HYDROFOIL LIFE CYCLE COST CONSIDERATIONS
FOR FIXED
AND RETRACTABLE FOILS

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1.0 Introduction

This report discusses the potential life cycle cost (LCC) differences for 2 different hydrofoil configurations, with either fixed or retractable struts and foils.

The study was initiated in response to a report issued by LCDR W.R. Starchuk, C.F. in July 1980 entitled "A 500 ton ASW Hydrofoil Design for the Canadian Forces Future Ship Study" (Reference 1). The report presented a design for a fixed strut hydrofoil ship. A second report was also issued (Reference 2) in November of 1980 which presented design characteristics of two hydrofoils, one using fixed and the other retracting struts and foils.

In both of these studies life cycle costs were estimated using the Hydrofoil Analysis and Design (HANDE) program (3). The program uses simple cost estimating relationships to derive the values for the various elements which compose the total life cycle cost.

This study will investigate each of the cost estimating relationships used in the HANDE program to determine if there are substantial differences between fixed and retractable hydrofoil designs. Where major differences exist they will be identified and a quantitative assessment of the impact on life cycle cost will be made if possible.

2.0 Background: Life Cycle Cost

Life Cycle Costs are the total costs borne by a user in designing, building, operating, and retiring a ship over its entire useful life.

These costs are often directly attributable to the ship itself such as material and labor costs for construction, but they are also indirectly caused by the costs required to support a ship during operation such as additional manpower required to provide maintenance support for several ships at a shipyard.

Itemizing each of the costs associated with a particular ship is a tedious process when done at the lowest cost level. However, since LCCs are usually very important in the design stage when trade off studies are made, a good basis for estimating cost differences is essential. Without detailed information the designer will only be able to estimate the qualitative impacts of different design and operational changes. This problem is further compounded when dealing with novel ship types for which no life cycle cost data exist or where the cost data base is insufficient to generate confidence in the cost estimates.

For hydrofoils the cost estimating relationships (CERs) have been defined and one set has been incorporated in the HANDE program. It should be pointed out, however, that these relationships provide information on LCC for designs at the feasibility level and do not consider many finite changes in the later design stages and operations which could change LCC. This results from the requirement of having to sufficiently limit the data base from which the cost estimating relationships were formed so that an easily useable and affordable set of CERs can be defined by the program.

This study will attempt to categorize the life cycle cost changes between fixed and retractable foils in a manner similar to that used by the HANDE program. This should allow changes to be made in the CERs to account for any cost differences which are evident in the two configurations,

3.0 HANDE COST CATEGORIES

The HANDE program divides life cycle costs into three major elements: Research & Development, Investment, and Operations and Support. Each of these is further divided and subdivided so that there are a total of 19 individual cost items which are covered by the program. Table 1 lists these cost elements as categorized by the HANDE manual. The program also provides a listing by recurring and non-recurring costs for the ship, payload and other costs and for the recurring cost of operations and support.

3.1 The first cost category is Research and Development. Within this category there are two cost elements: 1) Design and Development and 2) Test and Evaluation.

3.1.1 Design & Development is defined to include the cost of preliminary research and design studies, development engineering and fabrication of test articles, development instrumentation, component test operations and industrial facilities required to proceed through a development program. Necessary fuels and lubricants used during laboratory, in-plant, and component testing are included, as well as costs of development and qualification of specific component technologies not currently available as state-of-the-art for use in hydrofoils.

3.1.2 Test & Evaluation includes the program costs required for a ship class with associated payloads and spares to support major subsystems during test operations. Also included are operational activites associated with the systems testing, test equipment, test facilities, test instrumentation, additonal fuels and lubricants, data reduction and analysis, maintenance, supply and miscellaneous items necessary to conduct systems tests.

Except for unusually complicated ships or new designs which require a substantial amount of research and subsystem proof of concept testing, these cost elements usually do not result in a significant portion of the life cycle cost. Furthermore, a construction program which incorporates a large number of ships will lessen the cost of R&D per ship since **R&D** costs are non-recurring.

3.2 Investment costs include equipment, facilities and initial spares costs. Of these, the prime and support equipment costs represent the largest percentage and are primarily acquisition costs of these equipments. Not included in life-cycle cost are costs of conversions and modernizations which entail major changes to ship configuration that alter the military characteristics of a ship. Included are costs of incremental improvements, such as subsystem modernization, accomplished during periodic overhauls or reworks. As evidenced by both past and current ship programs, major conversions or modernizations may not occur during service lifetimes.

3.2.1 Equipment costs includes prime and support equipment.

3.2.1.1 Prime Equipment is defined to include the estimated initial cost of the required number of ships, payloads, and other installed equipment items including GFE, necessary to operate a ship -- the ship and payload together.

3.2.1.2 Support Equipment is defined to include both peculiar and common support equipment whichmustbe procured to perform all threelevelsofmaintenance for the ship and payload. Peculiar support equipment includes tools and test equipment used in the maintenance of a particular class of ship. Common support equipment includes tools and test equipment necessary for maintaining more than a single ship class.

TABLE 1

ELEMENTS OF LIFE-CYCLE COST

1. RESEARCH & DEVELOPMENT

- o DESIGN & DEVELOPMENT
- o TEST & EVALUATION

2. INVESTMENT

- o EQUIPMENT
  - Prime
  - Support
- o FACILITIES
- o INITIAL SPARES AND REPAIR PARTS

3. OPERATIONS & SUPPORT

- o PERSONNEL
  - Pay and Allowances
  - Temporary Additional Duty (TAD)
- o OPERATIONS
  - Utilities
  - Repair Parts
  - Supplies
  - Training Expendable Ordnance
- o MAINTENANCE
  - Intermediate
  - Depot/Industrial
- o ENERGY
- o REPLENISHMENT SPARES
- o MAJOR SUPPORT
  - Training
  - Indirect Personnel Support
  - Other Logistics

3.2.2 Facilities costs are defined to include the cost of constructing, converting, altering, or modifying facilities dedicated to the maintenance, training, and logistic support of a single ship class. The facilities may include intermediate and and depot level maintenance facilities, naval shipyards, piers, docks, anchorages, fuel storage sites, and ammunition depots.

3.2.2 Initial Spares and Repair Parts costs are defined to include the cost of initial spares and repair parts required to be stocked for the service and repair of a ship for the first 4 years of operation. Spares are recoverable components, assemblies, subassemblies, equipments, or end items which are installed or placed in use while replaced items are undergoing maintenance, repair, or overhaul. Repair parts are those individual parts required for the maintenance or repair of installed equipments or spares but which are not themselves considered repairable.

Investment costs are usually about half of the total life cycle costs.

3.3 Operations and Support costs include personnel costs, major support costs , operations, maintenance, energy and replenishment spares costs. Some of the costs incurred in this group include indirect costs incurred by the Navy to support the fleet.

3.3.1 Personnel costs includes Pay and Allowances Costs and Temporary Additional Duty costs for active ship personnel.

3.3.1.1 Pay and Allowances costs include basic and hazardous duty pay, quarters, subsistence, and clothing allowances, incentive and special pay and miscellaneous expenses for vehicle active personnel.

3.3.1.2 Temporary Additional Duty costs include cost incurred due to temporary assignment of personnel away from the ship for training, administrative or other purposes.

3.3.2 Operations costs are defined to include part of the direct costs associated with operating a ship. Included are the costs of utilities, repair parts, other ship consumables, and training expendable ordnance. Energy, which is also a direct operating cost, is treated as a separate cost element.

Each of the cost categories is described below.

3.3.2.1 Utilities: The cost of energy used to power a ship which is not provided by the ship itself. For example, ships require utilities from shore facilities when not underway.

3.3.2.2 Repair Parts: The cost of repair parts used in the organizational maintenance of the ship. Repair parts are those individual parts used for equipment repair but which are not themselves repairable.

3.3.2.3 Supplies: The cost of consumable supplies and equipage items of a general nature, i.e., janitorial supplies, office material, personnel support supplies, medical and dental material, etc., which are not directly related to the support of specific equipment or ship systems.

3.3.2.4 Training Expendable Ordnance: The cost of the expendable ordnance, ammunition, pyrotechnics, missiles, ballistic weapons, guided weapons, torpedoes, mines, depth charges, sonobuoys , etc., used by the ship in training exercises.

3.3.3 Maintenance costs, as defined by the HANDE program, include the costs of intermediate maintenance and industrial/depot level maintenance. Organizational maintenance is covered by personnel and operations cost elements.

3.3.3.1 Intermediate Maintenance includes the cost of direct labor and material, supplies, and repair parts expended during intermediate maintenance activities. For example, the cost of direct labor and materials expended by tenders and repair ships represents an intermediate maintenance activity. This maintenance is performed onboard the ship by members of the ships crew assisting personnel from an intermediate maintenance facility,

3.3.3.2 Depot/Industrial Maintenance includes the cost of direct labor, material, other direct costs, and applied overhead chargeable to job orders for overhaul, progressive maintenance, analytical rework, modifications, repair, inspection and test, manufacture, reclamation, and storage of ship subsystems, components, parts and support equipment at naval shipyards, commercial facilities, and any other industrial facilities which perform depot level maintenance.

Depot/industrial maintenance includes regular overhaul; non-scheduled ship repair (i.e., restricted or technical availability, RA/TA); Fleet Modernization Program (i.e., SHIPALTS, ORDALTS, etc.); and scheduled ship repair (i.e., Selected Restricted Availability (SRA)).

3.3.4 Energy costs include the cost of fuel consumed by the ship and any aircraft on the ship. Increases in the cost of fuel during the last decade have made energy costs a significant portion of the operations costs.

3.3.5 Replenishment Spares costs are defined to include the cost of recurring procurement of spares required to replenish rotatable pools of repairable components depleted through abandonment, loss, or survey. Spares are recoverable components, subassemblies, assemblies, equipments, or end items which are installed, or otherwise placed in use, while items are undergoing maintenance, repair, overhaul, or salvage at other than the organizational level. These spares cover four year periods after the initial four years of ship operation.

3.3.6 Major Support Costs include the costs of Training, Indirect Personnel Support and Logistics which are defined below.

3.3.6.1 Training: The costs of training all personnel, both general and specialized training. This includes operating and support costs of training facilities and staff, which are allocated over trainees.

3.3.6.2 Indirect Personnel Support: The cost of indirect support to personnel, such as medical, recruiting and examining, transient and prisoner billets, and permanent change of station (PCS).

3.3.6.3 Logistics: Includes the cost of base operating support, second destination transportation of material required for the ship subsequent to its initial receipt by the government, engineering and technical services not supplied by intermediate or industrial maintenance activities, proportional operating costs of Inventory Control Points (ICPs), Supply Depots, other field support, technical documentation update, and other logistics activities.

A final value is taken as a credit in the life cycle cost calculations. This is the residual value which accounts for the sale of the ship at the end of its useful life.

4.0 Relative Importance of Different Cost Categories

Having defined the cost categories used by the HANDE program a review of the relative importance of each category is valuable to indicate in which groups the most significant impacts can be made on life cycle cost.

The cost information used for this review is derived from three reports. The report by Starchuk (1) provides a breakdown by different cost category. The second report issued in November of 1980 (2) provides values of acquisition cost and life cycle for fixed and retractable foil designs. The third report used to provide cost data is the Life Cycle Cost for NATO PHM report issued by PMS 303 in April 1976 (4).

The report by Starchuk assumed a procurement of four ships with a useful life of 20 years with a crew of 8 officers and 40 enlisted men per ship. Details of the costs are given in Appendix A. Table 2 contains a summary of the costs broken down by cost category and showing the percentage of total LCC for each category.

The table demonstrates that Equipment, Operations, and Support costs are the largest proportion of the life cycle costs, comprising over 90% of the total.

The R&D costs are only 5.4% of the total cost and are evenly split between Design and Development and Test and Evaluation. The Investment costs are almost solely caused by investment in the prime equipment, the ship and payload.

The second report issued in November 1980 provided information on the acquisition and life cycle costs of four additional ships and compared these costs to the ships designed in the previous study. The variations in the ship design included fixed or retractable foils and separate or combined hullborne and foilborne machinery systems. The original design performed in the Starchuk report was labelled FLF (F). The new designs were labelled FLF (C1) for the separate machinery plant design and FLF (C2) for the combined plant design. In the case with fixed foils and struts the fuel weight was increased to compensate for decreased lightship weight. Table 3 presents the results of the study.

TABLE 2

FLF LIFE CYCLE COSTS

Cost Category	Life Cycle cost ($\$10^6$)	Percent of Total Cost
Research & Development	57	5.4
Design & Development	30	2.8
Test & Evaluation	27	2.6
Investment	467	44.3
Equipment	439	41.7
Prime	402	38.1
Support	37	3.5
Facilities	4	0.4
Initial Spares	23	2.2
Operation & Support	565	53.6
Personnel	61	5.8
Operations	27	2.6
Maintenance	216	20.5
Energy	107	10.2
Replenishment Spares	94	8.9
Major Support	60	5.7
Residual Value	-35	-3.3
Total Life Cycle Cost	1054	'100.0

TABLE 3

COHPARISON OF LIFE CYCLE COSTS

SHIP	FLF(F)	FLF(C1) RETRACT	FLF(C1) FIXED	FLF(C2) RETRACT	FLF(C2) FIXED
Light Ship WT (L Tons)	356.0	395.0	381.8	394.8	382.0
Fuel WT (L Tons)	112.7	112.6	125.8	109.3	119.8
Relative Acquistions cost	1.0	1.04	1.03	1.04	1.02
Relative Life Cycle Cost	1.00	1.02	1.01	1.02	1.01

The table does indicate that the relative acquisition cost is 1 or 2 percent less for a fixed foil design as opposed to a retracting foil design. The life cycle cost estimates are 1 percent less for the fixed foil designs.

The third report to be reviewed for an indication of relative costs of different categories is the NATO PHM Life Cycle Cost Report of April 1976. Some caution must be used in reviewing the costs developed in this report for two reasons. First, the report is five years old and so many of the costs are out of date. As an example, the report *uses* a fuel cost of $16.38 per barrel or $.39 per gallon which is about one-third of current fuel costs. The second reason has to do with the different maintenance and support philosophies used for the PHM and the 500 *ton* ASW ships described in the reports mentioned above. The PHM used an AGHS support ship to provide intermediate maintenance for the entire squadron so the cost of the ship was included in the life cycle cost calculations. If such a ship were not used a higher value would have to be attributed to the PHM maintenance costs for maintenance at shoreside facilities. The report also shows the first PHM being constructed under R&D funding. Table 4 provided a summary of the life cycle costs attributed to just the PHM ship. In addition to the costs shown in Table 4 the program life cycle cost also includes $44 million for procurement and operation of the AGHS and **$11** million for squadron staff and the Mobile Logistic Support Groups. Table 4 also estimates costs based on a 10 year service life where the FLF studies all considered a 20 year service life.

Due to the differences in financing the PHM class as opposed to the FLF class hydrofoils, the PHM cost information is provided as a reference of relative costs only.

TABLE 4

PHM LIFE CYCLE COSTS
(6 SHIPS 10 **YEARS)**

COST CATEGORY	LIFE CYCLE COST ($ 10% (1976)	PERCENT OF TOTAL COST
Development •	$105.2	19.9
Procurement	302.2	5'7.0
Weapons Procurement	22.3	4.2
Operation & Maintenance	100.3	18.9
Manpower	18.2	3.4
Ship Operations	28.3	5.3
Fuel	23.8	4.5
Utilities	.4	.1
Repair Parts Consum	2.6	.5
Other Ship O&M	1.5	.3
Ship Maintenance	26.0	4.9
Annual Overhaul	22.7	4.3
RA/TA	1.8	.3
Intermediate Maint	1.5	.3
TAD	.1	-
Logistics	19.0	3.6
Base Operations	.6	.1
Training	.3	.1
Medical	.4	.1
Recruiting & Exam	.1	
Modernization	3.0	.6
Expendable Ordnance	4.3	.8
Total	530.0	100.0

• Development costs shown enclude the procurement of the first PHM which would normally be included in the procurement cost category.

5.0 Analysis of Previous Life Cycle Costs

From the three sets of LCCs reviewed, trends are evident as to the relative importance of each category to the total life cycle cost and the relative cost differences between fixed and retractable foil systems.

Of the three major categories; R&D, Investment, and Operations and Support, Investment and Operations and Support represent the bulk of the total LCC. R&D costs can be expected to be on the order of 5% of the total. Although the R&D costs for the PHM were shown at 20% of the total it must be pointed out that the first PHM was built under R&D funds not under SCN funding. If the average acquisition cost were subtracted from the R&D costs and added to the acquistion costs the R&D costs would be in the range of 10% of total LCC. This cost would be further reduced when the one time costs incurred during first ship construction are further subtracted from R&D costs.

Investment costs range between 45 and 65 percent of the total LCC for the different ships. The largest part of this is due to the acquisition of the prime equipment, the ship and weapons. Support equipment and initial spares contribute about 5% of the total LCC.

Operations and Support costs range from about 25 to 50 percent of the total LCC in the studies reviewed. This assumes that the cost of the PHM support ship is charged as an operational cost. The range also covers the difference in fuel costs used between 1976 and 1980. The most significant costs in the Operation and Support category are fuel, maintenance and replenishment spares.

6.0 Potential Cost Impacts of Fixed and Retractable Foils

6.1 Research and Development

The research, design, development and testing of a fixed foil system will be slightly less complicated and costly than that of a retractable foil system. However, this reduction in cost will be so slight that it will probably not make a noticeable difference in the cost estimated in the HANDE program.

The reason for the reduction is due to the omission of research, design, and testing of the retraction system. Research on a new retraction system design would be minimal since several successful retraction designs have been accomplished. The design of a new retraction system would still require some time, but an equivalent amount of time would also have to be spent on the design of a fixed foil system to insure proper structural attachment. However, because several successful fixed foil designs have been performed the time required to study the structural attachment of the struts on a fixed foil system would not be a large portion of the R&D costs. Testing of the retraction system would be eliminated in a fixed foil design and would also contribute to a slight reduction in R&D costs.

6.2 Investment

Cost estimates for investment show that the largest cost in the category is procurement of the ships themselves, the prime equipment. Estimating these costs during feasibility level designs is usually carried out by applying cost factors to the different SWBS groups weights.

For a fixed foil system there will be a reduction in weight due to the deletion of the retraction mechanism, the reduction in foundation weight for the struts and foils, and reduction in hull structural weight due to the simplified construction of the hull in way of the strut attachment points.

In designs performed by HANDE on the FLF (C1) and FLF (C2) with fixed and retractable foil systems, the SWBS group 1 weight including hull structure and foundations was about 3% less for the fixed foil design and the group 567 weight for struts and foils was about 23% less for the fixed foil design. All other weights were the same for both designs.

The reduction in weight (equipment and structure) resulted in a reduction in lead and follow ship hardware costs of 2% with equivalent reductions in design and engineering and construction services costs. Overall the average acquistion cost per ship decreased 1.5% for the fixed foil design or about $1.5 million per ship.

For the 4 ships acquired this resulted in a life cycle cost difference of less than 1%.

In addition to the prime equipment costs, there is the cost of support equipment. No major changes are envisioned in the support equipment costs although some minor changes would be required in the support equipment. For example, a ship designed with retractable foils might require some special tools used for maintenance of the retraction mechanism. Although these tools might not be necessary for the fixed foil design another set of equal cost would probably be required for maintenance of the fixed foils. Furthermore, any tools or equipment which would be required for work on the retraction or fixed versions would be a small cost of the special equipment necessary to maintain the other ship subsystems. The final cost of any such equipment would be too small to even show up in the life cycle costs.

Facilities costs are another category of investment costs and will show no significant change as a result of the switch from fixed to retractable foils. The costs are such a small percentage of total life cycle cost that any change in the facilities which might occur as a result of the change in foil system would not affect the total life cycle cost.

There is one effect of the change from retractable to fixed foils which has the potential to impact the facilities costs. That change is the large increase in navigational draft required by the fixed foil design. For retractable foil designs the maximum draft of the ship is on the order of 7 feet with foils up. This allows the ships to use shallow draft areas of the ports. However, the fixed foil navigational draft is on the order of 27 feet which is much deeper than many of the frigates and destroyers now in operation. If this deep draft required channel or dockside dredging or special location of the hydrofoil support equipment at the deep water docks at the maintenance facilities the facilities cost could increase substantially. It is assumed for purposes of this report that the fixed foil hydrofoil ships will operate only from ports which are deep enough to require no additional dredging. However, the question of navigational draft must be addressed when considering the maintenance of fixed foil ships.

Initial Spares and Repair Parts are the last category of the investment costs. Of these about 40% are ship related and 60% are payload related. The most significant cost for spares would be in the propulsion area with very little in the area of struts and foils. If any spares were to be maintained for the strut retraction mechanism these would not be a very expensive item. Even if comparable spares were not required for the fixed foil design, the cost of this group would not change due to the small contribution of these spares to the total cost of the group.

6.3 Operations and Support

Operation and Support costs represent the largest fraction of life cycle costs and include substanial costs for maintenance, energy and replenishment spares. Also included are costs for personnel, operations and major support. The groups in which a life cycle cost change might occur due to the switch from retractable to fixed foils are maintenance and energy.

6.3.1 Personnel costs would not change since both fixed and retractable designs would have the same crews. Although some additional organizational maintenance hours might be required of the crew to maintain the fixed foils in a clean unfouled condition this extra time would be minimal and would probably be comparable to the time required to maintain the retraction system on the retractable foil design.

6.3.2 Operations costs include pierside utilities costs, ship consumables costs, expendable training ordnance costs and the cost of repair parts used in organizational maintenance. For ships with similar payloads, crew and ship sizes , the utilities costs to heat and power the ship when in port and the consumables costs to cover personnel, janitorial, office and other supplies will be identical. The training expendable ordnance costs would also be identical for similar ships. Therefore there will be no change in these categories between the fixed and retractable foil designs. The repair parts costs for the retractable foil design might be slightly higher than for the fixed foil design simply because there would be a retraction mechanism to repair. However this would be a small part of the overall repair parts cost and would not change the overall cost of the operations category.

6.3.3 Major Support costs include training for all personnel, indirect personnel support costs and logistics costs associated with mantaining support activities other than intermediate or depot level maintenance facilities. The first two categories pertain only to personnel requirements which are identical for both fixed and retraction designs and would therefore have the same costs for either design. The logistics category pertains only to the facilities required to supply equipment and engineering and management services to the deployed ship and would not be affected by a change in the foil. design. Therefore, no change should be expected in the major support life cycle cost category.

6.3.4 Replenishment Spares costs represent about 20 percent of the total operations and support cost according to the estimates developed using the HANDE program for several fixed and retraction designs. The designs indicate a $1 million reduction in the 20 years life cycle cost for four ships when the fixed foil system is used instead of the retraction design. Al though some change in replenishment spares might be possible to account for retraction mechanism spares, this cost would probably not approach $1 million dollars over the life of the four ships and appears to be only the result of a round off error in the program.

6.3.5 Maintenance costs as predicted by the HANDE program are essentially equivalent for both the fixed and retractable designs. These costs, which are nearly 40% of the total operation and support costs, are composed of the costs of intermediate maintenance and depot and industrial maintenance.

Depot and industrial maintenance includes the regular ship overhaul scheduled

(SRA) and unscheduled ship repair (RA/TA). This category might show an increase when using the fixed foils for the following reason. Reference 5 indicates that the struts and foils required 52.3 maintenance actions per 1000 underway hours. These failures resulted in some 3357 hours of corrective maintenance by either the ships force (10%) or intermediate maintenance personnel (90%). Certainly some of this maintenance was performed with the foils accessible when they were retracted. For the fixed foil design all maintenance on the struts, foils and pod mounted gears would have to be performed in a depot when the ship could be drydocked. Balanced against this increase would be a decrease in maintenance on the retraction mechanism. Determining this total change in maintenance is quite difficult with the limited information available but an estimate can be made to indicate the cost of this increase.

A review of the individual maintenance actions on the PHM-1 has shown a large number of actions (73 out of 363 reviewed) were caused by cracks in the foils and pods. In almost all cases these cracks were ground out and welded when the ship was moored with the foils retracted. Although several cracks were repaired while the ship was drydocked it was not necessary to drydock the ship for these repairs. However, with the fixed foil design the ship would have to be drydocked for all repairs.

In addition to the actions to repairs cracks in the foils and pods there were 18 actions which were required to repair or replace loose or missing fasteners in pod access plates and fairings. Many of these actions took place when the ship was moored with foils retracted. None required that the ship be drydocked. But for the fixed foil case almost all would required that the ship be drydocked.

It is difficult to estimate the increased cost of maintaining a fixed foil ships since it is nearly impossible to predict the number ofadditionaldrydockings required to repair the foils and replace fasteners. The lack of predictability is compounded by the fact that the problems experienced by the PHM-1 might be solved by improved design practices such as the use of higher strength steels in the foils and the use of locking fasteners for all underwater uses. Further compounding the problem is the reduced visibility of the fixed foils which will lead to fewer inspections. If the foils crack or fasteners loosen corrective action to repair the problem may not be taken for weeks or months simply because the problem will not be evident.

Another reason for the delay in locating cracks in the foils might be due to the use of a new foil coating discussed in section 6.3.6. This coating is extremely elastic and might serve to prevent discovery of small cracks underneath even during close inspection.

One final consideration which might cause an increase in maintenance for the fixed foil design would be maintenance of the pod mounted gear boxes. Obviously, all maintenance of these gear boxes would require drydocking. In previous hydrofoils which incorporated propulsion gears in the pods, PCH-1 and AGEH, substantial difficulties have been encountered. The difficulties have been caused by water entering the pods and contaminating the lube oil system, by misalignment of the gearing and by other problems. Water entering the lube oil could be a serious problem when considering the high level of maintenance required to repair cracks in the pods including access plates and to maintain secure fasteners on the pods. For the PGH-1 and the AGEH the bearing life for the pod mounted gearing was in the 2000 to 2500 hour range. Yet each of these ships suffered failures within a few hundred hours. From the lessons learned from these designs it is concievable that a bearing life of 2000 to 2500 hours might be possible. If so then the ship which utilizes separate foilborne and hullborne transmission systems would only need to be drydocked once every 3 or 4 years to replace the foilborne transmission bearings. This is based on 25% foilborne out of 2500 underway hours per year. The ship which used combined foilborne and hull borne transmission would required one drydocking per year for bearing replacement.

In addition to the increase in maintenance costs for the additional drydockings for bearing replacement and foil repair, there is a reduction in maintenance costs due to the deletion of the retraction mechanism. This reduction can be estimated using the following method.

Reference 9 indicated that 3357 hours of corrective maintenance were performed on the PHM for each 1000 underway hours. Review of the individual maintenance hours indicated that approximately 550 manhours per 1000 underway hours were due to corrective maintenance of the retraction mechanism. Based on 2500 underway hours per year this would be a savings of 1,375 manhours of corrective maintenance. Assuming a cost of $30 per manhour, savings for the four ships over 20 years would be $3.3 million.

Estimating the increase in maintenance due to the repair of foil cracks and fasteners in not as simple since there is no accurate method of estimating the increase in the number of drydockings per year. If it is assumed that the ship will required drydocking two additional times per year for foil or fastener repair then the increased cost can'be estimated as follows:

Reference 9 indicated a cost of $27,000 for one drydocking and repair on the PHM in 1976. If that value is assumed to inflate according to the escalation indices in reference 9 then the 1980 cost for a single drydocking and repair would be $50,000. If this value is used to estimate the increased cost of drydocking the fixed foil design then the cost for 2 additional drydockings per year would be $100,000 per ship. For 4 ships over 20 years this would be an increase of $8.0 million.

It should be pointed out that this approach of estimating increased cost is tentative at best since improved design practices could eliminate many of the corrective maintenance problems.

Another increase in maintenance cost will result from the need to regularly clean the fixed foils and struts using a diver operated brush or similar system. Such cleaning was not necessary with retractable foils since the fouling on the foils and struts could be cleaned by the crew when the foils were retracted. But with fixed foils, a special diver operated system must be employed. Furthermore, since the fixed foils are continuously immersed, the fouling will occur more rapidly than with the retractable foils. The rate of fouling will depend on location and operating tempo of the ship and effectiveness of any antifouling paints or coatings which have been applied.

Although fouling causes an increase in energy costs; the removal of the fouling is costed out as a maintenance cost item. It is assumed here that a regular hull and foil cleaning operation will be maintained for either a fixed or retractable foil design. However, since such a program was not common practice when the HANDE cost module was developed the additional cost of hull and foil cleaning must be calculated and added to the HANDE estimate for maintenance costs.

The increase in cost required to maintain clean foils might be estimated in the following manner. Reference 6 indicates a minimum cost of hull cleaning of $4000 per cleaning. If the ship is cleaned at 6 month intervals the cost will be $8,000 per year per ship. (In actuality the cleaning interval would depend on the rate of fouling and the increase in fuel consumption. A more detailed discussion is provided under the fuel cost section.) For the 4 ships operated over 20 years the total cost would be $640,000.

With the exception of these two areas, increased drydocking for repairs and increased foil and hull cleaning, all other maintenance costs would be expected to be similar for the fixed and retractable designs. The increase to be expected in life cycle maintenance costs from these two areas might be on the order of $5 million for the 4 ships.

6.3.6 The last area of operational and support costs to consider is the fuel costs. As mentioned in the maintenance cost section, fuel costs will depend on fouling and cleaning rates, on the difference in ship weight between the fixed and retractable designs and on any change in powering due to hullborne operation with fixed foils down as opposed to retracting foils up.

Designs performed by the HANDE program indicate that fuel costs are about 10% of the total life cycle costs. However, severe fouling can increase the resistance of the ship to a value well above the 15% margin provided in the program. Since fixed foils suffer continuous immersion and can not be easily cleaned they would tend to be fouled more heavily than retractable foils. This fouling, increases the fuel consumption for the fixed foil design. In addition to this difference in fuel consumption for the fixed and retractable designs there is a weight difference which will cause a decrease in fuel consumption for the fixed foil design. The only other difference in fuel consumption would result from an increase in hullborne powering for the fixed foil design operating with foils down.

As was mentioned in the preceeding discussion on maintenance costs, a hull and foil cleaning program has been assumed for both fixed and retractable foil designs. If such a program is initiated there will be no significant difference in fuel cost between the different designs due to a difference in fouling. However, there may be a reduction in fuel costs estimated for both ships due to a reduction in the powering margin applied to account for fouling.

The life cycle cost estimate for the FLF design included a margin for power of 15% to account for fouling. This margin applies to both foilborne and hullborne fuel consumption. However, if a 6 month hull. and foil cleaning interval is assumed a 15% power margin appears too large and costs the ships too high a penalty in fuel costs. The margin appears too large for the following reason.

References 7 and 8 indicates that after six months in the water the foilborne resistance of the PCH was 20% higher than when tested with clean, newly coated foils. Although this is higher than the 15% margin assessed in the program the average foilborne resistance of the ships over the six month period would be expected to be less than 10% over the clean foil resistance. This is so because when the ships first entered the water at the beginning of the 6 month interval its struts and foils were clean. Fur thermore, there is some delay before serious fouling begins. During that period the added resistance due to fouling is essentially zero. Only in the later months does the onset of fouling cause an increase in resistance. Therefore the average foilborne resistance would be less than 10% greater than the resistance with clean foils. At the end of the six month period the hull and foils would be cleaned again so that the average added foilborne resistance for the fixed foil ship would be 10% or less for the entire year. (For the retracting foil design this figure would be even lower, perhaps 5%, due to regular maintenance of the retracted foil by the ships crew.>

Hullborne resistance would also be expected to be less than 15% greater than clean hull resistance. Reference 9 indicates an average increase in powering for carriers of about 1% per month after hull cleaning. Reference 10 estimates a similar figure for average fuel consumption for destroyers. Therefore if the hull were cleaned at six month intervals the average increase in hullborne power due to hull fouling would be on the order of 3%. Assuming some degradation of the hull between cleanings, a 5% allowance for hull fouling seems reasonable.

Based on a weighting of the hullborne and foilborne operating hours a total reduction in fuel consumption of about 8% would be possible for the fixed foil design. Based on a life cycle fuel cost of $107 million, the reduction would save nearly $9 million dollars. The reduction in fuel cost for the retraction design would be closer to 9% or a $10 million dollar savings.

If the 15% power margin for fouling can be considered accurate for ships which are not regularly cleaned, then the $9 million dollar savings resulting from $.7 million in cleaning fees indicated a substantial cost benefit which would warrant further investigation.

In addition to hull and foil cleaning as a method of reducing fouling power margins, antifouling coatings can also be used to prevent initial growth of marine fouling. However, after several years of research and testing reference 8 indicates that no suitable coating had been found for the struts and foils. If such a coating could be found it would not only reduce the fuel consumption due to fouling but would also reduce the frequency and cost of cleaning the underwater hull and foils.

Despite the lack of suitable antifouling coatings found in reference 8, research continues to develop such a coating. One prospect, is being developed by Daedaleon Associates, Inc., of Woodbine, Maryland. The coating is an elastomer of high bonding strength and has been used with success to coat eroded propeller sections. Some research is now underway to detemine if the coating can be impregnated with an anti-fouling toxin which would leech out over time.

Even if such an anti-fouling capability were not possible the.coating itself offers excellent wear and adhesion capabilities and might be used to coat the struts and foils to provide long lasting protection from contact with seawater. Such a coating would be expected to last much longer than conventional paints when subjected to brush cleaning. Costs of the coating are highly dependent on the complexity of the application and can not accurately be estimated for strut and foil application with limited information available.

Another coating which might be used on the struts and foils would be flame-sprayed Nylon-11 discussed briefly in reference 10. This coating does not contain any anti-fouling toxin to inhibit fouling growth but instead acts to prevent the adhesion of fouling to the coated surface. This material has also been used to coat propeller blades and has adhered well in areas of minimal cavitation. No costs are avaiable for strut and foil coating applications.

For the hull, newly developed organometallic polymer paints appear to offer some promise. Such paints are now undergoing evaluation by the Navy and have shown long life antifouling properties.

Although no costs have been provided for any of the coatings mentioned their inclusion in this section is valuable as an indication of new technologies which might provide some cost savings in the future.

In addition to fouling-related fuel costs there will be a fuel cost difference between the fixed and retractable foil designs due to the lighter weight of the fixed foil design. This is best demonstrated by the difference in HANDE calculated fuel rates for the FLF (C1) design shown in Table' 5. Based on a weighted average of hullborne and foilborne operating hours, the fixed foil design would required 0.6% less fuel than the retraction design. However, this considers the design of two ships with dissimilar fuel loads to provide equivalent full load displacement. If the fuel loads were equated then the fixed foil design would be lighter and have a lower resistance.

TABLE 5

FLF Cl FUEL RATES

MODE OF OPERATION	SPEED (KNOTS)	FUEL RATE (MI/L TON) RETRACTION	FIXED
Hullborne	13	46.99	47.29
Foilborne	43	14.70	14.75

One way to estimate the effect of the lighter ship is to utilize the curves developed in reference 3 which plot resistance against speed for varying displacements. If the full load displacement of the fixed foil ship is reduced by the reduction in light ship weight from the retraction design a lighter full load displacement can be assumed which will provide nearly equal range and speed characteristics. If this displacement is used to enter the curves in reference 3 a new value of resistance can be found for the lighter, fixed foil design. When this new value of resistance is used to ratio fuel consumption a difference of 1-2% in fuel consumption can be realized. This difference amounts to a reduction in life cycle cost of about $1 million dollars for the four ships.

One final effect on fuel consumption pertains to the ability of the retraction design to operate in the hullborne mode with foils retracted. This results in a lower hullborne drag than the fixed foil design can achieve. This is not expected to make any significant difference in fuel cost because the normal hullborne operation is with foils down in the sprint and drift mode or in the generalized patrol mode.

7.0 Summary of Results

The most significant categories of life cycle cost are prime equipment, maintenance, energy and replenishment spares. Of these, only the replenishment spares costs does not change substantially for fixed or retractable foil designs.

The changes which do result from the differences between fixed and retractable foil designs are summarized below for the FLF ships:

- Research and Development costs do not change.
- Prime Equipment costs decrease for the fixed foil design by about **1.5%** due to reductions in hull structural, foundation and strut and foil system costs. This represents a reduction in life cycle cost of less than 1%.
- Support Equipment costs do not change.
- Facilities costs should not change unless the navigational draft of the fixed foil design requires port dredging.
- Initial Spares costs do not change.
- Personnel costs do not change.
- Operations costs do not change.
- Major Support costs do not change.

- Replenishment Spares costs show little or no reduction for the fixed foil design due to the elimination of the retraction mechanism spares.
- Maintenance costs should increase for the fixed foil design by about 2.5% due to the necessity of drydocking the ship for all strut and-foil repair work and due to regular hull and foil system cleaning and including a reduction in maintenance due to the deletion of the retraction system. The increase cost is less than 1% of the total life cycle cost.
- Energy costs can probably be reduced by about 9% of the predicted value for the retraction design due to a reduction in the power margin for fouling. This results from the reduction in fouling added resistance from regularly cleaning the struts and foils. The reduction amounts to a 1% change in the total life cycle cost.

Energy costs for the fixed foil design can be reduced by about 10% of the predicted value due to reduction in the power margin for fouling due to underwater cleaning. In addition, the fixed foil design would be about 1-2% more fuel efficient due to its lighter weight. The total reduction in life cycle cost would amount to about 1%.

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Appendix A

Cost Summaries from FLF Hydrofoil

Life Cycle Cost Report

FLF-HYDROFOIL

TABLE 9a

PRELIMINARY COST SUMMARY ESTIMATES

YEAR $	1980.	NO OF SHIPS ACQUIRED	4.
INFLATION RATE, PERCENT	10.0	SERVICE LIFE, YR	20.0
LEARNING RATE	.900	ANNUAL OPERATING HRS	2500.0
FUEL COST, $/US GAL	1.500	PERCENT FB HRS	25.0
LIGHTSHIP WT, LTON	356.8	FULL LOAD WT, LTON	498.5
MILITARY P/i, LTON	60.0		

	COSTS (MILLIONS OF U.S. DOLLARS)		
COST ITEM	TOT SHIP +	PAYLOAD =	TOTAL
LEAD SHIP	115.5	36.0	151.5
FOLLOW SHIP	71.1	26.0	97.1
AVG ACQUISITION COST/SHIP (4 SHIPS)	72.0	28.5	100.5
LIFE CYCLE COST/SHIP (20 YEARS)			263.5
TOTAL LIFE CYCLE COST (20 YEARS)			1054 .o

FLF-HYDROFOIL

TABLE 9b

UNIT ACQUISITION COSTS

SWBS GROUP		LEAD SHIP COSTS (US$K)	'FOLLOW SHIP COSTS (US$K)
100	HULL STRUCTURE	2217.	1773.
200	PROPULSION PLANT	8548.	6839.
300	ELECTRIC PLANT	1787.	1430.
400	COMMAND + SURVEILLANCE	6396.	5116.
5-567	AUX SYSTEMS LESS F/S	12094.	9675.
567	FOILS/STRUTS	3875.	3100.
600	OUTFIT + FURNISHINGS	3041.	2433.
700	ARMAMENT	341.	272.
	MARGIN	3830.	3064.
800	DESIGN + ENGINEERING	20862.	4246.
900	CONSTRUCTION SERVICES	12233.	9786.
	TOTAL CONSTRUCTION COST	75223.	47735.
	CONSTRUCTION COST	75223.	47735.
	PROFIT (15 % OF CONSTRUCTION COST)	11283.	7160.
	PRICE	86506.	54895.
	CHANGE ORDERS (12/8 % OF PRICE)	10381.	4392.
	NAVSEC SUPPORT (2.5 % OF PRICE)	2163.	1372.
	POST DELIVERY CHARGES (5 % OF PRICE)	4325.	2745.
	OUTFITTING (4 % OF PRICE)	3460.	2196.
	H/M/E + GROWTH (10 % OF PRICE)	8651.	5489.
	TOTAL SHIP COST	115485.	71059.
	ESTIMATED PAYLOAD COST	36000.	26030.
	SHIP PLUS PAYLOAD COST	151485.	97089.

ADJUSTED FIRST UNIT SHIP COST, $K	88861.1
COMBAT SYSTEM WEIGHT, LTON	60.0
PROPULSION SYSTEM WEIGHT, LTON	46.9
ADJUSTED FIRST UNIT SHIP COST EQUALS FOLLOW SHIP TOTAL COST DIVIDED BY	.800

TABLE 9c: FLF-HYDROFOIL
LIFECYCLECOSTS

IOC YEAR	1995.	R+D PROGRAM LENGTH, YRS	2.
NUMBER OF SHIPS ACQUIRED	4.	TECH ADV COST, $M	0.00
SERVICE LIFE, YRS	20.	ADDL FACILITY COST, $M	3.01
NO OF OFFICERS/SHIP	8.	DEFERRED MMHRS REQ, HR/WK	0.
NO OF ENLISTED MEN/SHIP	40.	PRODUCTION RATE, SHIPS/YR	2.00

'20 - YEAR SYSTEMS COST
(MILLIONS OF YEAR 1980 DOLLARS)

COST ELEMENT	SHIP NONREC	PAYLOAD NONREC	OTHER NONREC	TOTAL NONREC	SYSTEM R ECUR	TOTAL SYSTEM
R + D TOTAL	42.	15.	0.	57.		57.
DESIGN + DEVELMNT	30.		0.	30.		30.
TEST + EVALUATION	12.	15.	0.	27.		27.
INVESTMENT	311.	152.	4.	467.		467.
EQUIPMENT	302.	137.		439.		439.
PRIME	288.	114.		402.		402.
SUPPORT	14.	23.		37.		37.
FACILITIES			4.	4.		4.
INITIAL SPARES	9.	15.		23.		23.
OPERATIONS + SUPPORT					565,	565.
LESS RESIDUAL VALUE						35.
LIFE CYCLE TOTAL SYSTEMSCOST						1054.
DISCOUNTED AT 10 PERCENT						140.

COST PER VEHICLE - UNDISCOUNTED	263.5
COST PER VEHICLE-DISCOUNTED	35.