, than a conventional ship. Figure 3 shows the speed capabilities of several types of craft as a function of the sea state. It will be noted that a very large conventional ship, like a nuclear carrier, suffers only a slight degradation of usable speed until the significant wave height is 20 to 25 feet. Conventional destroyers escorts begin to have degraded speeds in 10-foot seas and for significant wave heights of 20 feet can be optimistically credited with an average speed of 15 knots. The large surface Effect Ship with calm water capabilities of 80 knots, must give up much of this performance, in high sea states, for the same reasons as displacement hulls. The 50 knot DEH though not entire immune to rough seas retains its speed because the main hull is decoupled from the sea surface and its seaway response is governed by the design length of the struts and the specific type of dynamic control system employed. There are numerous tactical benefits of the DEH, most notably the fact, that as speed increases, the number of ships required for most tasks decreases, and the number of escorts per task force is smaller. The DEH is conceived with various characteristics from baseline ASW to multi-mission roles. The helicopter ASW profile is shown opposite.

The Limiting Factors

53. One wonders why, with so many advantages; the hydrofoil craft has not proliferated more rapidly than it has. Baron Von Schertel, in an interview, on 3rd December, 1977, gave the following factors as limiting development of future hydrofoils:

[a] Size and Speed: It is extremely difficult to avoid cavitation of foils, above 50 knots. This is the region where air fed foils with super cavitating foil sections and a low co-efficient must be used, which in both cases is associated with a high drag.

[b] New Hydrofoil Systems: Although no fundamentally new foil systems are likely, air feeding of foils developed at Supramar promises to lead to substantial improvements in foil systems. Measurements have shown that in certain flow conditions drag can be reduced by air feeding, to 75 per cent. Lift control can also be achieved, by air feed, with lower drag than would occur with flap control. Hereby, the change of lift is brought about without the energy input required for the actuation of flaps or incident control.

[c] Super Cavitating Foils: A grave hindrance to greater speeds is the onset of cavitation. The base ventilated foil, super cavitating foil sections and transiting foils are some innovations which could enable prevention of cavitation or at any rate a smooth transition from sub cavitating to super cavitating speeds.

DO WE NEED THE HYDROFOIL

54. Having discussed the hydrofoil craft, it is now necessary to examine whether we can afford such craft and more importantly, whether we can afford not to make the investment. To arrive at the correct perspective a brief survey of the present geo-political scenario must be made.

Threat Perceptions

55. India is undoubtedly the major power in South Asia and on her shoulders falls the responsibility of maintaining stability in this region. Our destiny is inextricably linked with the sea, as by all counts we are a maritime nation. There are a number of countries
near and not so near us, whose interests are inimical to ours. To do justice to the responsibility, we have an imperative of obtaining for ourselves, sea power which is credible.

56. In the concept of sea power, as enunciated by Mahan, it has two distinct elements, namely; sea power and sea force. Sea power is built up of the nations merchant marine, bases, geographic location, people and natural wealth. In these terms India is on a reasonably firm base. On 1st January, 1978 the GRT of Indian Shipping was 5.35 million. Although this is sufficient to carry, only about eight to nine per cent of our total overseas trade, Indian tankers in 1976-77 carried 99 per cent of our coastal cargo and 70 per cent of our overseas oil cargo. Another significant fact is that 60 per cent of our vessels, are below 10 years of age and more are on the assembly line.

57. The picture is less rosy with regard to sea force. Although naval power is not the end product of sea power, it is an important adjunct of it. For the twin missions of sea denial and sea control, we must be capable of projecting our naval power, in the seas surrounding us, when we want it, where we want it. Without a doubt the maritime environment has today become more an more dangerous, with most of our neighbours having acquired a hard kill capability. The threats as perceived could be from various sources.

In the Arabian Sea

58. *Pakistan*: Pakistan has always been hostile towards us. Although in terms of a wholly conventional Navy, Pakistan may be somewhat weaker, its latest acquisitions of Atlantic LRMP aircraft, with the AM 39 missiles, Komar class missile boats and Hu Chwan class hydrofoil craft from China; has given it a fairly decent punch which can be rapidly deployed, over vast areas. It is also known that the fledgling Pakistani Coast Guard, operates a few BH 7 Wellington hovercraft, which could be used on naval missions of interdiction. The trend them is on fast small non-targetable craft, which are none the less formidable, due to their excessive speeds, for which we may not have an answer.

59. *Iran*: In the present situation, and for some time in the future, no direct confrontation is likely to occur. The recently proclaimed Islamic Republic could, however, view with favour the fact, that the Zia in Islamabad is waxing eloquent on the Islamic theme. The possibility of a transfusion of naval arms, and financing of purchases, of naval vessels, in the near future therefore exists.

The Bay of Bengal

60. *Bangladesh*: The threat from Bangladesh is its weakness. The hostility and resentment of Bangladesh, towards India, despite our help in its formation and massive aid thereafter, is well known. Presently Bangladesh is increasingly coming, in the orbit of the Chinese grand design and is heavily influenced by China. An agreement in the future, for base facilities in Bangladesh, for the

Chinese, is not at all inconceivable and would substantially increase the risk in our eastern theatre. With the Karakoram Highway, on the one hand, and base facilities available to China in Bangladesh on the other, the specter of a two front war, at least at sea, becomes a reality.

61. *Indonesia*: Indonesia has a very large Navy, which for the last decade has been mothballed, due to the abrupt cutting off, of spares, by the Soviet Union, after the termination of their honeymoon, in the sixties. The political scene is also unstable, or at least not sufficiently stable for anything to be done about this. However, the Indonesian island of Sumatra is a mere 20 miles from the southern most island in the Nicobars, whilst it is more than 750 miles, from our mainland. Indonesia, being in the OPEC is in today's world a 'have'. Added to this are reports that there are personalities in the Indonesian armed forces, with the ability to pull the country out of the morass and put it back on the rails. At the best of times the relations between India and Indonesia have been cordial and the fact that it is the most populous Muslim state, does not help matters. Over navy must therefore be capable to rapid deployment in the islands and operation from forward unprepared bases within the islands.

The Indian Ocean

62. In the last few years the Indian Ocean has caught the eye of the Super Powers and hectic activity is under way by each of them to gain access and basses in this region. The US base at Diego Garcia and a Russian base, also in the Chagos Archipelago, capable of accommodating an entire fleet in the lagoon anchorage, are some indications of the fact, that they mean business. The Russians have reportedly placed under-surface tanks with associated Single Buoy moorings in a number of locations in these islands to facilitate refueling of ships. The reported US plans, to station the planned Fifth Fleet, in the Indian Ocean and expand Diego Garcia are other pointers of the increasing activity. The upshot of this would inevitably be pressures on littoral states, of various kinds. India being a major power in this region, it devolves upon us to ensure that Super Power rivalry does not engulf the Arabian sea and Bay of Bengal.

Our Tasks

63. *Sea Control/Denial*: The primary mission of our Navy, as for any other navy, is to keep our sea lines of communication open, whilst preventing the use of the same, by our enemy. To achieve this our Navy must have a rapid deployment capability, which is commensurate with the requirements of operating, in a high threat maritime environment.

64. *Defence of Our Islands*: The most vulnerable of our maritime possessions are our island territories. The Lacadives Islands, being within 150 miles from our mainland, would not pose a major problem with regard to maritime safeguarding.

The Bay Islands, however, are a different kettle of fish. The shortest distance from the mainland is 750 miles. The islands, themselves are flung over 500 miles, from North to South, with a base existing only in Port Blair. Although our Navy has some amphibious capability it is incomplete. Our capability for rapid deployment is negligible.

The Capability of our Navy

65. At the moment our significant naval strength, consists of one carrier [with obsolete or insufficient aircraft, six frigates [two with Styx SSMs], 10 patrol vessels, two tankers and eight submarines. This force is, by no stretch of imagination, sufficient to project credibility, in the ocean area, of consequence to us. In terms of cost-effectiveness too the situation is bleak. For instance a Leander class frigate required a capital cost of approximately 60 crores. The running costs, in terms of fuel bills, crew costs and upkeep can be extrapolated from a recent study carried out by Boeing for the Royal Navy [10]. These annual costs, on a comparative basis were calculated, for 10 x 19 knot ships, 12.5 x 15 knot ships and five hydrofoils, as the time on task, for these three categories, was the same when used in the EEZ patrolling role. The results were as follows:

[a]	Five Hydrofoils	£ 0.45	£ 1.35 [in millions]
[b]	12.5 x 15 knotters	£ 1.9	£ 2.0 [in millions]
[c]	10 x 19 knotters	£ 1.55	£ 3.3 [in millions]

66. The significant factor with regard to these costs is that after allowing for down time for refits and maintenance each frigate is available for 66 per cent of the time, only; i.e., to keep a two frigate force on task the year round a minimum of four vessels would be required. After all is said and done, the question which requires to be answered urgently, is can we afford to lose one such vessel? If we are to face facts, we cannot. If this is the tale, for a lowly frigate, what of the carrier? How then can we best achieve credibility without making holes in our pocket, especially in a high threat environment, which is bound to prevail in any maritime conflict, in future. The answer is undoubtedly in small craft. No wonder them that small fast craft, such as missile equipped boats, with a formidable punch are so sought after.

67. Even these, however, lack or to put it more accurately, do not possess, a sufficiently high degree of tactical flexibility, derived from a rapid deployment capability. If one can imagine such a missile boat with a speed of 50 knots plus, this flexibility could be attributed to it. From imagination, to translation into practical reality, is fortunately a short step today. That step is to apply hydrofoil technology, to the already existing characteristics of craft, such as the OSA class

missile boat.

68. There is yet another scenario, which is ideal for the application of hydrofoil technology - amphibious warfare. Our Navy possess six LST to Polish origin. All these vessels are rather large, and therefore do not guarantee, that our troops will come ashore dry-shod. Then again the LSTs are not primarily designed to carry troops. In fact, they would form the second echelon, in any amphibious operation, when troops have secured a beachhead and armour can safely made ashore, without any immediate opposing fire. Our capability to put the first few waves of foot soldiers ashore is negligible, as this requires small sized LCA [Landing Craft Assault] and amphibians like the DUKW and LCVX, referred to earlier in the study.

69. Any amphibious assault can be expected to be opposed, by shore based missiles and heavy accurate fire. It is therefore imperative for the assault force, to spend the shortest possible time, in their most vulnerable phase - that of getting to the beach from the troop carrying ships. Every nation dabbling in amphibious warfare, has realized the need for rapid envelopment. The concepts of vertical envelopment, using helicopters and use of hovercraft to transit the short run up to the beach are manifestations of this realization. Just as a DUKW and a LCVX can be given enhanced speed using hydrofoil technology, the Indian Army, amphibian APCs, such as Topaz and Skot, could also be provided with comparable capabilities. Additionally LCAs equipped with foils could be produced, within the country, at a shipyard like Garden Reach Calcutta; which has experience in building small fast patrol boats.

THE POSSIBLE OPTIONS

70. Hydrofoil technology is still recent enough, for the hardware to run to exorbitant costs. This, however, is the case only with the ultra sophisticated craft, being built for the US Navy, by the Boeing Aircraft Corporation. A recent purchase of a single jet foil of the Pageus type, but minus the missiles, acquired by the Royal Navy cost £ 7.5 million [11]. India cannot certainly go in for such a buy, even though this is less than a quarter of the 60 crores cost, of one of our Type 16 frigates, being built in Mazagaon Docks. What we require is a cheap acquisition, which will have an enhanced value, due its cost effectiveness.

71. The Soviet Union, which has been operating hydrofoil craft for a much longer time, could provide us with an alternative. The possible options are either outright purchase or an adoption of the Soviet idea, of conversion of the FP 8 hulls, by adding struts and foils.

72. *Outright Purchase*: With our present rapport with the Russians, at least where purchase of warships are concerned, outright purchase of a hydrofoil craft may not prove to be too difficult. The only shortcoming in outright purchase of

warships, from foreign countries, is the tie up due to spares. Having purchased a number of craft from foreign countries, the spares problems attendant to these acquisitions, are only too well known to require elaboration. This then may not be the best solution.

73. *New Indigenous Design*: Hydrofoil technology is nothing but an offshoot of aerofoil design. The Hindustan Aeronautics Limited has acquired sufficient expertise in this field, to produce an excellent airframe for the Marut aircraft flown by the Air Force. With minimal R & D effort, it is conceivable, that they could come up with a feasible hydrofoil design. From there to production, would be a fairly easy and not too costly step, given our industrial infrastructure. As regards the hull of the hydrofoil craft, Garden Reach Calcutta, has for long been involved in the construction of small fast patrol craft, of the Ajay and Akshay class, and should have no difficulty in designing a hull if the correct QRs' are provided to them. The marine diesel propulsion engine technology is still not sufficiently developed to provide the main propulsion system. Therefore, this and the "on board" equipment, especially the navigation and fire control software and perhaps, the anti-submarine equipment [if this role is envisaged], will be the imported components, in the craft.

Conversions

74. Another option is the conversion of some of our small craft into hydrofoil-equipped craft. The Indian Navy possesses many of these craft. These craft are ideally suited for our tests, to ascertain the feasibility of this type of conversion, if it requires proving. The Soviets have converted an OSA hull with hydrofoils [the Turya Class] and have proved that it is possible. The requirements them are two fold. Firstly, to design a workable strut and foil assembly and secondly, to design a propulsion system.

75. *Strut Foil Assembly*: The indigenous design of a strut-foil assembly will involve the design of the hydrofoil section and a strut structure which can withstand the stress. Most of these assemblies in craft being built abroad are made of stainless steel which may have to be imported. Even if Hindustan Aeronautics Limited can produce a design the testing of the first prototype will have to be done abroad as we do not possess the towing and manoeuvering tanks and cavitation tunnels required for the purpose. The design and testing of the prototype abroad would cost approximately Rs. 2 crores, if the exorbitant charges of hiring testing facilities, is taken into account. Since fully submerged foils require an associated auto control system, the best thing would be best the vee foil, as the fairly good sea keeping ability of this type of foil is proven by the Canadian FHE-400. A collaboration agreement is likely to reduce this cost somewhat as also the time required to manufacture the assembly.

76. *Propulsion*: When a hydrofoil is foil borne since the entire hull is out of the water the propeller shaft has to be inclined by twelve to fifteen degrees downwards to ensure propeller immersion. This is a problem mainly requiring a

modification to the transmission of the engine output through a V or Z drive and is likely to be well within the capacity of the design departments of technical institutions, like IIT Kharakpur or possibly even of the Directorate of Naval Design. The existing diesels on the OSA's may be suitable for this modification.

77. *Auxiliary Systems*: Since in the foil borne mode the hull of the craft is out of the water the existing sea water systems would require modification to enable operation in this mode. Perhaps an intake via the strut and foil assembly is the answer and would not involve a very heavy financial outlay.

THE FINANCIAL BURDEN

Outright Purchase

78. As brought out earlier, a sophisticated, fully submerged foil craft, built by Boeing costs £ 7.5 million. Although crafts manufactured by Italian and Swiss yards, may be cheaper, a fully submerged foil craft would be expensive, due to the need for an automatic control system and the associated software. The option of a vee-foil craft therefore is more attractive. At present price levels even a vee-foil craft purchased from Italy, USA or Switzerland would still be around £ 5 million or about Rs. 8.5 crores.

Indigenous Design

79. *Hull*: The design of a FPB hull is already available with the Garden Reach Calcutta and would need some expenditure to improve structural strength to cater for non-displacement operation. By using the existing OSAs in our inventory even this cost may be reduced.

80. *Strut and Foil Assembly* : The design, development, prototype manufacture and testing of a stainless steel strut and foil assembly would cost approximately Rs. 2 crores. If subsequently assembly line production commences, each unit would cost approximately Rs. 2 lakhs or less. The acquisition of the strut and foil design by technology transfer would be cheaper and faster.

81. *Propulsion System*:

[a] New Indigenous Design: The cost of designing a suitable marine diesel, with inclined shafting and adaptation of the existing assembly line, at Garden Reach Calcutta, to manufacture these engines would be in the region of Rs. 8 crores. The time factor involved in the process would be around five to six years.

[b] Collaboration: With the already existing collaboration with MAN [West Germany], the Garden Reach Shipyard or Kirloskars should not find it difficult to negotiate a collaboration for smaller high speed diesel of the type required for hydrofoil craft. The cost of transferring such technology would be in the region of Rs. 3 crores with a time factor of about two years before production could start in India.

[c] Redesigning Gearbox/Drive: As discussed earlier the redesigning of the gear box and drive train for the existing engines in the OSA class missile boats would involve even lesser expense and is estimated to be about Rs. One crore.

Total Outlay

82. *Conversion*: The cost of conversion or modification of the existing OSAs would involve four distinct parts namely hull, strut and foil assembly, main drive and gearbox and auxiliary systems. The total financial outlay for the entire modification in each case is estimated to be as follows:

Item	Cost [Crores of Rs.]
[a] Hull [strengthening of structural etc.]	0.5
[b] Strut and Foils	2.0
[c] Main drive/gear box	1.0
[d] Auxiliary systems	0.5
Total	4.0 Crores

83. *Logistic Infrastructure*: In addition to the above expenditure there will be a requirement of converting existing assembly lines to cater for the further conversion and repair and maintenance of these craft. With the already existing assembly lines in Mazgaon Docks, and Garden Reach, this would take up to Rs. 6 cores.

84. *The Pay Off*: The pay off of this venture when considered in its long-term effect is remarkable. If the first two test craft as envisaged are successful, the other OSA's could also be converted, missiles et.al., into hydrofoil craft. Although the weight factor with four Styx missiles would need looking into, it is estimated that at least two of the missiles could be retained. It is not

inconceivable also, that a foil assembly could be designed and manufactured, which could lift the craft, with all four missiles. The pay off would then be the availability, to the Navy, of a dozen missile hydrofoils, for an initial cost of approximately Rs. 10 crores and a retrofit cost of about Rs. 2.5 to 3 lakhs each i.e., for a total outlay of less than Rs. 11 crores, twelve of our small craft could be converted. In fact, with the retention of the existing conventional diesel, the craft could be given and emergency "get home" capability, along with enhanced mission times. It is also possible that the present 500-mile radius of action would not be degraded and could well improve, since for a given speed, a hydrofoil requires only 50 per cent of the power, as a displacement vessel.

CONCLUSION

85. The advanced naval concepts for the navies of the late eighties and nineties invariably center around surface skimmer technology. The effort and expense spared by most developed nations on this field is evident, from the variations of this technology, that are being tested. Even the fledgling air cushion vehicle and hydrofoil technology is in danger of being regarded as rather conventional. Ram Wing craft, wing in ground [WIG] effect craft, small water plane area twin hull ships [SWATH] and others are today common terms. The Indian Navy cannot ignore this trend, particularly when viewed with the cost effectiveness of these craft.

86. Closer home we see the need for these craft even more. Our most antagonistic neighbour, Pakistan has invested in Atlantique MR aircraft with an anti ship missile capability, improved Daphne submarines and ASM armed Sea Kings. This amounts to Pakistan acquiring a capability to effectively neutralize our substantial advantage in surface combatants. One question which is exercising the mind of every naval tactician is how to counter the Atlantique and the Daphne. The loss of even one of our highly priced Leanders is almost unbearable to contemplate.

87. The Indian Navy requires a potent system to counter these threats and which does not strain the financial back. With the conversion of the missile boats into hydrofoil craft, within the realms of possibility, this system is ours for the asking – a system which is virtually immune to both the threats looming so ominously large on the tactical horizon.

88. An offshoot of this conversion is the availability of a method for operating these converted craft in our islands from froward in prepared bases. A Logistic Support Mobile Train consisting of six modular units a d capable of providing support to three converted craft could be acquired for a nominal cost. This logistic support mobile train would be on "the same lines as being put in the market by the Italian firm Cantiere Navali Riuniti.[12]

89. The acquisition of expertise, in hydrofoil technology would also open up new vistas in water transportation. The immediate result could be the conversion of the amphibians in the Army to fulfil the role of an LCA [Land Craft Assault] so solely lacking with the Navy. The feasibility of applying this concept, to civilian uses, for the Coast Guard and for recreation is always possible.

90. This study after examining the hydrofoil technology in its applicability to existing Indian conditions has arrived at a few recommendations which could be the first step in harnessing the advantages of this unique concept for the enhancement of the creditability of the Indian Navy.

91. *Recommendations*: The following recommendations are made in order of priority:

[a] Hindustan Aeronautics Limited should be contracted to study and develop a design for a hydrofoil section.

[b] IIT Kharakpur, and the DND, NHQ should be asked to study the modification of the existing diesels on the OSAs to achieve inclined shafting through a V or Z drive.

[c] Failing this, Garden Reach Workshop [GRW] Calcutta or Kirloskars should be asked to arrange for technology transfer of suitable small sized marine diesels from a suitable foreign firm. The collaboration arrangement should also include the technology transfer of inclined shafting.

[d] If feasibility is proved all our small craft could be retrofitted with this.

[e] A logistic support mobile train based on the Cantiere Navali Riuniti Shipyards [Italy] [10] concept should be developed, by the Naval Dockyard Vishakhapatnam, to enable forward operation, from unprepared bases, by these craft.

APPENDIX "A"

GLOSSARY OF TERMS

Aeroplane Foil System: Also called the conventional foil system it is a foil arrangement in which the main foil is located forward of the center of gravity to support 75 per cent to 85 per cent of the load, and the auxiliary foil, supporting the remainder, is located aft as a tail assembly. The forward and aft foils may be retractable to reduce hull borne draught.

Angle of Attack The angle made by the mean chord line of an aero or hydrofoil with the flow.

Angle of Incidence: The angle made by the mean chord line of a hydrofoil in relation to the fixed struts or hull.

Automatic Control System [ACS]: Although fully submerged foils are the most versatile in operation they are inherently unstable and are workable only with an automatic control system. There are three types of control systems namely sonic, mechanical and pneumatic. The ACS has to stabilize the craft from take off to touch down in heave and all the three axes – roll, pitch and yaw. It must also see that the craft makes coordinated banked turns in heavy seas to reduce the side loads on the foil struts, ensure that vertical and lateral acceleration are kept within limits in order to prevent excessive loads on the structure and finally ensure a smooth ride by maintaining the foils at the correct depth.

Base Ventilated Foil: A system of forced ventilation designed to overcome the reduction in lift/drag ratio of a foil at super cavitating speeds. Air is fed continuously to the upper surface of the foil unwetting the surface and preventing the formation of critical areas of decreased pressure. Alternatively air may be fed into the cavity formed behind a square trailing edge.

Canard Configuration: In this arrangement the main foil of wide span is located near the stern, aft of the center of gravity and bears about 65% of the weight while a small central foil is placed at the bow. The fore and aft foils could be made retractable to reduce hull borne draught.

Cavitation: This is the formation of vapour bubbles due to the pressure decrease on the upper surface of the foil, or the back of propeller blades at high speeds, and falls into two categories, unstable and stable. Non-stable cavities or cavitation bubbles of aqueous vapour form near the leading edge of the foil and extend down stream expanding and collapsing. At points of collapse positive pressure peaks may rise to as high as 20,000 psi. These cause erosion and pitting of metal. Cavitation also causes an unstable flow of water flow over the foils which results in abrupt changes in lift and therefore discomfort to those abroad the craft. Foil sections have now been developed which wither delay the onset of cavitation by reduced camber, thinner sections or sweepback, or if the craft is required to operate at super cavitating speeds, stabilize cavitation to provide a smooth transition between sub cavitating and super cavitating speeds.

Foil Flaps: Foils are frequently fitted with [a] trailing edge flaps for lift augmentation during take-off and to provide control forces [b] upper and lower flaps to raise the cavitation boundary.

Foil Systems: There are three foil system current in use:

[a] <u>Surface Piercing Foils</u>: Surface piercing foils are more often than not vee

shaped and are also called vee foils. The upper part of the foils from the tip of the vee and pierce the surface on either side of the craft. The forces restoring the normal trim are provided by the area of the foil that is submerged. A roll to one side means the immersion is increased on that side, thus generating greater lift to counter the roll, restoring the craft to even keel. Similarly a pitching movement generates greater lift either in forward or aft foil. This system is also called the emerging foil system as a vee foil craft increases speed greater lift is generated raising the craft and the foil with it further out of the water. This results in decreased lift. The hull therefore rides at a predetermined height above the water.

[b] Shallow Draught Submerged Foil: This foil system is used for craft plying along long calm stretches of water like rivers and are used widely in hydrofoil craft designed in the Soviet Union. The system is also known as the immersion depth effect system and was invented by Dr. Alenyev. It carries two equal area foils forward and aft which are submerged. These foils lose their lift gradually as the foil approaches the surface from one chord [distance between leading and trailing edge of foil] submergence, which prevents, it from rising completely to the surface. Means therefore have to be provided to assist take-off and to prevent the vessel from sinking back to the displacement mode. Two planning sub foils are therefore located in the vicinity of the forward strut so that when they are touching the water surface the main foils are submerged at a depth of approximately one chord.

[c] Submerged Foils: This system consists of forward and rear foils which are fully submerged well below the surface. Modern constructions generally prefer this system as the surface piercing foil suffers from the following disadvantages.

i] The inability of vee foil craft without control surfaces to cope with the downward orbital velocity at wave crests when overtaking waves in a following sea; a condition which decreases the foil angle of attack causing reduction of lift resulting in hull slamming or a stall. Submerged foils, on the other hand are capable of platforming, contouring or an intermediate response, when automatically controlled.

ii] On large craft, the weight and size of vee foils is considerably larger than a corresponding submerged foil system.

iii] Since restoring forces in the vee foil system have to pass above the center of gravity of the craft, the foils have to be placed only a short distance beneath the hull. This means a low wave clearance thus making to vee foil unsuitable for rough weather operations. Crafts like the FHE 400 have however proved that this is not strictly correct.

iv] Vee foil systems are susceptible to waves and provide a rough ride whereas the fully submerged foil system being below water is immune to wave disturbance providing a smoother ride.

The greatest disadvantage of the submerged foil system is that these foils are inherently unstable and require on ACS to control the depth of the foils. These auto control systems add to the cost of this system. The various types of auto control systems are:

i] Sonic System: This system is probably the most expensive and sophisticated. The key element of a typical acoustic electronic autopilot is the sonic height sensor located at the bow. Craft motion input is received from dual sonic ranging devices which sense the height above the water of the bow in relation to a fixed reference; from three rate gyros which measure yaw, pitch and roll; from forward and aft accelerometers which sense vertical accelerations fore and aft and from a vertical tyro which senses the angular position of the craft in both roll and pitch. The information is processed by a computer and fed to hydraulic actuators of the foil control surfaces which then move to maintain the craft stability through wave action and during turns.

ii] <u>Mechanical Incidence Control</u>: The most successful purely mechanically operate incidence control system was developed by Christopher Hook who pioneered the development of submerged foils. The control surfaces are generated either by deflecting flaps at the trailing edge of the foil or varying the angle of incidence of the entire foil surface. To achieve this a fixed high riding crash preventer plane is mounted ahead of and beneath the bow. The fixed plane, which is only immersed when the craft is in the displacement mode, is also used as a platform for mounting a lightweight pitch control sensor, which is hinged to the rear. The sensor rides the waves and transits continuously their shape through a connecting linkage to vary the angle of incidence of the main foils, as necessary to maintain the required depth. A filter system ensures that the craft ignores all waves with a height below that of the keel above the water. The additional sensors on either side provide roll control. The pilot of the craft has overriding control through a joystick control.

iii] <u>Air Stabilization Control</u> : This is a system designed by Baron Hans Von Schertel. Air from the free atmosphere is fed through air exits to the foil upper surface and under certain conditions the lower surface also [into the low pressure regions]. The airflow decreases the lift, and deflects the flow away from the foil section; with an effect similar to deflected flaps, the air cavities extending out behind producing a virtual lengthening of the foil profile. Life is reduced and varied by the quantity of air admitted, this being controlled by a valve actuated by a damped pendulum and rate gyro. The pendulum causes righting moments at static heeling angles. If exposed to a centrifugal force in turning, it causes a moment, which is directed towards the center of the turning circle, thereby avoiding outside banking. The rate gyro responds to angular velocity and acts dynamically to damped rolling motion.

Grunberg Foil System: This system has a main mid-ship foil which carries about 90 per cent of the load and small planning foils, set forward, carrying the remainder. An adaptation of this system is the Aquavion System, which has the main foil located slightly abaft the center of gravity carrying 85 per cent of the load. An aft stabilizer foils carries about 10 per cent while the remainder is carried by a pair of bow planning sub foils. These sub foils give a variable response to wave shapes and turn the angle of the hull, in order to correct the angle of attack of the main foil.

Inclined Shaft: A marine drive shaft used in small vee foil and shallow-draught submerged foil craft, with keels only a limited height above the water level. The shaft is generally short and inclined at about 12 to 14 degrees to the horizontal. On larger craft, designed for operation on higher waves, the need to fly higher necessities alternative drive arrangements such as a vee drive and Z drive, the water jet system and even air propulsion.

Tandem Configuration: This configuration consists of equal area foils fore and aft balancing the loading between them.

Thruster: Controlled aperture through which air can be expelled to assist control at low speeds.

Transcavitating and Super Cavitating Foils: Since at very high speeds foils cannot avoid cavitation, sections are being designed which induce the onset of cavitation from the leading edge and cause the cavities to proceed downstream and beyond, the trailing edge before collapsing. These are called super cavitating foils. Lift and drag of these foils is determined by the shape of the leading edge and under-surface. Foils which are required to operate at super cavitating speeds also have to cater for a smooth transition from sub-cavitating to super cavitating speeds. Foil sections have been designed to achieve this. By loading the tip of the foil more highly than its root, cavitation is first induced at the tip and then extends span wise over the foil to the roots as speed increases. These are known as Transcavitating or Transiting foils.

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[1] Michael Coster, "Introducing PCOs Jetfoil Service" p. 25, Hovercraft and Hydrofoil, October 1977, Vol. 17, No. 1.

[2] Roy McLeavy "Forward", Janes Surface Skimmers, 1974-75.

[3] An interview with Baron Von Scherkel – Interviewed by the International Hydrofoil Society, p. 12, Hovercraft and Hydrofoil, February/March, 1978

[4] *Ibid*.

[5] Waldemar Graig – Grunberg Hydrofoil Pioneer Interviewed by Mark Thornton. P. 7, Hovercraft and Hydrofoil, November, 1977.

[6] Hanns Von Schertel, Egon Faber and Eugen Schette, Military Hydrofoils, p. 301, Janes Surface Skimmers, 197273.

[7] R.C. Macgregor, Small Fast Warships and Security Vessels, p. 27, Hovercraft and Hydrofoil.

[8] *Ibid*

[9] Roy McLeavy James, Surface Skimmers, 1975-76.

[10] Anthony Preston, The Royal Navy's New Jetfoil Hovercraft and Hydrofoil, April 1979.

[11] *Ibid*.

[12] Francesco Cao Sparviero "Swordfish" Type Multi Role Combat Hydrofoil, Hovercraft and Hydrofoil, May, June 1978