A COMPUTER AIDED METHOD

FOR PRELIMINARY DESIGN OF SWATH SHIPS

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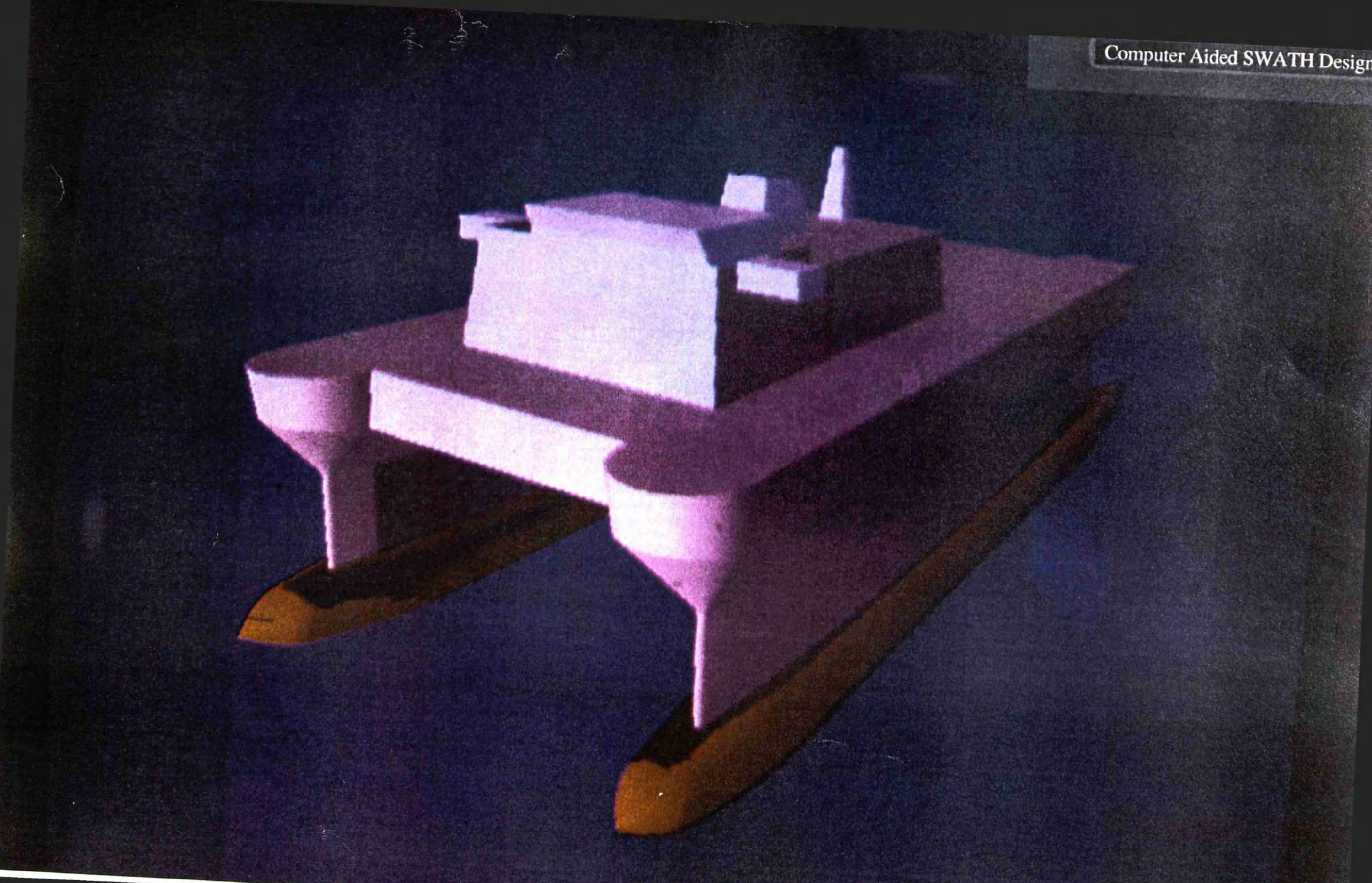
Computer Aided SWATH Design

DECLARATION

Except where reference is made to the work of others
this thesis is believed to be original.

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NOMENCLATURE

<u>Geometry</u>

BC	Box clearance
BD	Box depth
B_H	Lower hull breadth
D_H	Lower hull depth
C_p	Hull prismatic coefficient
C_w	Strut waterplane area coefficient
DMD	Depth to main deck
DWD	Depth to wet deck
LBP	Length between Perpendiculars
LOA	Length overall
L_H	Lower hull length
L_S	Strut length
SS	Strut setback
T	Design draught
T_S	Strut thickness
V	Displaced volume

<u>Physical Properties</u>

g	Acceleration due to gravity
ρ	Density of water
ν	Kinematic viscosity

<u>Propeller Design</u>

d	Propeller diameter
BAR	Blade area ratio
n_o	Open water efficiency of screw propeller
n_h	Hull efficiency
n_{rre}	Relative rotative efficiency
QPC	Quasi-propulsive coefficient
R_T	Vessel resistance
t	Thrust deduction factor
V	Speed of advance of vessel
Va	Speed of advance of propeller
w_T	Taylor wake fraction
w_n	Nominal wake fraction

SUMMARY

This thesis describes a computer aided method for integrating the preliminary design and hydrodynamic analysis of SWATH ships. A considerable quantity of data for use in the design of these vessels is also provided.

The thesis begins with a brief outline of the development history and the advantages and disadvantages of the SWATH concept. Some difficulties associated with the efficient design and operation of SWATH ships are described. A related need for integrating advances in hydrodynamics with a means of producing balanced designs is identified.

A large collection of SWATH design data is presented and analysed. Several well defined expressions relating principal vessel dimensions are identified and proposed as aids in initial design.

Current practices in the fields of ship design and computer aided engineering design are reviewed. These aspects are discussed with particular reference to SWATH design. From this background, an approach to the design of SWATH ships with computer assistance is developed.

A number of methods for the initial sizing of SWATH ships are developed. These are; a computer database, a mini-synthesis program, a weight equation approach, and manual approaches based on curves relating SWATH size to desired seakeeping characteristics, payload weight and/or volume, deck area and enclosed volume. These are designed to increase the efficiency of more complex synthesis tools.

The development and validation of a method for hull definition and associated hydrostatic analysis is described. This is a necessary link between simple geometry definitions and those required for full synthesis including hydrostatics, resistance, seakeeping, and graphics. A family of SWATH designs produced by this tool is introduced as a basis for parametric studies.

A review is made of available methods for predicting the resistance of SWATH ships. The integration of these techniques with the synthesis model is described and results of some comparative and parametric studies presented.

Methods currently used in preliminary design of propellers for SWATH ships are reviewed and a collection of model test data is presented. The available data is used to develop expressions relating self propulsion factors to basic design parameters. These are integrated with the open water characteristics of Troost B-series propellers in a

computer program. A study of the propulsion aspects of a family of typical SWATH designs is presented.

The machinery options available to the SWATH designer are considered. A collection of relevant data is provided as a basis for power plant selection and weight estimation, and a computer model to aid in SWATH machinery design is described. Results from studies carried out using this tool are used to illustrate important factors in this aspect of SWATH synthesis. Limiting powers and speeds are identified for a wide range of prime movers and hullforms.

A method for estimating SWATH ship structural weight is developed. Design for primary wave loading and slamming impact is considered. The validation of this tool and its use in parametric studies is described. Data is provided to assist in the preliminary arrangement of structure and its weight estimation.

A regression analysis performed on a collection of data is used to develop a parametric method for weight estimating. The development of a generalised computer program for estimating the space requirements of escort warships is also described. These weight and space routines are applied to the design of SWATH escort vessels and a strong conflict between space and weight demand is identified. The importance of vehicle density in balancing SWATH designs is illustrated.

Some additional systems which provide greater design definition are briefly discussed. In particular, a graphics interface and link with a 3D motions and loading program are described.

The use of the SWATH design method is illustrated by means of examples. The application of the procedure to two conceptual SWATH designs for the UK MoD and the design of the first SWATH ship to be constructed in the UK is described.

CHAPTER 1

INTRODUCTION

This chapter briefly outlines the development history and the advantages and disadvantages of the SWATH concept. Some difficulties associated with the efficient design and marketing of SWATH ships are described. A related need for integrating advances in hydrodynamics with a means of producing balanced designs is identified. Finally, the structure of the thesis is outlined.

1.1 Historical Development of SWATH Ships

As is now well known, SWATH is a descriptive acronym for Small Waterplane Area Twin/Triple Hull ship. This abbreviation was coined by the US Navy in the early 1970's to remove confusion in the nomenclature associated with their extensive (and expensive) research programme into this type of vessel. It is now the preferred terminology for such ships, and effectively replaces other, earlier, names.

Semi-Submerged-Ship (S^3)	at	Naval Ocean Systems Centre
Modified Catamaran (MODCAT)	at	DTNSRDC
Low Waterplane Area Catamaran (LWP)	at	Naval Ship Engineering Centre
Trisected Ship (TRISEC)	at	Litton Industries USA
Semi-Submerged Catamaran (SSC)	at	Mitsui, Japan

Provision of a stable platform in a seaway is the prime attribute of the SWATH form. A related benefit is that both voluntary and involuntary speed reduction in waves may be expected to be lower than for conventional ships. The vessel geometry is optimised to reduce motion in a seaway by removing most of the buoyancy from the wave action at the free surface, and also by its potential for long and decoupled resonant periods of motion. Thus, not only are wave excitation forces reduced, but the designer may manipulate the shape of the motion transfer functions to avoid not only the peaks of ocean energy spectra but also coupling of heave, pitch and roll responses.

Although it is only in the last two decades that significant attention has been paid to the SWATH concept, the basic philosophies behind this arrangement have been well known for centuries. Practical seafarers and shipwrights have long been aware that deep submergence of the buoyancy of a vessel is desirable for good seakeeping. Many deep draughted traditional coastal craft are examples of this approach. More explicitly semi-submerged vessels are also an old idea, with an 1880 patent by Lundborg [12] describing a single hulled 'spar' ship design similar to the high speed 'shark form' designs of NAVSHIPS [20] in 1959.

Unfortunately, such optimisation of one specific design feature usually proves detrimental to other properties. In comparison with modern designs, traditional sailing vessels are heavy and slow, while the monohulled semi-submerged ship has poor stability characteristics as a result of its slender waterplane.

A solution to the latter problem lies in the other distinguishing feature of the SWATH arrangement; its multi-hulled form. The use of more than one slender hull to achieve high speed while maintaining stability has been well known in the Pacific for centuries. Combining the two philosophies [1] leads to a definition of the SWATH as now known; twin/triple submerged streamlined hulls connected to an abovewater bridging structure by slender surface piercing struts (Frontispiece).

Table 1.1 lists the principal events in the process by which the SWATH eventually emerged from the twin strands of multi-hull and semi-submerged ship development. Perhaps appropriately, this table begins and ends (SSP *Kaimalino*) with a reference to the Pacific ocean. It is also interesting to note the broad technical and popular [31] interest in the semi-submerged ship during the inter war years. A fuller description of this development process may be found in [2].

1.2 Modern Developments in SWATH Technology

Following the appearance of the *Duplus* (now *Twin Drill*) and *Kaimalino*, the Japanese firm of Mitsui have constructed six vessels, including a small prototype, fast ferry, hydrographic survey ship, diving support vessel, and two small leisure craft. Mitsubishi also constructed a hydrographic survey ship for the Japanese Ministry of Transport.

In the USA, despite the large Naval research and development effort, only four small (< 100 tonne) private vessels have been built so far. However, a 3500 tonne SWATH designed [35] to deploy the SURveillance Towed Array Sonar System (SURTASS) is due for delivery to the US Navy in early 1990. This ship is intended to fulfil a role [36] which the monohulls originally employed for the task are incapable of performing. SWATH ferries for Hawaii [37] and Madeira [38] are under construction in the USA and UK at the time of writing. Appendix 1 lists the particulars of these vessels and identifies sources from which further details may be obtained.

Meanwhile, several countries are actively researching the concept. In recognition of the fundamental reasons for the SWATH configuration these studies have concentrated on hydrodynamics. Development and validation of tools to predict the motions, loads and drag of SWATH ships has occupied many researchers around the world and produced an extensive literature on the subject of SWATH. The RINA Conferences on SWATH Ships and Advanced Multi-hulled Vessels of 1985 [3] and 1988 [4] reflect this interest and are useful sources of further information.

Table 1.1 Historical Development of the SWATH Ship Concept

Date	Innovator(s)	Contribution	Ref.
	Polynesia, Melanesia	Fast multihulled canoes employed for trade and war	[5]
	Tamil peoples	Origin of term *catamaran* from *kattu* (tie), *maram* (tree)	
1777	Polynesia, Melanesia	Second Pacific voyage of Cook documents multihulled war canoe	[5]
1662	Sir William Petty	Successful 18kt catamaran *Simon and Jude*	[6-9]
1663	Sir William Petty	Fast catamaran *Invention II* which could *run ye best packett boat quite out of sight in less than a watch*	[6-9]
1664	Sir William Petty	Ill-fated (lost Bay of Biscay 1665) 50 man catamaran *The Experiment*	[6-9]
1684	Sir William Petty	Unsuccessful (poor sail carrying ability) 128 ton catamaran *St Michael the Archangel*	[6-9]
1817	19th century UK engineers	Catamaran steamboat ferries for Liverpool and Glasgow	[5]
1821	19th century UK engineers	30m paddle wheel catamaran ferry*Union* built for River Tay service	[5]
1850	19th century UK engineers	Underpowered 52m catamaran ferry *Gemini* built for Thames service	[5]
1879	Leslies Ltd, Tyneside	Popular 90m cross channel ferries *Castalia* and *Calais-Douvres*	[10]
1914		Two submarine salvage catamarans constructed	[11]
1880	C.G. Lundborg, USA	US patent granted for monohull semi-submerged ship	[12]
1905	Albin Nelson, USA	Filed for US patent on twin hulled semi-submerged ship. Reasoning was principally related to handling of temperature sensitive cargo in Great Lakes climate, not hydrodynamics.	[13]
1927	John Faust, USA	Filed (granted 1932) for patent on low waterplane area four hull semi-submerged ship. Not a convincing argument for the semi-submerged arrangement.	[16]
1929	William Blair, USA	Filed in June (granted 1930) for patent on diesel-electric multihulled semi-submerged ship to improve performance in a seaway. Basically sound arguments employed.	[14]
1929	Henry Stack, USA	Filed in August (granted 1931) for patent on impractical <u>many</u> hulled semi-submerged ship intended to reduce resistance rather than motions.	[15]
1933	UFA (German Film Co)	Conrad Veidt appeared in German film *Floating Platform 1*, co-starring a floating airport supported by tubular columns. Originally released in German as *FP1; Antwortet Nicht*	[31]
1937	E.L. Rossignol, France	Lodged patent for twin submerged hull warship *pour combattre les oscillations longitudinales et transversales que subissent les navires sous l'action de la houle et des vagues*	[33]
1941	AG Weser, Germany	**Construction** and (unsuccessful) testing of experimental naval semi-submerged ship *VS5*	[32]
1942/43	Frederick Creed, UK	Filed (granted 1944/46) for UK and US patents on SWATH like aircraft carrier intended to improve performance in a seaway. Essentially similar to modern SWATH designs.	[18,19]
1943	Frederick Creed, UK	Filed for UK patent on twin hulled, ten column semi-submersible marine salvage vessel.	[34]
1959	William Boericke, USA	Published results of NAVSHIPS study on *sharkform* semi-submerged ships designed to have reduced wavemaking resistance. Some forms similar to modern SWATH demihulls.	[20]
1960-	International oil industry	Development of low motion semi-submersible offshore drilling rigs	
1969	J.J. Stenger, Holland	Design/**construction** at Boele Bolnes of Medium Waterplane Area Twin Hull seabed operations vessel *Duplus* (later *Jaramac 57*, now *Twin Drill*)	[27]
1967/68	Reuven Leopold, USA	Filed for US and UK patents (granted 1969/71) on SWATH type vessels. Leopold worked at Litton Industries, who believed that the *trisected* (SWATH) form would overcome the wavemaking barrier restricting the speed of conventional ships.	[21-23]
1970	Litton Industries, USA	Proposal to build gas turbine driven 40-80 knot SWATH container ships	[24]
1971	Litton Industries, USA	**Construction** of 6m manned experimental SWATH demonstrator *TRISEC1*	[25]
1950s/60s	Dr Tom Lang, USA	Private investigations into semi-submerged ship hydrodynamics and control.	
1970	Dr Tom Lang, USA	Filed for patent (granted late 1971) on the control fin systems required for SWATHships.	[30]
1968	NUC (USN), San Diego	Design study for Semi-Submerged Platform, leading to design of 190 ton prototype beginning in 1970. Dr Lang was responsible for hydrodynamic design of the SSP.	[28]
1973	NUC (USN), San Diego	**Launch** in April at USCG Yard of the first SWATH *Kaimalino* (meaning *calm water* in Hawaiian)	[28]

1.3 Resistance to SWATH in the Marine Community

1.3.1 General

The excellent seakeeping qualities of SWATH ships have been demonstrated [39,40,41] by the SWATH ships already at sea, and by experimental and analytical studies [42-45]. However, the small number of SWATHs at sea is evidence that the marine community has not been convinced of the utility of the concept. There are several possible reasons for this state of affairs.

Perhaps the most optimistic is the view of Betts [46] that 'any new invention or major innovation seems to take around 20 years to mature and become accepted'. This would mean that SWATH is now close to full acceptance and that the uncertainties of previous years are a natural part of the development process. It may well be that the performance during the next few years of the USS *Victorious* (T-AGOS 19) and the SWATH ferries for Hawaii and Madeira will be decisive factors. Until then, more fundamental reasons must also be considered.

1.3.2 Drawbacks Associated with SWATH Ships

As mentioned earlier, optimisation of one attribute normally leads to penalties in other characteristics. A multi-hull geometry implies a large surface area, which leads to high steelweight and frictional resistance. In addition, for a given speed, SWATH ships operate at higher Froude numbers than their (longer) monohull competitors. However, in the early stages of development, it was suggested [21] that the SWATH would offer the possibility of very high speeds (@ 80 knots) by overcoming the wavemaking resistance barrier afflicting conventional surface ships. Speeds of 45 knots were mentioned [22] during the design of the ultimately 22 knot *Kaimalino*. In practice, although there does come a point at which the low wavemaking associated with the slender waterplane does favour the SWATH, the propulsion powers involved are so large as to prohibit realistic exploitation of this feature.

There is no doubt that the image of SWATH has been harmed [47,48] by over optimistic claims of this nature made during the early stages of development. Related to this is the fact that SWATH has been considered with hydrofoils and surface effect ships under the generic title of *Advanced Marine/Naval Vehicles* [49,50]. To those in positions to invest finance in ships, an undesirable degree of novelty and immaturity may be suggested by this and other futuristic [63-66] associations. Indeed, FBM Marine of the UK decided to market (successfully) their 'SWATH' ferry design as a 'fast displacement catamaran (FDC)' because of a perceived resistance to the acronym SWATH [38].

Because of the twin hull arrangement it is often necessary to duplicate some SWATH ship systems, thus adding to the weight penalties in machinery, fuel and structure. In addition, large amounts of space in the struts and haunch areas are difficult to utilise effectively. These factors imply that a SWATH ship must be larger than a monohull designed to carry a given payload. Since cost is traditionally related to weight, this has been a disadvantage in promoting the SWATH solution to decision makers. In addition, the load carrying problem is compounded by the low waterplane area of the SWATH which does not permit large variable loads, and which requires ballast/fin systems to control draught and trim. Accurate estimation and control of shipboard weights is therefore more critical than for a conventional surface ship design.

Large beam and draught can also exceed constraints imposed by certain mission requirements, although they do offer advantages. Contrary to popular belief, SWATH ships do not [51] automatically have larger useful deck areas than monohulls of the same displacement, but the greater width is advantageous for aircraft operations. In addition, underwater operations can be conducted efficiently through a centrally located moonpool with sufficient space for craneage, equipment and storage around the edges. It is hoped that the deep draught, coupled with reduced motions, will lead to enhanced sonar performance from reduced bubble sweepdown and propeller aeration.

Problems arise in SWATH ship synthesis because of the lack of previous experience, and the complexity involved in dealing with a large number of design variables. These factors combine to make cost effective and efficient design more difficult than for monohulls but also offer a freedom to propose novel solutions.

Further discussion of the pros and cons of the SWATH arrangement may be found in a number of review papers [46, 52-54]. An overview of the differences between monohull and ship characteristics is presented in Table 1.2. This information is extracted from a publication [53] discussing US Navy combatant and auxiliary designs.

Table 1.2 Summary of Differences in SWATH and Monohull Combatant Characteristics

Displacement for same (traditional) requirements	30-60% more than monohull
Cost for same (traditional) requirements	c. 20% more than monohull
Total enclosed volume for same displacement	20-30% more than monohull
Length for same displacement	30-[illegible]% less than monohull
Deck area for same displacement	Marginally greater than monohull
Waterplane area (TPI) for same displacement	20-40% of monohull value
Moment to change trim 1cm	10-20% of monohull value
Moment to heel 1° for same displacement	Marginally greater than monohull
Beam for same displacement	60-70% more than monohull
Draught for same displacement	60-70% more than monohull
Wetted surface for same displacement	c. 60% more than monohull
Depth to main deck for same displacement	50-75% more than monohull
Freeboard for same displacement	c. 25% more than monohull

It is now becoming apparent that the SWATH concept must be aimed at roles where its seakeeping ability may be demonstrated to provide a cheaper or better solution than its competitors. At the same time, its disadvantages must be accepted and minimised. Conservative design solutions and construction methods are part of the attempt to make the SWATH acceptable to those used to conventional ship practice. In illustration, it is probably true to say that many modern SWATH designs are closer in several respects to the conservative *Duplus* (as launched) than to the truly 'advanced' *Kaimalino.*

1.4 Marketing the SWATH Concept

In order for the number of SWATH ships at sea to grow, the presentation of its seakeeping ability as part of a complete, balanced, and realistic ship system is required. To do this, potential missions and presentation techniques which emphasise seakeeping ability must be found. At the same time, the complete ship design must be developed to minimise the previously described failings of the SWATH and inspire confidence in the overall package.

As mentioned earlier, a SWATH ship will usually be of greater size than a monohull designed to traditional (essentially calm water) requirements, This is often assumed to imply increased cost, although with modular and/or line production of the regular SWATH components, this may not be the case. A comprehensive study of the construction costs associated with SWATH is needed to clarify this situation.

Traditional performance requirements which do not properly account for speed loss in a seaway penalise not only the SWATH concept but also the potential ship operator. In many cases the real value of a design will not depend on its calm water speed, and the correct emphasis must be carefully chosen. Since SWATH ships are only likely to be proposed for operation in adverse environmental conditions, their high smooth water power requirements are not necessarily a drawback. SWATH ships are less likely to be forced to reduce speed because of adverse motions while the resistance augment in waves is less than for comparable monohulls. The 35 metre Japanese fast ferry *Seagull* reports [40] a speed loss of only 2% in high sea state four. More dramatically, recent work at the University of Glasgow by Chun [55] has measured significant reductions in resistance for a tandem strut model at certain speed and wave combinations.

If design requirements were modified to include a comprehensive assessment of seakeeping performance, the case for SWATH ships would obviously be further improved. While a SWATH must be larger than a monohull to carry the same payload at the same (calm water speed), a monohull with the same seakeeping as the SWATH would be much larger. A study for a US Navy frigate design [56,57] produced alternative solutions depending on initial requirements.

Payload Monohull	SWATH	Seakeeping Monohull
5330 LT	6950 LT	9030 LT

Sources within the US Navy have suggested privately that the monohull required to provide the same seakeeping as the SWATH is in fact some 50% larger than the size published. Intuition would seem to confirm this, but even disregarding 'political' interference with the study results, a significant saving in size is seen to be possible with SWATH if seakeeping is incorporated into design criteria.

1.5 Study Objectives

As mentioned in section 1.2, considerable effort has been expended in the development of tools to predict the motions of SWATH ships. Extensive experimental programmes have provided validation of these techniques. However, published SWATH motions naturally tend to relate to the models used in these validation studies [58], and not to balanced designs for realistic roles. On the other hand, those design efforts which have examined basic naval architectural considerations in detail are often published [59-61] without a comprehensive seakeeping analysis. Because of this, very few [56,62] publications combine discussion of a practical role and vessel characteristics with ship motion performance.

A need to integrate available hydrodynamics theories with a means of developing realistic SWATH designs for a given role was therefore felt to be necessary. Two main benefits were anticipated from such a study. Development of such a capability would enable the completion of comprehensive design and seakeeping studies as discussed above. Secondly, efficient exploration of the 'design space' by means of parametric studies would permit 'design experience' to be gained rapidly and some guidelines in preliminary SWATH design established.

A large number of variables is involved in examining alternative SWATH configurations with respect to geometry, structural design, carrying capacity, powering, and motion response. Because of this, it was decided that a computer based approach would be necessary for exploring all possible design options.

1.6 Structure of Thesis

The main part of this thesis begins with an analysis of over 100 published SWATH designs. Chapter 2 presents preliminary design guidance derived from this study. This is intended to provide a convenient source of information for deriving and checking dimensions for a new SWATH design. In Chapter 3, aspects of ship design, CAD, and

SWATH design are synthesised to formulate the approach used in the development of the design method. The philosophy employed in the integration of the main design disciplines and their interface with the designer is given particular attention.

A number of low level approaches to initial sizing of SWATH ships are described in Chapter 4. These methods can provide data for use in the earliest stages of SWATH design. Chapters 5 to 11 deal more thoroughly with individual components of a design system. Disciplines such as hull definition, resistance and powering, machinery and structural design, weight estimation and graphics have been examined in some depth. Development of these design tools, and their validation and use in parametric studies is described. A family of typical SWATH ships is used as a suitable basis for the latter, and as a consequence the characteristics of these vessels are ultimately presented in some detail.

Finally, the study closes with a number of examples of the use of this integrated design system in proceeding from initial requirements through to seakeeping analysis.

References to Chapter 1

1. McGregor, R. C. "An Illustration of Some SWATH Vessel Characteristics", *Proceedings*, High Speed Surface Craft Conference,1983

2. MacGregor, J.R., "Historical Development of the SWATH Ship Concept", University of Glasgow, Department of Naval Architecture & Ocean Engineering Report NAOE-87-44, 1987

3. *Proceedings*, International Conference on SWATH Ships and Advanced Multi-Hulled Vessels, RINA, London, 17-19 April 1985

4. *Proceedings*, International Conference on SWATH Ships and Advanced Multi-Hulled Vessels II, RINA, London, 28-30 November 1988

5. Corlett, E. C. B. "Twin Hull Ships", *Transactions* RINA, Vol 111, 1969

6. Petty, Sir William, Pepys, S. and others: Manuscripts concerning "Ye Double Bodyed Shippe", National Maritime Museum, SPB/16

7. "The Double Bottom or Twin Hull Ship of Sir William Petty", Oxford University Press, (published by the Roxburghe Club)

8. "Book of Miscellaneous Illustrations", Pepys Library, Cambridge

9. Royal Society Manuscript Letters, Vol. P, folio 34a

10. Mackrow, G. C. "Twin Ship Propulsion", *Transactions*, INA, 1879

11. Brown, A. C. "Twin Ships", Publication No. 5, The Mariners Museum, Newport News, Virginia

12. Lundborg, C. G. "Construction of Ships", US Patent No. 234 794, 1880

13. Nelson, A. "Vessel", US Patent No. 795 002, 1905

14. Blair, W. R. "Ocean Going Water Craft", US Patent No. 1 753 399, 1930

15. Stack, W. R. "Construction in Water Craft", US Patent No. 1 817 780, 1931

16. Faust, J. G. "Marine Vessel", US Patent No. 1 861 338, 1932

17. Telfer, E. V. Discussion to Oo, K. M. and Miller, N. S. "Semi-Submersible Design: The Effect of Differing Geometries on Heaving Response and Stability", *Transactions* RINA, 1977

18. Creed, F. G. "Improvements in and Relating to Floating Structures", UK Patent No. 561 741, 1944

19. Creed, F. G. "Floating Structure", US Patent No. 2 405 115, 1946

20. Boericke, H. "Unusual Displacement Hull Forms for Higher Speeds", *International Shipbuilding Progress*, Vol. 6, No. 58, June 1959

21. Leopold, R. "Marine Vessel", US Patent No. 3 447 502, 1969

22. Leopold, R. "Marine Vessels", UK Patent No. 1 232 687, 1971

23. Leopold, R. "Marine Vessels", UK Patent No. 1 232 688, 1971

24. "Litton Develops Fast Gas Turbine Twin Hull Vessel", *Motor Ship*, Feb. 1970

25. Marbury, F. "Small Prototypes of Ships-Theory and a Practical Example", *Naval Engineers Journal*, October 1973

26. "Twin Hull Vessel *DUPLUS* for Netherlands Offshore Company", reprinted from *Holland Shipbuilders*, February 1969

27. "Fact Book for MV *TWIN DRILL*", International Underwater Contractors Inc., Houston, Texas, June 1985

28. Lang, T. G., Hightower, J. D., Strickland, A. T., "Design and Development of the 190 Ton SSP", ASME Paper No. 73-WA/Oct-2, 1973

29. Hightower, J. D. and Seiple, R. I. "Operational Experiences with the SWATH Ship SSP *KAIMALINO*", AIAA/SNAME Advanced Marine Vehicles Conference, San Diego, Ca., 1978

30. Lang, T. G. "High Speed Ship With Submerged Hulls", US Patent No. 3 623 444, 1971

31. Clemmetsen, O.M. Discussion to "Preliminary Design of Semi-Submersibles", by Penney, P.W., *Transactions* NECIES, 1984

32. Heppenstall, I. E. "Special Catamaran Ship Types", *Seaways*, March 1988

33. Rossignol, E.L. Brevet d'Invention No. 824885, demande le 28 juillet 1937, Paris

34. Creed, F.G., "A Floating Structure for Salvaging Sunken Vessels", UK Patent No. 568612, 1 July 1943

35. Covich, P., "SWATH *T-AGOS* A Producible Design", *Proceedings*, AIAA 8th Advanced Marine Systems Conference, San Diego, Ca., September 1986

36. Preston, A., Item on "Surveillance Ships" in 'Naval News', *The Naval Architect*, September 1983

37. "Pacific Marine Building $2 million SWATH Test Ship", *Maritime Reporter/Engineering News*, October 1987

38. Warren, N.F., "Presentation on FDC400 Ferry Design", at International Conference on SWATH Ships and Advanced Multi-Hulled Vessels II, RINA, London, 30 November 1988

39. Hightower, J.D. and Seiple, R.I., "Operational Experiences with the SWATH Ship SSP *Kaimalino*", AIAA Paper 78-741, AIAA/SNAME Advanced Marine Vehicles Conference, San Diego, 1978

40. Narita, H., Mabuchi, T., Kunitake, Y., Nakamura, H. and Matsushima, M., "Design and Full Scale Test Results of Semi Submerged Catamaran Vessels", *Proceedings*, 1st Marine Systems Design Conference, London, April 1982

41. Pollack, J.G., "Motion Comparison Between a 64-Foot SWATH and a 65-Foot Monohull", Report No. NBDL-85R001, Naval Biodynamics Laboratory, New Orleans, February 1985

42. Gersten, A., "Seakeeping Characteristics of the Baseline Design for a SWATH T-AGOS Ship", DTNSRDC Report No. SPD-1007-01, February 1982

43. Dallinga, R.P., "Seakeeping Tests for a Small Waterplane Area Twin Hull Ship", NSMB Report No. 43755-2-ZT, November 1981

44. Lee., C.M. and Curphey, R.M., "Prediction of Motion, Stability and Wave Load of SWATH Ships", *Transactions*, SNAME, Vol. 85, 1977

45. Djatmiko, E.B., "Experimental Investigation into SWATH Ship Motions and Loading", *M.Sc Thesis*, University of Glasgow, November 1987

46. Betts, C.V., "A Review of Developments in SWATH Technology", *Proceedings*, International Conference on SWATH Ships and Advanced Multi-Hulled Vessels II, RINA, London, 28-30 November 1988

47. O'Neil, W.D., "Advanced Naval Vehicles: Who Needs Them?", *Marine Technology*, Vol. 14, October 1977

48. Barnes, W.C., "SWATH: Advanced Technology or Mythology?", *Proceedings*, US Naval Institute, Vol. 112, September 1986

49. Eames, M.C., "Advances in Naval Architecture for Future Surface Warships", *Transactions*, RINA, Vol. 123, 1981

50. Bebar, M.A., Kennell, C.G., White, D.R. and Lavis, D.R., "Advanced Marine Vehicles - A Review", *Proceedings*, Workshop on Hull Form Design, Wageningen, October 1985

51. Cannon, T.R. and McKesson, C., "Large SWATHs - A Discussion of the Diminishing Returns of Increasing SWATH Ship Size", AIAA Paper 2385, AIAA 8th Advanced Marine Systems Conference, San Diego, September 1986

52. Gore, J.L. (editor), "SWATH Ships", *Naval Engineers Journal*, Feb. 1985

53. Kennell, C., "SWATH Ship Design Trends", *Proceedings*, International Conference on SWATH Ships and Advanced Multihulled Vessels, RINA, London, April 1985

54. Report of ISSC Committee V-4, "Novel Design Concepts - SWATH", ISSC'88, Lyngby, Denmark, August 1988

55. Chun, H.H., "Theoretical and Experimental Studies on the Resistance of SWATH Ships", *Ph.D Thesis*, University of Glasgow, March 1988

56. Kennell, C., White, B. and Comstock, E.N., "Innovative Naval Designs for North Atlantic Operations", SNAME Annual Meeting, New York, November 13-16, 1985

57. Serter, E.H., "Comparative Studies for new US Frigate Hull", *International Defence Review*, 2/88, 1988

58. Fishler, Y., "A Comparative Study of Seakeeping Operations Between a SWATH and a Monohull", *Proceedings*, 19th Israel Converence on Mechanical Engineering, Beer-Sheva, Israel, June 1985

59. Betts, C.V., Ferreiro, L.D., Grzeskowiak, S.R., McDonald, N.A. and Parlett, P.J., "Design Study for an Anti Submarine Warfare SWATH Frigate", *Proceedings*, International Symposium on Anti Submarine Warfare, RINA, London, May 1987

60. Poloydorou, G. and Santos, R., "Design and Hydrodynamic Aspects of a SWATH Car-Passenger Ferry", *Proceedings*, International Congress on Marine Technology, Athens, May-June 1984

61. Lee, K.Y., Lee, D.K., Kim, E.S., Kim, J.G. and Kim J.H., "On the Design Technology of SWATH Ship for High Speed Coastal Passenger Vessel", *Proceedings*, High Speed Surface Craft Conference, January 1988

62. Smith, S.N., "Design and Hydrodynamic Performance of a Small Semi-submersible (SWATH) Research Vessel", *Transactions*, RINA, 1983

63. Veazey, S.E., "The SWATH Saucer Concept", *Proceedings*, US Naval Institute, February 1985

64. Morriseau, F., "Age of Sail - Is it Over?", ASNE *Naval Engineers Journal*, April 1981

65. Irving, R., "The SWATH - Sailing Hull of the Future", BMT abstract 63536

66. Superconductive Electromagnetic Propulsion Ship Development Gets Underway", Japan Ship Exporters Association Brochure, 1987

CHAPTER 2

ANALYSIS OF SWATH DESIGN DATA

A large collection of realised and projected SWATH designs is presented and analysed. Several well defined expressions relating principal vessel dimensions are identified. These are proposed as aids in initial design.

2.1 Introduction

Design data collected from existing vessels has always been of importance to the naval architect. When kept up to date, and suitably analysed, simple relationships can be constructed to aid initial sizing of new designs [1,2,3]. Confidence in the use of such relationships depends on the similarity of the proposed design with the vessels forming the database. By their very nature, initial sizing formulae of this type cannot lead to radical improvements in design, and are inadequate when applied to situations far removed from previous experience.

Because of this, early SWATH ships owed nothing to such traditional design methods, and were developed using first principles, and through the use of theoretical and experimental studies. The SWATH concept is at the same time an example of what may be achieved by a departure from previous practice and also the difficulties which arise from a lack of historical design data.

In the early stages of SWATH development there existed such a severe lack of design data. However, this decade has seen a fourfold increase in the number of SWATHs at sea. In addition, the open literature now contains a large number of design proposals and feasibility studies by respected authorities. The basis for this chapter is a collection (Appendix 1) of published SWATH designs. This data has been stored and analysed using a spreadsheet package (*EXCEL*) on a microcomputer (*Apple Macintosh*).

Many of these designs have been published since 1985. Consequently, it is felt that a stage has now been reached in SWATH development where it is both possible and useful to propose some basic relationships for initial sizing. In 1988, the open literature contained only one comprehensive collection [4] of SWATH design data. This valuable information is limited in use because no equations are provided to the curves. Furthermore, it is based completely on US Navy SWATH design practice, while other valid approaches are excluded. Plots of indiscriminately gathered data can allow general design approximations to be derived.

All known SWATH ships are included in the database used for the present study, together with a considerable number of design proposals from various sources. The number of designs in both groups is continually increasing. However, it is believed that subsequent additions to the database will not distort the well defined relationships which have emerged. It is important to note that the base data is not dominated by US Navy SWATH design practice.

2.2 Basic Vehicle Assessment

Following the work of work of von Karman and Gabrelli in 1950 [5], comparisons between various forms of transportation have become common. This tendency has been especially noticeable in the marine field since the emergence of the numerous advanced marine vehicle concepts. This section contains a brief evaluation of the SWATH concept in the terms currently used in basic vehicle assessment.

Historically, several formats have been used as a basis for comparison, each with its own advantages and disadvantages. Naturally, comparisons between the different concepts are of most use to those who have to choose an alternative to fulfill a certain role. However, some methods display trends which are of most use to designers concerned with one particular vehicle type. This is perhaps the safest use of performance evaluation techniques because of the dangers of employing outdated data in the comparison type presentations. Because of the number of design and performance variables it is apparent that any single method can be misleading or inadequate as an aid to determining the best operating conditions for SWATH vessels in general. A number of techniques are therefore employed in this section. It is intended that together they may provide an overall picture of the characteristics of the SWATH concept at different parts of the speed-size envelope.

2.2.1 Von Karman Analysis

SWATH data from Appendix 1 has been plotted in the formats originally used by von Karman and compared with other vehicle data. It must be noted that the curves depicting the traditional marine vehicles represent best 1950 and 1967 technology. A simple attempt has been made to differentiate between the principal drag regimes in which the various SWATHs operate. SWATHs are classified separately depending on whether the volumetric Froude Number is below or above 0.865. This approximately represents the transition from the *prismatic* to the *main* wavemaking resistance peaks which occur at Froude Numbers around 0.3 and 0.5 (based on body length).

The classic von Karman *specific power* plot is shown in Figure 2.1. Installed power is in horsepower, displacement in long tons, and speed in miles per hour. It can be seen that there are two main groupings in the data. SWATH ships can have relatively low power/weight ratios if designed for volumetric Froude Numbers below 0.865, where wavemaking resistance is not completely dominant. Within the other grouping, two subgroupings of power/weight ratio-speed values are evident. This is most probably due to the influence of various degrees of effort in minimising the large wave drag associated with the high Froude Numbers. Some designers employ slender and/or contoured hulls to reduce powering while simple hullforms will tend to increase the required power/weight ratio.

However, it is apparent that low speed SWATH ships require much higher power/weight ratios for a given speed than 1950 merchant ship designs. For a given type of vessel, wetted surface/displacement ratio decreases with increasing displacement. The small size of most SWATH designs and the inherently high wetted surface of the SWATH form are undesirable in terms of frictional resistance. Comparison with the larger commercial ships developed since 1950 will tend to be even more unfavourable. High Froude number SWATH designs approach the curve representing the best 1950s US destroyer designs.

The so called *specific resistance diagram* (specific tractive force) plots power (in lb-ft/s) divided by the product of displacement (in lbs) and speed (in ft/s) versus speed (in mph). Inverting the first function gives the transport efficiency term, although strictly the displacement term should be replaced by the payload weight. The diagram (Figure 2.2) shows the curves of the traditional vehicles studied by von Karman and the curves of the newer types investigated by Mantle [7] together with the lines of best achievement suggested by those authors. Such achievement lines are effectively lines of constant economic efficiency.

The SWATH data contains trends similar to those described for the specific power diagram. High speed SWATH vessels exhibit less flattering characteristics than other high speed vehicles. The high specific resistances (low transport efficiencies) imply that drag is high relative to lift, so that either payload, or range, or both, must be sacrificed. In hydrofoil technology the choice has generally been for reduced endurance, while SWATH is expected to require a reduced payload ratio compared to monohulls.

Vehicles lying away from the von Karman and Mantle achievement lines are of low economic efficiency, and like helicopters or ACVs, they must possess special qualities to justify their existence. Unlike these vehicles and very high speed craft, SWATH does not possess a unique capability since large monohulls also offer good motions, and to be successful, its seakeeping ability will need to be more effectively demonstrated in the future.

2.2.2 Rainey Assessment

In 1976, Rainey [8] proposed a method of assessing marine vehicle performance by relating the operational parameters of speed, endurance and payload to the design parameters of propulsion power, vehicle weight and length.

The maximum speed in knots achieved by a vehicle is plotted against a function of the installed power, size and length needed to achieve that speed. In this case, the function is : -

$$0.5924 \times [(P\ g\ LOA)/\Delta]^{1/3} \qquad \text{Eqn. 2.1}$$

where, P is installed power in lb ft/s
g is 32.2 ft/s^2
LOA is in feet
Δ is in lbs

and the factor 0.5924 gives a 'speed' in knots. The actual maximum speed of the vehicle divided by this function gives a non-dimensional parameter α.

$$\alpha^3 = \frac{\text{Weight x Speed}}{\text{Power}} \times \frac{\text{Speed}^2}{g\ \text{Length}}$$

i.e. Transport Efficiency x (Froude Number)^2

Figure 2.3 shows data points from Appendix 1 superimposed on Rainey's original diagram. For several types of marine vehicles, α is expected to remain constant over a large speed range, although each type of vehicle will possess differing α values.

Of interest is the way in which SWATH vessels, in common with the other displacement ships, appear to lie in a fairly well demarcated zone. This is in contrast to the large scatter indicated for hovercraft and hydrofoils. It is not clear whether the wide zone occupied by the latter indicate immature or versatile technologies.

SWATH ships have α values very close to 1.5, in common with conventional frigate, destroyer and cruiser type monohulls. Essentially they possess characteristics similar to shortened combatant ships.

Primarily, the value of this representation lies in the facility it provides for making first order estimates of the effects of increased speed on installed power, e.g. assuming length and displacement remain constant.

2.2.3 Lang Performance Assessment

Dr Thomas Lang, who was later responsible for the development of the first SWATH ship *Kaimalino*, completed his doctoral dissertation on a generalized engineering design procedure [9]. This developed a method for relating principal performance related variables such as speed, power and weight. Based on this work, a performance assessment of several marine vehicles, including SWATH, was published recently [6]. A particular advantage of this presentation is the inclusion of Froude Number in the analysis.

The method requires the derivation of a non-dimensional term

$C_d/E = (10.716\ P)/(\Delta^{2/3}\ V^3)$ Eqn. 2.2

where P is in HP, Δ is in long tons, V is in knots

Reference [6] may be consulted for an explanation of how this parameter is related to the drag coefficient divided by the propulsive efficiency of a given vehicle. Minimisation of C_d/E will produce a vessel requiring minimum power for a given displacement and speed. The volumetric Froude Number can be calculated (using the above units) from : -

$U = 0.1647\ \text{Speed}/(\text{Displacement}^{1/6})$ Eqn. 2.3

Figure 2.4 from [6] by Lang and Sloggett shows lower bound curves drawn through plots of C_d/E versus U for different vehicle types. Data from Appendix 1 is superimposed on this diagram. It is worth noting that their SWATH curve [6] was constructed using 15 data points (6 of which came from 3 vessels operating at 2 speeds). Appendix 1 provides a much broader database for comparison.

It may be seen that the curve for SWATH ships drawn by Lang and Sloggett is different in character from the curves for the other vehicles. However, the Appendix 1 data (although scattered) suggests that the lower bound should in fact attain a peak value similar to that of the catamarans and should thereafter follow a path lying between the catamaran and SES, ACV and hydrofoil curves.

As the diagram indicates, C_d/E for SWATHs is about 75% greater than that of monohulls in the *subcritical* region. This is because of the importance of frictional resistance in this speed regime. In the *supercritical* zone beyond Fn=1.3, where wavemaking is dominant, C_d/E is less for SWATH than monohulls or catamarans, but not to such an radical degree as suggested by [6].

2.3 Leading Dimensions

This section presents an analysis of the SWATH ship dimensions contained in Appendix 1. This is intended as a guide to good SWATH design practice and for use in developing leading dimensions for a vessel, beginning with very basic information. Principal considerations involved in selecting SWATH dimensions are also discussed.

In spite of the strong relationships identified in this chapter, the freedom to depart from the norm should be appreciated. Part of the appeal of the SWATH concept lies in the freedom which its form and novelty give to the naval architect. Certain requirements may best be satisfied by designs bearing little resemblance to previous practice. Of course, this is true of monohull design, where unusual demands have resulted in unorthodox designs. The SWATH designer has the advantage that he has no rigid orthodoxy from which to depart.

Plotting data from Appendix 1 gives regression equations which may be simplified to give design expressions for the principal particulars. All dimensions in this section are in metres. For simplicity, linear relationships have been derived wherever possible. However, the original equations and correlation coefficients may be found on the relevant figures if required. The ⁻rincipal SWATH ship dimensions are defined in Figure 2.5.

2.3.1 Length Overall and LBP

The overall length of a SWATH is a function of the length of the struts, hulls and their relation one to another. Early designs envisaged [74] a *short* strut and box structure, and, therefore, an overall length equal to the hull length. US Navy opinion [34,35] continues to favour this option. Many modern designs employ a *long* strut which overhangs the hull at the aft end. This gives an overall length greater than that of the hulls. It is also possible for a prospective owner to demand that no portion of the submerged structure shall project beyond the abovewater envelope. However, the available data does not (Figure 2.6) reveal significant differences in LOA dependent on strut arrangement.

Figure 2.7 plots LOA against the cube of the full load displacement (Δ) in tonnes. Some scatter is present, but a well defined trend is evident. This is approximated by

$$LOA = 5.33\ \Delta^{1/3} \qquad \text{Eqn. 2.4}$$

The constant may deviate as much as $\pm$ 2 from the mean value of 5.33. It is interesting to note that this simple relationship is just as useful as one which attempts to include speed in the relationship.

Figure 2.8 illustrates a Posdunine type function, which yields the expression

$$LOA = 6.24\,[\Delta^{1/3}][V/(V+2)]^2 \quad \text{(V in knots)} \qquad \text{Eqn. 2.5}$$

There is some confusion as to what constitutes the length between perpendiculars of a SWATH vessel. It is useful to be able to quickly estimate LBP for registration and legislatory purposes. A trivial approximation to the available data (Fig. 2.9) shows that typically

$$LBP = 0.886\ LOA - 0.47 \qquad \text{Eqn. 2.6}$$

2.3.2 Overall Beam

Beam is required to provide transverse stability, a good distribution of waterplane area for seakeeping purposes, and a useful deck area. The small waterplane area of the SWATH arrangement must be situated far from the vessel centreline to give adequate roll stiffness, and this results in vessels with low L/B ratios (Figure 2.10). Excessive beam will result in high bending moments in the cross structure, and high roll stiffness. For published designs, L/B can be seen to vary between 1.4 and 4.2, with the higher ratios coming in at the Panama Canal limiting beam. The mean line is

$$BOA = 0.959\ \{LOA\}^{0.782} \qquad \text{Eqn. 2.7}$$

It can be seen from Figure 2.11 that normal SWATH designs will be restricted to very small displacements if they are to transit Panama. The upper limit on the beam to $\Delta^{1/3}$ values is 3.3, with a lower bound of 1.1. The mean line is

$$BOA = 3.05\ [\Delta^{1/3}]^{0.835} \qquad \text{Eqn. 2.8}$$

SWATH ships with displacements above 5000 tonnes will thus be forced to deviate from normal proportions if they are to transit Panama. Displacements of about 8000 tonnes should be possible without excessive distortion, and Panamax designs of 24000 tonnes have been proposed [56]. This has been made possible by increasing the waterplane area and L/B ratio. However, this results in vessels with inferior seakeeping characteristics, and higher structural weight fractions compared to SWATHs of normal proportions.

Ability to transit the Panama Canal is often required of a passenger ship by its owners, although the capability may never be exercised. It is conjectured [82] that operators of cruise liners could be convinced that a SWATH liner would not need such a capability. For strategic reasons, most warships (especially in the USA) are required to transit Panama, and such a fundamental requirement may exclude SWATH from competition in certain roles.

The beam of a SWATH is most likely to cause problems where docking is concerned. Suitable drydocking for larger SWATHs would be difficult and costly to obtain at short notice, especially in certain areas. Berthing of SWATH vessels could also be awkward, especially in congested naval bases. In addition, the construction of such vessels could be difficult for traditional shipyards, especially those arranged for modern small warship construction.

2.3.3 Draught

Deep draught is implicit in the SWATH concept because of the need to locate most of the buoyancy away from the water surface. Typically, SWATH vessels will have draughts some 60-70% greater than a conventional ship of the same displacement. This has obvious consequences with regard to docking and berthing, but it also has some beneficial effects. In conjunction with reduced motions, the removal of the propellers from the air/water interface should reduce cavitation and ventilation. Improved sonar performance should also follow from a reduction in bubble sweepdown and keel slamming [102].

The final choice involves a compromise between resistance and seakeeping characteristics within the constraints on draught for the intended operational role. Generally, as the draught is increased, the seakeeping performance will improve while frictional drag will increase. However, wavemaking should decrease. Choice of hull cross section is also a factor in determining draught. Figure 2.12 and equations 2.9 and 2.10 show that employing elliptical or other non-circular hull sections can help in reducing draught (T).

$T = 0.588\,[\Delta^{1/3}]^{0.972}$	Circular hulls	Eqn. 2.9
$T = 0.583\,[\Delta^{1/3}]^{0.917}$	Non-circular hulls	Eqn. 2.10

2.3.4 Box Clearance

An air gap or box clearance (BC) is required to reduce the incidence and severity of wave impact on the underside of the vessel. The correct choice of box clearance depends on the maximum speed and sea state at which the vessel is to operate, together with a definition of the degree of slamming which is acceptable.

Slamming can never be eliminated completely, and stability and structural problems accompany increases in box clearance. Coupled with the development of control systems to aid vessel contouring in waves, these factors have led to the acceptance of an upper limit to box clearance.

For catamarans, the following values have been suggested [101] for BC/LOA at Froude Number 0.35.

0.05 at bow
0.03 amidships
0.04 at stern

There is a wide scatter in the available SWATH data, and Figure 2.13 illustrates the box clearances which are possible on given displacements. Regression analysis suggests a tendency for box clearance to increase with Froude number (Figure 2.14).

BC/LOA = 0.041+0.038 [Froude Number based on LOA]   Eqn. 2.11

2.3.5 Box Depth

The cross structure of a SWATH vessel must be able to resist the splitting/squeezing forces and moments imposed by the seaway through the struts. In addition, it must provide a platform for deckhouses and equipment, perhaps including weapons and helicopters. In the larger vessels, use may be made of the space enclosed by the box, and this can result in practical box depths (BD) being multiples of 'tween deck heights.

Figure 2.15 shows that it is possible to have one full deck in the cross structure of SWATHs with displacements as small as 400 tonnes. However, this is not usual, and 1000 tonnes is a more typical lower limit. Two 'tween deck heights can become possible above 2000 tonnes

2.3 6 SWATH Ship Depth and Freeboard

The depth of a SWATH from the keel to the underside of the cross structure is equal to the draught plus the box clearance. It is useful to estimate SWATH ship depth as an independent function for comparison with the value implied by T+BC. Figure 2.16 reveals a simple approximation to the depth to the wet deck (DWD)

DWD = 0.833 [$\Delta^{1/3}$]   Eqn. 2.12

Adding box depth to box clearance and draught gives the depth to main deck (DMD) of a SWATH (Figure 2.17). This parameter is clearly highly dependent on the philosophies adopted in choosing BC and BD.

$$DMD = 1.167 [\Delta^{1/3}\}$$ Eqn. 2.13

For conventional vessels, a plot of draught versus depth produces a straight line [1] because of the influence of the freeboard rules. It is interesting to note from Figure 2.18 that the mean lines through the SWATH design points are also virtually linear. (According to these relationships, box depth is typically 0.55 T).

$$DWD = 1.55\ T$$ Eqn. 2.14

$$DMD = 2.10\ T$$ Eqn. 2.15

SWATH ship freeboard is typically 25% larger than for a comparable monohull [4]. As a consequence, SWATH ships are expected to have very dry working decks, and indeed the MWATH vessel *Twin Drill* has never [10] shipped green seas on the main deck. However, high freeboard may lead to problems in roles dependent on existing shoreside facilities such as linkspans. Figure 2.19 plots freeboard versus the cube root of displacement.

$$Freeboard = 0.134 + 0.593 [\Delta^{1/3}]$$ Eqn. 2.16

2.4 Lower Hull Form

2.4.1 Hull Cross Section

Before deciding on the dimensions of the lower hulls, the designer must first choose the type of hull to be used from a number of options. Firstly, a cross section must be selected. The most common sections are circular, elliptical/oval, and rectangular (with radiused corners). Other (rarer) options include circles flattened at the top and keel, and vertical oval sections.

For a given sectional area, circular hulls provide the greatest internal headroom, but also the greatest draught. Structurally, they are the most efficient in resisting hydrostatic pressure, and they are also relatively easy to fabricate. A circular hull also provides the lowest wetted surface area, frictional resistance, and structural weight for a given sectional area. Most early SWATH designs, and all the US SWATH ships at sea employ this section.

Elliptical hull sections can be used to reduce draught at the cost of reducing internal headroom, although more deck area is provided. In addition, elliptical hulls generate smaller wave loads than circular hulls in beam seas, and can offer improved motions through higher AVM and damping. However, steel weight and fabrication costs would be expected to be higher than for circular hulls. All of the Japanese SWATH ships at sea employ this cross section.

By the end of the 1970s [102], the US Navy had also started to consider oval sections in conjunction with contoured hulls. The T-AGOS 19 is being constructed with this type of hull [34,35]. Essentially, the comments relating to elliptical sections apply equally to oval hulls. As with elliptical hulls, the added mass and damping are greater than for a circular section, and this is a primary attraction of such forms. In addition, draught reductions of 12%, compared with circular hulls, are claimed for a given hull centreline submergence. In common with all non-circular sections, a transition should ideally be made to a circular section at the tail because of propulsion considerations. This will add to the difficulty of construction.

No SWATH ships have been built with rectangular hulls, although several have been designed [60,79,97]. This section is structurally inefficient in resisting hydrostatic loads, but is cheap and simple to fabricate, although heavier than the alternatives. Its prime advantages are its producibility, possibility of offering low draught, and high AVM and damping.

Figure 2.20 shows the relationship between breadth and depth for non-circular hulls. The mean B_H/D_H ratio is 1.33, but ratios as high as 1.54 can be seen. Reference to figure 5.4 in Chapter 5 will give guidance on the draught reductions possible with non-circular hull sections.

Figure 2.21 shows the demihull sectional areas which can be obtained on a given hull length, depending on the cross-section employed. Normal non-circular hulls allow some 15% more sectional area in the hulls than circular sections.

$A_H = 0.0124\,[L_H]^{1.676}$	Circular hulls	A_H in m^2	Eqn. 2.17
$A_H = 0.0182\,[L_H]^{1.654}$	Non-circular hulls	A_H in m^2	Eqn. 2.18

Typical hull section dimensions may be estimated from Figures 2.22 and 2.23, which plot hull diameter (for circular hulls) and maximum non-circular hull breadth and depth versus the cube of displacement.

$Dia = 0.330\,\Delta^{1/3}$	Circular hulls	Eqn. 2.19
$D_H = 0.305\,\Delta^{1/3}$	Non-circular hulls	Eqn. 2.20
$B_H = 0.415\,\Delta^{1/3}$	Non-circular hulls	Eqn. 2.21

2.4.2 Hull Shape

The second choice facing the designer is the longitudinal section of the hulls. The basic options are illustrated in Figure 2.24. Further variations are possible on several of the fundamental concepts, particularly the contoured hulls.

The hull cross section may simply remain constant along the midlength with the only shape in the nose and tail. Ellipsoidal noses of $0.4L_H$ and parboloidal tails of $0.3L_H$ are typical, and give a useful parallel middle body length. However, for realistic nose and tail configurations, it is practically impossible to achieve prismatic coefficients less than 0.7 with simple hulls [102]. Prismatic coefficients up to 0.8, and even 0.93, are accepted for this type of hull. This leads to high residual resistances, against which must be set low frictional drag. Simple hulls also offer ease of construction, but may not permit installation of machinery in smaller sizes. Local bulging of a small simple hull [2,9,10] allows machinery to be fitted in the lower hulls at the expense of added resistance at high Froude numbers.

For simple, circular hulls with ellipsoidal and paraboloidal entrance and run, the prismatic coefficient (C_p) can be calculated as a function of the nose and tail lengths (L_N, L_T).

$$C_p = 1 - (1/3)(L_N/L_H) - (7/15)(L_T/L_H) \qquad \text{Eqn. 2.22}$$

Contouring hulls amidships [102], as in T-AGOS 19 [34], offers increased internal volume near the mid length to accommodate machinery, and also gives the designer greater control over LCB. Prismatic coefficients may be reduced to 0.45, and the residual resistance at Froude numbers about 0.3 is lowered. However, this form of contouring results in increased drag at higher speeds, and this has led to the development of the highly contoured hull [102].

The addition of bulges at the hull extremities [81,87] reduces the resistance penalty at high speeds, and permits even greater control over buoyancy distribution. Inevitably, such hull forms are costly to construct, and, in practice, a contoured keel would be difficult to build, and drydock safely.

By combining simple geometric shapes, an approximation to the continuously contoured hulls can be obtained. This reduces constructional difficulties, while adding little in terms of resistance [102]. The drydocking problem can be solved by introducing a flat keel but this complicates the geometry of the upper hull as the bulges become non symmetrical about a horizontal plane.

2.4.3 Hull Slenderness

From a powering point of view, one would expect hull slenderness to increase with increasing Froude number. In fact (Figure 2.25) the reverse is true for the vessels contained in Appendix 1. The explanation for this feature may be found in Figures 2.26 and 2.27. For the designs of Appendix 1, plotting hull slenderness versus the cube root of displacement reveals the governing factor in hull slenderness. In smaller SWATH ships, the demand for internal hull space is pressing, and consequently fuller hulls are accepted. Larger vessels are less constrained by this requirement, so that more slender hulls can be selected. For a given speed, larger ships have a lower Froude number, and this explains the appearance of slender hulls at low Froude numbers in Figure 2.25. It should be noted that owing to the large scatter in the data, the curve fits in Figure 2.25 are not intended for serious use.

Most ratios of hull length to √[demihull sectional area] lie between 12 and 23 (Figure 2.26). For most circular hulled SWATHs (Figure 2.27), L/D ratios range from 11 to 18. Up to about 1000 tonnes displacement, ratios below 15 are normal, while more slender hulls become feasible above this size.

2.4.4 Hull Length

The primary influences on hull length are the requirements of buoyancy, powering, internal arrangement, and strut configuration.

Usually, between 65% and 90% of the buoyancy of a SWATH is provided by the lower hulls, with 80% [4] being a typical value. Having selected this ratio, and with a cross-section and prismatic coefficient provided by resistance and/or machinery installation considerations, a value for length may be derived. The relationship between length and diameter, and between strut and whole-ship dimensions has many possible solutions.

Resistance calculations, even for simple circular hulls, are complex. Basically, for a given section, a longer hull will increase the wetted surface, but will tend to decrease the residuary resistance at higher speeds. However, there is some evidence (Chapter 7) to suggest that propulsive efficiency falls away with increasing hull slenderness, so that a compromise may exist in this area.

Machinery considerations affect the hull length indirectly through the breadth/depth requirements for prime mover installation in the lower hulls. Chapter 8 discusses this aspect of SWATH design in more detail. Space for fuel and ballast is not difficult to obtain in the hulls but the longitudinal distribution of such items is important.

Structurally, slender hulls may be more efficient in resisting hydrostatic loading, but the increase in surface area and associated structural weight will tend to cancel this attribute.

In addition to the above considerations, guidance may be obtained from current practice. For a *short* strut design, hull length (L_H) may be taken as 100% of the overall vessel length as estimated above. For ships with a portion of the strut overhanging the hull tail, a shorter hull must be used. Figure 2.28 illustrates Equation 33 which gives

$L_H = 0.931\ LOA - 0.91$ for *long* strut designs Eqn. 2.23

2.4.5 Hull Submergence

The submergence of the hulls below the surface has implications for resistance, seakeeping and draught. US practice has changed from early centreline submergences (CS) of $0.4\Delta^{1/3}$ to about $0.32\Delta^{1/3}$. This recognises predictions by theory and model tests that resistance considerations do not require deeply submerged hulls. In addition, model tests are said to have shown that propeller emergence was likewise little affected by these reductions in submergence [102].

Plotting Appendix 1 data reveals that the $CS/\Delta^{1/3}$ ratio varies from 0.23 to 0.57, with circular hulls tending to have the deepest submergence. Ignoring hull section differences, the mean ratio is around 0.36. A more useful relationship can be derived using draught as a base (Fig. 2.29). Smaller vessels with draughts less than 7m tend to have smaller centreline submergences than larger SWATHs, but the difference is slight. A mean line through all the points gives

$CS = 0.68\ T$ Eqn. 2.24

2.5 Strut Arrangement

2.5.1 Number of Struts

Selection of the number of struts per hull is one of the fundamental choices available to the SWATH designer. All but one of the SWATH ships currently at sea have a single *long* strut on each hull. The exception (*Kaimalino*) uses *twin* or *tandem* struts, also with an aft overhang allowing a spade rudder to be hung in the propeller race. Dr Lang's Semi-Submerged Ship Corporation [95,6] is now virtually the only advocate of twin strut SWATH ships although Pacific Marine's *Navatek* ferry [36] is building with this arrangement. The *TAGOS-19* design has a single *short* strut, with canted fins [34] ('stabiludders' or 'ruddilizers').

Other things being equal, twin struts per hull offer smaller turning circles, wave induced splitting forces of the order of half that generated by a single strut, and longer natural periods of motion. Lower structural weight follows from the use of twin struts, but structurally the problems become more acute because of the reduced sections transmitting load. Four independent struts offer a large degree of control over LCB and LCF so that motion characteristics may be tuned. Theoretically, twin struts can offer reduced resistance at high Froude Numbers (in the same manner as bulges fore and aft on the hull). In practice this seems difficult to achieve because of increased spray and miscellaneous drag etc being contributing factors.

Modern SWATH design opinion does not favour this option for practical reasons, mainly related to the sensitive hydrostatics. Static trim problems arise immediately if it is desired to locate machinery at the hull extremities (for access through the struts). Thickness to chord ratio can become rather large if access to, or withdrawal of, machinery is required. Also, the application of naval requirements prohibiting longitudinal access in the lower hulls would effectively eliminate many twin strut designs from consideration. However, recent experimental work at the University of Glasgow [93] has indicated *significant resistance reductions in waves* at prismatic hump Froude numbers for tandem strut designs. This extremely unusual phenomenon, if confirmed, could reinstate the twin strut SWATH as a favourite once more.

Single struts offer easier access to the hulls, and a freer choice regarding machinery installation. Control over LCF-LCB separation is reduced, but greater hydrostatic stiffness and increased payload flexibility can be provided. This has also become desirable because low roll stiffness, while apparently desirable from a motions point of view, can lead to higher quasi-static heel angles [102], which may be avoided by using higher GM_T.

Selecting a single strut as opposed to a twin strut design will result in increased structural weight. This is due to an increase of about 100% in the wave induced 'beam-on' bending moment, and the greater shell area . This aspect will be more marked for long strut versions. However, the load bearing structure has greater continuity, so that design and construction should be simpler than for a twin strut vessel.

Longer struts also possess more directional stability, and this operates against the advantages of placing the rudder in the propeller race.

2.5.2 Strut-Hull Relationship

To exploit the seakeeping potential of the SWATH arrangement, the buoyancy in the struts should be kept low in proportion to the hull buoyancy. Offshore semi-submersibles which seek to obtain a zero heave force condition within the range of working frequencies generally have lower column/hull volume ratios than SWATH designs. This is because the influence of forward speed in the latter alters the encounter frequencies so that one becomes less concerned about the exact location of the zero heave force condition. For SWATH ships, extreme values of strut/hull volume ratio are 1:9 and 3.5:6.5, with 2:8 most common. The proportions of the maximum sectional areas of struts and hulls are somewhat different. Figure 2.30 plots maximum strut sectional area versus maximum hull sectional area. Typically, strut sectional area is about 41% of hull sectional area, although values of 80% and 12.5% are possible.

The relationship between strut thickness and hull breadth is also important for seakeeping reasons. A wide strut will tend to 'mask' the hull, and reduce its added mass and inertia. Significant reductions in damping will also result, and this can lead to large motions at resonant frequencies. This relationship is influenced by the number and type of struts on the vessel. The shorter struts (single and tandem) are usually wide in order to provide sufficient waterplane area. Figures 2.31 and 2.32 show maximum strut thickness plotted against hull diameter and breadth (in the case of non-circular hulls). Ignoring differences in hull and strut type, strut thickness is typically 42% of the hull breadth. For circular hulls with long struts, a ratio as low as 25% appears common, while short strut designs are concentrated around 50%.

2.5.3 Strut Form

It is possible that bulging the strut, in the manner described for the lower hulls (section 2.4.2) may be of advantage in reducing power at certain speeds [93]. Local bulging of the struts for access or machinery withdrawal may thus be a viable design option. However, the vast majority of proposed SWATH designs employ simple struts, with (usually) elliptical noses and parabolic tails. Nose and tail lengths are typically 30% to 40%, in order to give a suitable length of parallel midbody. Corresponding waterplane area coefficients are between 0.7 and 0.85 for single strut designs. Twin strut SWATHs normally employ lower values to offset their usually higher thickness to chord ratios.

For struts employing such regular geometric shapes, the waterplane area coefficient can be calculated simply.

$$C_W = 1 - 0.215\,(L_{NS}/L_S) - (1/3)\,(L_{TS}/L_S) \qquad \text{Eqn. 2.25}$$

2.5.4 Strut Slenderness

Figure 2.33 shows that twin struts must normally use high thickness (t_S) to chord ratios in order to provide adequate hydrostatic stiffness. It is unusual to find a tandem strut SWATH able to employ a t_S/L_S ratio less than 10%. The same effect may be seen to a lesser extent for short and long single struts. Generally, the long strut can have a lower t_S/L_S ratio (@ 2-4%) than the shorter (@3-5%).

2.5.5 Strut Length

A reasonable estimate may be made of the length of strut from a previously selected value of LOA, using Figures 2.34 to 2.36.

$L_S = 0.21 + 0.903$ LOA	for *overhanging* struts	Eqn. 2.26
$L_S = 0.75$ LOA	for *short* struts	Eqn. 2.27
$L_S = 0.25$ LOA	for *tandem* struts	Eqn. 2.28

2.5.6 Strut Setback

The separation between the forward extremities of the lower hull and strut is commonly known as the 'strut setback'. The correct value for this parameter must ultimately be determined from resistance calculations in order to minimise hull-strut wavemaking interference effects. Strut setback (SS) is also important in determining seakeeping performance through the offset between LCF and LCB. These considerations mean that a universally applicable approximation is difficult to identify. At present an estimate may be made from Figure 2.37, which shows that SS/LOA ratio varies around 7%.

2.5.7 Strut Thickness

Recent US Navy design practice has shown a tendency towards strut thickness (t_S) to $\Delta^{1/3}$ ratios of 0.17. The data from Appendix 1 shows (Figure 2.38) that the mean value for single struts is 0.149, being rather greater for tandem struts. Below displacements of 1000 tonnes, some long single struts display ratios around 0.1.

$t_S = 0.149\ \Delta^{1/3}$	for single struts	Eqn. 2.29
$t_S = 0.13 + 0.155\ \Delta^{1/3}$	for tandem struts	Eqn. 2.30

2.6 Conclusions

This chapter has presented an original analysis of SWATH ship performance characteristics and linear dimensions. A large number of designs from many different sources have been included in the analysis. Several well defined relationships between the main dimensions of SWATH ships have been identified. This information has been presented graphically, and, where reasonable, in the form of equations.

In effect, the efforts in the fields of SWATH resistance and motions have influenced many designers to select vessel proportions which reflect the desire to optimise hydrodynamic performance, but which also meet practical needs. A consensus of opinion is revealed by these well defined relationships.

Thus, although the number of SWATH ships at sea is small, the extensive research and development effort of the last decades, and the resulting design work, has produced a useful database for these vessels. The information and equations presented in this section can therefore serve as a guide to 'good practice' in SWATH design, and also form the basis for simple design tools.

Collectively, the design data offers a quick means of estimating the preliminary dimensions of a new SWATH ship design. At the same time the data provides a baseline against which new designs may be assessed. In a similar way, the performance comparisons provide a facility for determining the likely effects of increased speed or size on performance of a design. The performance penalties which must be paid for selecting a SWATH ship as opposed to another vehicle are also illustrated in these diagrams.

References to Chapter 2 and Appendix 1

1. Lamb, T., "A Ship Design Procedure", SNAME, *Marine Technology*, October 1969

2. Miller, R.T., "A Ship Design Process", SNAME, *Marine Technology*, October 1965

3. Watson, D.G.M. and Gilfillan, A.W., "Some Ship Design Methods", *Transactions*, RINA, Vol. 119, 1977

4. Kennell, C., "SWATH Ship Design Trends", *Proceedings*, Intl. Conference on SWATH Ships and Advanced Multihulled Vessels, RINA, London, April 1985

5. Gabrelli, G. and von Karman, T.H., "What Price Speed?", *Mechanical Engineering*, October 1950

6. Lang, T. and Sloggett, J.E., "SWATH Developments and Performance Comparisons with Other Craft", *Proceedings*, International Symposium on SWATH Ships and Advanced Multihulled Vessels, RINA, London, April 1985

7. Magnusson, A. and Sahin, I., "Marine Vehicle Performance Limits and Economic Potential", AIAA/SNAME Paper 79-2007, Advanced Marine Vehicles Conference, Baltimore, October 1979

8. Rainey, P.G., "Basic Ocean Vehicle Assessment", ASNE *Naval Engineers Journal*, April 1976

9. Lang, T.G., "A Generalised Engineering Design Procedure", *Ph.D Thesis*, The Pennsylvania State University, June 1968

10. *Fact Book for MV Twin Drill*, International Underwater Contractors Inc., June 1985

11. "Twin Hull Vessel DUPLUS for Netherlands Offshore Company", *Holland Shipbuilding*, February 1969

12. Trillo, R. (editor), item on *Duplus* in section on Multi Purpose Vessels, *Ocean Technology 1979/80*, Jane's Yearbooks, London

13. Marbury, F., "Small Prototypes of Ships - Theory and a Practical Example", *Naval Engineers Journal*, October 1973

14. Trillo, R. (editor), entry on *Kaimalino* in section on Multi Purpose Vessels, *Ocean Technology 1979/80*, Jane's Yearbooks, London

15. "Navy Completes Semi Submersible Ship", *Ocean Industry*, December 1973

16. "Innovations in Marine Design - Semi Submersible Ship - Vessel With a Future", *Ocean Industry*, November 1971

17. Hightower, J.D. and Seiple, R.I., "Operational Experiences with the SWATH Ship SSP *Kaimalino*", AIAA Paper 78-741, AIAA/SNAME Advanced Marine Vehicles Conference, San Diego, 1978

18. Lang, T.G., Hightower, J.D. and Strickland, A.T., "Design and Development of the 190 Ton SSP", ASME Paper 73-WA/OCT-2, Winter Annual Meeting, American Society of Mechanical Engineers, Detroit, November 11-15, 1973 August 1976

19. "Offshore Services Semi - Designed for High Speed, Stability", *Ocean Industry*, April 1982

20. Lang, T.G., "S^3 - New Type of High Peformance Semisubmerged Ship", *Journal of Engineering for Industry*, November 1972

21. Pennington, H., "SSP - Semi Submerged Platform - New Style Ship for Stormy Seas", *Oceans Magazine*, March 1977

22. Mulcahy, M., "US Navy's *Kaimalino* - A Stable Semi Submersible Platform", *Sea Technology*, August 1976

23. Kocivar, B., "Semi Submerged Platform", *Popular Science Magazine*, Dec. 1975

24. "Worlds 1st Commercial SSC Under Construction", *Zosen* Vol. 24, May 1979

25. "*MESA'80* - Mitsui's Semi Submersible Catamaran as a Fast Ferry", *The Motor Ship*, July 1980

26. "*Kaiyo* - Dynamic SWATH Ship From Mitsui", *The Motor Ship*, November 1985

27. Saeki, M. and Miyata, N., "The Largest Semi Submerged Catamaran *Kaiyo* (For Underwater Experimental Works)", 8th Joint Meeting of UJNR Panel on Diving Physiology and Technology, June 1985

28. Mabuchi, T., Kunitake, Y. and Nakamura, H., "A Status Report on Design and Operational Experiences with the Semi-Submerged Catamaran (SSC) Vessels, *Proceedings*, International Conference on SWATH Ships and Advanced Multihulled Vessels, RINA, London, April 1985

29. McLeavy, R. (Editor), "Semi Submerged Catamarans", *Jane's Surface Skimmers 1985*, Jane's Yearbooks, London 1985

30. Luedeke, G., Montague, J., Posnansky, H. and Lewis, Q., "The RMI SD-60 SWATH Demonstration Project", *Proceedings*, International Symposium on SWATH Ships and Advanced Multihulled Vessels, RINA, London, April 1985

31. Luedeke, G. and Montague, J., "RMI's Small Waterplane Area Twin Hull (SWATH) Boat Project", San Diego Local Section Paper, SNAME, November 1984

32. "RMI's Prototype SWATH on Sea Trials at San Diego", *Combat Craft*, May/June 1985

33. "RMI Launches SWATH at San Diego Yard", *High Speed Surface Craft*, March/April 1985

34. Covich, P., "T-AGOS 19: An Innovative Program for an Innovative Design", ASNE *Naval Engineers Journal*, May 1987

35. Covich, P., "SWATH T-AGOS A Producible Design", *Proceedings*, AIAA 8th Advanced Marine Systems Conference, San Diego, Ca., September 1986

36. "Pacific Marine Building $2 million SWATH Test Ship", *Maritime Reporter/Engineering News*, October 1987

37. Pollack, J.G., "Motion Comparison Between a 64-Foot SWATH and a 65-Foot Monohull", Report No. NBDL-85R001, Naval Biodynamics Laboratory, New Orleans, February 1985

38. Kelley, T.D., "Actual Experiences with US SWATH Designs", *Proceedings*, International Symposium on SWATH Ships and Advanced Multihulled Vessels II, RINA, London, November 1988

39. Ozawa, H., "The Design and Operation of Catamaran Vessels", *Transactions*, NECIES, Vol. 103, 1986-1987

40. Orders and Rumours Section, *Ship and Boat International*, July/August 1988

41. Lamb, G.R., "Influence of Seakeeping Requirements on SWATH Ship Geometry", SNAME Local Section (Chesapeake) Paper, June 1987

42. *65ft Mitsui SSC Cruiser*, Mitsui Engineering and Shipbuilding Publication RD85-15, 1985

43. "Chubasco", *Yachting World*, June 1988, p. 166

44. "Semi-Submerged Catamaran Survey Ship *Kotozaki*", *High Speed Surface Craft*, April 1982

45. "SWATHs Come a Step Nearer", *Ship and Boat International*, Winter 1986/87

46. Warren., N., "The Case for SWATH Type Offshore Patrol Vessels", *Combat Craft*, November 1983

47. Warren, N.F., "SWATH Design for Offshore Patrols", *The Naval Architect*, Small Craft Supplement, No. 2, 1982

48. "1,600 Tonne SWATH Design From Vosper Thorneycroft", *Combat Craft*, November/December 1985

49. "1600 Tonne SWATH", Vosper Thorneycroft Brochure, Royal Navy Equipment Exhibition, Portsmouth, September 1985

50. Allen, R.G. and Holcomb, R.S., "The Application of Small SWATH Ships to Coastal and Offshore Patrol Missions", *Proceedings*, 2nd Symposium on Small Fast Warships and Security Vessels, RINA, London, May 18-21 1982

51. Holcomb, R.S. and Allen, R.G., "Investigation of the Characteristics of Small SWATH Ships Configured for United States Coast Guard Missions", DTNSRDC Report No. SDD-83-3, June 1983

52. "A 23m SWATH Patrol Craft Design From Fairey Marine", *Combat Craft*, November/December 1985

53. Fernandez-Gonzalez, F., "Mission Related Preliminary Design Solutions for Small SWATH Ocean Patrol Vessels", *Proceedings*, International Symposium on SWATH Ships and Advanced Multihulled Vessels, RINA, London, April 1985

54. "Mitsui Sea Saloon Makes a Dream Come True", Mitsui Brochure OP4001JE8512N3000AHA

55. Barton, J.G., "SWATH Design at University College London", Short Presentation at International Symposium on SWATH Ships and Advanced Multihulled Vessels, RINA, London, April 1985

56. Cannon, T.R. and McKesson, C.B., "Large SWATHs - A Discussion of the Diminishing Returns of Increasing SWATH Ship Size", AIAA Paper 2385, AIAA 8th Advanced Marine Systems Conference, San Diego, September 1986

57. "Wartsila's Cruise Liners of the Future", *The Naval Architect*, July 1983

58. "SWATH Patrol Boat", *Combat Fleets of the World*, p. 705

59. Betts, C.V., Ferreiro, L.D., Grzeskowiak, S.R., McDonald, N.A. and Parlett, P.J., "Design Study for an Anti Submarine Warfare SWATH Frigate", *Proceedings*, International Symposium on Anti Submarine Warfare, RINA, London, May 1987

60. Poloydorou, G. and Santos, R., "Design and Hydrodynamic Aspects of a SWATH Car-Passenger Ferry", *Proceedings*, International Congress on Marine Technology, Athens, May-June 1984

61. Gaul, R.D., and McClure, A.C., "Development of the SWATH Ship Concept for Research Ship Design", IEEE, 1984

62. Lang, T., Becker, N., Kaysen, D. and Price, K., "RAYTHEON/SSSCO Oceanographic SWATH Ship Design", *Proceedings*, Oceans'82 Conference, Washington, D.C., September 20-22 1982

63. Wilkie, L.J., "A SWATH Crew Boat Design", Hawaii Local Section Paper, SNAME, April 1983

64. Drummond, S., "Hydrographic Applications of SWATH Ships and SWATH Survey Systems", *Proceedings*, Oceans'82 Conference, Washington, D.C., September 20-22 1982

65. Lee, K.Y., Lee, D.K., Kim, E.S., Kim, J.G. and Kim J.H., "On the Design Technology of SWATH Ship for High Speed Coastal Passenger Vessel", *Proceedings*, High Speed Surface Craft Conference, January 1988

66. Rice, M.S. and Harmon, J., "Prospects for the Development of a SWATH Fishing Vessel", *Proceedings*, Oceans'78 Conference, IEEE, Washington, DC, 6-8 September 1978

67. Harmon, J.B. and Nicinski, S.A., "The Case for a SWATH Interisland Ferry System", *Proceedings*, Pacific Congress on Marine Technology, Honolulu, 24-27 April 1984

68. Pike, D., "SWATH Ferry Concept Developed in UK", *Lloyds List*, January 1987

69. "Mitsui SSC Type Diving Support Vessel", Mitsui Shipbuilding & Engineering Co. Ltd, Brochure OP3108E7903N2000NAL

70. "The SCSS Vessel", Brochure from Wartsila, Worley Engineering Ltd, 1984

71. Serter, E.H., "Comparative Studies for new US Frigate Hull", *International Defence Review*, 2/88, 1988

72. Kennell, C., White, B. and Comstock, E.N., "Innovative Naval Designs for North Atlantic Operations", SNAME Annual Meeting, New York, November 13-16, 1985

73. Lang, T.G. et al, "Preliminary Design Study of a 3000 Ton S^3", Report NUC TN 574, Naval Undersea Center, San Diego, 1971

74. Hawkins, S. and Sarchin, T., "The Small Waterplane Area Twin Hull (SWATH) Program - A Status Report", AIAA Paper 74-324, AIAA/SNAME/USN Advanced Marine Vehicles Conference, San Diego, Ca., February 25-27 1974

75. Childers, K.C., Gloeckler, F.M. and Stevens, R.M., "SWATH - The V/STOL Aircraft Carrier for the Post 1990's", ASNE *Naval Engineers Journal*, February 1977

76. "High Speed and Special Performance Ship", pp 200-202, *Proceedings*, SNAME STAR Symposium, 1979

77. Moritz, G., "Coast Guard Vessels to do the Job", ASNE *Naval Engineers Journal*, February 1985

78. Gupta, S.K. and Schmidt, T.W., "Developments in SWATH Technology", ASNE *Naval Engineers Journal*, May 1986

79. Smith, D.L., Cuthbertson, W., MacGregor, J.R. and McGregor, R.C., "SWATH Design - A Shipbuilders View and a Practical Example", *Proceedings*, International Symposium on SWATH Ships and Advanced Multihulled Vessels II, RINA, London, November 1988

80. Pattison, D.R. and Rose, P.H.A., "SWATH - The UK MoD Design and Assessment Programme", *Proceedings*, International Symposium on SWATH Ships and Advanced Multihulled Vessels II, RINA, London, November 1988

81. Koops, A. and Nethercote, W.C.E., "SWATH Model Resistance Experiments", *Proceedings*, International Symposium on SWATH Ships and Advanced Multihulled Vessels, RINA, London, April 1985

82. Routa, T., "Application of the SWATH Principle to Passenger Vessels", *Proceedings*, International Symposium on SWATH Ships and Advanced Multihulled Vessels, RINA, London, April 1985

83. McClure, A.C., "Design for a Semi-Submersible Support Ship", *Ocean Industry*, August 1972

84. Pike, D., "SWATH Development at Lockheed", *Combat Craft*, Sept/October 1985

85. "SWATH Ship for Safer Personnel Transport", *The Naval Architect*, January 1981

86. "The S3 - Semi-Submerged Ship", Brochure form British Shipbuilders, SSSCO, Manderstam Technical Services Ltd, 1980

87. Pieroth, C.G. and Lamb, G.R., "The SWATH Option as a V/STOL Aircraft Carrier", *Proceedings*, 7th AIAA/SNAME/ASNE Marine Systems Conference, New Orleans, February 1983

88. Kaysen, H.D., "SWATH AGS Deep Ocean Survey Ship", Chesapeake Section , SNAME, October 1985

89. Aronne, E.L., Lev, F.M. and Nappi, N.S., "Structural Weight Determination for SWATH Ships", AIAA/SNAME Paper 74-326, Advanced Marine Vehicles Conference, San Diego, 1974

90. "Licence to Build US Designed Semi-Submersible in the UK", *The Naval Architect*, July 1980

91. Kerr, G.D., Anderson, A. and Kennell, C., "SWATH Ship Design - State of the Art", AIAA Paper 78-737, AIAA/SNAME Advanced Marine Vehicles Conference, San Diego, Ca., 1978

92. "Catamaran Design is Key to Ferry Safety", *The Motor Ship*, November 1988

93. Chun, H.H., "Theoretical and Experimental Studies on the Resistance of SWATH Ships", *PhD Thesis*, University of Glasgow, March 1988

94. Luedeke, G. and Farnham, R.B., "Commercial Applications of Advanced Marine Vehicles for Express Shipping", ASNE *Naval Engineers Journal*, May 1983

95. Lovie, P.M. and Lang, T.G., "Commercial Opportunities for SWATH Vessels", *Proceedings*, International Symposium on SWATH Ships and Advanced Multihulled Vessels II, RINA, London, November 1988

96. Unclassified Letter from MoD (ref. D/SSC/DGFMP/3/3/102) to Yarrow Shipbuilders, 14th December 1987

97. Jones, A.H., "A Comparison Between Royal Princess and an Equivalent SWATH Ship", *Proceedings*, IMAS'88 Design and Development of Passenger Ships, London, 18-20 May 1988

98. Lee, K.Y., Lee, D.K., Kim, E.S., Kim, J.G. and Kim, J.H, "On the Design Technology of SWATH High Speed Passenger Ship", *Proceedings*, International Symposium on SWATH Ships and Advanced Multihulled Vessels II, RINA, London, November 1988

99. "IKO Concepts", *Scandinavian Shipping Gazette*, No 15, 1988

100. "US News", *International Defence Review*, March 1988

101. Unozawa, M. and Shimitzu, K., "The Design of Catamarans", *Proceedings*, PRADS, Tokyo, October 1977

102. Bebar, M.A., Kennell, C.G., White, W.N. and Lavis, D.R., "Advanced Marine Vehicles", *Proceedings*, Workshop on Hull Form Design, Wageningen, October, 1985

103. Betts, C.V., "Some Developments in UK SWATH Design Research", *Proceedings*, International High Performance Vehicle Conference, Shanghai, November 1988

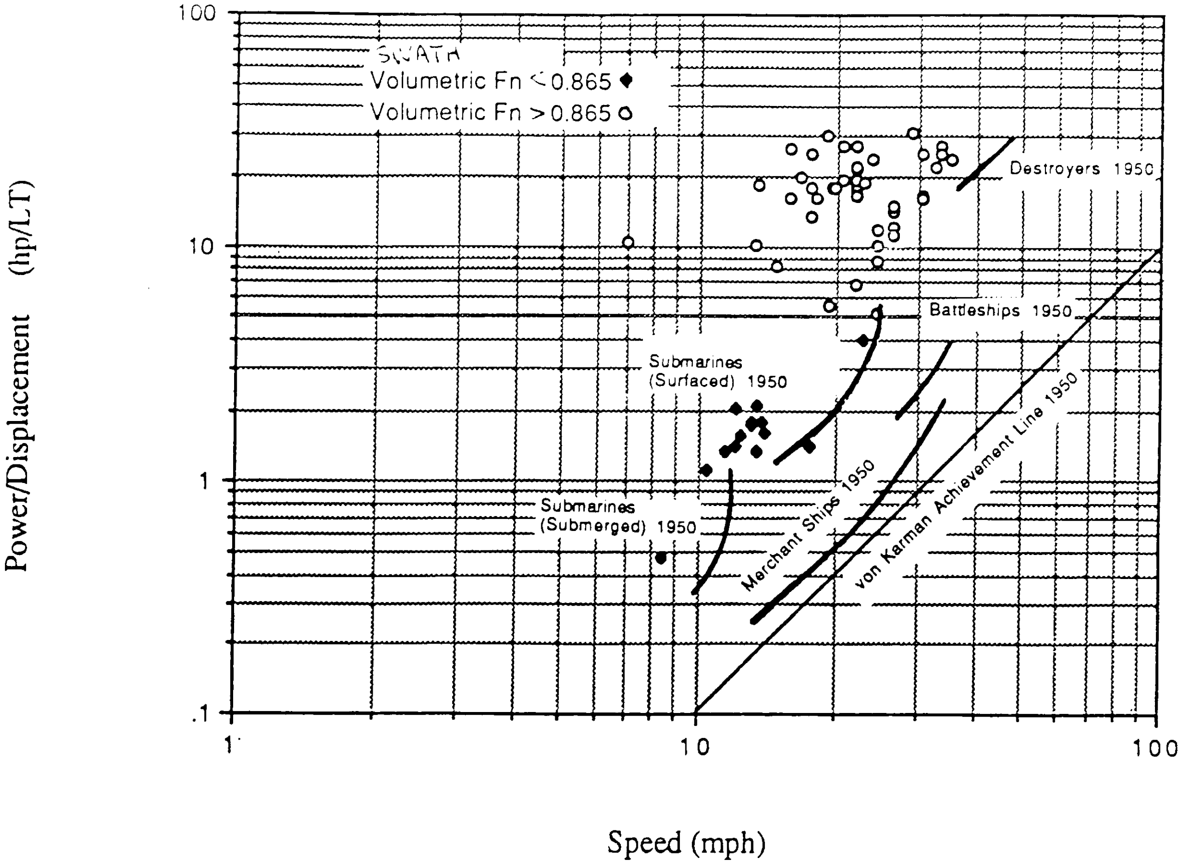


Figure 2.1 von Karman *Specific Power* Diagram with SWATH Data

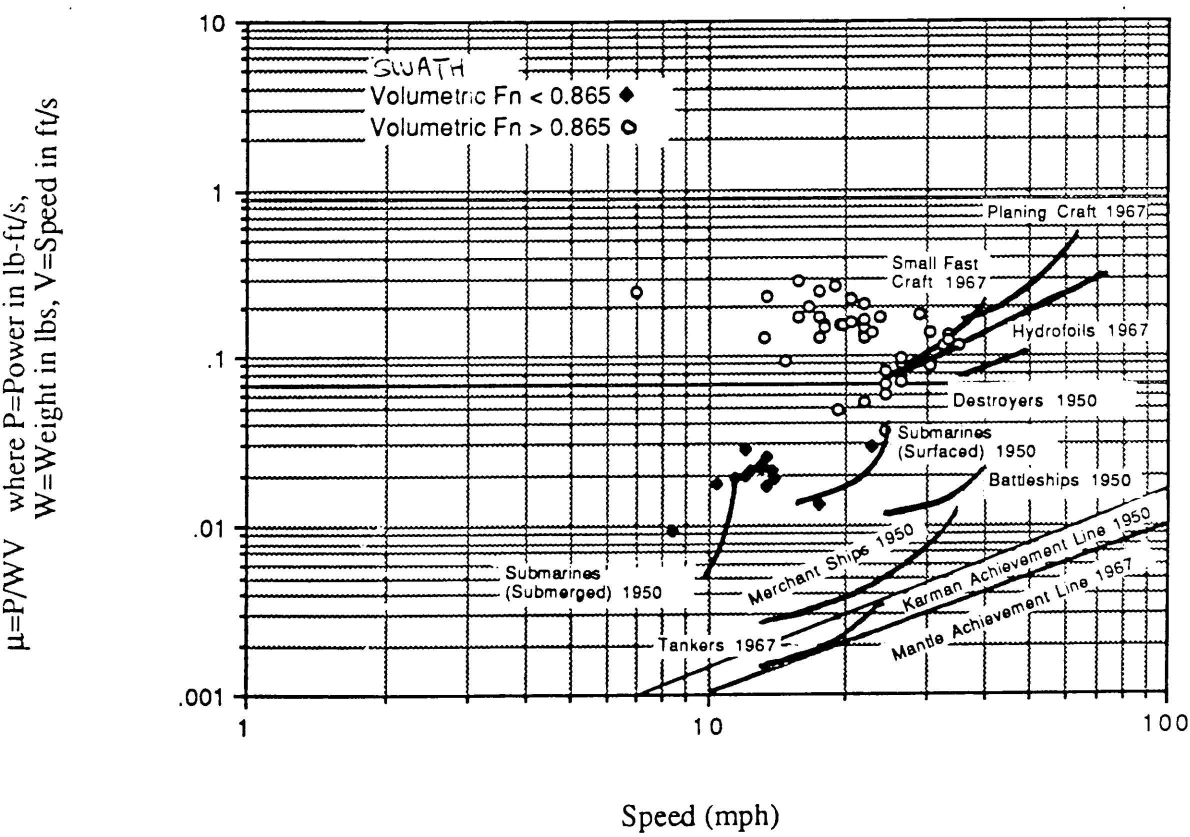


Figure 2.2 von Karman Specific Resistance Diagram with SWATH Data

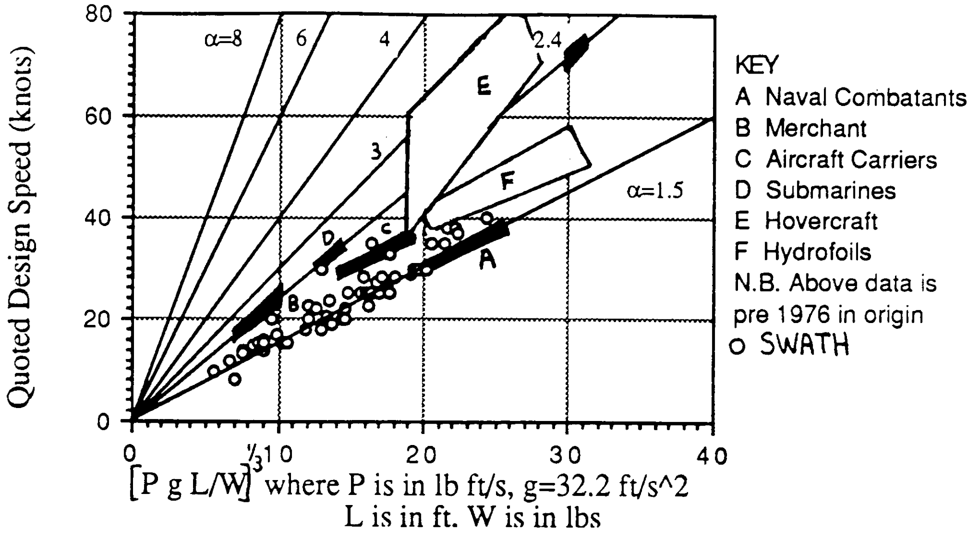


Figure 2.3 Rainey Speed-Power-Length-Displacement Diagram with SWATH Data

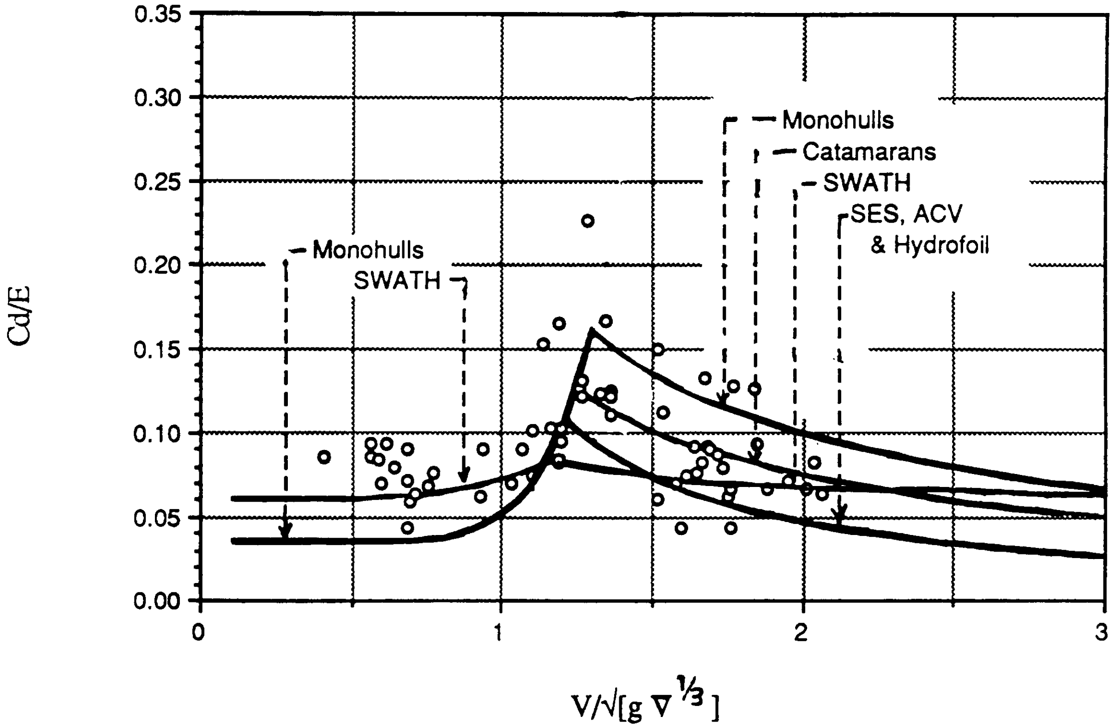
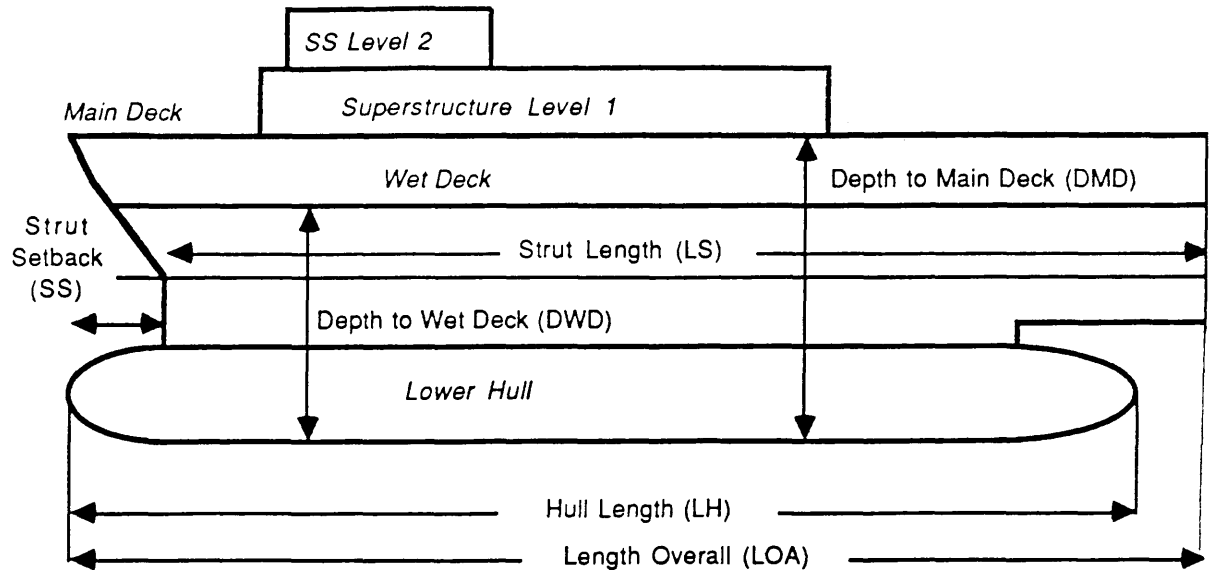
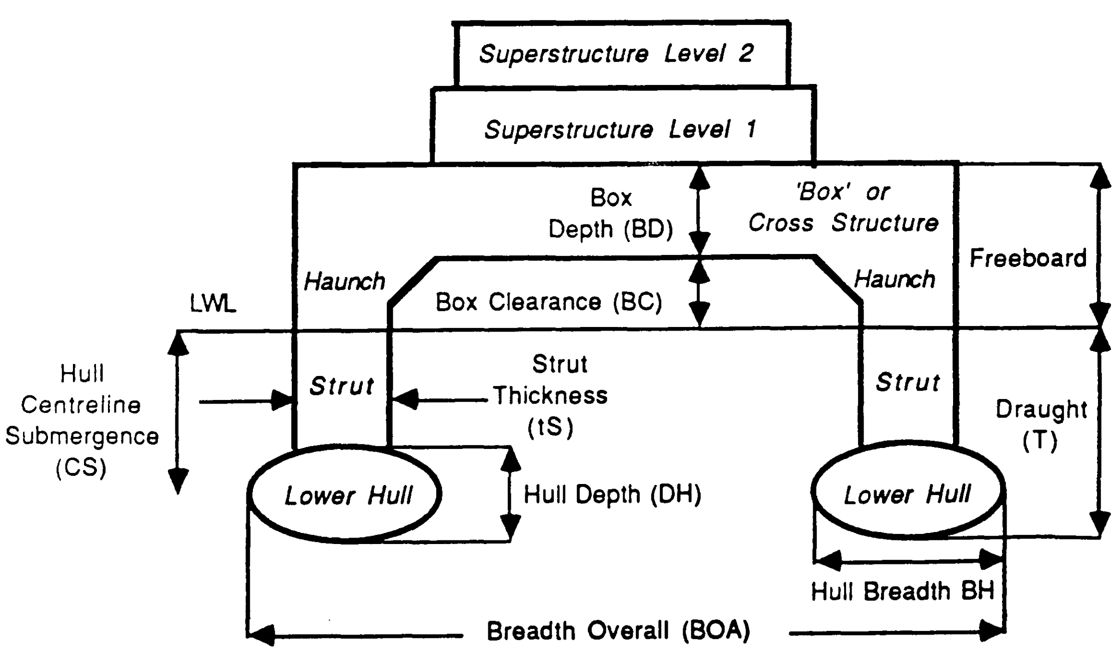


Figure 2.4 Lang C_d/E - Froude Number Diagram with SWATH Data

Figure 2.5 - Definition of Principal SWATH Dimensions





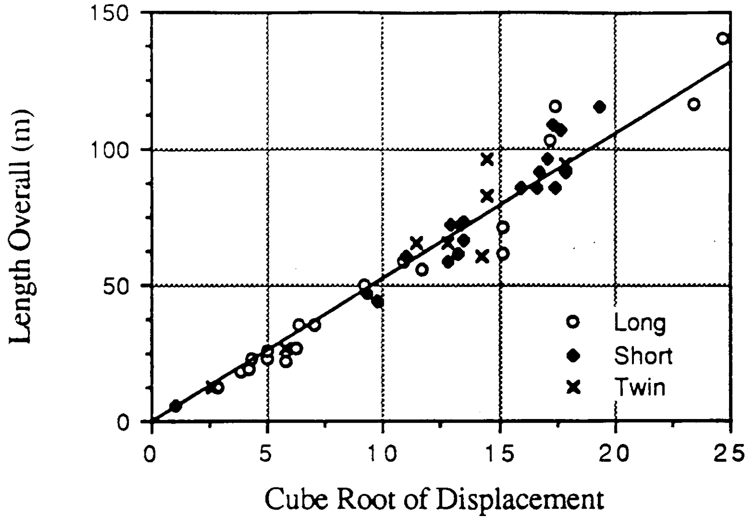


Figure 2.6 LOA - Displacement$^{1/3}$ Relationship Dependent on Strut Type

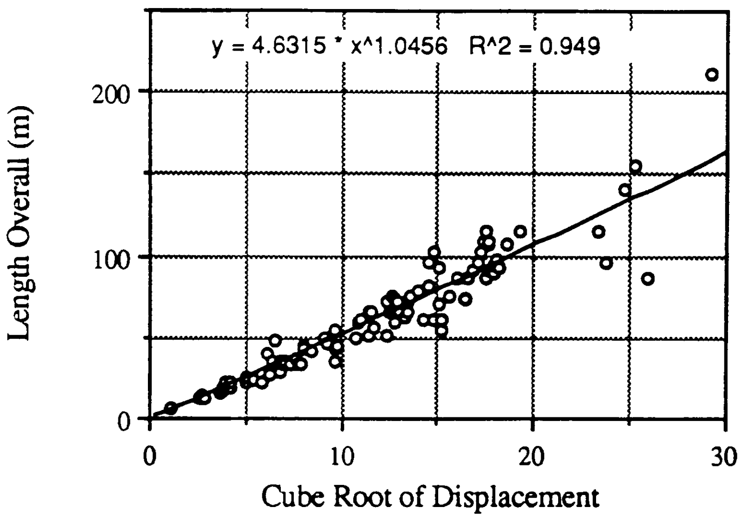


Figure 2.7 LOA - Displacement$^{1/3}$ Relationship

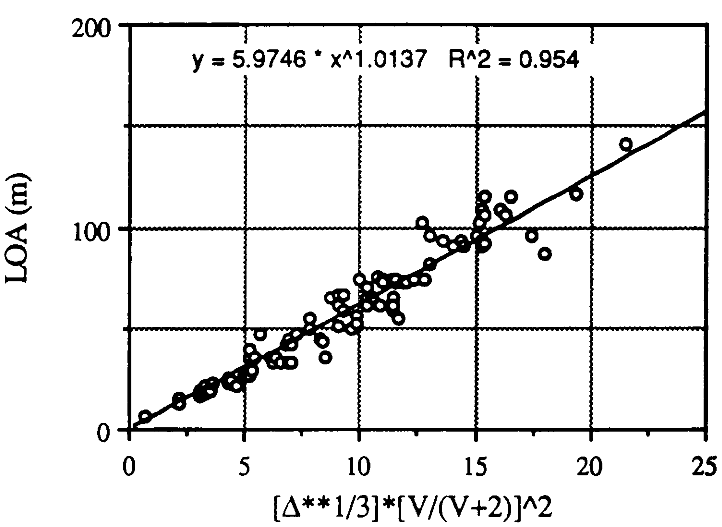


Figure 2.8 Posdunine Function for SWATH Ships

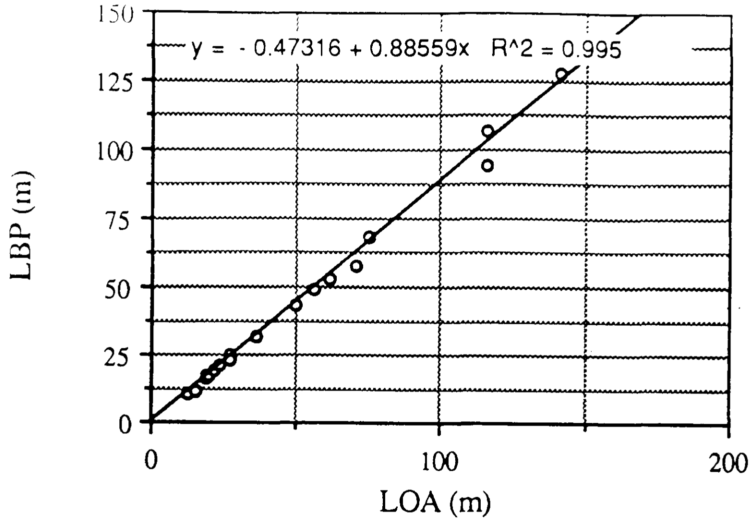


Figure 2.9 SWATH Ship LBP as a Function Of Length Overall

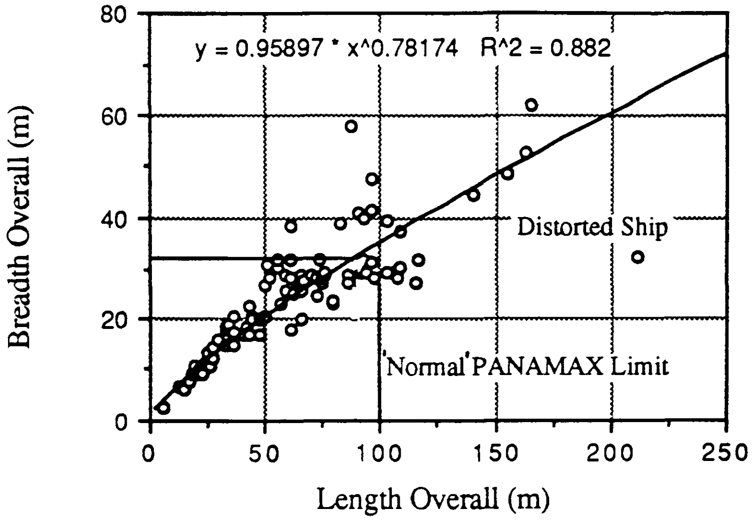


Figure 2.10 Length Overall - Breadth Overall Relationship

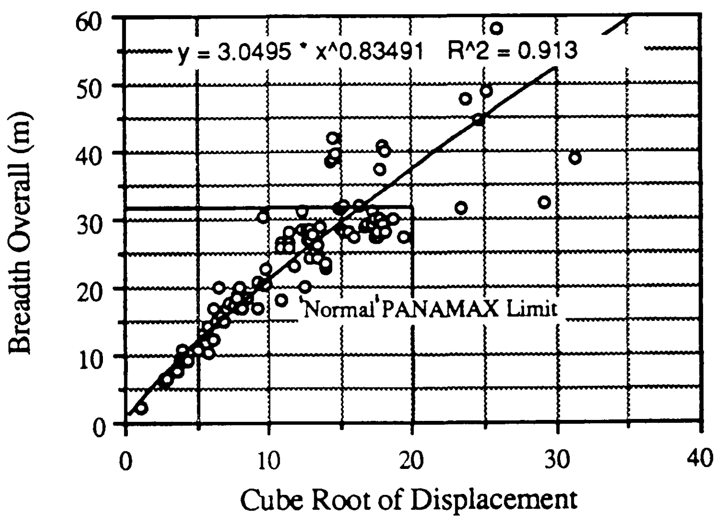


Figure 2.11 Breadth Overall - Displacement$^{1/3}$ Relationship

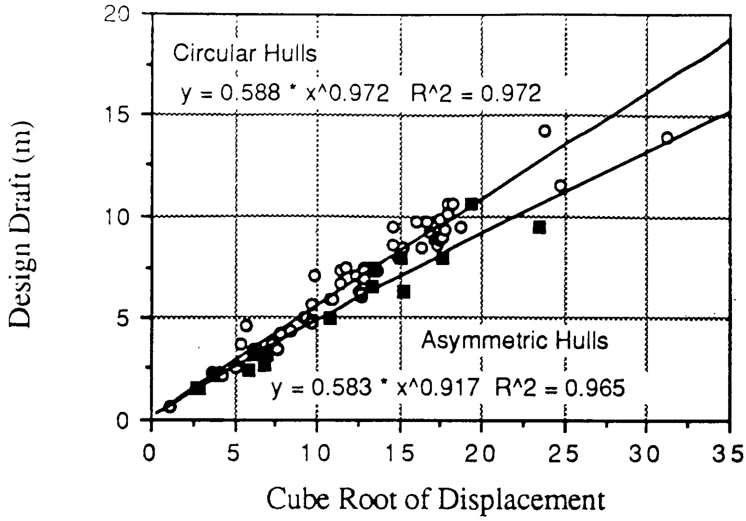


Figure 2.12 Draught - Displacement$^{1/3}$ Relationship

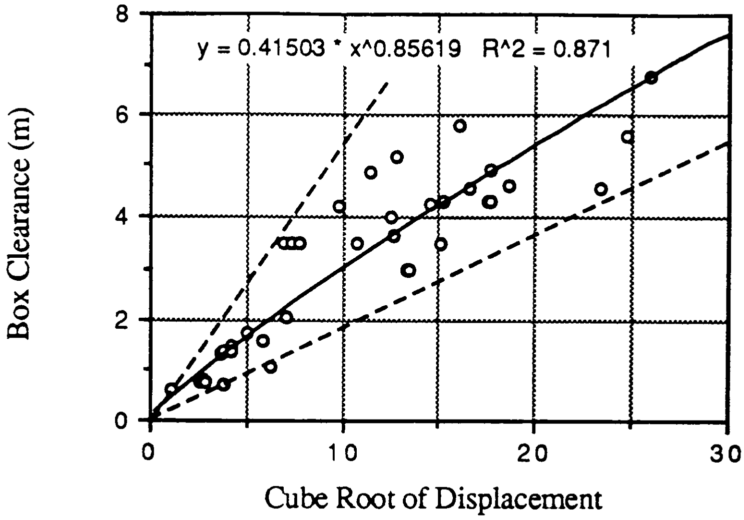


Figure 2.13 Box Clearance - Displacement$^{1/3}$ Relationship

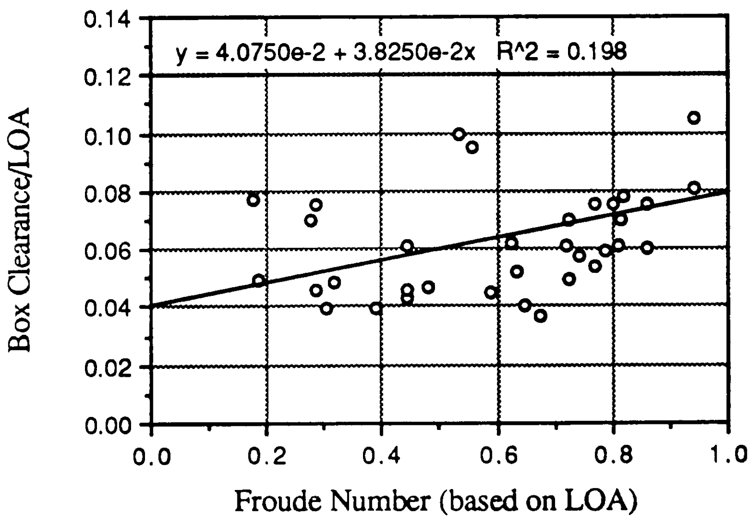


Figure 2.14 Box Clearance/LOA versus Froude Number

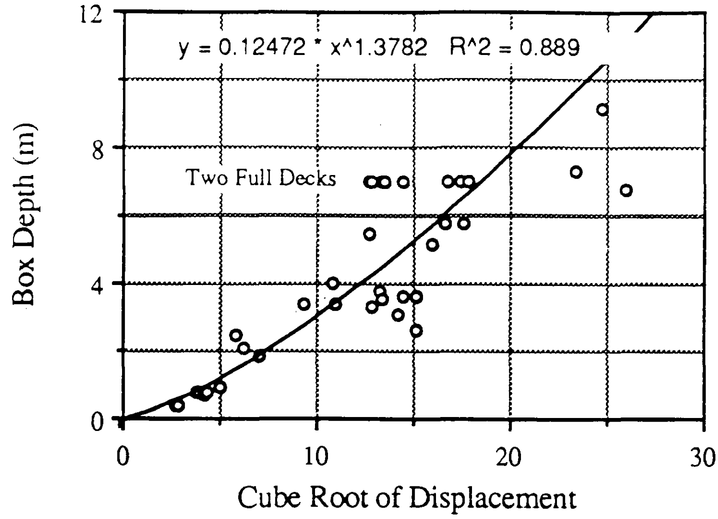


Figure 2.15 Cross Structure Depth - Displacement$^{1/3}$ Relationship

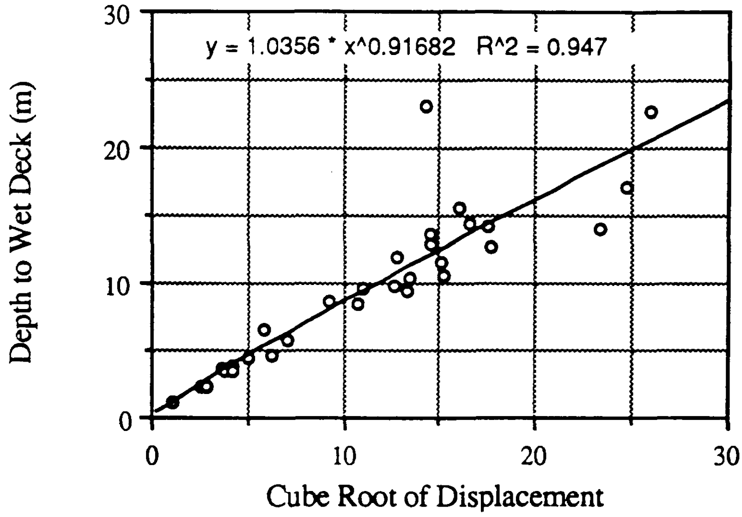


Figure 2.16 Depth to Wet Deck - Displacement$^{1/3}$ Relationship

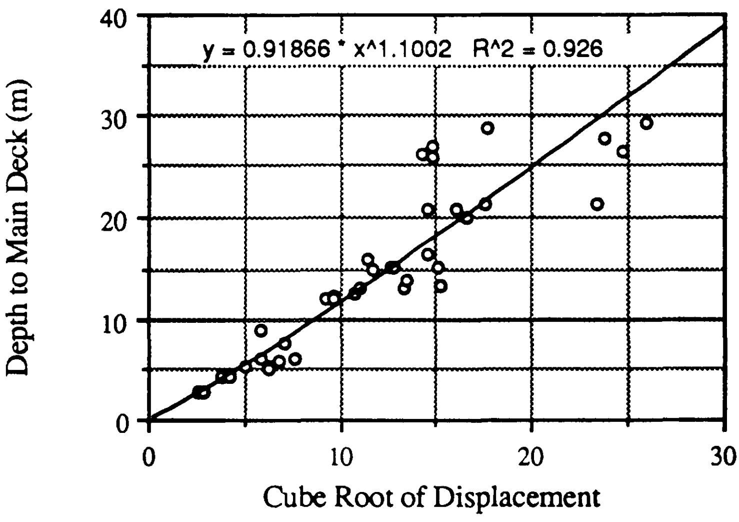


Figure 2.17 Depth to Main Deck - Displacement$^{1/3}$ Relationship

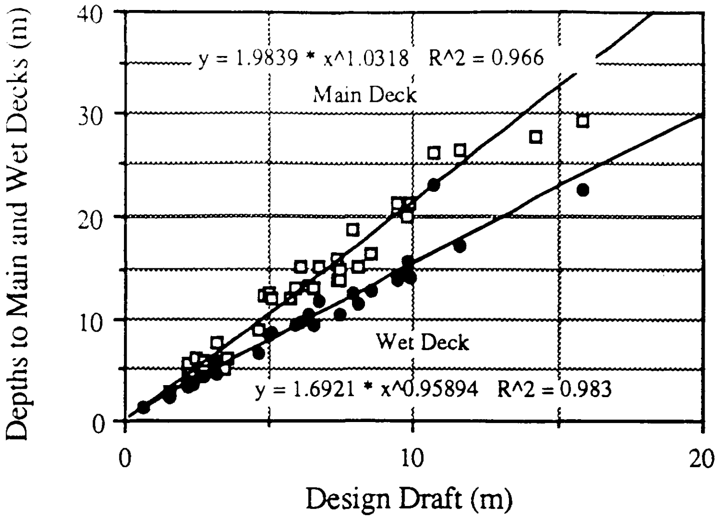


Figure 2.18 SWATH Ship Depth - Draught Relationships

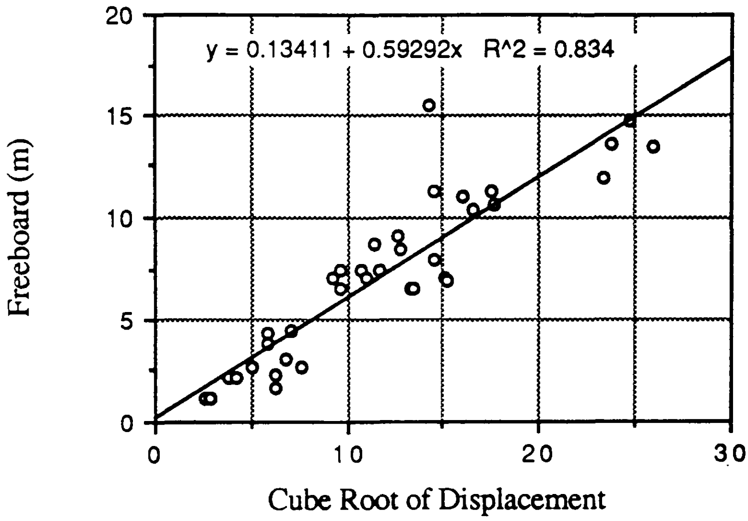


Figure 2.19 Freeboard - Displacement$^{1/3}$

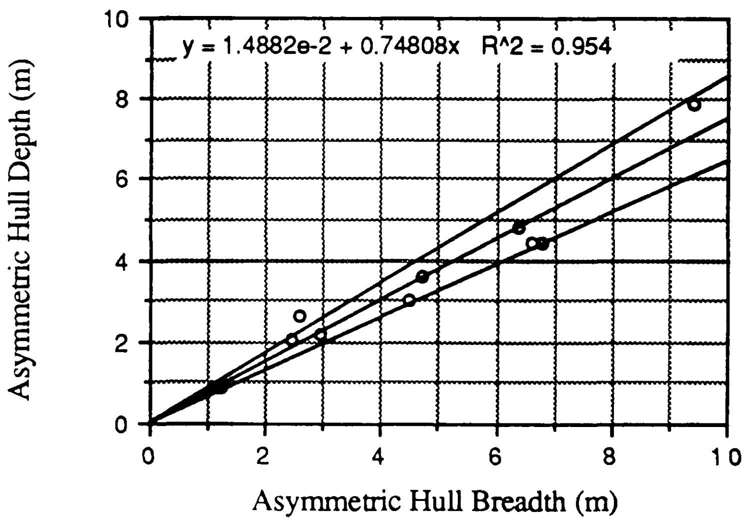


Figure 2.20 Asymmetric Hull Breadth - Depth Ratios

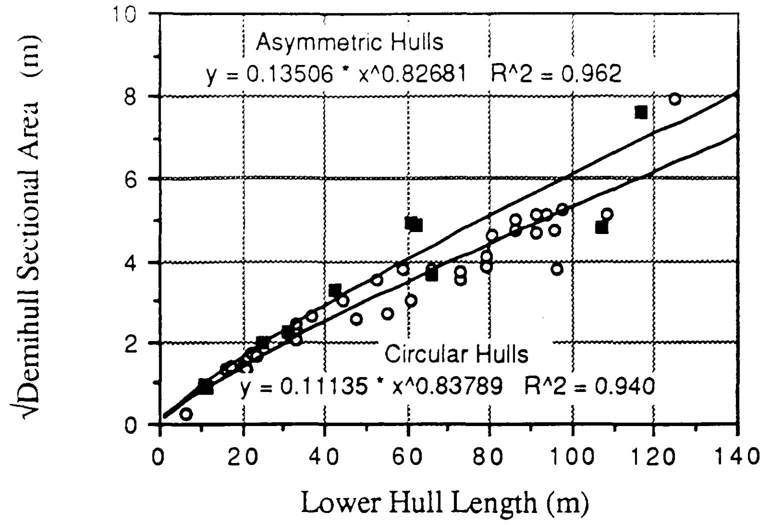


Figure 2.21 Demihull Sectional Area - Hull Length

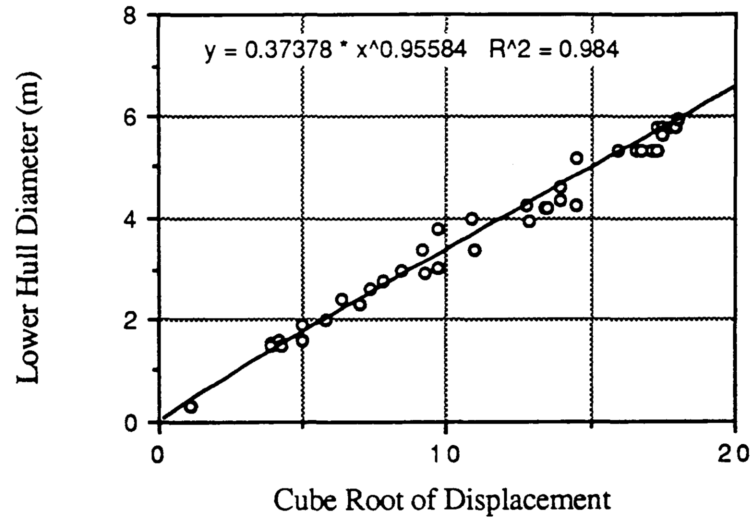


Figure 2.22 Lower Hull Diameter versus Displacement$^{1/3}$

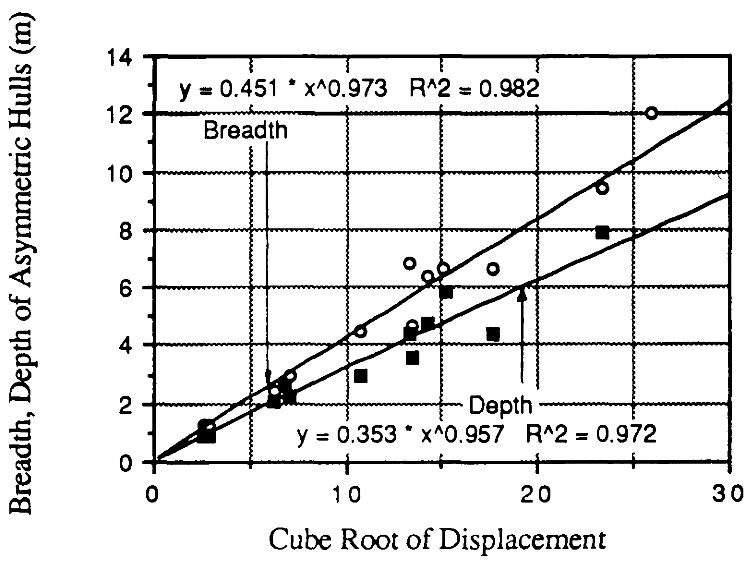
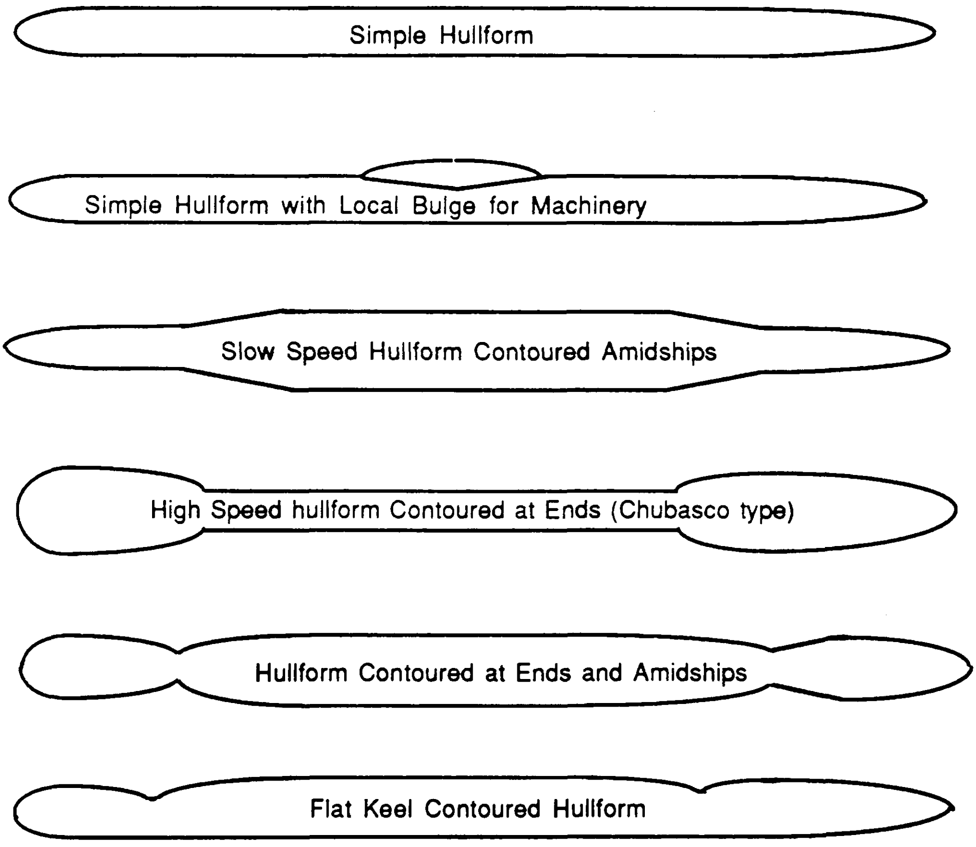


Figure 2.23 Asymmetric Hull Breadth and Depth versus Displacement$^{1/3}$

Figure 2.24 Principal SWATH Hullform Options



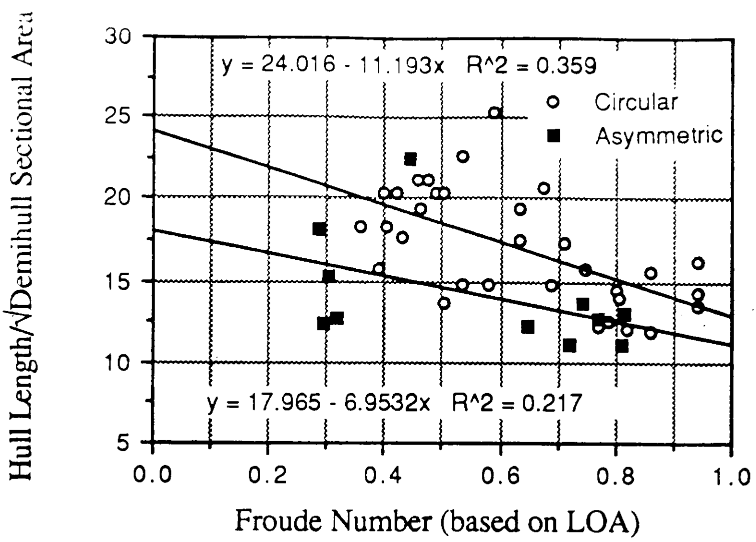


Figure 2.25 Lower Hull Slenderness - Froude Number Relationship

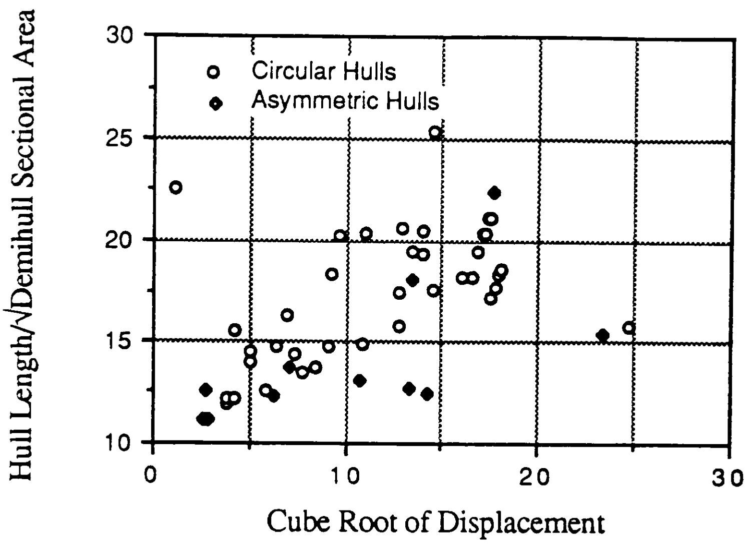


Figure 2.26 Lower Hull Slenderness - Displacement$^{1/3}$ Relationship

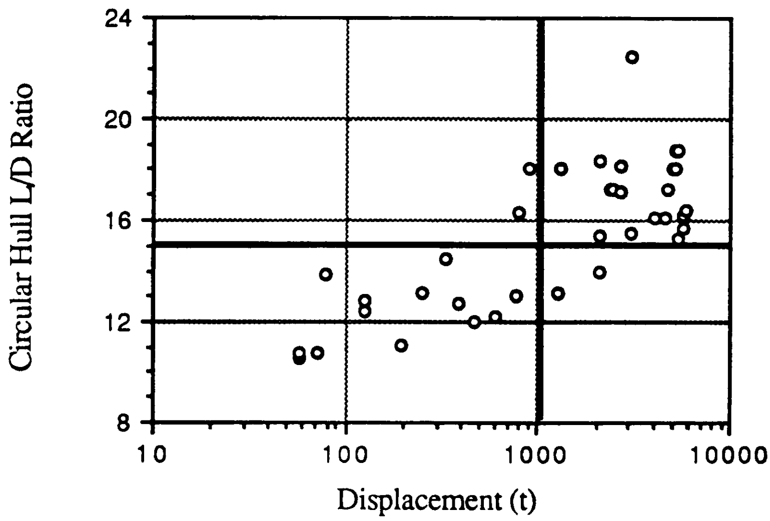


Figure 2.27 Circular Hull L/D - Hull Diameter Relationship

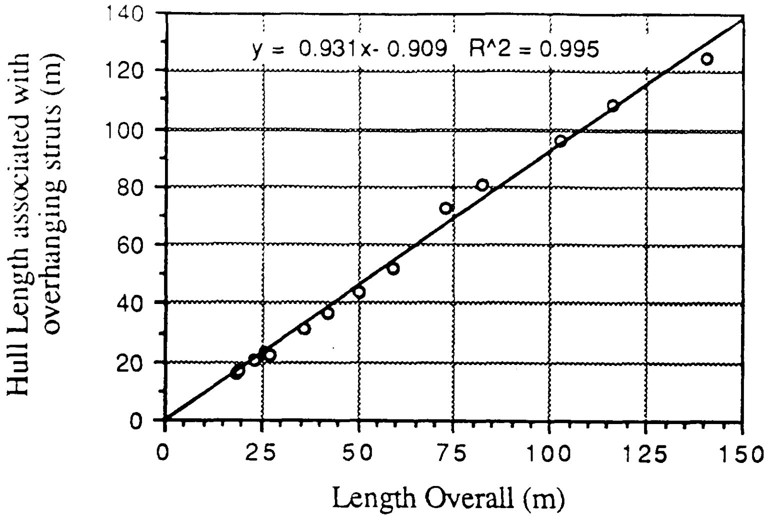


Figure 2.28 Hull Length versus Length Overall for 'Long' Strut SWATHs

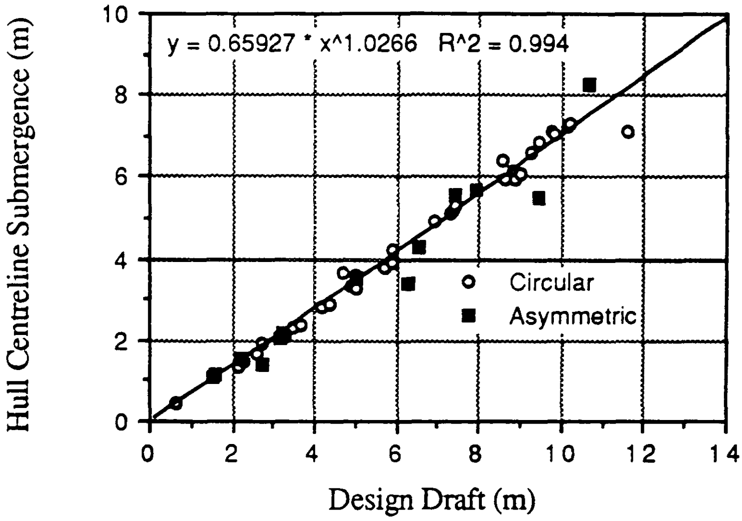


Figure 2.29 Hull Centreline Submergence versus Draught

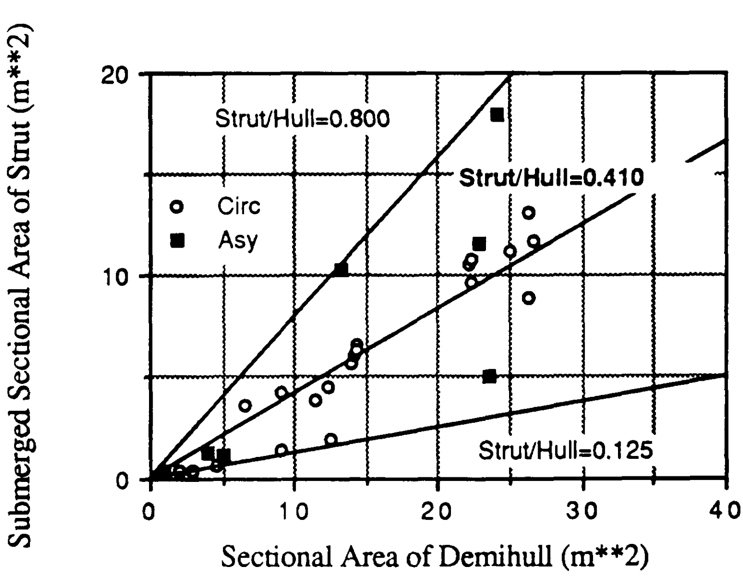


Figure 2.30 Strut Sectional Area versus Hull Sectional Area

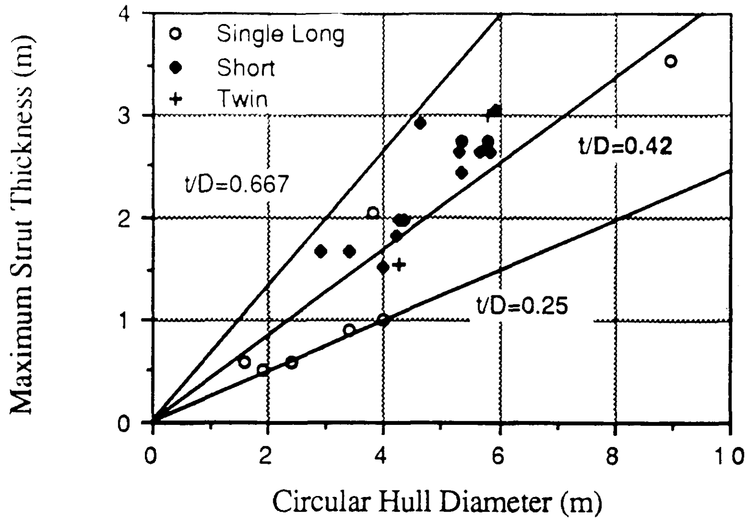


Figure 2.31 Strut Thickness versus Hull Diameter

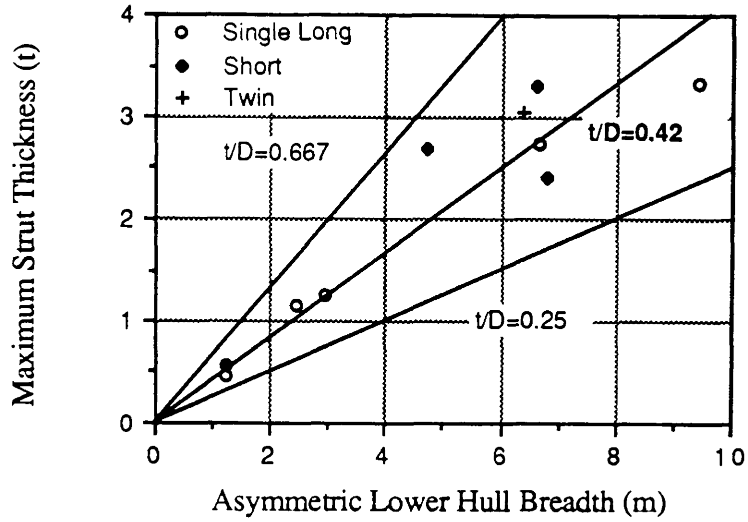


Figure 2.32 Strut Thickness versus Asymmetric Hull Breadth

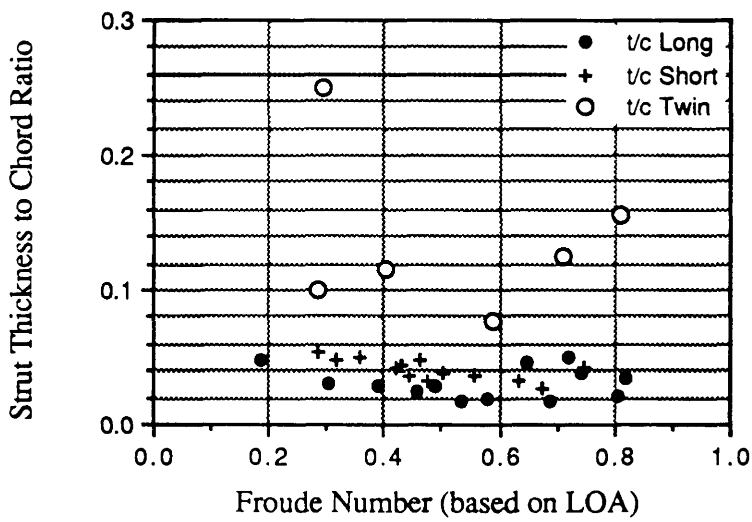


Figure 2.33 Strut Thickness to Chord Ratio

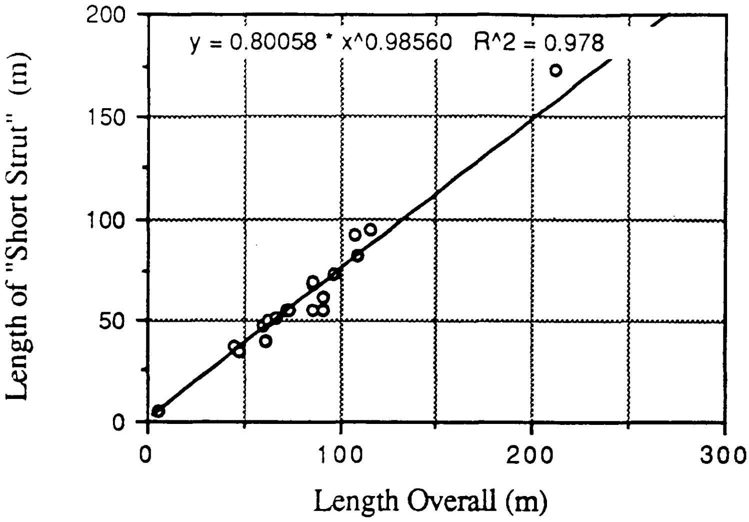


Figure 2.34 Short Strut Length versus Length Overall

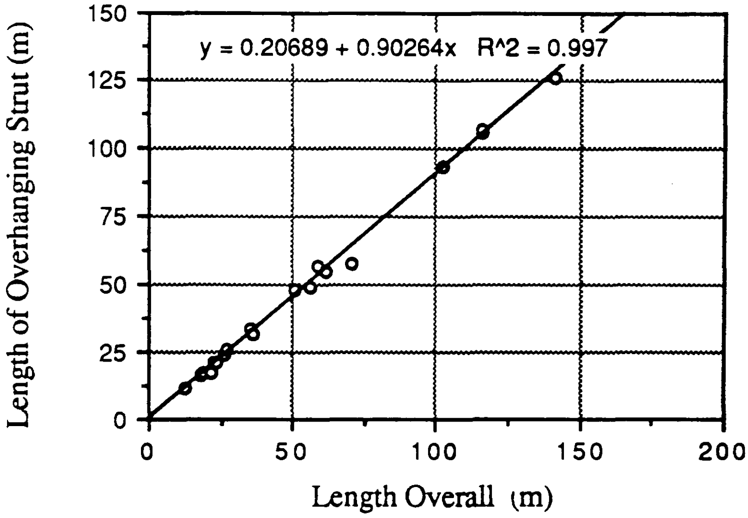


Figure 2.35 Overhanging Strut Length versus Length Overall

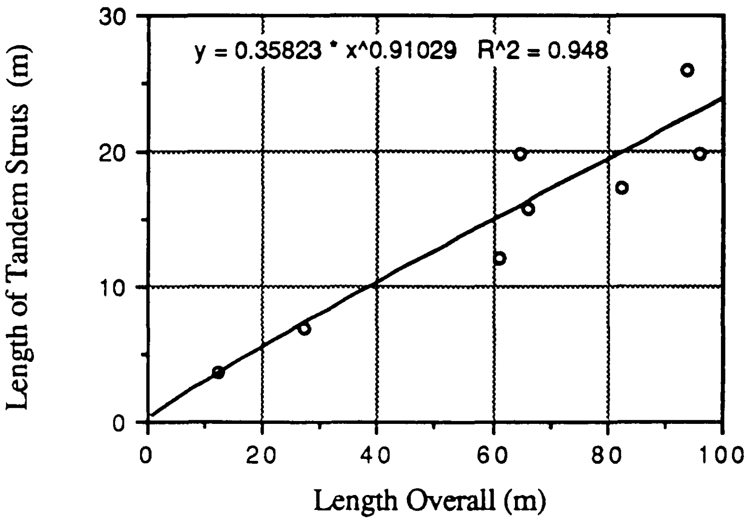


Figure 2.36 Tandem Strut Length versus Length Overall

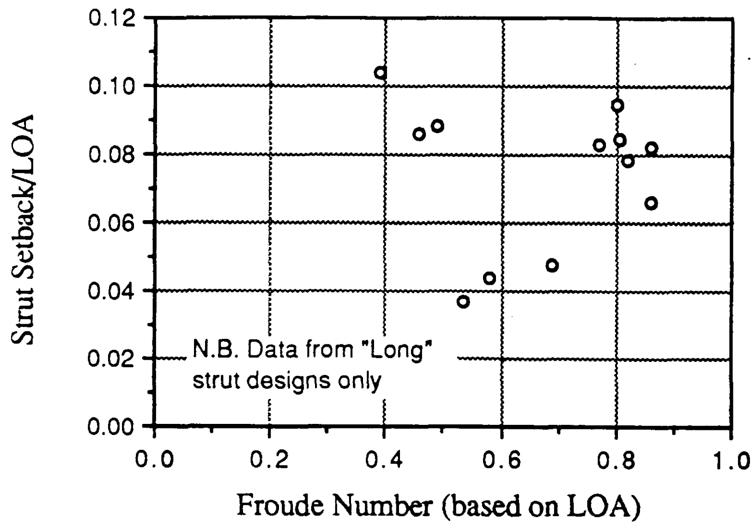


Figure 2.37 Strut Setback/Length Overall Ratio

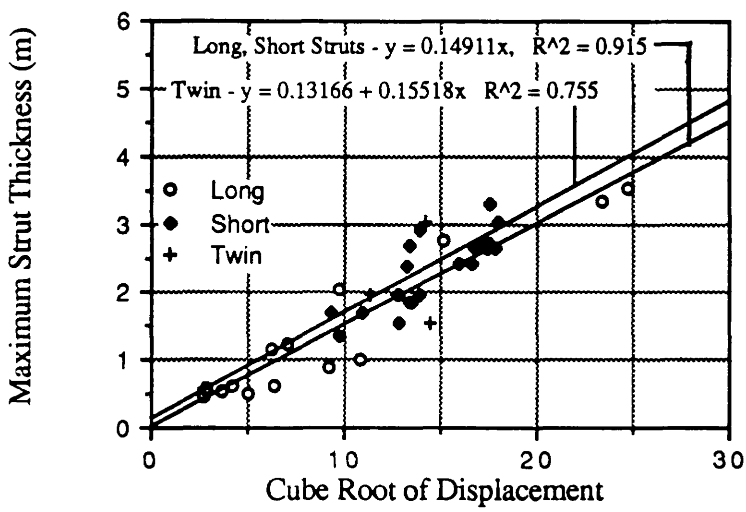


Figure 2.38 Strut Thickness - Displacement$^{1/3}$ Relationships

CHAPTER 3

DESIGN OF A SWATH SYNTHESIS MODEL

Current practice in the fields of ship design and computer aided engineering design is reviewed. These aspects are discussed with particular reference to SWATH design. From this background, an approach to the design of SWATH ships with computer assistance is developed.

3.1. Ship Design

3.1.1 Design in Naval Architecture

Many writers have attempted to define design in the context of naval architecture. The definition given by Rawson [1] is probably one of the best; *'design is a creative, iterative process serving a bounded objective'*.

This activity is one of the most subjective aspects of naval architecture, and relies heavily on accumulated experience and information. Attempts to rationalise or formalise this process are difficult and continue to occupy many researchers in other creative professions such as architecture.

Despite the reasonable view that '*the raison d'etre for the naval architect is the design of ships*' [2], there are few publications which concentrate on the theory and practice of ship design. Compared to other fields such as structures, hydrodynamics and economics, there is little published research on this aspect of naval architecture. This statement excludes work on specific designs and design tools (in which some view of the design process is necessarily implicit, however understated).

In academia, ship design theory has been the subject of only three doctoral dissertations in English. However, this is perhaps understandable, given the importance of practical experience in this field. Indeed, two of these studies were conducted by senior naval designers (Leopold[1], USA, 1977 [3] and Andrews, UK, 1985 [4]). Andrews' thesis and publications [5,6] report an extensive study of synthesis in ship design, and [4] contains an large, interdisciplinary bibliography on the theory of design, and computer aided design.

Andrews has drawn attention to the contrast between the established forums of the International Ship Structures Congress (ISSC) and International Towing Tank Conference (ITTC), and the recently formed International Marine Systems Design Conference. The former maintain a high standard of review and recommendation through prestigious standing committees, while the IMSDC has so far failed to produce similar support for the theory of ship design.

[1] It may be noted in passing that Reuven Leopold and Thomas Lang share the distinctions of being granted patents in SWATH technology and also submitting doctoral dissertations on engineering design.

3.1.2 'Rationalising' the Design Process

Although it is difficult to conceive of the design process in its entirety, various authors have sought to provided some insight to the activities involved. Watson [7], Miller [8], Lamb [9] and Brown [10] have written papers on ship design, and most textbooks refer in passing to the subject. Discussions of general design methods for offshore semisubmersibles may be found in [11,12]. Views on design can also be found in research dealing with computer aided models of ship design and economics.

Many writers make reference to the well known *'design spiral'* [13] in an attempt to lend some definition to the design process. Harvey-Evans [14] has been credited with the first published represention in this way of the activities involved in creating a new merchant ship design. However, a number of respected authors have declined to include an iconic spiral in their design model, notably Lamb [9], Watson and Gilfillan [15], and Meek [16]. The last named does however include a particularly useful list of the procedures involved, which may be further improved by addition of appropriate feedback loops. In warship design, spiral idealisations of the creative process are basically similar (Rawson [2], Gillmer [17], Johnson [18], Eames [19]). A notable exception is Andrews' [4] use of a three dimensional spiral. This approach is intended to illustrate the time component, and the external influences on the design.

The primary virtue of the design spiral is its illustration of the 'knock-on' effects of decisons in one area of the synthesis on other, later areas. Also, its (usual) form of an inward spiral is appealing in that it implies convergence with time. However, it must be conceded that while convergence to a solution requires discipline, the search for solutions in a designers mind is usually undisciplined [1]. According to Brown [10], *'the naval architectural aspects of the design are difficult to structure and are not properly represented by flow diagrams such as the design spiral'*.

The view adopted in this thesis is therefore that it it probably impossible to fully idealise a process as complex as ship design, but that some order of events must be defined in a computer based model of the process.

3.2. Computer Aided Ship Design

Computer Aided Design (CAD) is *'a technique in which man and machine are blended into a problem solving team, intimately coupling the best characteristics of each, so that this team works better than each alone'* [20]. The obvious expression of this philosophy in engineering design is to allow the man to concentrate his attention upon the design process while the machine is calculating and presenting information. Because of the high speed of evaluation and iteration, design by trial and error (or *'synthesis by analysis'*) becomes an acceptable design strategy [21]. However, the first attempts at computerizing the ship design process did not place enough decision making responsibility with the user.

During the 1960s naval architects were quick to exploit the increasing availability of cheap computing power. Large and tedious calculations such as strength and stability were successfully computerised so that as early as 1973, Gallin claimed [22] that *'ship design without the computer is no longer imaginable'*. At the same time many ambitious attempts were made to model the merchant ship design process. Early models [23,24] employed enumeration techniques to determine the best design based on some measure of merit. Later, optimisation methods were introduced to maximise economic performance [25,26] or other features.

Despite the efforts of many researchers these tools have not become widely used. This is understandable in view of the complexity of the activity modelled, and the limitations in computer hardware and software which existed at that time. Although the batch processing of the era led researchers to rationalise preliminary design, it also introduced an inflexible *'black box'* approach to the creative process. Practising designers have therefore largely continued to rely on the much more controllable traditional manual techniques.

CAD methods for warships [31 to 46] are considerably more sophisticated than those for merchant ships. This is particularly true of the ship synthesis tools developed for the US Navy which are used [28] during feasibility studies to produce from 50-300 designs, aiming at 5% accuracy in weights.

Computer aided ship design is unpopular in some circles because of a perceived loss of understanding of the underlying methods among potential users. This is a problem which can be overcome to some extent by adequate documentation. Program documentation [27] to commercial standards has been associated with the development of the CASD system described in this thesis. In addition, the automated selection of an 'optimum' design which is often associated with CASD also has many critics. Many practical designers prefer to base such a decision upon a manual examination of results from a systematic variation of design parameters.

In recent years these shortcomings have been acknowledged, and in 1979 Benford [29] called for *'more effort to be put into asking for menus rather than decisons from design systems'*.

Modern interactive processing, and the use of menus and graphics, has improved the interface between designer, program and data. These developments have permitted naval architects and software engineers to develop synthesis tools which are more closely related to manually performed design and are consequently attractive to practising designers. The aerospace industry [52 to 62] and US Navy ship designers [32 to 46] have been foremost in these advances.

Table 3.1 lists some of the more important programs developed recently for the design of high performance marine vehicles. The SWATH design program described in this thesis has been heavily influenced by these developments. In general, these programs operate on a more refined model of the vessel than the early ship design programs and the applied analysis techniques are correspondingly sophisticated. For advanced concepts such as SWATH or hydrofoil, this degree of complexity is necessary because of the lack of validated empirical or paramteric design methods. The large computational effort required by these methods usually forbids analytical optimization methods. In any case, SWATH ships are most likely to be employed in service occupations (including naval roles), which are not amenable to rating by traditional economic measures of merit.

Table 3.1 Some Computer Models for High Performance Marine Vehicle Design

Program	Vessel Type	Developer	Ref
DD08	US destroyers	NAVSEA, USA	[28,30]
HOSDES	Frigates/destroyers	MARIN, Netherlands	[31]
-	US fast patrol boats	AME Inc, USA	[32]
ASSET/HYDROFOIL (ex *HANDE*)	US hydrofoil combatants	DTNSRDC/Boeing, USA	[33-36]
ASSET/MONOSC	US monohull combatants	DTNSRDC/Boeing, USA	[36]
ASSET/SWATH (ex *SWATHET*)	US SWATH combatants	DTNSRDC/Boeing, USA	[36,42]
-	Military monohulls	Spectrum Associates, USA	[38]
PHFMOPT	US planing combatants	DTNSRDC, USA	[41]
GODDESS	RN monohulls	RCNC, UK	[45]
RECBOT	Leisure powerboats	Washington University, US	[47,48]
SWATY	US SWATH combatants	C Kennell, NAVSEA, USA	
CONDES	Monohulls	RCNC, UK	
CDSYS	RN monohull combatants	RCNC, UK	

3.3 Computer Aided Aircraft Design

Computer aided methods for aerospace vehicle design tend to be more advanced than similar methods for ship design. A large amount of research has been carried out in this field, and this has yielded CAD systems used regularly in aircraft design offices. A study of publications [52 to 62] on aircraft design models therefore offers an indication of what may yet be achieved in CASD. Reference [51] contains an extensive (177 entries) bibliography on the use of optimisation and CAD in aircraft design. Table 3.2 lists the most important of these tools.

Table 3.2 Software Tools for Aerospace Vehicle Synthesis

Program	Vehicle	Developer	Ref	Date	Comments
CPDS	Aircraft	Boeing	[51]	1972	
-	Aerospace vehicles	NASA	[51]	1972	Advanced aircraft design
-	Aerospace vehicles	Boeing	[54]	1981	Multivariate optimisation
CAPDA	Commercial aircraft	Technical Uni, Berlin	[55]	1985/6	
FEPSY	Commercial aircraft	Technical Uni, Berlin	[55]	1984	Preliminary sizing
-	Fighter aircraft	NASA, Langley, Va.	[56]	1986	Preliminary sizing
CAPS	Miliary aircraft	BAC (Military)	[57]	1977	CAD project studies
ESCAPE	Commercial aircraft	BAC (Commercial)	[57]	1977	Optimisation
-	Subsonic jet airliner	Indian Inst Technology	[62]	1980	Multivariate optimisation
NAPSAP	Naval airships	US Navy	[58]	1981	

Programs *CAPDA* and *FEPSY* developed at the Technical University of Berlin are versatile tools which have influenced the development of the SWATH synthesis model reported in this thesis. These systems have beem well described in [55] where it is their stated intention to *'retain the flexibility and transparency of manual design by limiting the scope of the system'*. In other words, the programs are used to perform well understood operations under the control of the engineer, rather than automatically producing complete designs showing little signs of human influence. Graphics help the engineer visualise the geometries he is dealing with and aid his decision making.

Another system developed at Boeing [54] transforms the complex relationships of a sophisticated design synthesis into simple second-order expressions through the use of a postprocessor. It is possible to perform a regression analysis on data produced from a limited parametric survey of potential configurations. The resulting relationships are then used to determine constrained optimal designs for a wide variety of measures of merit. Similar advances may be made in ship design by linking a high level ship synthesis model with suitable systems for data management/regression and multivariate optimisation. In effect, this would allow useful mathematical optimisations to be performed using data derived from rational methods rather than explictly parametric equations, without excessive computation costs. It is considered that this is one direction in which the present SWATH synthesis model could be usefully extended.

3.4 SWATH Design Considerations

The many different configurations which are available to the SWATH designer allow ship characteristics to be 'tailored' to suit specific operational requirements. However, this high degree of flexibility presents difficulties as well as opportunities.

In conventional ship design, the major elements of design are often decoupled and treated independently. Checks for interaction effects are minimal and rarely reveal problems.

For instance, practical adjustments in hull shape for purposes of enhancing seakeeping can be made while imposing only minor or second order changes upon the resistance characteristics or available machinery space. However, for ships such as SWATH, a much higher order of sophistication and integration is needed in design. This is a consequence of the increased number of design variables and the greater coupling between them.

As a result, a fully integrated approach to the complete design is important if the full potential of the SWATH arrangement is to be exploited and valid designs are to be produced. All the major marine design disciplines must be addressed in a consistent manner, with full account taken of the influence of decisions in one area upon other aspects of the design. At the same time, a degree of sophistication is necessary in the design calculations because of the lack of validated empirical design methods. A related reason for this approach is the fact that the difference between a *'new'* and an *'existing'* advanced marine vehicle is typically far greater than the corresponding difference between a *'new'* and a *'basis'* ship design.

These difficulties, and the relative youth of the concept, mean that a mature, consistent SWATH design methodology has not yet evolved. Additional uncertainty arises from a lack of historical data and evidence to assist the SWATH designer in developing reliable estimates of vessel characteristics.

For these reasons, a computer based approach which addresses the key marine disciplines under the executive control of the designer is especially appropriate to SWATH design. In this way the major part of the effort involved in exploring the numerous options is borne by the machine, with control resting with the user.

3.5 A SWATH Design Program

3.5.1 Development of a SWATH Design Tool

As stated earlier, the design of a SWATH involves many disciplines, which must be interfaced in a synthesis process. The interaction between major areas such as hydrodynamics and hydrostatics, structures and weights, performance and economics is great, especially for SWATH ships. SWATH synthesis has the attributes of a variational problem of a very high order which does not have a closed solution. Problems of this nature are suited to solution by iteration and this approach is used in the synthesis tool discussed in this thesis. This also reflects the common idealisation of (manual) ship design as a spiral.

SWATH design and analysis tools discussed in subsequent chapters have been integrated with ship system design data and methods to create such a SWATH design model. Key areas such as resistance and propulsion, seakeeping, structural design and weight estimation are addressed using dedicated techniques. Design synthesis is performed by iterative execution of the distinct computational modules until a balance is achieved between *required* and *available* values for the key design parameters of power, weight and space.

This development was accomplished through the utilization of technology developed at Glasgow University and that published in the open literature, together with access to the database of a modern marine consultancy. The software was developed using the FORTRAN 77 language and the VMS operating system.

3.5.2 Design Tool Philosophy

The general philosophy of the program (provisionally named *DESIN*) is based on a view of the design process as consisting of three primary elements:

a) designer,
b) design program, and
c) data

These aspects are idealised in Figure 3.1, where the communication links between the principal elements are also represented. This system allows the designer to use the design program to manipulate data describing the ship, and also general data relating to machinery and weights in order to synthesize or analyse a design. The data describing the ship is referred to as the *'ship description'*, and the synthesis process consists of the continuous modification of the ship description until a balance is achieved.

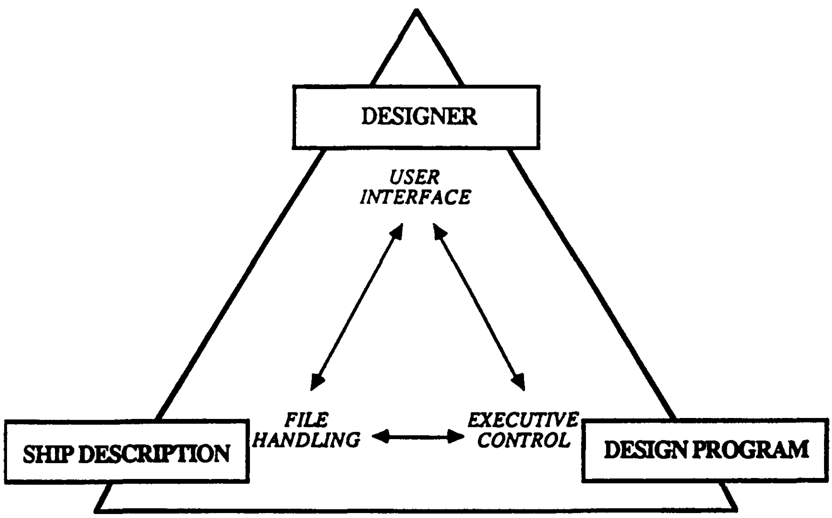


Figure 3.1 Elements in the Design Process

DESIN is nominally composed of three sections containing different types of program; 'baseline', 'synthesis' and 'analysis'. All the program modules in *DESIN* may be run independently, but the usual procedure is to execute the sections in a prescribed order. Figure 3.2 illustrates the main technology modules in *DESIN* and their intended mode of operation. The three main sections perform the following functions:

a) baseline - generates the first version of the ship description for use by synthesis tools,
b) synthesis - modifies the ship description or current model until convergence is attained,
c) analysis - does not modify ship description but provides greater design definition, including graphics and links to more advanced hydrodynamics tools

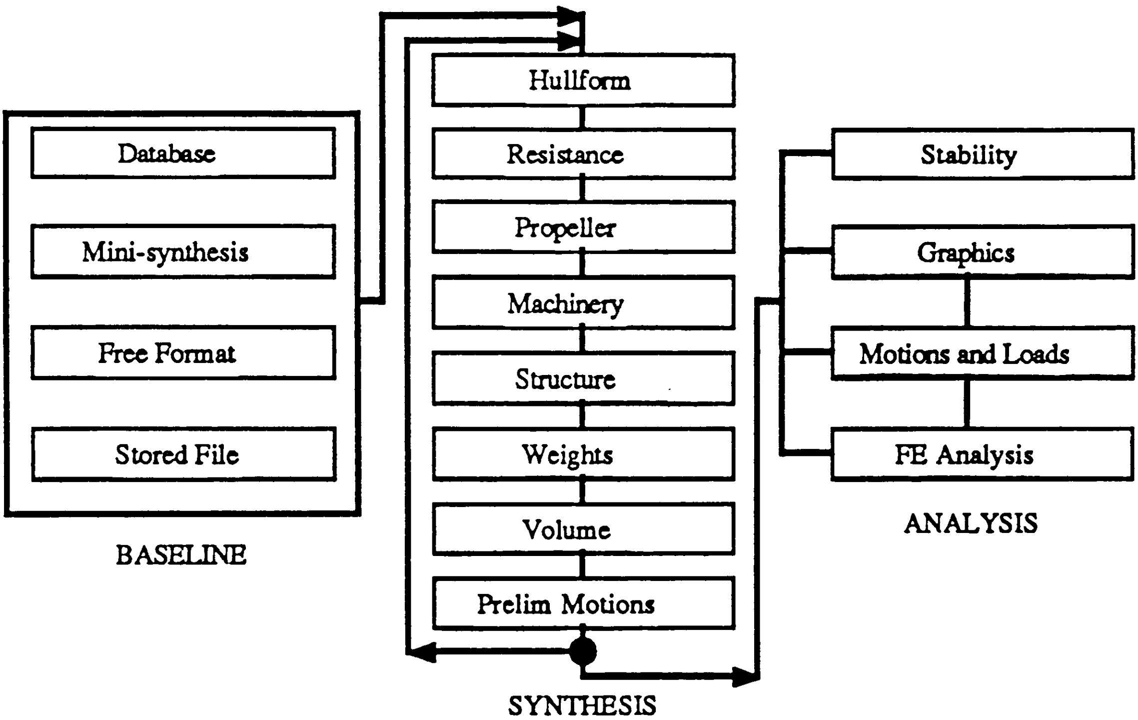
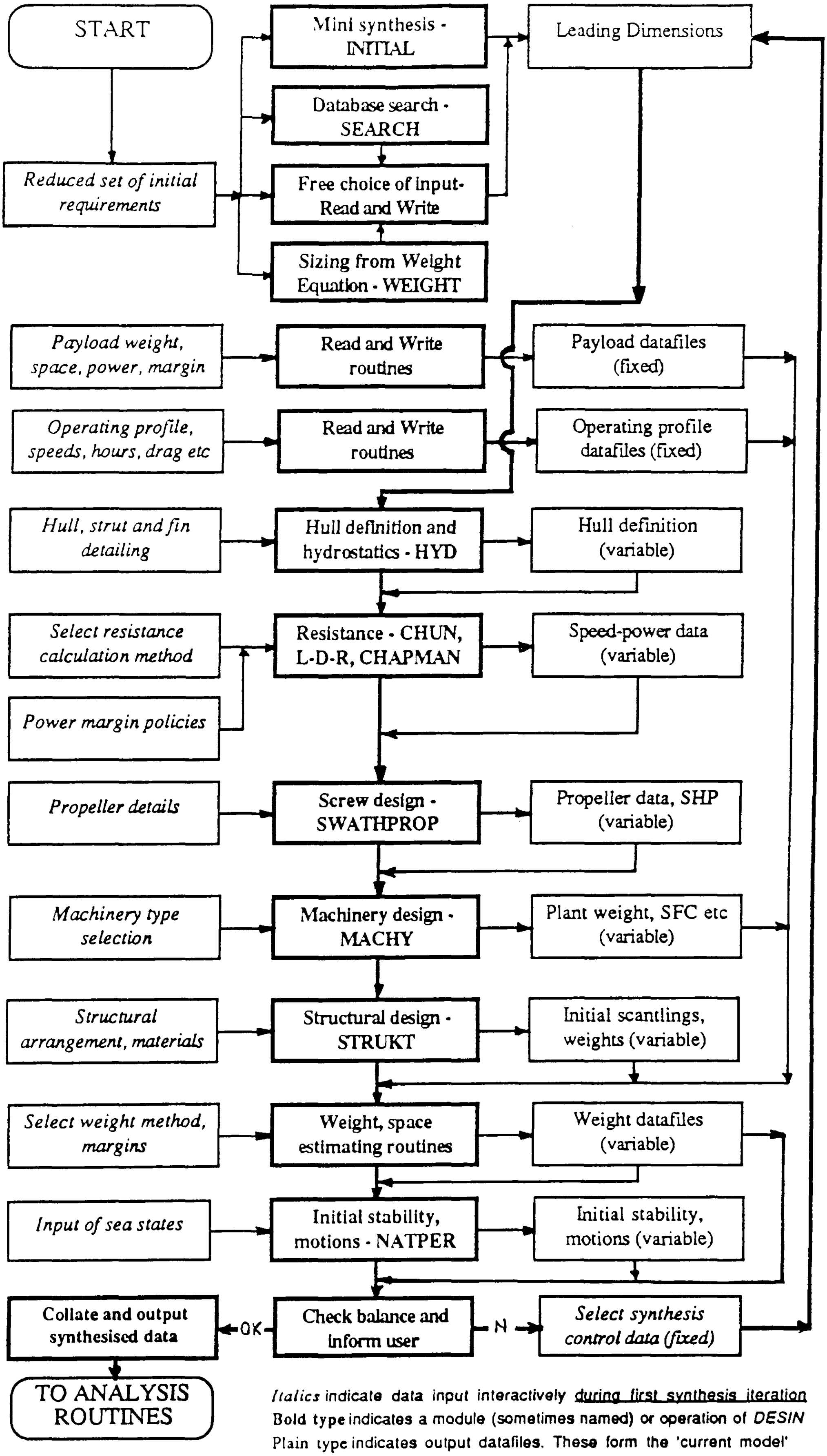


Figure 3.2 Principal Components of SWATH Synthesis Method

Chapters 4 and 5 of this thesis describes some of the methods used to develop the baseline or initial ship description. Chapters 6 to 10 detail the individual modules used to perform the calculations within the main synthesis loop, while some analysis capabilities are introduced and illustrated in Chapters 11 and 12 respectively. Figure 3.3 lists the individual components of *DESIN* with their input and output files and the main synthesis loop.



Italics indicate data input interactively <u>during first synthesis iteration</u>
Bold type indicates a module (sometimes named) or operation of *DESIN*
Plain type indicates output datafiles. These form the 'current model'
The main synthesis loop is indicated by a **bold** line

<u>Figure 3.3 Flowchart for Program *DESIN*</u>

Some functions or qualities expected of a design system are discussed below, with reference to their role in *DESIN*.

DESIN attempts to model some of the heuristic aspects of design by including a self-informing or feedback function in its iterations. Thus, for example, heavier scantlings to deal with external loads may result in higher self-weight loads, which may require increases in platform size, which may increase bending moments, and so on.

Convergence is implicit in the production of a successfully balanced new design. In the present model, initial imbalances between weight and displacement, available and required volume, and power are reduced to acceptable levels in an iterative manner. The designer controls the rate at which certain design parameters are to be altered in the iterations.

The qualities of decison making, compromise and creativity which are required of the naval architect are not modelled by the computer. It is not considered that these aspects of design can be satisfactorily handled by machine at present, and they have therefore been left to the user wherever possible. This statement is qualified by the need to perform detailed calculations using certain fixed methods. This does imply a degree of inflexibility but basic design requirements and major choices such as internal arrangement, machinery scheme, and hull form are fixed by the designer in the first design iteration. Consequences of these decisions are calculated by the programs, and their influence felt in other areas of the synthesis.

The effects of 'need' or 'compromise' driven decisions can be analysed because it is possible to run the program in a non-iterative mode. Thus, *DESIN* may be run to determine the payload capacity available on certain specified hullforms, or the speeds attainable with certain power plant. Analysis can provide further evidence from which decisions can be made, and can lead to further refinement in design.

A design is a *'description of an object and a prescription for its construction'*. In the case of a preliminary ship design tool, information must be generated and communicated in the form of drawings and data to enable the further development of the design. This function is recognised by the provision of an interface with a recognised computer aided draughting tool, described in Chapter 11. In addition, documentation [27] of the program so that its numerical output can be interpreted and communicated to others has been an aim of the present study.

One definition of design states that it 'is the optimum solution to the sum of the true needs of a particular set of circumstances'. This gives rise to the question of what is a true optimum and the expense justifed in attaining such an objective. Optimisation was not applied in the present study largely because of the difficulties in assigning measures of merit, and applying available optimisation routines [26,49,50] to the complex SWATH synthesis model. In addition, in many ship design problems, there exists flat laxity in the region of the 'optimum'.

3.5.3 Program Operation

Both the general structure and the operation of program *DESIN* are indicated in Figure 3.3. A brief description of the basic steps is useful as an introduction to the subsequent chapters.

Initialisation or development of a baseline hullform may be approached in a number of ways, with varying degrees of user input. Thus, a geometry may be proposed purely from experience, or a mini-synthesis program used. Chapters 4 and 5 discuss these aspects.

Once this stage has been completed, the full synthesis loop is entered. During the first design iteration, certain fixed design requirements are supplied by the user and stored in datafiles accessed continuously by various components of the system. Figure 3.4 illustrates the standard input sheet used to define the principal requirements for a new SWATH design.

Vessel payload is defined in terms of weight, space, and electrical power demand together with appropriate margins. The ship's speed/time profile, together with any tow drag is supplied by the user. This is used to calculate power and fuel requirements. A choice of alternative resistance calculations is made by the designer, and the margins to be applied in the powering calculations are specified. The number of blades, intended RPM and blade area ratio to be used in the propeller design are indicated. A machinery scheme is specified from a large range of possible options. For the structural design, initial choices are made regarding bulkhead and frame spacing, material and loading. The weight calculation method is specified, together with required margins.

A number of small routines have been written to accept this data from the user, and store it in datafiles in a format readable by the main calculation routines. The contents of these files remain fixed throughout each design process. During design iterations, the various technology modules operate upon this initial data, and other files (the contents of which vary) created previously by other modules, updating the latter. These files form the 'current model' or 'ship description'. The technology modules operate in the order illustrated in Figure 3.3.

SWATH DESIGN INITIALISATION DOCUMENT

DESIGN NAME	DATE

VESSEL TYPE/ROLE

OPERATING PROFILE (ranges in nautical miles at speeds in knots)

PAYLOAD REQUIREMENTS (personnel,weight,space,electrical power,tow drag)

DESIGN SEA STATES (modal periods, significant wave heights)

LIMITING MOTION CRITERIA	DESIGN LIMITS; DISPLACEMENT LENGTH BEAM DRAUGHT OTHER

CREW ACCOMODATION STANDARD (RN/RFA/MERCHANT)	NUMBERS OF;		
	OFFICERS	CPO	MEN

HULL CONTOURING (sketch)

TYPICAL HULL SECTION (B/D ratio etc)

STRUT NUMBER (1/2) PER HULL	AFT STRUT OVERHANG (Y/N)
MACHINERY FIT	STRUCTURAL MATERIALS/LOCATION (Materials-MS,B-Qual,HY80,NP8N alloy) Main Design Areas Lower Hulls Struts Haunch Haunch/Outer Wet Deck Inner Wet Deck Main Deck Superstructure
MARGIN POLICIES FOR;	

WEIGHT	SPACE	PROPULSION	ELECTRICAL

Figure 3.4 Proforma for Recording Design Requirements Input to *DESIN*

On completion of the first design iteration, the user is presented with a statement of the required and available weights and volumes of the ship. In the case of an unsatisfactory condition existing, he is allowed to modify the baseline design in an attempt to attain balance. Percentage increments to a wide range of dimensions may be selected to apply throughout subsequent design iterations. Thus, if available space is inadequate, the dimensions of the upperworks only may be incremented from the initial conditions. If the vessel is in possession of large margin on both weight and space, a smaller geosim satisfying the requirements may be sought.

Details of the various components of this design method are described in the following chapters, culminating in Chapter 12 with examples of the operation of the system.

References to Chapter 3

1. Rawson, K.J., "Maritime System Design Methodology", *Proceedings*, Symposium on Advances in Marine Technology, Trondheim, 1979

2. Rawson, K.J. and Tupper, E.C., *Basic Ship Theory*, Longman, London, 1976

3. Leopold, R. "Innovation Adoption in Naval Ship Design", *Ph.D Thesis*, Massachusetts Institute of Technology, 1977

4. Andrews, D.J., "Synthesis in Ship Design", *Ph.D Thesis*, University College London, 1985

5. Andrews, D.J., "Creative Ship Design", *Transactions*, RINA, Vol. 123, 1981

6. Andrews, D.J., "An Integrated Approach to Ship Synthesis", *Transactions*, RINA, 1985

7. Watson, D.G.M., "Estimating Preliminary Dimensions in Ship Design", *Transactions*, IESS, 1962

8. Miller, R.T., "A Ship Design Process", SNAME, *Marine Technology*, Oct. 1965

9. Lamb, T., "A Ship Design Procedure", SNAME, *Marine Technology*, Oct. 1969

10. Brown, D.K., "Defining a Warship", ASNE *Naval Engineers Journal*, Mar. 1986

11. Ghosh, S., Chou, F.S. and Huang, E.W., "A Rational Approach to the Design of a Pipelay/Derrick Semisubmersible Barge", *Transactions*, SNAME, Vol. 87, 1979

12. Penney, P.W. and Riiser, R.M., "Preliminary Design of Semi Submersibles", *Transactions*, NECIES, Vol. 101, 1984-1985

13. Snaith, G.R. and Parker, M.N., "Ship Design with Computer Aids", North East Coast Institution of Engineers and Shipbuilders, Newcastle, 20th March 1972

14. Harvey-Evans, J., "Basic Design Concepts", ASNE *Naval Engineers Journal*, November 1959

15. Watson, D.G.M. and Gilfillan, A.W., "Some Ship Design Methods", *Transactions*, RINA, 1977

16. Meek, M., "The Effect of Operational Experience on Ship Design", *Proceedings*, 1st IMDSC, London, 1983

17. Gillmer, T.C., *Modern Ship Design*, Naval Institute Press, Annapolis, Md, 1970

18. Johnson, R.S., "The Changing Nature of the US Navy Ship Design Process", ASNE *Naval Engineers Journal*, April 1980

19. Eames, M.C., and Drummond, T.G., "Concept Exploration - An Approach to Small Warship Design", *Transactions*, RINA, Vol. 119, 1977

20. Allan, J.J., "Foundations of CAD", in *Computer Aided Design*, North Holland Publishing Company, 1978

21. Clarke, A., "Review of Computer Aided Design", *Engineering*, October 1978

22. Gallin, C., "Which Way Computer Aided Ship Design?", *Proceedings*, ICCAS, Tokyo, 1973

23. Gilfillan, A.W., "Preliminary Design by Computer", *Transactions*, IESS, vol. 110, 1966/67

24. Gilfillan, A.W., "The Economic Design of Bulk Cargo Carriers", *Transactions*, RINA, 1969

25. Murphy, R., Sabat, D. and Taylor, R.J., "Least Cost Ship Characteristics by Computer Techniques", SNAME, *Marine Technology*, vol. 2, No. 2, April 1965

26. Mandel, P. and Leopold, R., "Optimisation Methods Applied to Ship Design", *Transactions*, SNAME, vol. 74, 1966

27. MacGregor, J.R., "SWATH Design Programs and Associated Reports - Volumes 1 & 2", YARD Limited 1987, 1988

28. Johnson, R.S., "The Changing Nature of the US Navy Ship Design Process", *Proceedings*, International Symposium on Advances in Marine Technology, Trondheim, June 1979

29. Benford, H., "The Changing Scene in Marine Design Techniques", *Proceedings*, International Symposium on Advances in Marine Technology, Trondheim, June 1979

30. Carlson, C., Johnson, R.A. and Helming, F.W., "Computer Aids for Ship Design, Integration and Control", ASNE *Naval Engineers Journal*, April 1980

31. "A New Design Tool: The Concept Exploration Model", MARIN Report No. 35, February 1989

32. Jons, O., and Sheldon, R., "Integrated Computer-Aided Design of Fast Patrol Boats", *Proceedings*, ICCAS'85, International Conference on Computer Applications in the Automation of Shipyard Operation and Ship Design V, 1985

33. King, J.H. and Devine, M.D., "HANDE - A Computer-Aided Design Approach for Hydrofoil Ships", ASNE *Naval Engineers Journal*, April 1981

34. Clark, D.J., O'Neill, W.C. and Wight, D.C., "Balancing Mission Requirements and Hydrofoil Design Characteristics", Paper No. 78-725, AIAA/SNAME Advanced Marine Vehicles Conference, April 1978

35. Hawkins, S., King, J. and Meyer, J., "Hydrofoil Operational Performance Enhancement Using Hybrid Design Options", Paper No. 78-750, AIAA/SNAME Advanced Marine Vehicles Conference, April 1978

36. Devine, M.D., "ASSET - A Computer-Aided Engineering Tool for the Early Stage Design of Advanced Marine Vehicles", Paper No. 78-725, AIAA/SNAME Advanced Marine Vehicles Conference, April 1978

37. Clark, D.J., Fein, J., Jones, R., and Sheridan, D., "The ASSET Program - A Current Navy Initiative", *Proceedings*, SNAME STAR Symposium, April 1984

38. Brower, K. and Walker, K.W., "Ship Design Computer Programs - An Interpolative Approach", ASNE *Naval Engineers Journal*, May1986

39. Pantazopoulos, M.S., "An Automated Optimization Approach to Conceptual Design of Naval Combatants Aided by Computer Graphics", *Ocean Engineering*, Vol. 12, No. 4, 1985, pp 321-340

40. Nethercote, W.C.E., and Schmitke, R.T., "A Concept Exploration Model for SWATH Ships", *Transactions*, RINA, Vol. 124, 1982

41. Hadler, J.B., Hubble, E.N., Allen, R.G. and Blount, D.L., "Planing Hull Feasibility Model - Its Role in Improving Patrol Craft Design", *Proceedings*, Symposium on Small Fast Warships, RINA, 1978

42. Mulligan, R.D. and Edkins, J.N., "ASSET/SWATH - A Computer Based Model for SWATH Ships", RINA Conference on SWATH Ships and Advanced Multi-Hulled Vessels, London, April 1985

43. Mulligan, R.D. and Edkins, J.N., *Small Waterplane Area Twin Hull Advanced Surface Ship Evaluation Tool - Preliminary Theory Manual*, DTNSRDC Advanced Concepts Office, April 1983

44. Yuille, I.M., "The Forward Design System for Computer Aided Ship Design Using a Mini-Computer", *Transactions*, RINA, 1978

45. Holmes, S.J., "The Application and Development of Computer Systems for Warship Design", Transactions, RINA, 1981

46. Keane, A.J., *Ship Concept Design System*, MSc Dissertation in Naval Architecture, University College London, September 1981

47. Calkins, D.E., "An Interactive Computer-Aided Design Synthesis Program for Recreational Powerboats", *Transactions*, SNAME, Vol. 91,1983, pp 49-87

48. Calkins, D.E. and Ishimaru, J., "Computer Animation and Graphics Come to Ship Designing", *Computers in Mechanical Engineering*, July 1984

49. Kupras, L.K., "Optimisation Method and Parametric Study in Precontracted Ship Design", *International Shipbuilding Progress*, vol 23, May 1976

50. Parsons, M.G., "Optimisation Methods for Use in Computer Aided Ship Design", SNAME STAR Symposium, Washington, DC, August 1975

51. Ashley, H., "On Making Things the Best - Aeronautical Uses of Optimization", AIAA, *Journal of Aircraft*, January 1982

52. Raymer., D.P., "Developing an Aircraft Configuration Using a Mini-computer", AIAA, *Astronautics and Aeronautics*, November 1979

53. Galloway, T.L., and Smith, M.R., "General Aviation Design Synthesis Utilizing Interactive Computer Graphics", SAE Paper 760476, Society of Automotive Engineers Business Aircraft Meeting, April 6-9, 1976

54. Jensen, S.C., Rettie, I.H. and Barber, E.A., "Role of Figures of Merit in Design Optimization and Technology Assessment", AIAA, *Journal of Aircraft*, February 1981

55. Haberland, C., Fenske, W. and Thorbeck, J., "A Computer Augmented Procedure for Commercial Aircraft Configuration Development and Optimization", AIAA, *Journal of Aircraft*, May 1986

56. Coen, P.G. and Foss, W.E., "Computer Sizing of Fighter Aircraft", AIAA, *Journal of Aircraft*, May 1986

57. Hitch, H.P.Y., "Computer Aided Aircraft Project Design", *Aeronautical Journal*, February 1977

58. Lancaster, J.W. and Bailey, D.B., "Naval Airship Program for Sizing and Performance (NAPSAP)", AIAA, *Journal of Aircraft*, August 1981

59. Galloway, T.L., and Waters, M.H., "Computer Aided Parametric Analysis for General Aviation Aircraft", SAE Paper 730332, 1973

60. Talcott, N.A., "Computer Graphics Display Technique for the Examination of Aircraft Design Data", AIAA, *Journal of Aircraft*, May 1986

61. Stewart, D.J. and Campion, B.S., "New Technology in Commercial Aircraft Design for Minimum Operating Cost", AIAA, *Journal of Aircraft*, May 1980

62. Dixit, C.S. and Patel, T.S., "Multivariate Optimum Design of a Subsonic Jet Passenger Airplane", AIAA, *Journal of Aircraft*, June 1980

CHAPTER 4

INITIAL SIZING METHODS

A number of methods for initial sizing of SWATH ships are described. These are; a computer database, a mini-synthesis program, a weight equation approach, and manual methods based on curves relating SWATH size to desired payload weight and/or volume, deck area, or enclosed volume. These are designed to increase the efficiency of more complex synthesis tools.

4.1. Intoduction

As discussed in Chapter 3, the design philosophy adopted in the present study includes the creation of a *baseline* model of the vessel under consideration. It is intended that a baseline design will be sufficiently well balanced to reduce the effort involved in more detailed synthesis. In this case, a baseline version of a design specifies the displacement, leading dimensions and basic hull and strut dimensions. The type of hullform, structure and machinery used in the design are indicated, but individual group weights and an exact definition of the geometry are not required explicitly. Provision has been made for four different means of generating a first attempt at defining a new project at this low level of detail. These are,

a) interrogation of a database,
b) use of a dedicated initialisation program,
c) a weight equation approach,
d) free choice by designer

Each of these methods has its own particular advantages, and will be discussed in turn.

4.2 Use of SWATH Design Database

It is important for practising naval architects to possess information describing previous designs. This often forms a convenient starting point for a new project and provides an approximate means of checking a proposed solution. For SWATH ships, validated designs are rare, but the many published conceptual designs provide another source of this type of information. It is reasonable to question the value of designs which are untested by successful construction and service, and which in many cases are low level studies. However, the distinct trends exhibited in the analysis of such data in Chapter 2 suggest that this information is of some value. Use of the SWATH design data introduced in Chapter 2 is therefore recommended as one means of developing a baseline for a new design.

Appendix 1 presents ship data in a form useful to a designer who wishes to compare vessel characteristics manually, but this can prove tedious. This information was therefore mounted on computer files (SWATHDATA.DAT) and a routine (*SEARCH*) created to allow the user to extract data for a previous ship similar to the current project. (SWATHDATA.DAT may be updated by use of the program *WRITEDATA*). When beginning a new design, the user is requested to supply information regarding required displacement and/or length, beam, draught, performance, hullform, strut arrangement, prime mover type and location, structural material, payload, intended role. It is usual to specify only one or two items and indicate 'no preference' for the others. Input of an allowable deviation from the requested values allows a range of stored designs to be investigated. Designs having characteristics falling within the limits on the specified items are displayed to the user. A full description of the use of this program in given in [26].

4.3 A SWATH Initialisation Program

4.3.1 The Need for a Basic SWATH Design Program

In many conventional ship design programs empirical or parametric methods are used to facilitate calculation of ship characteristics. However, the lack of a large database of validated SWATH designs makes such techniques difficult to develop and justify for use in SWATH design. Also, the difference between a *new* and an *existing* advanced marine vehicle such as SWATH is typically far greater than the corresponding difference between a *new* and *basis* conventional ship design. This further increases the difficulty in designing from a basis ship. It is therefore preferable, even in the earliest stage of SWATH design, to employ rigorous analytical techniques for the computation of ship data [1].

Such a computer aided SWATH design model is described in subsequent chapters of his thesis. Design synthesis is performed by iterative execution of the different computational modules until a balance is achieved between *required* and *available* values for key design parameters. However, the time required to close the design loop varies considerably depending on the accuracy of the data used to initialise the process. For example, the Boeing/DTNSRDC *ASSET-SWATH* evaluation tool may require 20 minutes to synthesize a new design (on a VAX 11/730) and may at worst fail to converge at all.

In the absence of experience or suitable basis ship data, parametric techniques are therefore acceptable and useful in the first stages of SWATH design. Effort in using more sophisticated approaches are reduced by using data prepared by a simple initialisation model.

This section describes a computer program (*INITIAL*) which has been developed to provide estimates of SWATH characteristics, depending on basic input requirements. In effect this module mirrors the more rigorous approaches in seeking to perform a *mini-synthesis* employing simple iterative and parametric techniques. Design balance is sought on the basis of weight, as this is the primary limitation in SWATH design. Trends observed in existing SWATH designs have been used in estimating weights and dimensions.

As well as its primary function in providing a starting point for a ship design, to be further refined by other means, *INITIAL* also offers a non-detailed synthesis function. Rapid solutions to specified operational requirements may be generated using the tool in this way. Preliminary designs produced in this manner conform to the state-of-the-art in SWATH technology, and are therefore likely to be feasible, even if not offering novel features tailored to specific roles.

In addition, the ease with which the program may be used to generate large quantities of data lends itself to use in basic trade-off studies. The user may rapidly explore the *design space* in an efficient manner by use of such a tool.

4.3.2 Program Concept

The approach employed in the construction of *INITIAL* has been directed towards providing a tool which will produce output from an interaction between program and user in a form suitable for use by more involved design programs. The role of the program in this process is basically to serve as an automatic calculating, advising and checking device for the designer.

Therefore, the program allows the user to make all the major design decisions such as number and style of struts, type of machinery and structure etc. Consequences of these decisions are calculated numerically by the program.

The program may be operated to derive a displacement from a given combination of payload/speed/range, but may equally be used to provide a weight check on a vessel whose size is selected by the user. In both cases guidance on linear dimensions will be provided by the program. Though the program will issue explicit warnings and advice, the user remains free to proceed with an unbalanced design or select unsuitable dimensions if these are the characteristics with which he wishes to initialise his design process.

INITIAL is a flexible tool, the precise use of which lies with the user. It's primary role is to help in the selection of a vessel size and dimensions which will facilitate an efficient closing of the design spiral by more sophisticated means. It is not a full Concept Exploration Model.

4.3.3 Weight Breakdown Approach

The basic approach used by *INITIAL* is that of seeking to balance the displacement with the weight of structure and all other shipboard items, using simple relationships to determine individual group weights. It is acknowledged that although SWATH is intrinsically a weight limited concept, initial sizing may be controlled by other factors such as requirements for deck area, or volume [19] which are discussed in section 4.5.

Classification and control of the different weight groups is fundamental to *INITIAL*. Because of the influence of the US Navy on the development of the SWATH concept, much of the available weight data for SWATH vessels is presented in terms of the USN Ship Work Breakdown System (SWBS) [2]. The weight classification schemes employed by other Western nations are broadly similar. Consequently, the weight breakdown used in *INITIAL* is closely related to the USN system.

The full load displacement is equated to the sum of the group weights by

$$\Delta = WS+WM+WAUX+WO+WF+WSM+WP \qquad \text{Eqn. 4.1}$$

WS is hull structural weight, and includes plating and framing of hull and superstructure, and all associated closures, foundations, masts and towers etc.

WM is the weight of the main propulsion plant, and includes prime movers, reduction gears, shafting, propellers and all associated control and support systems. Generators, motors and cabling associated with electric propulsion are also included in this group.

WAUX is the weight of all auxiliary systems, including ship service electrical generating plant. Important elements of this group are steering gear, navigational equipment, and systems for lighting, heating, air conditioning, firemain and ballast.

WO is the weight of the hull outfit and furnishings. This group includes non structural bulkheads and closures, deck fittings, gratings, ladders, deck covering, insulation, upholstery and fittings for internal spaces etc.

WF is the weight of fuel carried to supply propulsion and generating requirements.

WSM is an allowance which covers the weight of personnel and effects, a design margin, and weights of fresh water (FW), stores, lubricating oil etc.

WP is the useful payload. This may be passengers or cargo, or armament and ammunition in the case of a warship. Special equipments required to fulfil ship function are included in this group if necessary.

For the purposes of initial design, equipment specifically required in order for the ship to perform its function may conveniently be specified as part of the payload. This could include, for example, extensive hospital equipment, or powerful firefighting pumps. Such items should, strictly speaking, be included in the outfit and auxiliary weights, respectively. Because the present model is based upon data from *normal* designs, such a rigorous approach would prove inaccurate, and the inclusion of such weights as payload is justified.

4.3.4 Structural Weight Estimation

4.3.4.1 General

SWATH structural weight typically contributes up to half of the vessel displacement, and its accurate estimation is necessary if confidence is to be placed in a particular design. It is difficult to provide an accurate estimate of this weight simply by empirical methods. Chapter 9 discusses some methods for SWATH structural weight estimating.

As well as the possibilities presented by use of different structural materials, ship configuration has a significant influence on SWATH structural weight. Internal arrangement of structure may be manipulated to reduce structural weight, while the external dimensions of the vessel determine the magnitudes of the applied loads and the shell area. In view of the large number of permutations possible in SWATH geometry, and the dearth of validated structural designs, it is difficult to identify reliable parametric relationships between dimensions and structural weight. Indeed, considerable variation is possible in detailed design for any specific vessel. Table 4.1, from ref. [7], illustrates the variation in estimated structural (and other) weights (in tonnes) for the T-AGOS 19 at different stages of the design process. Shipyard estimates and *as built* weights may differ still further.

Table 4.1 Variation in T-AGOS 19 Weight Estimates from. ref. [7]

Weight Group	Initial Weight Baseline	Weight 'Budget'	'Final' Weight
Hull Structure	1398.5	1412.7	1593.9
Propulsion	72.6	72.8	66.1
Electrical	118.7	110.7	130.3
Command/Control	48.7	48.2	41.5
Auxiliary Systems	475.7	374.1	350.3
Hull Outfit	247.4	234.4	236.2
Armament	0.2	0.2	0.3
CD Margin	165.3	153.0	---
Lightship Weight	2527.1	2406.1	2419.3

The uncertainty involved in this area of SWATH technology is further illustrated by the generally held view that the T-AGOS 19 scantlings are conservative [21], and probably adequate for a ship some 50% larger.

4.3.4.2 Derivation of Estimation Equations

One initial design approach has been developed by Nethercote and Schmitke [6] for use in a Concept Exploration Model for SWATH ships (*SWACEM*). This method employs the concept of structural densities and estimates structural weight on the basis of volume enclosed in the major components of the geometry.

Structural densities for the box, struts and hulls were derived [8] from analysis of results from the USN Ship Structural Synthesis Program (as adapted for SWATH). The amount of geometrical variation possible in SWATH design would make a fully comprehensive parametric survey of loads and structure an enormous and expensive computational task. It may therefore be safely assumed that the data used to generate the design algorithms was based on a relatively small sample of results from certain SWATH designs. In addition, although some measure of ship size is implicit in enclosed volume, the influence of external dimensions on applied loads (and hence on structure) is difficult to trace in this approach.

The structural density approach to SWATH structural design has been studied (Chapter 9) using available structural weights and vessel dimensions. Owing to the fact that published steelweights relate to the ship in its entirety, and not to the box, struts and hulls separately, an overall structural density had to be employed. Under this limitation, the following approximations were derived for structural density.

Material	Structural Density
Mild Steel	$1.231\ FTEV^{-0.257}$
'Advanced' Structures	$0.096\ FTEV$
Aluminium	$0.270\ FTEV^{-0.159}$

FTEV is a function of the total enclosed volume in cubic metres, and may be employed with the appropriate structural densities to produce structural weight estimates for SWATHs where FTEV is known.

FTEV = 2 (Hull cross-section area *x* hull length)
+ 2 (Strut cross-section area *x* strut length)
+ (Box depth *x* box beam *x* box length) Eqn. 4.2

The equations give reasonable agreement with the data used in their derivation. However, these relationships have not been incorporated in *INITIAL* because of their requirement for knowledge of the exact geometry of the SWATH. *INITIAL* was designed to allow the user to choose the precise dimensions after the weight balance had been achieved so this approach is inappropriate. In a process governed solely by the computer, it is an acceptable technique, but impossible in an iterative process where the user is intended to select dimensions for the design. The equations may however be used as checks on structural weights derived by other means.

Operating at a much higher level of sophistication is the *ASSET-SWATH* structural design module [9], which employs a first principles approach to SWATH structural design. The degree of complexity in this program implies that input data be supplied at a level of detail too high for the preliminary design stage. Use of this module is therefore not as rapid and simple as is desirable in an initial design situation. Also, at the level of detail for which it is intended, difficulties have arisen in reconciling known structural weights with output from *ASSET*.

Since *INITIAL* was conceived as a program operating at a lower level of sophistication than either *ASSET* or *SWACEM*, a cruder approach was deemed acceptable. Structural weight fractions from a collection (Appendix 1) of conceptual SWATH designs were plotted (Figures. 4.1 to 4.3) against Full Load Displacement. As expected, a high degree of scatter was evident in the data, but basic design relationships relating to three distinct types of construction were extracted.

a) Conventional shipbuilding steel, High Strength steels (not HY or HTS steels)
b) Advanced techniques, employing special materials (aluminium, HTS, HY), perhaps in a hybrid mix with mild steel, in a drive to reduce structural weight without resorting to universal use of aluminium.
c) Marine grade aluminium alloy. This is the generally used technique for small SWATHs (below 100t), and has been proposed for larger high speed designs, where low weight is crucial.

The derived equations are-

Mild Steel	$WS/\Delta = 0.425-0.00000175\Delta$	Eqn. 4.3
Hybrid	$WS/\Delta = 0.417-0.0000085\Delta$	Eqn. 4.4
Aluminium	$WS/\Delta = 0.388-0.0000311\Delta$	Eqn. 4.5

Despite the degree of variance, the data does confirm that mild steel structures are the heaviest, with aluminium the lightest. The fact that all three options exhibit a maximum fraction at the lowest displacements is also realistic. In practice, the smallest SWATHs would tend to employ Aluminium structure only, while larger, commercially viable designs would not consider it's use.

As may be observed from the figures, data on Aluminium and Hybrid designs is limited to vessels of less than 6000 tonnes. Practically, the upper limit on the size of aluminium SWATHs is likely to be even lower.

Table 4.2 and Figure 4.4 illustrate the correlation between structural weights obtained by the above methods, and the original concept design estimates used to derive the relationships.

Table 4.2 Structural Weights by *INITIAL* and Manual Design

Design (see Appendix 1)	Δ (t)	Structural Weight by - Manual	*INITIAL*
Aluminium Structures			
1	77.5	33.7	29.9
5	128.4	44.6	49.3
6	255.9	78.6	97.2
7	763.8	257.5	278.0
8	1273.9	408.3	443.0
15	57.9	22.8	22.4
16	57.9	27.6	22.4
50	4572.0	1096.0	1124.0
42	3048.0	1006.0	893.0
Advanced Structures			
12	1950.0	800.0	780.8
49	4064.0	1965.0	1554.0
50	4572.0	1843.0	1728.8
51	5334.0	1662.0	1959.7
54	480.0	180.0	198.2
86	160.0	78.4	66.5
Mild Steel Structures			
49	4064.0	2136.0	1780.0
56	5029.0	2087.0	2093.0
57	5125.0	2163.0	2132.0
58	5189.0	2351.0	2158.0
59	5317.0	2648.0	2210.0
72	7183.0	2403.0	2962.0
88	15067.0	6292.0	6006.0
92	12786.0	4090.0	5148.0
TAGOS	3450.0	1593.0	1445.0
103	2415.0	1056.0	1012.0
104	2330.0	1050.0	980.7

4.3.5 Machinery Weight Estimation

4.3.5.1 General

Correct estimation of required power is the fundamental starting point for an accurate calculation of propulsion machinery weight. For conventional ships, the long history of predicting required propulsive power has led to the development of reliable estimation techniques which are regulary used in preliminary design.

The usual approach computes total resistance, and hence effective power, from the sum of frictional, residuary, appendage and aerodynamic drag. Calculation of frictional resistance does not present any particular problems for the SWATH designer but the correct estimation of residuary resistance is an extremely complicated problem. For monohull ships there exists comprehensive series data on residuary resistance which may be used with confidence in preliminary design. No such database exists for SWATH ships, and the SWATH designer must ultimately resort (Chapter 6) to the use of one of the computerised theoretical prediction techniques employing linearised wave theory and the thin ship assumption [10, 11, 12].

These techniques, while providing accurate predictions of the wavemaking resistance contributions of the individual submerged components and related interferences, require input of extensive geometry description data. They also involve substantial execution and CPU time and, as such, are not suitable for use as initial design tools. Alternative approaches are therefore necessary.

Three alternative approaches have been investigated with a view to their use in an initialisation model.

4.3.5.2 Power Estimation by 'Admiralty' Approaches

Regression analysis of available SWATH dimensions, performance and installed power has been used to construct simple preliminary SWATH powering formulae. Equations of this so called 'Admiralty' type seek to relate installed power to a function of ship size and speed. Consequently there is no possibility of explicitly accounting for the complicated wavemaking resistance effects characteristic of the SWATH form.

Even when used in connection with conventional monohull ships, such equations demand caution on the part of the user. Generally they are only assumed to be valid within the confines of a well defined ship class, or when used with well matched *type* ships.

'Admiralty' Method

The traditional 'Admiralty' powering approach relates installed power to $k\Delta^{2/3}V_m^3$, where V_m is the design speed. Correct use of this method involves selection of a similar *type* ship for which the power, displacement and speed are known. The constant k may then be derived and applied to the *new* displacement and speed, thus providing an estimate of power.

It is desirable to define a value of k which is applicable for a wide range of ships, and this is the approach which has been adopted in this study. For a large number of SWATH designs, values of installed power have been plotted (Fig. 4.5) versus $\Delta^{2/3}V_m^3$. Instead of defining k as a simple constant, a more accurate correlation was determined from regression analysis. Power was observed to follow a close logarithmic relationship with the function of size/speed raised to the power 0.897. This yields the expression

$P_M = 0.035\Delta^{0.598}V_m^{2.691}$ Eqn. 4.6

where P_M is in metric HP
Δ is in tonnes (SW)
V_m is in knots

Modified 'Admiralty' Approach

It has been suggested [22, 23] that each identifiable type of marine vehicle may be expected to exhibit a constant value of α over a wide range of Froude Numbers, where α is defined as the ratio between V_m and $(P_M gLOA/\Delta)^{1/3}$. This fact has been confirmed for SWATH ships (Section 2.2.2 of this thesis). The equation may be rearranged, and the gravitational constant eliminated, in order to relate P_M to $k\Delta V_m{}^3/LOA$. This formulation also incorporates some measure of viscous resistance and the dimensions of wetted surface, in this case Δ/LOA. The concept of vessel slenderness is introduced by means of the displacement/length term. In addition, the quantities on both sides of the equation have the same physical dimensions (ML^2/T^3) . However, these refinements do not lead to marked improvement in accuracy, and the relationship plotted in Figure 4.6 exhibits the same degree of correlation as the original 'Admiralty' method. Introduction of logarithmic regression yields the expression

$P_M=0.657(V_m{}^3\Delta/LOA)^{0.928}$, giving

$P_M=0.657V_m{}^{2.784}\Delta^{0.928}/LOA^{0.928}$ Eqn. 4.7

where P_M is in metric HP
Δ is tonnes (SW)
V_m is in ms^{-1}
LOA is in metres

4.3.5.3 Power Estimation by Direct Calculation

General Approach

While both the above approaches perform well throughout a wide range of displacement and speed combinations, and are useful in preliminary design, a more rigorous power prediction method is preferable. The rational approach to SWATH power estimation may be mirrored using semi-empirical techniques.

Installed power may be related to total resistance as follows

$$P_M = (R_T V_m/(n))(SM+1) \qquad \text{Eqn. 4.8}$$

where P_M is installed power in kW
R_T is total resistance in kN
V_m is design speed in m/s
SM is percentage Service Margin
n is overall propulsion system efficiency, including propeller and transmission losses

Despite the existence of a large database of installed power for conceptual SWATH designs, information on appropriate Service Margins is virtually non-existent. Mitsui state [25] that a service margin of 10% was used in the design of the *Kaiyo,* but more information is difficult to obtain. Since reduced speed loss in waves is presented as one of the primary advantages of the SWATH form, such a relatively small service margin may be acceptable. On the other hand, the small number of SWATH ships operating at sea must introduce a realistic degree of conservatism into power estimates until prediction techniques are fully validated. In this study therefore, a Service Margin of 15% has been adopted, in line with monohull practice [4].

An overall drive train efficiency of 70% has been defined for the purposes of this study. This figure is based on a shafting/transmission efficiency of 97% and a QPC of 72%. Propulsive efficiency is typically high for SWATH ships, but like resistance, is strongly linked to changes in form and operating speed. There is a distinct absence of published information on this aspect of SWATH design, but Figure 4.7, from [6], offers some confirmation of the value selected for *INITIAL*. Detailed design should account for variation in QPC with form and speed, but in the first instance a simple assumption may suffice.

In summary, *INITIAL* takes SM=0.15 and $n = 0.70$

It should be noted that the above value of n relates to vessels having mechanical transmission. Use of electrical drive will introduce further inefficiencies. Electrical generation and transmission losses of 4% are accounted for by *INITIAL* if diesel or gas-turbo electric drive is specified. In these cases P_M is divided by 0.96.

The total resistance R_T may be computed as the sum of $R_F + R_R + R_{AP} + R_{AA}$ (frictional, residuary, appendage and aerodynamic drag)

Frictional Resistance

Frictional resistance may be found by using simple plate friction theory, defining

$R_F = 1/2\rho(C_F+C_A)S\,V_m^2$ Eqn. 4.9

where S is wetted surface in m^2,

ρ density of SW, 1025 kgm^{-3},

C_F is the Frictional Resistance Coefficient, and

C_A is a Correlation Allowance, accounting for roughness etc.

SWATH wetted surface S may be estimated using an equation from [14], giving

$S=\nabla^{2/3}(13.6-0.31(20-L/D))$ Eqn. 4.10

where L/D is the lower hull slenderness ratio. Most practical SWATH designs will have L/D ratios of about 14, and this assumption may be used to simplify the equation still further.

The same reference recommends the use of a roughness allowance of C_A=0.0005, as do [6] and [9]. This value has been adopted for *INITIAL*.

Although the *Schoenherr '47* formulation as used by Chapman [6,9,10,17] is also valid, the *ITTC'57* formulation as used by Lin [11, 17] has been used to calculate C_F.

$C_F=0.0075/(\log_{10}R_N-2)^2$ Eqn. 4.11

using $R_N=V_mLOA/\nu$ with $\nu=1.19\times10^{-6}\ m^2s^{-1}$ (15°C, SW)

Dedicated resistance prediction programs calculate separate values of R_N (and hence C_F and R_F) for the struts and hulls. For the present purpose however, the above approach is considered adequate [14].

Residuary Resistance

In this study, the term residuary resistance is taken to include wavemaking, eddymaking and spray drag. The latter effects may also be considered as form drag. From a theoretical point of view, it is relatively easy to predict the wavemaking component of SWATH residuary resistance using linearised wave theory. Considerable uncertainty exists in predicting the form drag of SWATH ships since no validated technique is available.

The influences of theoretically predictable wavemaking resistance, and the rather more uncertain form resistance, may be acknowledged by the following formulation for residuary resistance.

$$R_R = 1/2\rho(C_{FF}+C_R)S\ V_m^2 \qquad \text{Eqn. 4.12}$$

where S is wetted surface in m^2,

ρ density of SW, 1025 kgm^{-3},

C_{FF} is the Form Resistance Coefficient, and

C_R is the Residuary Resistance Coefficient

Form drag may be defined as the difference between the viscous resistance of a body and that of a flat plate having the same wetted surface and length. This difference arises because of the pressure drag and increased frictional resistance due to the three dimensional shape of the body. Because of the complex mathematical problems, an exact solution for this resistance component is extremely difficult to develop. This is reflected by the fact that, although theoretically correct in other respects, the existing SWATH resistance prediction techniques resort to the use of empiricism in the area of form drag.

The CEM for SWATH ships [6] calculates wavemaking resistance using Chapman's approach [10,17]. In this program, lower hull eddy-making resistance is taken as 10% of the hull frictional resistance. Strut eddy making resistance is calculated by multiplying the strut frictional resistance by an empirical eddy-making factor from Hoerner.

$$1+2\ (t/L)+60\ (t/L)^4$$

where t/L is the strut thickness-length ratio. Spray drag is determined using results from model tests. These techniques are suitable for application to a design in an advanced state of definition, but are not ideal for the first estimate of power. Methods which are not dependent upon exact hull geometry are more useful for this purpose.

The SWATH concept evaluation program *ASSET* [9] groups the above effects under the collective term form drag, and employs an unspecified empirical form factor in the computation.

In discussion to [6], Kennell [15] suggests that the use of a form factor (C_{FF}=0.0005) with the analytical wavemaking resistance coefficient provides good engineering estimates of residual resistance. Unspecified higher values are recomended for use in the region of the wavemaking peak (between F_N 0.27 and 0.33). This approach is considered to account for both eddy and spray drag.

In the Lin-Day-Reed SWATH resistance program [11,17], all form resistance is determined by a single empiricism. Based on a number of model tests with SWATH models, differences between computed and measured residuary resistances were defined as form drag. Figure 4.8 [17] illustrates the form drag coefficient defined in this manner. It can be seen that, apart from a marked peak, a basic value of C_{FF}=0.0005 was found.

Rather than adopt the Lin-Day-Reed method in its entirety, a simplified form drag coefficient was chosen for *INITIAL*. This approach was justified by the argument that, in the absence of a correct calculation of wavemaking drag, the residuary resistance coefficient C_R would necessarily contain a number of undefinable effects. It was therefore felt that all phenomena not conforming with known, simple trends should be considered in the formulation of C_R. For these reasons, a constant form factor of C_{FF}=0.0005 was selected for *INITIAL*.

The formulation of C_R in an initial design situation cannot include a correct theoretical calculation of the wavemaking resistance. Given a suitable theory, extensive geometry input data is required, and this, together with the computational problems, is prohibitive. A semi-empirical approach seeking to mirror the actual situation should therefore be adopted.

Some idealising of the wavemaking characteristics of SWATH ships is necessary in formulating an empirical solution to the problem. Figure 4.9 illustrates the relative contributions of the different wavemaking sources. Ref. [14], from which Figure 4.9 is taken, is a good general discussion of the complicated effects characteristic of SWATH forms.

Single strut per hull SWATH ships typically exhibit peaks in wavemaking resistance at Froude Numbers (based on hull length) of 0.3 and 0.5. These peaks occur as a result of large wavemaking contributions from each strut and each hull and unfavourable inteference between the two demihulls.

Typically, a distinct hollow in wavemaking resistance is expected at Froude Numbers around 0.36. This is a result of minimum contributions from each hull and each hull-strut interaction, and favourable interference between the two hull and two hull-strut wave systems.

At Froude Numbers greater than 0.5, a similar situation exists, except that interference between the port and starboard demihulls is unfavourable. This leads to a rather less marked reduction in wavemaking resistance.

The above effects should be present in any empirical representation for use in a power prediction program and although modern SWATH designs with contoured hulls do possess much flatter C_R curves than earlier ships. It is therefore surprising to see the simple form proposed for a *SWATH-ASSET* [18] initialisation model. This formulation (Fig. 4.10) assumes an initial variation of C_R with F_N and a constant value of 0.001 for volumetric Froude Numbers above 0.23.

In order to generate an idealisation of C_R for use in *INITIAL*, figures were obtained for the C_R values required to produce agreement between the proposed methods and known installed powers. These are illustrated in Fig. 4.11, plotted against volumetric Froude Number (roughly equal to 2.2 times Froude Number based on LOA). The results show a high degree of scatter, and this reflects the wide range of design margins, non- standard appendages, rough weather allowances, and de-rating of machinery implicit in the available data. Despite the many factors serving to confuse the issue, an underlying trend of peaks and hollows may be discerned in the values. The general trends of the data, and the known physical reality, were used to construct the simple approximation for C_R superimposed on the data.

However, although the proposed relationship between C_R and F_N does make allowance for the peaks and hollows peculiar to SWATH ships, it cannot be regarded as providing any theoretically sound measure of the wavemaking drag. All manner of factors are present in the approximation in addition to the wavemaking drag coefficient. For example, the augment to the form factor allowance discussed previously is considered to be incorporated in the formulation.

In *INITIAL*, C_R is defined as follows, expressed in terms of volumetric F_N

$0.000<F_N<0.688$	$C_R=F_N(0.003/0.688)$
$0.688\leq F_N<0.865$	$C_R=0.003-(F_N-0.688)(0.002/0.177)$
$0.865\leq F_N<1.300$	$C_R=0.001+(F_N-0.865)(0.004/0.435)$
$1.300\leq F_N<1.808$	$C_R=0.005-(F_N-1.300)(0.003/0.508)$
$F_N\geq 1.808$	$C_R=0.002$

Appendage Resistance

Data on appendage resistance for SWATH ships is extremely rare in the open literature, but in their CEM for SWATH ships, Nethercote and Schmitke [6] define R_{AP} as 10% of R_F as calculated by Chapman's program. In the light of other estimates, this is a rather optimistic view of the problem. Ref. [18], describing theory for a proposed ASSET initialisation module, recommends that 15% of R_F+R_R be used. The detailed ASSET resistance module employs a direct calculation assuming a NACA 0015 section for the rudders and fins. Typical results from this program indicate that R_{AP} may vary around 17% of R_F+R_R. Better agreement with the detailed calculations may be obtained by equating R_{AP} to a constant fraction of frictional resistance, typically about 28%.

In a CEM for small conventional warships [5], an allowance of 20% of R_F+R_R is included to account for appendages and service conditions. For merchant ships, ref. [4] refers to allowances on R_R+R_F of 3% for twin rudders, and 8-10% for twin screw bossings. These figures indicate the influence of relatively small appendages on powering requirements. Appendages for SWATH ships are generally more extensive than those for an equivalent monohull, mainly due to the large fin surfaces.

In the case of *INITIAL*, the simple assumption of

$$R_{AP}=0.15(R_F+R_R) \qquad \text{Eqn. 4.13}$$

has been used. This formulation acknowledges the significant non viscous drag arising from the presence of fins.

Aerodynamic Resistance

The Chapman resistance prediction program (as used in the CEM for SWATH ships) applies a constant drag coefficient of 0.5 [6,10,17] to the frontal area of the vessel. Other approaches, notably that employed by *ASSET* [9,18] suggest that C_D=0.7 be used. This higher value has been adopted for use in *INITIAL*, in conjunction with a frontal area [18] AF=0.04 LOA^2. Aerodynamic drag may therefore be obtained from

$$R_A = 1/2\, \rho_{air}\, C_D\, AF\, V_m^2 \qquad \text{Eqn. 4.14}$$

4.3.5.4 Comparison of Power Prediction Techniques

The direct method outlined above has been programmed as a subroutine of *INITIAL*. The module has been constructed so that the power supplied to the machinery weight calculation is the true maximum, and not some *post hump* power. This ensures that the vessel will have enough power to overcome peaks in the power curve. Calculations of installed power using the direct technique described above show good correlation (Figure 4.12) with published powering data. Performance of the direct method was tested against the two regression methods on a random sample of data relating to 55 SWATH designs (Table 4.3). The quasi-rigorous approach of the direct method was justified by the fact that it gave the closest agreement with the actual installed power in 56% of the cases. The two regression approaches each gave the closest answer on roughly 20% of the sample. Table 4.4 summarises the performance of the three prediction techniques.

Table 4.3 SWATH Ship Power Predictions Compared with Published Data

					'Actual' and Predicted Powers in metric HP			
Speed (kts)	LOA (m)	Δ (t)	LOA based FN	Volumetric FN	'Actual' Power	Direct Method	Admiralty	Mod. Admiralty
25	27.1	193	0.789	1.717	4200.000	3930.000	4713.746	4976.156
18	27.1	224	0.568	1.206	4200.000	2322.000	2128.906	2289.363
17.3	12.35	18.4	0.809	1.757	400.000	254.000	428.909	418.037
15.4	12.35	22.2	0.720	1.516	400.000	288.000	350.916	359.974
27.1	35.9	343	0.743	1.691	8100.000	7674.000	8261.308	8181.223
20.6	27	239	0.651	1.365	3800.000	3981.000	3181.866	3552.404
20.5	27	236	0.648	1.361	3800.000	3906.000	3116.806	3463.251
18	19.2	53	0.675	1.533	850.000	807.000	898.729	827.379
13.25	61.55	3500	0.277	0.562	7400.000	3909.000	4834.636	5841.100
22.4	18.3	57.9	0.860	1.880	1020.000	1076.000	1706.874	1726.534
18.2	15.1	19	0.769	1.839	500.000	277.000	501.161	411.575
20	23.2	125	0.682	1.476	2400.000	2095.000	1993.952	2063.737
22.5	44.25	935	0.556	1.188	16650.000	11384.000	9127.540	10183.741
23.5	16.8	48	0.942	2.034	1300.000	1096.000	1735.816	1794.506
25	26.1	125	0.804	1.846	3352.000	2508.000	3634.960	3443.360
25	35.7	254	0.687	1.640	5364.000	5341.000	5555.603	4971.665
25	50.3	765	0.579	1.365	13410.000	15534.000	10746.336	10061.852
25	59.0	1270	0.535	1.255	21456.000	21555.000	14553.718	13888.953
25	43.45	914	0.623	1.325	16650.000	18134.000	11952.933	13596.308
33	33.2	393	0.941	2.013	12000.000	12310.000	15227.073	17269.206
22	66	1950	0.445	1.028	10730.000	12349.000	13332.467	13053.181
28	92	5500	0.480	1.101	64400.000	62773.000	47453.000	49122.665
28	107	6500	0.445	1.071	64400.000	65662.000	52437.000	49864.619
20	18.3	57.9	0.768	1.678	1020.000	959.000	1258.218	1259.232
26	52	1500	0.592	1.269	28000.000	27623.000	17867.316	20324.381
35	72.9	1865	0.673	1.648	46000.000	54888.000	45286.500	41585.875
15.9	75.3	2534	0.301	0.711	4446.000	5969.000	6509.109	5962.878
15.2	19.5	60	0.565	1.268	600.000	647.000	614.147	571.571
25	40.23	230	0.647	1.667	4447.000	4836.000	5235.289	4058.386
15.4	90.53	5695	0.266	0.602	7577.000	8968.000	9695.367	9751.291
15.5	66.14	1514	0.313	0.755	3076.000	3421.000	4465.969	3885.492
25	47.55	280	0.596	1.614	4640.000	5987.000	5889.211	4171.183
14	60.96	2890	0.295	0.613	6000.000	4321.000	4999.777	5755.206
38	74.7	2032	0.722	1.763	54000.000	61872.000	59479.000	55378.866
35	96.01	3050	0.587	1.518	50000.000	90907.000	60784.500	50858.722
33	33.2	335	0.941	2.067	10200.000	11088.000	13841.032	14896.303
33	33.2	470	0.941	1.954	14340.000	13844.000	16948.336	20391.886
30	95.82	5029	0.503	1.197	69711.000	84544.000	54148.500	52756.196
30	102.47	5125	0.487	1.193	75965.000	85214.000	54768.000	50442.046
30	108.53	5189	0.473	1.191	62464.000	85706.000	55174.000	48388.326
30	115.77	5317	0.458	1.186	63092.000	86549.000	55986.000	46615.059
37	92.96	3400	0.630	1.576	75000.000	107004.000	75306.000	67656.143
25	115.8	7183	0.382	0.940	65040.000	35087.000	41034.000	37094.566
15	74	4380	0.286	0.613	7800.000	7311.000	7720.050	8564.166
14	55	3550	0.310	0.592	5000.000	5019.000	5654.531	7660.007
12	51	1903	0.276	0.563	2100.000	1939.000	2571.754	2999.171
38	74.5	2100	0.723	1.754	52000.000	64265.000	60665.500	57211.784
19	24.38	160	0.632	1.346	3120.000	2439.000	2013.329	2148.735
28	140.8	15067	0.388	0.931	77000.000	77983.000	86688.000	84337.826
20	42.4	600	0.505	1.137	8000.000	5410.000	5096.904	5056.192
28	107	5470	0.445	1.102	46667.000	60031.000	47295.500	42481.039
20	116.1	12786	0.305	0.683	17500.000	38394.000	31781.998	33938.941
14	64.9	1473	0.285	0.685	2953.000	3017.000	3340.650	2904.315
35	50	1250	0.813	1.761	20000.000	34775.000	35647.500	40720.085
30	36	900	0.821	1.594	10000.000	22637.000	19345.850	26513.889

Table 4.4 Performance of Three Power Estimation Methods

Table displays the number of occasions in which each method is most accurate, as a percentage of the sample (55 vessels)

METHOD	Best	Next	Worst
Direct	56.41	10.9	32.7
Modified 'Admiralty'	23.6	40.0	36.4
'Admiralty'	20.0	49.1	30.9

The only area where the direct method is seen to perform consistently worse than the alternative methods is in dealing with small SWATHs, having installed powers less than 500 metric HP. For this reason, *INITIAL* has been constructed so that whilst all power predictions are performed by the direct method, powers of less than 500 HP will trigger a calculation using the modified Admiralty approach.

All three methods display a significant degree of inaccuracy when applied to vessels having large installed powers. There are several factors contributing to this situation.

INITIAL may overpredict power requirements because of the influences of the practitioners concerned with developing these particular conceptual designs. For vessels having very high power requirements, more strenuous than normal efforts may be made to reduce the size of power plant at the expense of other desirable qualities. This may lead to less resistful forms than are the norm in other areas of the speed/size envelope.

Apart from such efforts, the SWATH concept has suffered from the publication of over optimistic claims in terms of performance. Generally such proposals make no allowance for margins and assume full efficiency for their chosen prime movers.

The above factors explain over-predictions of power by *INITIAL*, but under-predictions are also evident. This is due to two main effects. Firstly, many conceptual designs have large auxiliary power demands which are supplied by the main power plant and the precise propulsive requirement is not always explicit in the available data. Secondly, the published maximum speed may be significantly lower than the speed actually available. The case of the *Kaiyo* is a good example of these two factors. Her design speed is variously published as 12 knots or 13.25 knots, but at 100% MCR she is actually capable [25] of 14.1 knots at the designed draught. Additionally, the installed machinery is fully integrated diesel electric, with only about half of the total power dedicated to propulsion duties.

In spite of the above, it is felt that the methods presented in this chapter offer a useful first approach to the power required by a SWATH of given size and speed. Their inadequacies should of course be borne in mind when employing them in initial design. Reference to Table 4.3 can give an indication of the probable accuracy of the estimated power. Powers falling in a range which has been well predicted in Table 4.3 should be reasonably safe estimates.

Wherever possible, results from one of these techniques should be confirmed by those from another.

In addition to the version incorporated in *INITIAL*, a small independent program (*POWEST*) has been written to perform preliminary powering calculations for SWATH ships using the direct method. This permits generation of speed-power curves rather than calculation of a single required power. Chapter 6 contains a comparison of a power curve generated by *POWEST* with those generated by more sophisticated tools.

4.3.5.5 Machinery Weight Estimation Algorithms

General

Chapter 8 presents data for estimating SWATH ship machinery weights at a detailed synthesis level. At the present level of design the weight of main propulsion machinery may be estimated from a knowledge of required power, and the power to weight ratio of the chosen machinery installation.

Positioning of prime movers in the box structure or in the lower hulls, and the use, or otherwise, of CP propellers are factors which lead to variations in machinery weights for apparently similar SWATH ships. However, *INITIAL* is concerned primarily with feasibility rather than detail, and while potential for variation in machinery design is recognised as an important feature of SWATHs. certain simplifying assumptions are made. In this case, choice of machinery installations has been restricted to 5 basic options, as listed below.

1 High Speed (RPM>1000) Diesel, direct drive
2 Gas Turbines, direct drive
3 Medium Speed (250<RPM<1000RPM) Diesel, direct drive
4 Diesel (High Speed) Electric
5 Gas Turbo-Electric

Within each of the above definitions, power to weight ratios are assumed to follow a single defined trend, regardless of the possibilities for variation in arrangement.

Realistic power to weight ratios for the above alternatives as fitted to SWATH ships must be derived. Features peculiar to SWATH ships must be incorporated in any useful approximations. The mandatory duplication of drive train and associated support systems in SWATH is a factor which is optional in monohull design. Transmission of drive through 90 degrees may also have to be considered, with the attendant weight due to gearing and shafting. In most cases data derived from monohull experience is inapplicable, and use must be made of the sparse collection of developed SWATH machinery installations.

High Speed Diesel Machinery

High speed diesels are a popular choice in SWATH designs having installed powers below 20000HP. Given adequate space in the lower hulls, direct drive may be specified while the alternative of deck-box mounted bevel gear drive is considered feasible in this power range.

In a discussion on prospects for advanced naval vehicles [20], WM/P_M ratios for high speed diesel installations were considered as falling between 0.0045 and 0.0091. As illustrated in Figure 4.13, this is a significant variation, with actual values dependent on ship type and design philosophy. Machinery weights from a number of SWATH designs have been plotted (Fig 4.13) versus Total Installed Power, from which the following expression has been derived.

$WM=0.007P_M$ (WM in tonnes, P_M in metric HP) Eqn. 4.15

This lies very close to the mean of the values suggested in reference [20], and has been adopted as representative of the constraints and design philosophy currently important in SWATH design.

Gas Turbine Machinery

The high power to weight ratios provided by gas turbines are attractive to designers seeking to maximise the small payload capacity of the SWATH. High fuel consumption is an obvious drawback, as are the problems associated with ducting to and from engines in the lower hulls.

According to [20], gas turbine propulsion plants with specific weights of 0.00635 t/HP are attainable using available technology, and without compromising current standards. According to this study, reliable machinery with reduced specific weights of 0.00454 t/HP may be achieved by special development programmes. These values have been adopted for *standard* and *advanced* machinery, respectively, in the CEM for SWATH ships [6].

Regressing available data on gas turbine machinery installations for SWATH ships (Fig. 14) yields an expression which has been incorporated in *INITIAL*.

$$WM = 6.05 + 0.006 P_M \qquad \text{Eqn. 4.16}$$

It should be noted that the data used to construct the relationship excluded proposed machinery weights which were felt to reflect extremely low-weight design philosophy. In addition, gas turbine installations using epicyclic or planetary gears were not considered. Although these are a validated technology, and permit significant reductions in weight, they are expensive and also did not fit in with the regression analysis. The present formulation may therefore be regarded as conservative, in that resorting to epicyclic gears may provide a lower weight solution.

Medium Speed Diesel Machinery

Such engines are probably too heavy for serious consideration for all but the slowest large SWATH ships. In these particular circumstances, the lighter (higher speed) examples may be suitable choices owing to their favourable fuel consumption and relative ease of maintenance.

Reference [20] suggests that WM/P_M for medium speed diesel installations lies between 0.0113 and 0.0226. While many proposed SWATH designs specify high speed diesel machinery, medium speed installations are extremely rare. One available data point (detailed in Chapter 8) suggests a specific weight of 0.0073 for an installed power of about 13700 HP. This is extremely low, and falls within the range suggested for the higher speed diesels. This particular data point is considered to be very reliable, and one must conclude that, by careful design, weight of high performance medium speed diesel plant may be reduced to an acceptable level.

An alternative approach is proposed by Watson and Gilfillan [4], where machinery weight is considered as consisting of two main components. The primary component is the main engine weight, provided by $9.38(MCR/RPM)^{0.84}$. A remainder weight is given by $k(MCR)^{0.70}$. The constant k may be determined by making reference to a *type* installation providing the same standard of machinery fit. In the original paper this portion of the machinery weight included generators and auxiliaries which are included in a different group weight in the present analysis.

Fixing engine revolutions at a high value (900 RPM), and considering the existence of two separate prime movers, the above equation becomes

$$WM = 0.0345\, P_M^{0.84} + 1.23\, k\, P_M^{0.7}$$

Referring to the previously discussed machinery design, and fixing RPM at 900, k must be zero to provide agreement with the known machinery weight. In the light of such conflicts between the sparse available data, a crude assumption became necessary. It was decided to incorporate in INITIAL the lower bound value proposed in [20], i.e.

$$WM=0.0113\ P_M \qquad \text{Eqn. 4.17}$$

This compromise approach is obviously extremely simplistic, and the assumption must be considered when discussing results generated by INITIAL for medium speed diesel powered SWATHs, though such vessels are likely to be rare. Figure 4.15 illustrates the available data for medium speed installations.

Diesel Electric Machinery

Useful design data on the weights of diesel electric machinery is difficult to obtain, even for conventional ships. This is partly due to the fact that electrical drive is an unusual choice for conventional monohulls because of the associated high weight, space and cost penalties. A strong design requirement for qualities such as low noise or wide speed range is generally required to justify it's use.

For SWATH ships, electric drive permits complete freedom in the siting of prime movers relative to the propellers, and this is a very strong argument in it's favour. Bulky prime movers may be situated in the relatively spacious box structure, thus avoiding problems in fitting machinery into restricted lower hull spaces, or using complicated bevel drives. Diesel electric propulsion is therefore a popular choice for modern designs of moderate speed SWATH ships.

The problem of weight estimation is complicated by the considerable choice available to the designer of an electrical propulsion plant. Generators and motors may be AC or DC, with the possibility of rectification from AC generated current to DC propulsion current. Power may be generated at variable frequency for variable speed motors, or at constant frequency. Motor output may require reduction gearing and/or CP propellers. In view of these options, and the fact that ship service power may be generated from the same installation, the accurate preliminary estimation of weight for a diesel electric plant is extremely difficult.

In the absence of other suitable data, information on the machinery weights of several conceptual SWATH designs has been plotted (Fig.4.16) versus installed power. Logarithmic regression yields an expression suitable for *INITIAL*.

$$WM=0.543{P_M}^{0.679} \qquad \text{Eqn. 4.18}$$

The scattered nature of the data from which the equation has been derived should be noted. Although this means that detailed machinery design weights are unlikely to agree exactly with the approximation, this is directly due to the high degree of freedom involved in specifying such installations.

Gas Turbo-Electric Machinery

As with diesel generated electrical drive, use of gas turbine generated electrical propulsion power is a much more reasonable choice for SWATH ships than for monohulls. The arguments for and against this installation are generally as described in the previous section, with the gas turbine prime mover attractive because of it's high power to weight ratio. This arrangement has been proposed in several detailed design studies of large, fast (5000 to 15000t, 25 to 30 knots) SWATH ships.

Plotting and regressing the available data (Fig. 4.17) yields the design approximation

$$WM=0.664\ P_M^{0.61} \qquad \text{Eqn. 4.19}$$

4.3.5.6 Computer Estimates of Machinery Weight

In order to test the powering estimates, and subsequent machinery weight estimates, the computer program *INITIAL* was run for 20 conceptual SWATH designs for which machinery data was available. The results from the program, and the manually derived conceptual design group weights, are presented in Table 4.5.

The inaccuracy in some of the weight estimates is largely a result of the power prediction from *INITIAL* differing considerably from the conceptual design power. Plotting the computed and actual weights against one another, and superimposing an ideal one-to-one correlation line, the performance of the approximate techniques is illustrated graphically in Figure 4.18.

Table 4.5 Power Prediction/Machinery Weight Estimates

Design I.D. (Appendix 1)	Δ (t)	LOA (m)	Speed (kts)	Machinery Weight by - Manual	*INITIAL*
High Speed Diesel Machinery					
Halcyon	57.0	18.3	22.4	7.4	7.5
1	77.5	22.9	25.0	9.7	12.8
5	125.0	26.1	25.0	17.0	17.6
6	254.0	35.7	25.0	33.0	37.4
7	765.0	50.3	25.0	91.0	108.7
8	1270.0	59.0	25.0	165.0	151.0
19	2650.0	80.0	16.0	37.0	43.7
54	480.0	33.2	33.0	93.0	96.9
Gas Turbine Machinery					
19	4000.0	87.0	25.0	247.0	185.4
57	5125.0	102.5	30.0	472.0	517.0
Diesel Electric Machinery					
TAGOS	3450.0	76.8	9.0	66.1	58.8
103	2415.0	66.0	14.0	150.0	153.7
104	2330.0	61.7	14.0	130.0	151.8
19	1500.0	75.0	16.7	143.0	135.0
19	3000.0	84.5	21.0	395.0	292.0
Gas Turbo-Electric Machinery					
72	7183.0	115.8	25.0	462.0	393.0
88	15067.0	140.8	28.0	649.0	640.0
90	5470.0	107.0	28.0	674.0	563.0
19	3200.0	85.0	25.5	389.0	377.0
19	3200.0	85.0	25.5	422.0	377.0

4.3.6 Outfit and Auxiliary Systems Weight Estimation

4.3.6.1 Derivation of Auxiliary Systems Weight Algorithm

The weight grouping within *INITIAL* which represents Auxiliary Systems is roughly equivalent to the sum of the USN and RN Groups 3,4 and 5. This weight group includes a miscellany of items, few of which may be treated rigorously at an early stage in design.

The nature of the intended role of the vessel is important in determining the complexity and weight of required shipboard systems. Therfore, detailed estimation techniques (Chapter 10) are ultimately necessary, though simple approximations may be useful in initial design.

SWATH ships may be expected to require more complex ballast systems than equivalent monohulls because of the sensitivity of the small waterplane area to load changes. For related reasons, fin control sytems are also required. In addition, heating, lighting and air conditioning systems may be more extensive because of greater internal volume and surface area.

Weight estimation methods usable as first approximations in design simplify the problem by relating this group weight to functions of ship size and installed electrical power. A method suggested [18] for use in a proposed initialisation module for *ASSET-SWATH* deals with the problem as follows. (all weights in tonnes)

Electrical Plant $W_{300} = aP_G$

where P_G is installed generating capacity (kW), assumed to be 0.5Δ (Δ in t), and a=0.05 for diesel generators, so that

$$W_{300} = 0.025\Delta$$

Command &Surveillance $W_{400} = W_{420} + W_{430}$ (navigational systems and internal communications)

$$= 0.002\Delta + 0.004\Delta$$
$$= 0.006\Delta$$

Auxiliary Systems $W_{500} = 0.13\Delta$

Total $W_{300,400,500} = 0.161\Delta$ Eqn. 4.20

The approach adopted in *INITIAL* is based on regression analysis on a collection of SWATH designs. The relationship between Auxiliary group weight fraction and displacement is illustrated in Fig. 4.19, from which the following approximation (virtually a constant fraction) was derived.

$$WAUX/\Delta = 0.147\Delta^{-0.002}$$ Eqn. 4.21

4.3.6.2 Derivation of Outfit Weight Algorithms

Most published SWATH outfit weights tend to be derived from naval monohull practice, and in the early design process, simple relationships are employed. The different approaches may be compared.

The theory proposed for an *ASSET-SWATH* initialisation module suggests that the Outfit Weight may be expressed as

$W_{600}=0.07\Delta$ Eqn. 4.21

This is a very simple relationship showing the Auxiliary weight fraction to be constant. This may be a reasonable approximation for a homogenous group of SWATHs such as the medium sized warships *ASSET* was designed to deal with, but is not satisfactory in a general design situation.

Regression (Fig. 4.20) on the Glasgow University collection of conceptual SWATH designs provides an expression for use in *INITIAL.*

$WO/\Delta = 0.189\Delta^{-0.119}$ Eqn. 4.22

Other published methods for estimation of SWATH Auxiliary Weight consider the weight together with Outfit, and will be considered in the following section.

4.3.6.3 Performance of Weight Prediction Techniques

This section compares (Table 4.6) the alternative approaches to estimating SWATH ship Outfit and Auxiliary weights. Apart from the approximations described above, methods for computerised estimation of combined SWATH Auxiliary and Outfit Weight have been presented by authors employing the Canadian Forces Weight Breakdown System. These are largely based on similar techniques developed for use in a CEM [5] for monohull warships. The derivation of the SWATH approach may be considered.

In their Concept Exploration Model for Small Warship Design, Eames and Drummond [5] considered Groups 3,5,6 (Electrical Plant, Auxilary Systems and Outfit) under a common heading. They assumed that these weights depend primarily on

a) Ship Size, Δ
b) Upper Deck Area, LB
c) Ships Complement, N
d) Installed Electrical Power, P_G

The relationship used in the CEM was defined as $Wq=a\Delta+bLB+cN+dP_G$, where the coefficients a,b,c,d may be evaluated from existing ship data.

Useful guidance is provided in estimating the values for N and P_G. Figure 4.21 illustrates ships complement plotted as a function of displacement, corresponding to a 2/3 power law. i.e. $N=m\Delta^{2/3}$, where

m=1.3 for ships operating worldwide
m=1.1 for a mean line
m=0.9 for ships operated and maintained from a home port

For the present purposes $N=1.1\Delta^{2/3}$ is a reasonable choice.

Installed electrical power is an extremely difficult quantity to estimate in the concept exploration stage and a plot of installed power versus small warship displacement taken from Ref. [5] (Fig. 4.22) reveals the degree of scatter in the available data. Installed generating capacity appears to have increased in recent times and for modern warship designs the upper limit of 1kW/tonne is suggested. However, warships typically have a heavy electrical load, and so the mean value of 0.68kW may be reasonable for general estimation purposes.

Despite the fact that the above formulation for P_G has been used in a computer model for SWATH design [6], an independent plot was constructed of installed generating capacity versus SWATH displacement (Figure 4.23). Although based on a sparse collection of points, this indicates that approximately 1kW/tonne is typical.

$$P_G=1.002\Delta^{0.924} \qquad \text{Eqn. 4.23}$$

is a suitable approximation to the installed generating capacity for SWATH ships. This expression has been incorporated in *INITIAL*, although it is fundamentally incorrect in making no distinction between ships of differing type and function.

In a later paper dealing with a computer model for SWATH design [6], auxiliary and outfit weights are estimated using an approach heavily dependent on the monohull situation described above.

$Wq=0.14\,\Delta + 0.8\,N + 0.04\,P_G$, where N and P_G are calculated using the previously derived equations.

Auxiliary and Outfit Weights for 18 manual concept SWATH designs were assembled in reference [13]. These weights, and the corresponding predictions of the algorithms used in *INITIAL, ASSET* and *SWACEM* are presented in Table 6. Not surprisingly, the algorithms from *INITIAL* perform best, since they are effectively being compared with the data used in their construction. However, the last four entries in Table 4.6 were not used in the development of the weight algorithms, and *INITIAL* is seen to perform particularly well for these.

Total Auxilary and Outfit weights and weight fractions as calculated by *INITIAL* are plotted against published values in Figures 4.24a and 4.24b respectively. A line representing the ideal of a one-to-one correspondence is included for reference, and the performance of the approximation is seen to be good.

Table 4.6 Comparison of SWATH Ship Auxiliary and Outfit Weight Predictions

Δ (t)	From Concept Design Study			ASSET-SWATH Approximation			'INITIAL' Approximation			SWACEM
	Auxiliary (t)	Outfit (t)	Total (t)	Auxiliary (t)	Outfit (t)	Total (t)	Auxiliary (t)	Outfit (t)	Total (t)	Total (t)
57	7.6	5.1	12.7	9.2	4.0	13.2	8.3	6.7	15.0	11.93
77.5	8.7	7.9	16.6	12.5	5.4	17.9	11.3	8.7	20.0	22.56
125	23	12	35	20.1	8.8	28.9	18.2	13.3	31.5	32.1
254	44	31	75	40.9	17.8	58.7	36.9	24.8	61.7	65.7
765	132	65	197	123.2	53.6	176.8	111.0	65.6	176.6	179.9
1270	179	118	297	204.5	88.9	293.4	184.0	102.5	286.5	284.3
914	50	129	179	147.2	64.0	211.2	132.5	76.7	209.2	235.7
57.9	8.1	7	15.1	9.38	4.1	13.4	8.4	6.8	15.2	12.08
3050	396	207.7	603.7	491.1	213.5	704.6	441.2	221.9	663.1	630.0
480	22	57	79	77.3	33.6	110.9	69.7	43.5	113.2	134.2
7183	1129	452	1581	1156.5	502.8	1659.3	1037.3	471.9	1509.2	1610.0
15067	2280	934	3214	2425.8	1054.7	3480.5	2172.6	906.4	3079.0	3071.2
5470	861			880.7	382.9	1263.6	790.4	371.2	1161.6	1079.4
12786	1467	772	2239	2058.5	895.0	2953.5	1844.3	784.3	2628.6	2224.2
3450	392	236	628	555.5	241.5	797.0	499.0	247.3	746.3	777.6
5029			1066	809.7	352.0	1161.7	726.8	344.7	1071.5	1099.2
5125			1087	825.1	358.8	1183.9	740.6	350.5	1091.1	1118.5
5189			1079	835.4	363.2	1198.6	749.8	354.4	1104.2	1131.3
5317			1106	856.0	372.2	1228.2	768.3	362.1	1130.0	1157.1

4.3.7 Fuel Weight

4.3.7.1 General

The weight of fuel carried is calculated from the required propulsive and electrical power, operating time, and fuel consumption of the different installations. These considerations are incorporated in the expression

$$WF=(WF_M+WF_C+WF_G)(M+1) \qquad \text{Eqn. 4.24}$$

where WF_M and WF_C are the weights of fuel required by the propulsion engines for operations at design and cruise speed, and WF_G is the weight of fuel carried for generating purposes. M is a margin introduced to account for extra time at sea, and trapped fluids. Allowing for an extra 10% time at sea (2 days on 20 day passage) and unpumpables of 5% [5,6], gives M=0.15

Individual fuel weights may be defined separately.

$$WF_M=(R_M/V_m)\ (P_M SFC_M)/10^6$$
$$WFC=(R_C/V_c)\ (P_C SFC_C)/10^6$$
$$WFG=[(R_M/V_m) + (R_C/V_c)]\ (P_G SFC_G)/10^6$$

R_M, V_m, R_C, and V_c are the user defined operational requirements of range (in nautical miles) and speed (in knots) at the design and cruise conditions. P_M and P_C are the required propulsive powers (in kW) for the two modes of operation. P_G is the average generating load required by the ship services. SFC_M, SFC_C, and SFC_G are the fuel consumptions (in g/kWhr) of the prime movers delivering propulsive power at maximum and cruise speeds, and the electrical generating sets, respectively.

4.3.7.2 Determination of Operating Powers

The design and cruise powers required by the fuel weight calculation are obtained by using the method outlined in Section 4.3.5. In the calculation, power must be expressed in terms of kW, rather than the metric HP quoted in the earlier section.

Average generating load is defined as 25% [6] of the installed generator capacity. Therefore, using the expression for installed generating capacity defined in Section 4.3.6, P_G (in kW) may be defined by the equation

$$P_G=0.25(1.002\Delta^{0.924}) \qquad \text{Eqn. 4.25}$$

4.3.7.3 Fuel Consumptions

Prime Movers

Simple relationships, relating fuel consumption to required power, have been defined for use by *INITIAL*. The assumptions have been derived from analysis [13] of machinery systems, and are reproduced below.

Gas Turbines (Direct and Electric Drive)

59660 kW < P	SFC=250
P < 59660 kW	SFC=350-(100/29830)(P/2)

High Speed Diesels (Direct and Electric Drive)

1810 kW < P	SFC=200
P < 1810 kW	SFC=250-(50/905)(P/2)

Medium Speed Diesels

11190 kW < P	SFC=178
P < 11190 kW	SFC=230-(52/5595)(P/2)

P is the <u>total</u> (ship set) required prime mover power in kW at cruise <u>or</u> design speed and SFC is in g/kWhr.

The equations assume that two separate sets of prime movers will always be present, hence the factor 2. This ensures that the typically higher SFC of lower rated units is not ignored in the computation. Electric propulsion systems may of course have a number of prime movers unrelated to the number of propellers.

The same equations are used to estimate fuel consumption at both design and cruise loadings, the only variant being the power input. In strict terms, this approximation is inaccurate. Prime movers forced to operate at loadings less than the design point suffer from a deterioration in specific fuel consumption. This is especially the case for gas turbines, while diesels tend to suffer more in terms of maintenance life. An exact treatment of this problem was not developed for *INITIAL* in view of the generally low level of complexity of the program.

However, some measure of reduced fuel efficiency is provided by this simplistic formulation because of the fact that fuel consumption increases with a decrease in engine size (power) as well as operating load. Therefore, since the fuel consumption for cruise loading is effectively calculated on the basis of a smaller engine operating at it's design point, a higher specific fuel consumption will be calculated than for the maximum power situation.

Generator Fuel Consumption

For the purposes of *INITIAL*, electrical power is assumed to be supplied by diesel generating sets. Gen-set fuel consumption will vary with capacity, but the virtually complete freedom in choice of unit numbers renders any complicated formulation meaningless. It has therefore been decided to define a universally applied value of SFC_G=210 g/kWhr

4.3.8 Stores and Margin Weight

4.3.8.1 General

In *INITIAL*, for convenience, this group weight has been used to include a variety of items. A design margin is included, and weights of stores and FW are calculated if details of the intended complement are provided. If this is not the case, a simple assumption is made for weights of consumables other than fuel. The weight of the crew and effects (if known) is also included in this group. It is rather inconsistent to describe all the above items as *Stores and Margin*, and therefore in the output from *INITIAL* the individual items are presented separately.

The group weight is defined as follows,

$$WSM=WMARGIN+WCREW+WSTORES \qquad \text{Eqn. 4.26}$$

where WMARGIN, WCREW, WSTORES are the weights in tonnes of the Design Margin, crew and effects and consumables other than fuel.

4.3.8.2 Design Margin

Owing to their sensitivity to changes in weight and moment, it is prudent to incorporate a larger design margin for SWATH ships than would be the norm for a conventional vessel. At present the only guidance on a suitable value for margin is obtained from analysis of existing SWATH designs. From Fig. 4.25, an expression may be derived.

$$WMARGIN=0.0755\ WLIGHT^{1.075} \qquad \text{Eqn. 4.27}$$

where WLIGHT is the Lightship Weight (WS+WM+WAUX+WO).

INITIAL is structured to accept a user specified margin, or to proceed with the above default. In the former case, the margin is calculated as a user defined percentage of the lightship.

4.3.8.3 Crew and Effects

In the case where the user supplies the program with the number of crew, *INITIAL* uses the basic assumption that

$$WCREW=0.143\ NC \qquad \text{Eqn. 4.28}$$

where NC is the number of crew. This implies that seven persons, with effects, represent 1 tonne. If no data on crew size is provided by the user, no value is calculated for WCREW. The weight of any passengers and effects is included in the payload weight.

4.3.8.4 Consumable Stores

The following assumptions have been incorporated in *INITIAL*.

Provisions	$WPROV=0.005\ [NC+NP]\ [(R_M/V_m)+(R_C/V_c)]$ i.e. 0.005t per person per day	Eqn. 4.29
General Stores	$WGS= 0.0011\ [NC+NP]\ [(R_M/V_m)+(R_C/V_c)]$ i.e. 0.0011t per person per day	Eqn. 4.30
Fresh Water	$WFW=0.125*[NC+NP]*[(R_M/V_m)+(R_C/V_c)]$ i.e 0.125t per person per day	Eqn. 4.31

An upper limit of 50t is set for WFW, as this is the weight above which it is assumed distillation plant will be used.

The total weight of consumables is therefore

$$WSTORES=WPROV+WGS+WFW \qquad \text{Eqn. 4.32}$$

In the above calculations, the number (NP) of passengers (if known) is included. The weight of stores required to support a given number of passengers for a set time should therefore not be included in the payload weight.

It will often be the case that *INITIAL* is employed in such a preliminary capacity that crew numbers will be unknown. For this eventuality a simple default calculation (derived from Fig. 4.26) of stores weight has been included in the software.

$$WSTORES=0.018\Delta \qquad \text{Eqn. 4.33}$$

4.3.9 Payload Definition

In the context of *INITIAL*, payload may either be a design requirement, or an output from the design process. As far as the program is concerned, in the first case it is a weight which must be carried, and in the second a weight which may be carried.

This weight may consist of a variety of items, depending on the role of the vessel. Passenger or cargo carrying SWATHs present no problems in that the weight of the payload is easily determined. Vessels which perform a workboat/military function are treated differently.

Items of deadweight (e.g. drilling mud, ammunition, helicopter fuel) which are associated with the working role are obviously part of the deadweight. However, items of fitted equipment which are necessary for the fulfilment of the particular ship function must also be included in the definition of payload. This is because the estimation method for auxiliary systems provides a weight for *standard* ships. Identifiable weights for specialised items such as armament, fire pumps and monitors, diving spreads etc should therefore be included in the payload weight.

With reference to passenger ships, the convention employed by *INITIAL* is that the weight of the passengers should be considered as part of the payload, but that the stores and provisions necesary to support the passengers will be calculated separately.

The above conventions should be used when defining or interpreting payload weights associated with *INITIAL*.

4.3.10 Linear Dimensions

INITIAL has been constructed to issue advice on suitable dimensions for consideration by the user, who then selects the value he desires for his design. This permits the construction of an initial SWATH geometry in accordance with the designers wishes, not those of an inflexible machine. The adequacy, or otherwise, of the chosen geometry will be revealed in the full synthesis.

The equations which *INITIAL* employs to provide the user with advice on linear dimensions have been derived from regression analysis on a large number of conceptual SWATH designs. These have been reported in Chapter 2.

4.3.11 Program Operation

The program and its operation have been fully documented [13, 27]. Table 4.7 lists the input and output variables associated with the program. Typical output from a run of the program is illustrated in Table 4.8.

On completion of a run of *INITIAL* the geometry of a SWATH is defined in general terms. Weight groups have been calculated to a first approximation and the general style of the vessel is apparent. This level of definition may be improved upon by the subsequent stages in the SWATH synthesis process. However, decisions made in this 'baseline' stage will have a strong influence on the nature of the final design, and the time taken to achieve a balanced design.

Table 4.7 Input and Output Variables for Program *INITIAL*

Input Variables
Maximum (design) speed
Range in nautical miles at the above speed
Required operating (cruise) speed
Range in nautical miles at the above speed
Number of crew (if known)
Number of passengers carried (if any)
Select option to design for known ship displacement or required payload, followed by
Known displacement and/or required payload weight
Construction material from; mild steel, hybrid, or aluminium
Power plant from; high speed diesels, medium speed diesels, gas turbines, diesel electric, gas-turbo electric
Percentage of Lightship Weight to be used as Design Margin (or to select the default)
Ship length/displacement ratio
Select option; known number of decks in the box structure, or not
Number of full decks if known (up to 3)
Select number of struts per hull from; one or two
Select strut configuration aft from; short or overhanging

Output Variables
Final balanced displacement
Available payload weight
Maximum installed power
Propulsive power at cruise
Installed ship servce generator capacity
Weights of structure, propulsion machinery, outfit items, auxiliary and electrical systems, fuel
Weights of margins, crew and effects, stores and FW
Length overall
Overall beam
Draught
Depth to wet deck
Box clearance
Depth to main deck
Box depth
Lower hull, length, breadth, corner radius
Strut length, thickness, setback
Aft strut length, thickness and gap (if tandem strut design)
Hull prismatic coefficient-strut waterplane area coefficient relationship
Approximate natural heave period

Table 4.8 Sample Output from Program *INITIAL*

```
PRELIMINARY ESTIMATES
*********************
MAXIMUM SPEED   28.00KTS FOR    0.00 NM
RANGE 9000.00NM AT CRUISE SPEED OF   15.00KTS

DISPLACEMENT 15067.00T

MAXIMUM SHP   77747.16
CRUISE SHP    14541.75

PAYLOAD        884.21T

INPUT NUMBER OF CREW  690 PASSENGERS    0

STRUCTURE WEIGHT 6006.20T
MACHINERY WEIGHT  638.98T
OUTFIT WEIGHT     906.37T
AUXILIARY WEIGHT 2172.64T
FUEL WEIGHT      2746.06T
STORES+MARGIN    1712.55T (MARGIN 1448.13 CREW   98.67 STORES  165.75)

SHIP SERVICE GENERATOR CAPACITY 7267.16kW

LOA                   133.39M
BEAM                   50.00M
DRAUGHT                14.00M
DEPTH TO WET DECK      19.80M
BOX CLEARANCE           5.80M
DEPTH TO MAIN DECK     28.80M
BOX DEPTH               9.00M

HULL LENGTH         121.26M
HULL SUBMERGENCE      9.83M
HULL BREADTH          8.35M
HULL DEPTH            8.35M
CORNER RADIUS         0.00M

STRUT LENGTH           124.06M
STRUT THICKNESS          4.20M
STRUT SETBACK            9.34M
STRUT GAP                0.00M
LENGTH AFT STRUT         0.00M
THICKNESS AFT STRUT      0.00M

Cp=     1.11-     0.44*Cw

DESIRED GMT      8.64M
DESIRED GML     22.23M

APPROX HEAVE PERIOD       11.85S
```

4.3.12 Program Validation

The validity of *INITIAL* has been examined by comparing designs generated by the program with several conceptual SWATH designs from Appendix 1. Several such examples are presented in Table 4.9 where the performance of the program may be examined over a range of different ship types.

The comparisons have been made against well developed conceptual designs, having weights estimated at the two-digit level. Reputable commercial and government organisations are responsible for these particular studies and they therefore offer the best available yardstick by which to assess *INITIAL*.

The present state of the art in SWATH design is such that solutions to the same specification from different design teams are commonly different [28]. Even within one particular design exercise, such as *T-AGOS 19*, design evolution leads to quite significant variation in vessel properties at relatively late stages in the design process.

Assessment of the performance of *INITIAL* may be aided by reference to the variation in the *T-AGOS 19* weights (Table 4.1) throughout the design process. In general terms, the comparison of *INITIAL* designs with the published data has been within the accuracy of the differing NAVSEA *T-AGOS* approaches. The influence of different margin policies does however affect the individual group weight estimates to a certain extent.

The satisfactory performance of *INITIAL*, over the full range of currently considered SWATH sizes and speeds, is encouraging, and permits a degree of confidence in its use as a preliminary design tool. However, its limitations must also be recognised, notably the lack of a space balance in the mini-synthesis, and the rigid nature of the design approximations.

4.3.13 Parametric Studies

The facility which *INITIAL* provides for rapid parametric studies of design variables allows a great quantity of results to be generated. However, full coverage of all possible variables would require a separate report if the subject was to be treated adequately. This section contains only representative studies, illustrating the capability of the program. All the studies are based on vessels having $LOA/\Delta^{1/3}$ equal to 5.4, and lower hull length/diameter ratios of 14.

Most parametric studies employing *INITIAL* are based on fairly well defined requirements. Figure 4.27 illustrates typical results from a small parametric study of a SWATH ASW escort design. The baseline design has a maximum speed of 25 knots, an endurance range of 4500 nm, and a crew of 280. Structure is of mild steel, and gas-turbo electric propulsiuon is specified. Margins of 8% were applied to all lightship items in this study which illustrates (Figure 4.27) the variation of required displacement with payload and endurance speed.

Table 4.9 Comparison of SWATH Designs Produced by *INITAL* with Published Data

Design Identification	TAGOS-19 SURTASS Vessel		USCG Offshore Patrol Vessel Appendix 1 No. 8		DTNSRDC/Grumman VSTOL Carrier Appendix 1 No. 88		NAVSEA ASW Frigate Appendix 1 No. 72		RMI Offshore Crew Boat Appendix 1 No. 15		MoD(N) SSV Appendix 1 No. 104		YSL/UoG SSV Appendix 1 No. 103	
Data Source	App. 1	*INITIAL*	App. 1	*INITIAL*	App. 1	*INITIAL*	App. 1	*INITIAL*	App. 1	*INITIAL*	App. 1	*INITIAL*	App. 1	*INITIAL*
Main Particulars														
Displacement (t)	3450		1274		15067		7183		58		2330		2415	
Maximum Speed (kts)	9.6		25		28		25		20		15.1		14.2	
Performance	3000nm at 9.6 kts plus 30 days at 3 kts		5700nm at 15 knots		9000nm at 15 knots		6200nm at 14 knots		375nm at 18 knots		6560nm at 14 knots		16000nm at 8 knots plus 30 days at 3 knots	
Complement	33		90		690		-		3		24		24	
Structure Type	Mild Steel		Aluminium		Mild Steel		Mild Steel		Aluminium		Mild Steel		Mild Steel	
Propulsion Plant	Integrated Diesel Electric		High Speed Diesel		Gas-Turbo Electric		Gas-Turbo Electric		High Speed Diesel		Integrated Diesel Electric		Integrated Diesel Electric	
Propulsive Power (HP)	1600	*1244*	21456	*21565*	77000	*77747*	48500	*34850*	1020	*961*	4027	*5320*	3758	*4091*
Generator Power (kW)	3340	*2788*	1300	*742*	6000	*7267*	6000	*3670*	50	*43*	5044	*5258*	4000	*4387*
Weights (t)														
Structure	1593.4	*1445.4*	408.3	*444*	6297.0	*6006.2*	2403.0	*2962.5*	22.8	*22.4*	1056.0	*980.8*	1056.0	*1016.2*
Propulsion	66.1	*68.6*	170.2	*151.0*	649.0	*639.0*	462.0	*391.7*	8.0	*6.7*	132.0	*184.0*	145.0	*153.4*
Outfit	236.2	*247.3*	95.0	*102.8*	934.0	*906.4*	452.0	*471.9*	7.0	*6.8*	196.0	*175.0*	148.0	*180.6*
Auxiliary	522.1	*499.0*	179.6	*184.6*	2280.0	*2172.6*	1290.0	*1037.3*	8.1	*8.4*	265.0	*337.2*	266.0	*349.5*
Fuel	638.0	*640.0*	241.3	*198.2*	2455.0	*2746.1*	1043.0	*1065.8*	4.0	*3.7*	236.0	*359.2*	400.0	*378.5*
Margin	149.4	*301.8*	111.1	*109.9*	1113.0	*1457.8*	702.0	*523.6*		*3.5*	325.0	*219.0*	270.0	*223.1*
Stores	81.0	*97.6*	41.1	*59.6*	304.0	*165.8*	180.0	*258.6*	0.3	*2.9*	60.0	*53.1*	65.0	*63.4*
Remainder (Payload)	163.3	*150.3*	27.4	*23.9*	1035.0	*973.1*	651.0	*471.6*	7.7	*3.5*	60.0	*21.7*	65.0	*50.3*
Main Dimensions (m)														
LOA	70.70	*67.10*	59.00	*57.60*	140.80	*133.40*	115.80	*102.60*	18.30	*19.80*	61.80	*63.65*	66.00	*63.70*
BOA	28.65	*31.00*	24.60	*26.60*	44.80	*50.00*	27.40	*29.00*	9.10	*9.20*	25.20	*29.00*	26.00	*29.00*
Draught	7.54	*8.60*	5.91	*6.20*	11.58	*14.00*	10.67	*10.90*	2.13	*2.20*	6.50	*7.00*	7.40	*7.65*
Depth to Main Deck	15.09	*16.42*	-	*9.67*	26.33	*28.80*	-	*22.67*	4.27	*4.10*	13.00	*13.00*	13.90	*13.65*
Box Clearance	4.00	*3.60*	-	*3.47*	5.58	*5.80*	-	*6.10*	1.38	*1.23*	3.00	*3.00*	3.00	*3.00*
Hull Length	70.70	*67.10*	52.50	*52.40*	124.60	*121.30*	115.80	*102.60*	16.13	*18.00*	61.80	*63.65*	66.00	*63.70*
Hull Breadth	6.67	*6.50*	4.00	*3.70*	8.93	*8.30*	-	*8.50*	1.50	*1.30*	6.80	*6.00*	4.70	*4.50*
Strut Length	58.78	*51.70*	56.80	*53.60*	126.10	*124.10*	94.50	*78.00*	16.80	*18.40*	50.40	*49.00*	51.00	*49.00*
Strut Thickness	2.75	*2.57*	1.00	*1.80*	3.6	*4.20*	-	*3.28*	-	*0.66*	2.4	*2.34*	2.7	*2.28*

Broader studies may take the form of Figure 4.28 which illustrates the influences of speed and machinery installation on payload/displacement ratio for a mild steel vessel carrying 60t over 1000nm. The effects of the peaks and hollows in the C_R curves can be clearly seen. For this particular range, the most desirable machinery is high speed diesel until speeds of 30 knots are required. Thereafter, the better fuel consumption is offset by their lower power/weight ratio compared with gas turbines. The electrical drive options are clearly detrimental to deadweight ratio compared with the direct drive alternatives.

A similar study (Fig. 4.29) illustrates the influence of range on deadweight ratio for a 20 knot vessel carrying 60 tonnes. High speed diesel again proves the most desirable choice over the ranges considered. Gas turbines are the next best choice only for very short ranges; above 750nm, even the medium speed diesel is a better choice.

Different speed and range requirements would result in different conclusions as to the best machinery installation to employ. In any case, these examples relate to vessels operating at a constant speed setting, which is an unlikely scenario for most SWATH ships other than ferries.

Appendix 2 contains data produced by *INITIAL* as part of a typical parametric study. Fifteen permutations of structure type and machinery type were considered. Each of the three main structural types was considered separately, and within these primary groupings, the five propulsion options provided further subgroups.

For each of the fifteen groups thus defined, calculations were performed at six different operating ranges. These are 500, 1000, 2000, 4000, 6000, and 8000 nautical miles. In this context, range is defined as the distance which the vessel is required to cover at the specified design speed.

The calculations consisted of determining the SWATH displacement required to support a specified payload at various operating speeds. The operating profile of the vessels in this particular survey was one of constant speed operation. (There was therefore no distinction made between *maximum* and *cruise* speeds). Default calculations for the weight of stores (0.036Δ) and margins ($0.0755\ WLIGHT^{1.0747}$) were used in this study.

Sixteen different payload requirements were examined at eleven different design speeds. In this particular survey, *INITIAL* was therefore required to provide 15840 design solutions. On a VAX 11/780, this amount of data can be generated in six hours of batch processing.

The data contained in Appendix 2 is primarily intended as an example of the capabilities of the design method. However, if actual design requirements correspond to the constraints under which this study was performed (default stores, default margins, simple operating profile), the information may be used directly as a design aid. Curves may be constructed relating variables of interest and interpolation used to determine points of particular interest.

Some general trends may also be observed. The data confirms that for the same propulsion type, range, speed and payload, the lowest required displacements are provided by aluminium structures, followed by advanced structure SWATHs.

Apart from the largest and fastest vessels operating at ranges of 500nm, the combinations investigated appear to be unsuited to gas turbine propulsion. High speed diesel powered SWATHs are seen to require less displacement for given speed and payload. The influence of fuel consumption is clearly seen in this case. Shorter ranges would tend to be more favourable to the gas turbine option, especially for high power applications. Vessels having different maximum and operating speeds would show entirely different characteristics, and would tend to combine diesel plant for cruising with gas turbines available for high power demand.

Finally, although the increments in speed which are presented in the tables are rather coarse, localised hollows in payload/displacement ratio arising from increased power requirements at the prismatic hump are visible.

These examples indicate the capability of *INITIAL* as a preliminary design tool. Broad base trade-offs may be conducted rapidly to assess the likely impact on ship size of payload, structure type, machinery type, endurance speed and range, maximum speed and range, crew size etc.

4.4 Weight Equation for SWATH Ships

4.4.1 Introduction

An alternative approach to deriving the displacement of a baseline design is that of the *'weight equation'* approach [29]. In this method, known weight data from previous designs is manipulated using equations formed under certain simplifying assumptions to estimate weights for a new vessel. This method may readily be incorporated with the calculating capacity of modern computers to construct large numbers of reference tables for use in preliminary design.

The weight equation is intended to obtain, in a rational manner, the group weights for a *new* design which differs in deadweight from a *type* ship whose group weights are known. Extensions of the theory are designed to allow for deviations in endurance and speed. The method assumes that the deadweight is an independent variable, and that each of the remaining group weights may be expressed as a constant times the displacement raised to some power. This indice is unique to the weight group, and assumed to be constant over the change of displacement considered.

The main weaknesses of the weight equation approach are;

a) limitations of form and proportion are neglected
b) little data has been processed to determine the indices accurately (in the case of SWATH ships, there are no publications on weight group estimation)

4.4.2 Formulation of Approach

For SWATH ships, which will usually be designed for roles which demand more than one design speed, the formulation for deadweight carriers proposed by Cameron [29] must be extended to consider *design* speed, and *cruise* speed and endurance. In addition, the weight breakdown employed in *INITIAL*, is used to define the major weight groups. For a vessel balanced on the basis of weight, the sum of the group weights is equal to the designed displacement.

$$\Delta = WS + WM + WAUX + WO + WF + WSM + WP \qquad \text{Eqn 4.34}$$

where the constituent group weights are as defined in section 4.3.3.

If the design payload (deadweight) P, design speed V, cruise speed U and cruise endurance E are variables, then the displacement and group weights will alter as follows.

$$\begin{aligned}\Delta + \partial\Delta = {} & (WS + \partial WS) + (WM + \partial WM) + \\ & (WAUX + \partial WAUX) + (WO + \partial WO) + \\ & (WF + \partial WF) + (WSM + \partial WSM) + (WP + \partial WP) \qquad \text{Eqn. 4.35}\end{aligned}$$

Under the assumptions of the weight equation, individual group weights may be expressed as follows.

$$\begin{aligned} WS &= k_1 \Delta^p \\ WM &= k_2 \Delta^r V^s \\ WO &= k_3 \Delta^q \\ WAUX &= k_4 \Delta^x \qquad \text{Eqns. 4.36} \\ WSM &= k_5 \Delta^w \\ WF &= k_6 \Delta t\, U^u E^v \end{aligned}$$

Now, $\log WS = \log k_1 + p \log \Delta$

$$\log WM = \log k_2 + r \log \Delta + s \log V$$
$$\log WO = \log k_3 + q \log \Delta$$
$$\log WAUX = \log k_4 + x \log \Delta$$
$$\log WSM = \log k_5 + w \log \Delta$$
$$\log WF = \log k_6 + t \log \Delta + u \log U + v \log E$$

Differentiation yields equations,

$$\partial WS/WS = p\, \partial\Delta/\Delta$$
$$\partial WM/WM = r\, \partial\Delta/\Delta + s\partial V/V$$
$$\partial WO/WO = q\, \partial\Delta/\Delta$$
$$\partial WAUX/WAUX = x\, \partial\Delta/\Delta$$
$$\partial WSM/WSM = w\, \partial\Delta/\Delta$$
$$\partial WF/WF = t\, \partial\Delta/\Delta + u\, \partial U/U + v\, \partial E/E$$

which become,

$$\partial WS = p\, WS\, \partial\Delta/\Delta$$
$$\partial WM = r\, WM\, \partial\Delta/\Delta + s\, WM\, \partial V/V$$
$$\partial WO = q\, WO\, \partial\Delta/\Delta \qquad \text{Eqns. 4.37}$$
$$\partial WAUX = x\, WAUX\, \partial\Delta/\Delta$$
$$\partial WSM = w\, WSM\, \partial\Delta/\Delta$$
$$\partial WF = t\, WF\, \partial\Delta/\Delta + u\, WF\, \partial U/U + v\, WF\, \partial E/E$$

Subtracting equations 4.34 from 4.35, and dividing by Δ,

$$\partial\Delta/\Delta = \partial WS/\Delta + \partial WM/\Delta + \partial WO/\Delta + \partial WF/\Delta + \partial WAUX/\Delta + \partial WSM/\Delta + \partial WP/\Delta$$

Eqn. 4.38

Substituting equations 4.37 into 4.38, gives

$$\partial\Delta/\Delta = \frac{(\partial WP/WP)(WP/\Delta)+(\partial V/V)(sWM/\Delta)+(\partial U/U)(uWF/\Delta)+(\partial E/E)(vWF/\Delta)}{1 - p\, WS/\Delta - r\, WM/\Delta - q\, WO/\Delta - t\, WF/\Delta - x\, WAUX/\Delta - w\, WSM/\Delta}$$

Eqn. 4.39

Thus, the increase in displacement consequent upon changes in P, V, U, and E may be expressed as a function of known type ship weights, and the assumed indices. Changes in the individual group weights may be determined by using equation 4.37.

4.4.3 Choice of Indices

The choice of indices is the point upon which the usefulness of the weight equation depends. Badly chosen indices will mean that tables of results produced by the method are of little practical value. For this work, reference has been made to the regression analysis of SWATH ship data reported in section 4.3. The indices for the various group weights may be considered separately.

Structural Weight

If WS = k Δ, then the indice is 1.0. This is probably a fair assumption over small changes in Δ, but regression on the available SWATH data shows that the structural weight is not a strict linear function of displacement. The following relationships have been found to give the closest agreement to the known data.

Mild steel construction	$WS = 0.320\Delta^{1.029}$
Hybrid construction	$WS = 0.536\Delta^{0.955}$
Aluminium construction	$WS = 0.626\Delta^{0.918}$
(Basic relationship)	$WS = k\Delta^{1.000}$

Machinery Weight

It is common practice with the weight equation to relate machinery weight to power by a constant, and to estimate power from $\Delta^{2/3}V^3$. However, regression on SWATH data shows that better agreement between power and Δ, V is obtained by $P = \Delta^{0.598}V^{2.691}$. In addition, different machinery types do not necessarily have weights which vary linearly with power. Regression on available SWATH machinery data provides the following,

High speed diesel	$WM = k\ P^{1.000}$
Medium speed diesel	$WM = k\ P^{0.840}$
Gas turbines	$WM = k\ P^{1.000}$
Diesel electric	$WM = k\ P^{0.697}$
Gas turbo electric	$WM = k\ P^{0.610}$

Thus the indices for machinery group weight may be chosen from the following,

Basic equation	$WM = k\ \Delta^{0.667}V^{3.000}$
Modifed equation (non machinery specific)	$WM = k\ \Delta^{0.598}V^{2.691}$
High speed diesel machinery	$WM = k\ \Delta^{0.598}V^{2.691}$
Medium speed diesel machinery	$WM = k\ \Delta^{0.502}V^{2.660}$
Gas turbines	$WM = k\ \Delta^{0.598}V^{2.691}$
Diesel electric	$WM = k\ \Delta^{0.406}V^{1.827}$
Gas turbo-electric	$WM = k\ \Delta^{0.365}V^{1.642}$

Auxiliary Weight Section 4.3.6.1 yields $WAUX = k\,\Delta^{0.981}$

Outfit Weight Section 4.3.6.2 yields $WO = k\Delta^{0.881}$

Stores/Margin Weight

In order to maintain the same weight of stores in both the *type* and *new* ships, this indice should be set to zero.

i.e. $WSM = k\Delta^{0.000}$

Fuel Weight

The usual approach for fuel weight calculation is $WF = k\,\Delta^{2/3}V^3E^1/V$
i.e. fuel weight = (power x time at sea) where time at sea is calculated from the maximum (design) speed and the design range. For SWATH ships, which are unlikely to operate at a single speed, it is better to introduce a cruise speed U, which, with the modified powering approach, gives

$$WF = k\Delta^{0.598}V^{1.691}E^{1.000}$$

while the basic formula would be $WF = k\Delta^{0.667}V^{2.000}E^{1.000}$

Appendix 3 illustrates a typical calculation performed using the method and approximations described above.

4.4.4 Typical Results

A computer program (*WEIGHT*) has been written to perform calculations of the weight equation type. Tables may be constructed which vary payload, speed, and endurance separately, and the total effect of altering all three variables may be obtained by adding the separate effects. This approach is valid as long as the changes are reasonably small. The effect of a mixed combination of changes of up to 20% may be found by multiplication and addition.

Typical results from this program are given in Table 4.10. The *type* ships used in these examples are all SWATH designs from Appendix 1 which have been carried to a fairly high level of detail. The indices used in the calculations are those specific to the particular machinery and structure of each vessel. These results may be used directly in

Table 4.10 SWATH Ship Design Data Produced by Weight Equation Program

Design ID #	Full Load Weight - Δ (tonnes)	Max. Speed (knots)	Cruise Speed (knots)	Cruise Range (nm)	Group Weights (tonnes) Structure	Machinery	Auxiliary	Outfit	Fuel	Stores & Margins	Payload	% increase in Δ for 1% increase in Payload	Max. Speed	Cruise Speed	Cruise Range	Tonnes Δ increase for 1 tonne payload increase
[1]	77.5	25.0	20.0	1000	33.7	9.7	8.7	7.9	11.8	2.5	3.2	0.176	1.433	1.096	0.648	4.26
[5]	128.4	25.0	10.0	1490	44.6	19.7	22.4	10.1	10.7	16.2	4.7	0.122	1.380	0.471	0.279	3.33
[6]	255.3	25.0	12.0	3260	78.6	31.3	42.6	27.9	33.8	32.7	8.4	0.108	1.082	0.734	0.434	3.28
[7]	764.2	25.0	13.0	3800	257.5	87.7	129.5	61.4	115.8	91.8	20.5	0.091	1.049	0.870	0.515	3.39
[8]	1273.9	25.0	15.0	5700	408.3	170.2	179.6	95.0	241.3	152.8	26.7	0.068	1.165	1.038	0.614	3.24
[10]	914.0	25.0	15.0	6400	267.0	87.0	50.0	129.0	280.0	61.0	40.0	0.144	0.846	1.710	1.011	3.29
[16]	57.9	20.0	18.0	165	23.6	8.0	7.7	8.7	1.3	2.5	6.1	0.395	1.393	0.142	0.084	3.75
[54]	480.0	33.0	33.0	400	180.0	93.0	22.0	57.0	68.0	32.0	28.0	0.200	1.787	0.821	0.486	3.43
[72]	7183.0	25.0			2403.0	462.0	1129.0	452.0	1060.0	813.0	864.0	0.360	0.316	0.746	0.441	2.99
[86]	160.0	20.0	19.0	530	78.4	38.2	3.2	11.6	15.3	6.2	7.1	0.180	2.584	0.650	0.385	4.03
[88]	15067.0	28.0	15.0	9000	6297.0	649.0	2280.0	934.0	2455.0	1417.0	1035.0	0.271	0.279	1.086	0.642	3.95
[92]	12786.0	20.0			4090.0	1390.0	1467.0	772.0	3692.0	1338.0	37.0	0.010	0.689	1.694	1.002	3.46
[103]	2415.0	14.0	8.0	7700	1172.0	149.0	283.0	160.0	355.0	236.0	60.0	0.116	0.526	1.160	0.686	4.67
[104]	2330.0	15.1	8.0	10200	1056.0	132.0	265.0	196.0	236.0	385.0	60.0	0.097	0.391	0.648	0.383	3.77
TAGOS	3450.0	9.6			1660.0	65.0	513.0	242.0	610.0	230.0	130.0	0.205	0.187	1.626	0.962	5.44
																(3.75 average)

Numbers refer to identification of designs in Appendix 1

the estimating of displacement for a new design which has characteristics in common with one or more of the Table 4.10 designs. The program may of course be used to generate data on any arbitrary set of input group weights and performance data, as well as with different indices.

Table 4.10 shows that for the ships studied, increasing payload weight by 1 tonne, will on average result in an increase of 3.75 tonnes in ship displacement. This is in accordance with [33] (the source for ships 5 to 8 in Table 4.10) where it is stated that *'1 tonne of reserve load requires 3-4 tonnes of ship if a thorough redesign is done'*.

4.5 Free Choice by Designer

4.5.1 General

As well as using existing trends or output from a computer program to generate the first estimates of vessel particulars, it is important for a practical design system to allow the designer to control the character of a new design. Because of this the 'baseline' section of *DESIN* has been designed to accept any user defined configuration and transform it into the format required by downstream synthesis tools. In many cases a manual working out of a vessel arrangement based on deck area, or space requirements can provide the best starting point for a new design. This section briefly presents some guides for sizing SWATH ships to requirements not covered elsewhere in this chapter.

4.5.2 Design by Volume

Established methods exist for estimating the volumetric requirements of commercial [4] and naval vessels [30]. Ship displacement may then be estimated via a density, and a rough sketch of the general arrangement of spaces can indicate a suitable form for the vessel.

An iterative procedure used at UCL [19] for sizing a SWATH design includes the option to estimate overall enclosed volume from required payload volume. This can allow ship displacement to be estimated by means of a ship density. UCL have found that payload volume fractions for SWATH vessels are around 75% of equivalent monohull values, while densities are similar. The usefulness of their data (Table 4.11) depends on a knowledge of the UCL definition of payload volume. Experience with SWATHs designed to the UK MoD space classification indicates that payload volume fractions of 0.05 are typical for small combatant/auxiliary vessels.

Table 4.11 Initial Sizing by Volume for SWATH Ships from [19]

SWATH Type	Payload Volume Fraction	Ship Density (t/m^3)
Ro-Ro Ferry	0.53 - 0.57	0.33 - 0.37
Cruise Liner	0.53 - 0.57	0.18 - 0.22
Aircraft Carrier	0.27 - 0.31	0.21 - 0.25
Frigate/Destroyer	0.16 - 0.22	0.23 - 0.30
Research Vessel	0.18 - 0.20	0.30 - 0.34
Minehunter	0.12 - 0.18	0.22 - 0.26

Appendix 1 contains some designs where enclosed volume is known. These have been plotted in Figure 4.30, along with some NATO combatant and auxiliary monohull data. Apart from four small aluminium SWATHs with densities around 0.14 t/m^3, densities for both SWATHs and monohulls range from 0.22 to 0.30 for the limited sample examined. A US Navy study has suggested [31] that SWATHs should have similar densities to monohulls (USN ships have densities in a well defined range from 0.205 to 0.240 $tonne/m^3$).

4.5.3 Design for Payload Weight

The sizing of a vessel on the basis of weight must necessarily involve considerations of propulsion type and fuel weight as described in Sections 4.3 and 4.4. However, a simple analysis of payload fractions (as defined in Section 4.3.3) illustrates (Figure 4.31) the well known limitation of SWATH as a deadweight carrier. The mean line through the available data shows a payload fraction of 10%, with many designs having lower values. US monohull combatant ships have values between 15 and 25% [22] and this illustrates the disadvantage of the SWATH ship when compared with monohulls on a traditional basis.

4.5.4 Design for Deck Area

It has often been suggested that one of the secondary advantages resulting from the SWATH arrangement is large deck area. However, recent US Navy experience with practical designs does not support this claim [32]. For many roles, especially air capable missions, and small craft where all functions must be placed on the upper deck, deck area is a primary driver in design. Figure 4.32a presents the deck area/displacement ratios of designs from Appendix 1. Deck areas have been estimated by multiplying strut lengths by vessel beam. Small SWATHs may have as much as 3 m^2 deck area per tonne displacement, but above 2000 tonnes, values of 0.5 m^2/t (or less) are most common. As shown in Figure 4.32b long strut designs offer more deck area than short strut SWATHs.

Long strut SWATH Deck Area (m^2) $= 12.30\ (\Delta^{2/3})^{0.942}$ Eqn. 4.40

Short strut SWATH Deck Area (m^2) $= 11.18\ (\Delta^{2/3})^{0.922}$ Eqn. 4.41

4.5.5 Design for Seakeeping

Although good seakeeping performance is the principal reason for choosing a SWATH solution, this is not an automatic virtue of the arrangement [34] and care must be exercised in this area. Guidance on SWATH hull design for seakeeping may be found in [35]. At the earliest stages of design it is useful to estimate the size of vessel required to avoid resonant responses within the range of commonly occuring periods of maximum wave energy. Because of the inherent flexibility of the SWATH geometry, there exists considerable freedom in manipulating natural periods of heave, pitch and roll. This may be seen in Figures 4.33 to 4.35 which nevertheless provide an indication of the resonant periods typically associated with a given SWATH displacement. Regression on the data (from 8 built and 9 proposed designs) yielded equations 4.42 to 4.44.

Heave Period (s) $= 2.69\ \Delta^{0.162}$ Eqn. 4.42

Pitch Period (s) $= 2.72\ \Delta^{0.222}$ Eqn. 4.43

Roll Period (s) $= 5.04\ \Delta^{0.156}$ Eqn. 4.44

It is not immediately apparent what value of waterplane area qualifies for the term *'small'*. As a preliminary guide, data from Appendix 1 has been plotted in Figure 4.36. Waterplane area has been estimated from strut lengths and thicknesses, assuming C_w of 72% for tandem struts and 80% for single struts. Small SWATHs may have as much as 0.4 m^2 strut area per tonne displacement, but above 1000 tonnes, values about 0.05 m^2/t or less are most common.

4.6 Conclusions

Alternative methods for initial sizing of SWATH ships have been described. These are necessary steps in increasing the efficiency of more complex synthesis tools.

In particular, a distinct need for a simple-to-use design program for SWATH ships was identified. Such an initialisation tool is necessary as a preprocessor for more sophisticated synthesis techniques in order to increase the probability of satisfactory convergence. The wide interest in SWATH over the last decades has generated a substantial number of conceptual designs which offer the opportunity for deriving parametric methods for such early stage design methods.

Simple techniques have been developed to predict required power for SWATH ships of conventional form, and weight estimation methods have been derived. A design algorithm based on these parametric approaches has been programmed and tested satisfactorily. Designs produced by the program compare well with equivalent in-depth concept studies. The capability of the method as a tool for design studies has been demonstrated by representative parametric studies.

A *weight equation* method for initial sizing of SWATH ships using existing data has been developed and programmed. Studies using this tool give results which are in agreeement with the conclusions of manual design projects. It is shown that nearly 4 tonnes of SWATH displacement is required to support 1 tonne of extra payload. A number of published design studies have beeen assessed using the method to provide further data for use by designers.

In order to provide further data to aid in initial sizing of SWATH ships, information has been presented which links SWATH ship weight, volume, density, payload, deck area and seakeeping. It is recommended that these simple methods be used in parallel to confirm sizes developed by other means.

References to Chapter 4

1. Devine, M.D. "ASSET-A Computer Aided Engineering Tool for the Early Stage Design of Advanced Marine Vehicles", AIAA 8th Advanced Marine Systems Conference, San Diego, September 1986

2. "Ship Work Breakdown System", NAVSEA 0900-LP-039-9010, NAVSEA, 1977

3. "Classification of Weight Groups for Surface Ships", NES 163, UK MoD(N)

4. Watson, D.G.M. and Gilfillan, A.W. "Some Ship Design Methods", *Transactions* RINA, 1977

5. Eames, M.C. and Drummond, T.G. "Concept Exploration-An Approach to Small Warship Design", *Transactions* RINA, 1977

6. Nethercote, W.C.E. and Schmitke, R.T. "A Concept Exploration Model for SWATH Ships", *Transactions* RINA, 1982

7. Covich, P. "SWATH T-AGOS - A Producible Design", AIAA 8th Advanced Marine Systems Conference, San Diego, September 1986

8. Authors reply to Discussion on [4], 1977

9. Mulligan, R.D. and Edkins, J.N. "ASSET-SWATH - A Computer Based Model for SWATH Ships", RINA International Symposium on SWATH Ships and Advanced Multi Hulled Vessels, London, 1985

10. Chapman, R.B. "Hydrodynamic Drag of Semi-submerged Ships", *Transactions* ASME, Vol. 94, 1972

11. Lin, W.C. "The Force and Moment on a Twin Hull Ship in Steady Potential Flow", 16th Symposium on Naval Hydrodynamics, MIT, USA, 1974

12. Chun, H.H. "A Study on the Wavemaking Resistance of Multi-Hulled Vessels SWATH Ships", Report NAOE-86-63, Department of Naval Architecture and Ocean Engineering, Glasgow University, December 1986

13. MacGregor, J.R. "The Initialisation Section of a Design Tool for SWATH Ships", University of Glasgow, Department of Naval Architecture and Ocean Engineering Report NAOE-88-24, 1988

14. Numata, E. "Predicting Hydrodynamic Behaviour of SWATH Ships", *Marine Technology*, January 1981

15. Kennell, C. Discussion on [6], 1982

16. Chapman, R.B. "Spray Drag of Surface Piercing Struts", AIAA/SNAME Advanced Marine Vehicles Conference, July 1972

17. Private Communication to Department of Naval Architecture and Ocean Engineering, Glasgow University, from MARIN, Netherlands, 1986

18. "ASSET-SWATH User Manual, Volume 3B, Boeing Company, Seattle, 1987

19. Betts, C.V., "Some UK Developments in SWATH Design Research", *Proceedings*, International High Performance Vehicle Conference, Shanghai, November 1988

20. Eames, M.C. "Advances in Naval Architecture for Future Surface Warships", *Transactions* RINA, 1981

21. MacGregor, J.R. "Notes of meeting with Professor Owen Hughes at YARD Ltd, 23/11/87", Department of Naval Architecture and Ocean Engineering, Glasgow University, November 1987

22. Rainey, P.G. "Basic Ocean Vehicle Assessment", *Naval Engineers Journal*, April 1976

23. Mandel, P. "A Comparative Evaluation of Novel Ship Types", *Transactions* of SNAME, Vol. 70, 1962

24. MacGregor, J.R. "An Analysis of SWATH Ship Design and Performance Data", Report NAOE-86-30, Department of Naval Architecture and Ocean Engineering, Glasgow University, November 1986

25. Ozawa, H "SSC Support Vessel for Underwater Experiment, the *Kaiyo*", High Speed Craft Division, Ship and Ocean Project Headquarters, Mitsui Engineering & Shipbuilding Ltd

26. MacGregor, J. R. "SWATH User Guide- SEARCH", SWATH Program User Guides Vol. 1, YARD Ltd, YM5670/004/00A, 1987

27. MacGregor, J. R. "SWATH User Guide- INITIAL", SWATH Program User Guides Vol. 1, YARD Ltd, YM5670/001/00A, 1987

28. Pattison, D.R. and Rose, P.H.A., "SWATH - The UK Design and Assessment Programme", *Proceedings,* International Conference on SWATH Ships and Advanced Multihulled Vessels, RINA, London, November 1988

29. Cameron, R.M., "The Weight Equation", *Shipping World and Shipbuilder,* Sept. 1971

30. "Warship Volumetric Analysis", YARD Internal Memorandum YIM412/81 (Restricted)

31. Pieroth, C.G. and Lamb, G.R., "The SWATH Option as a V/STOL Aircraft Carrier", 7th AIAA/SNAME/ASNE Marine Systems Conference, New Orleans, February 1983

32. Cannon, T.R. and McKesson, C.B., "Large SWATHs - A Discussion of the Diminishing Returns of Increasing SWATH Ship Size", AIAA Paper 2385, AIAA 8th Advanced Marine Systems Conference, San Diego, September 1986

33. Holcomb, R.S. and Allen, R.G., "Investigation of the Characteristics of Small SWATH Ships Configured for United States Coast Guard Missions", DTNSRDC Report SDD-83-3, June 1983

34. "Care urged with SWATH Designs", *Lloyds List*, 20th November 1987

35. Lamb, G.R., "Some Guidance for Hull Form Selection for SWATH Ships", SNAME *Marine Technology*, October 1988

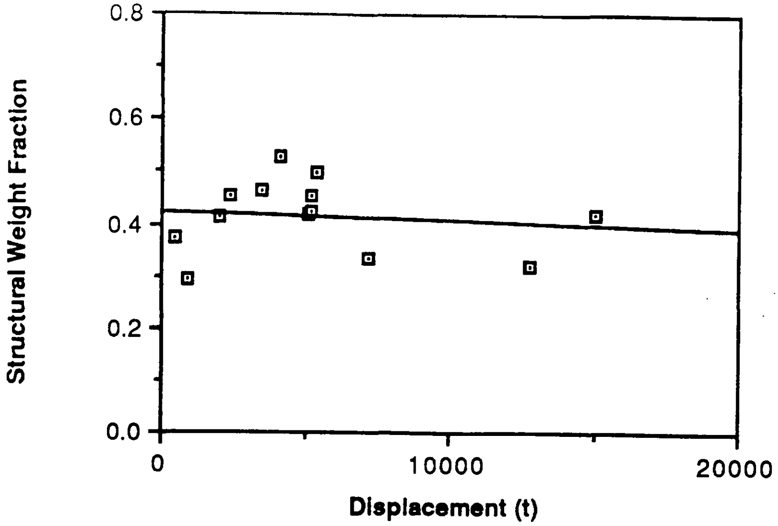


Figure 4.1 Weight Fractions - Mild Steel Structure

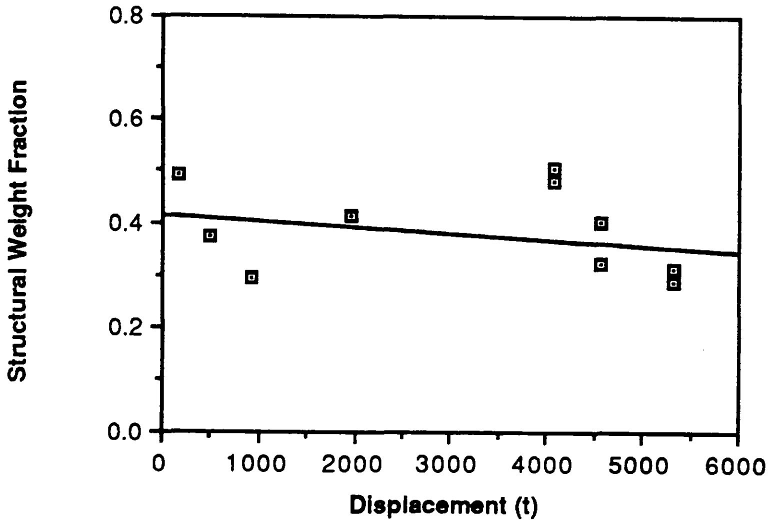


Figure 4.2 Weight Fractions - 'Advanced' Structure

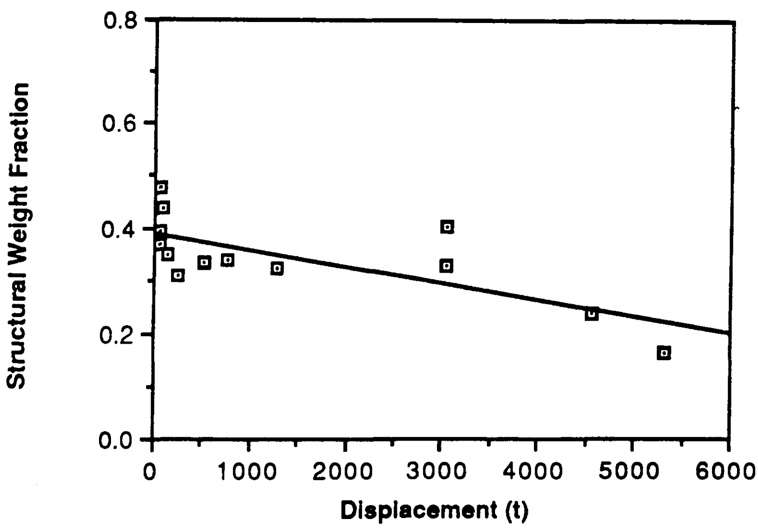


Figure 4.3 Weight Fractions - Aluminium Structure

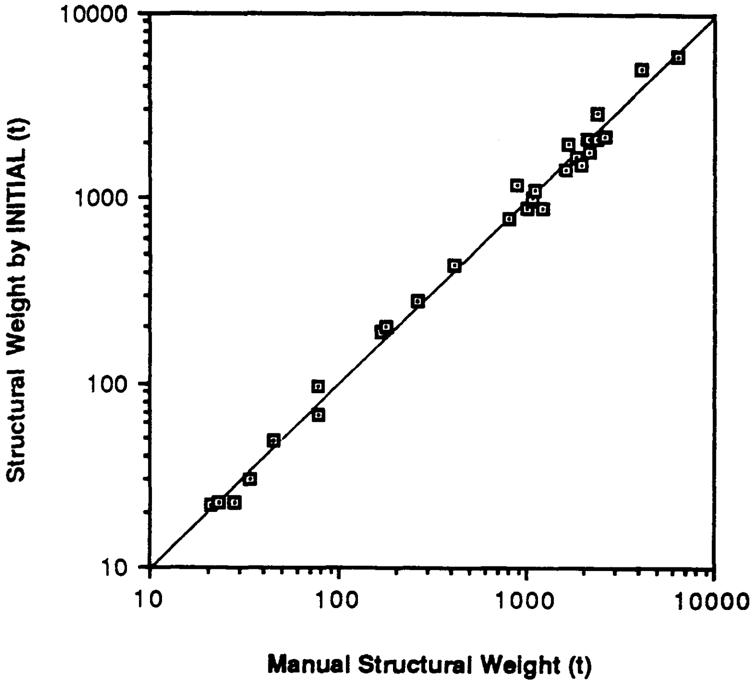


Figure 4.4a Comparison of Published and *INITIAL* Structural Weights

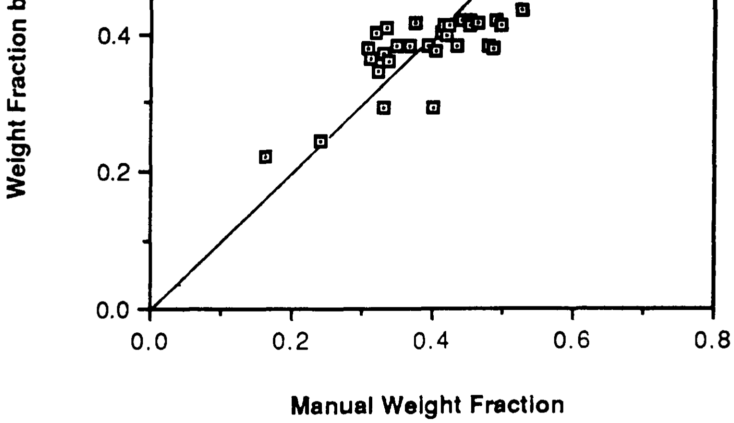


Figure 4.4b Comparison of Published and *INITIAL* Structural Weight Fractions

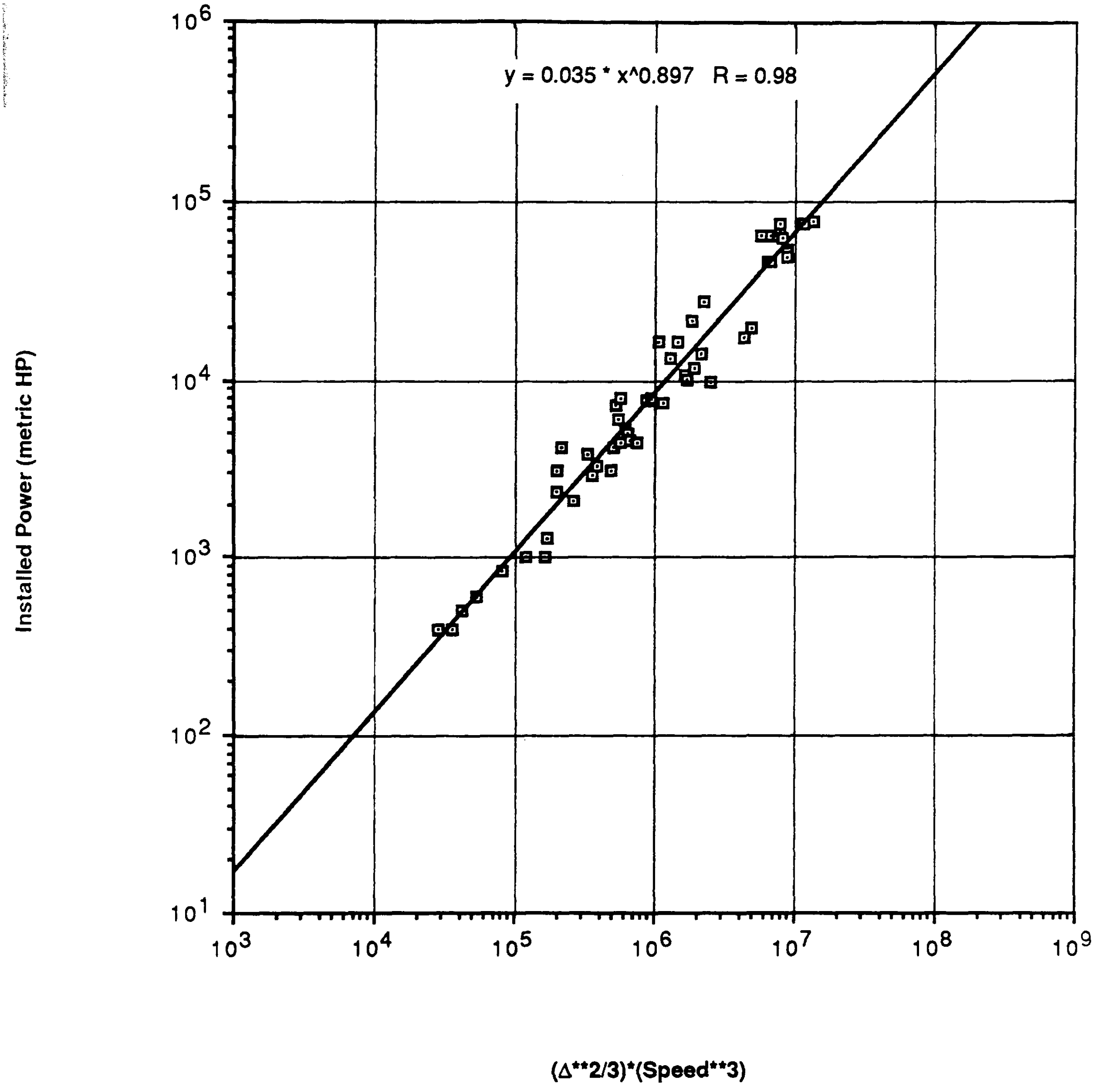


Figure 4.5 'Admiralty' Powering Approach

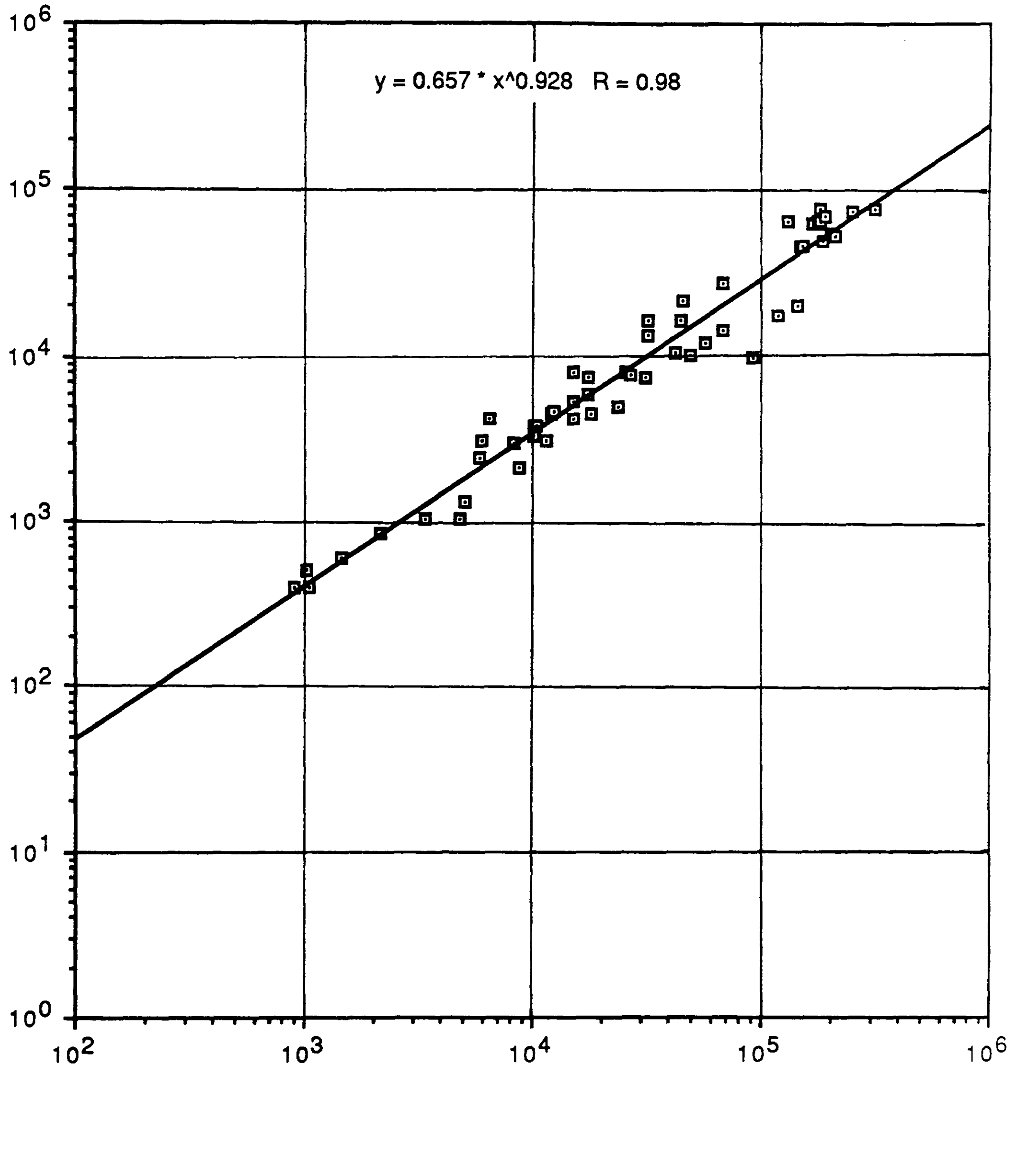


Figure 4.6 Modified 'Admiralty' Powering Approach

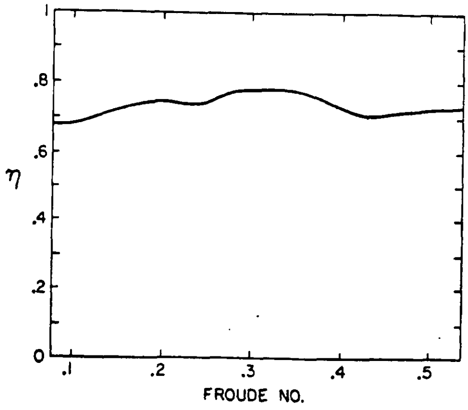


Figure 4.7 Overall Propulsive Coefficient (from [6])

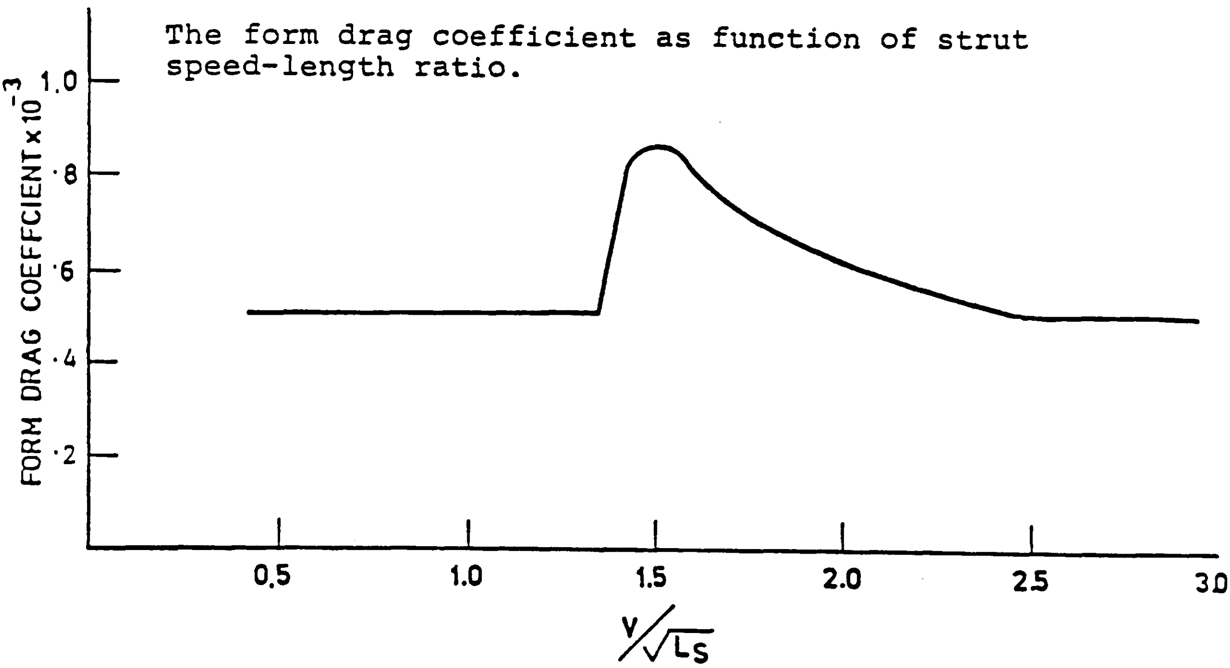


Figure 4.8 Form Drag Coefficient (from [17])

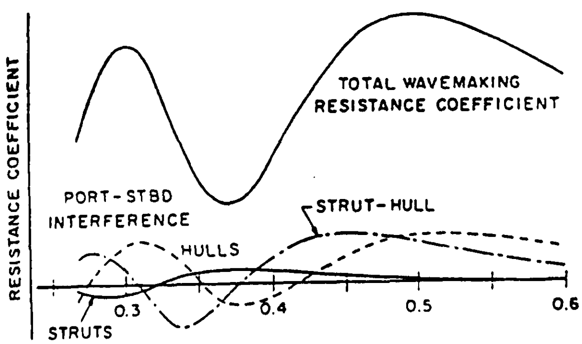


Figure 4.9 Typical Coefficients of SWATH Resistance (from [14])

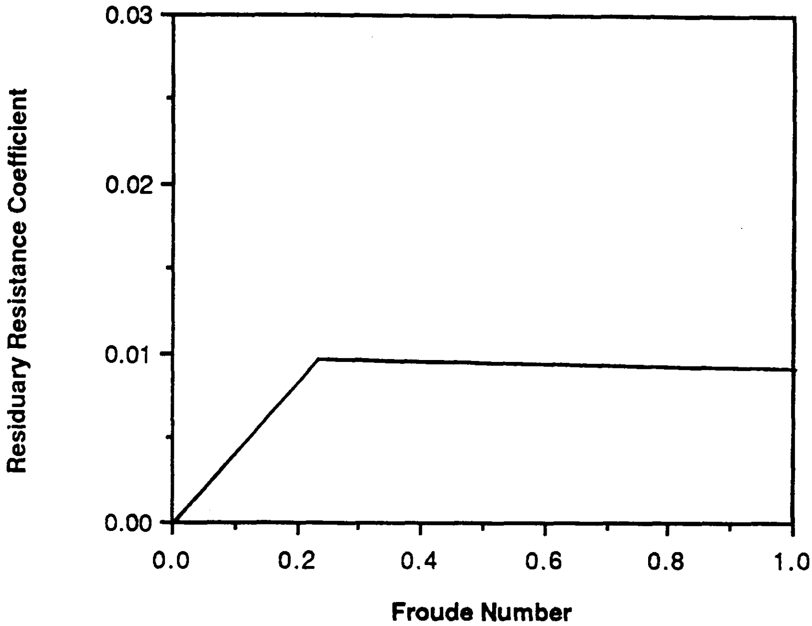


Figure 4.10 C_R Proposed for *ASSET* Initialisation

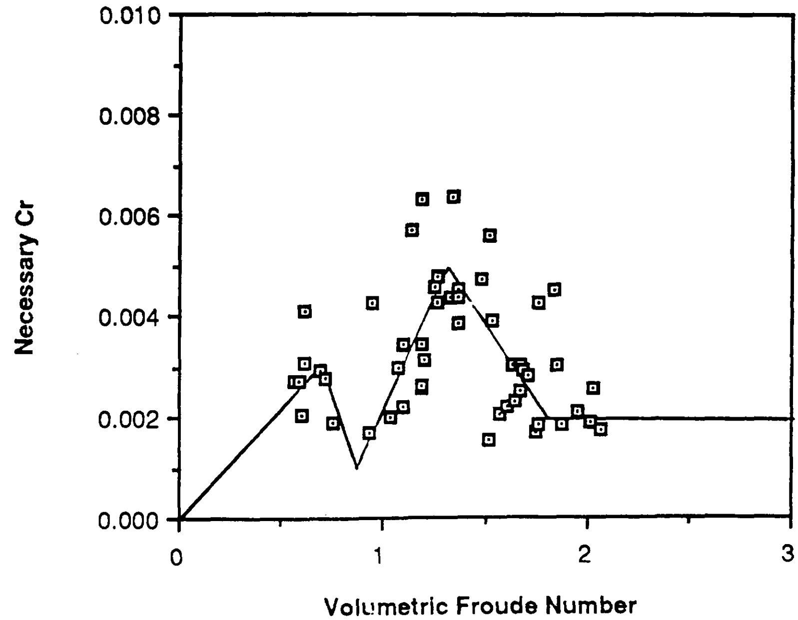


Figure 4.11 Required Variation on C_R for Direct Power Prediction

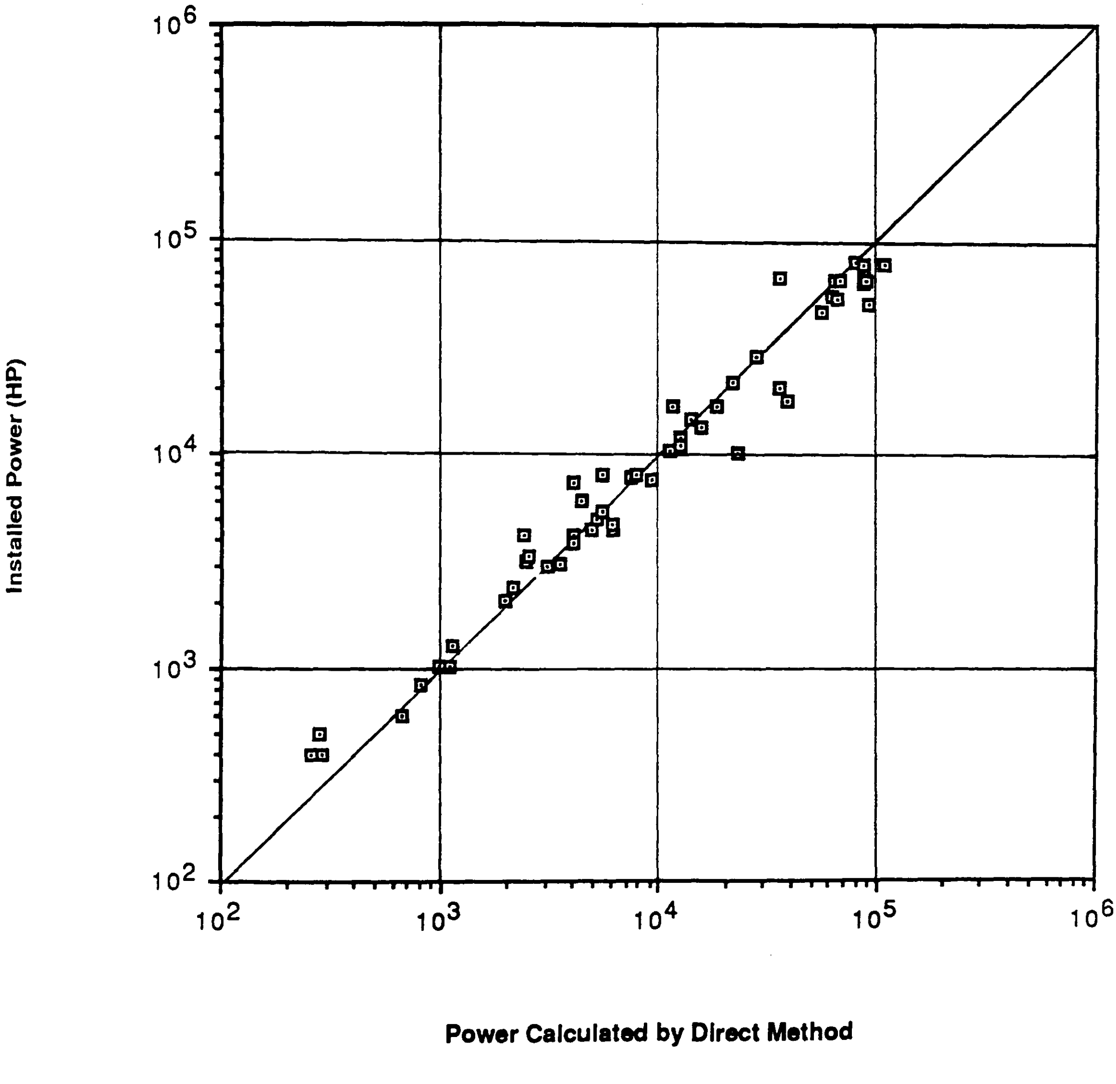


Figure 4.12 Performance of Direct Powering Method

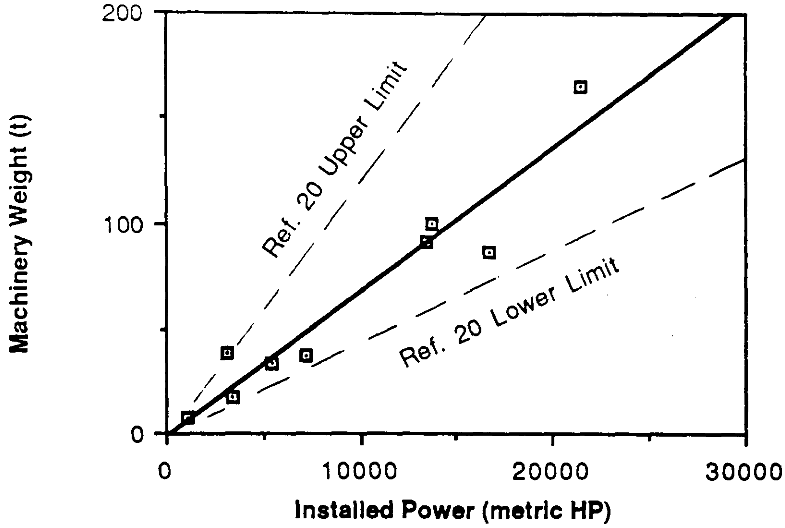


Figure 4.13 Weight of High Speed Diesel Machinery

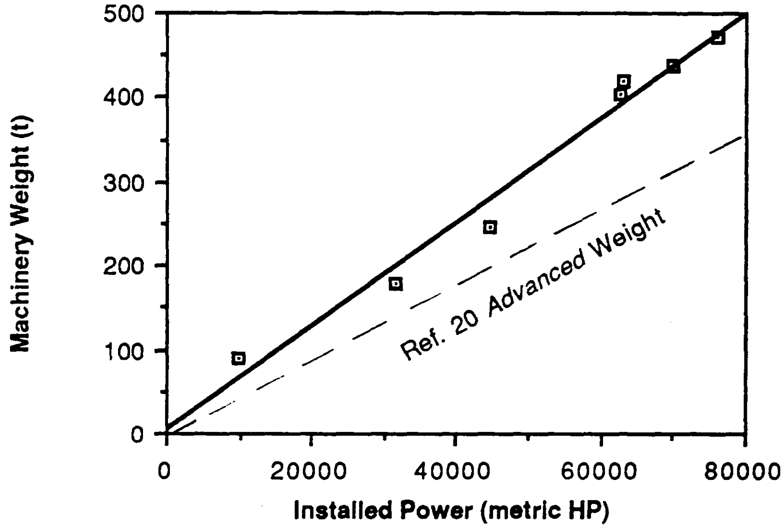


Figure 4.14 Weight of Gas Turbine

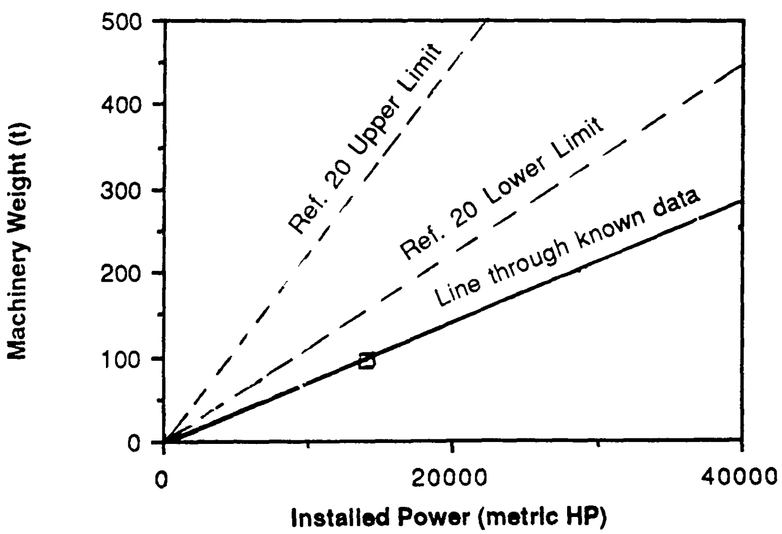


Figure 4.15 Weight of Medium Speed Diesel Machinery

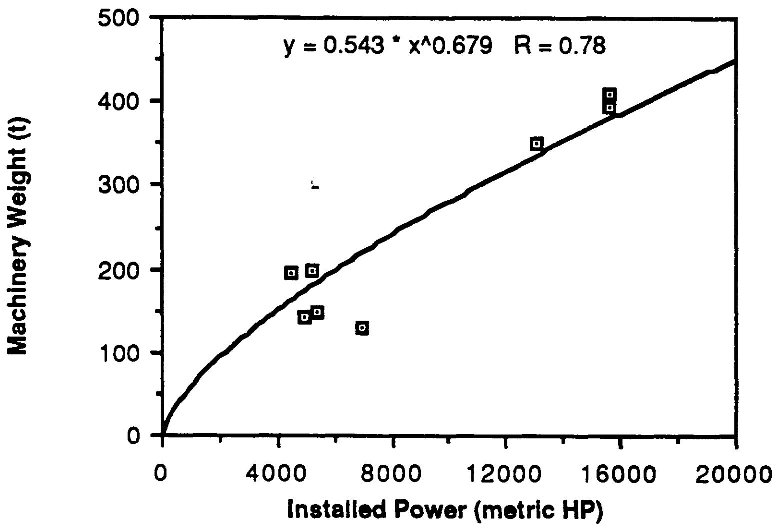


Figure 4.16 Weight of Diesel-Electric Machinery

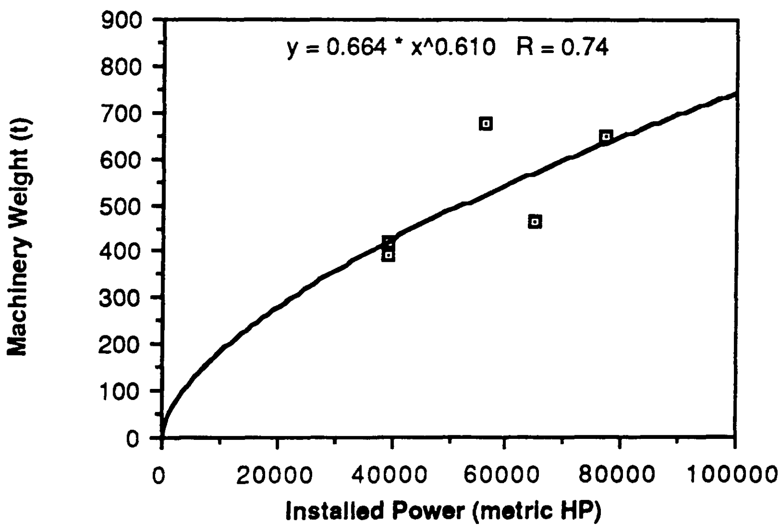


Figure 4.17 Weight of Gas-Turbo-Electric Machinery

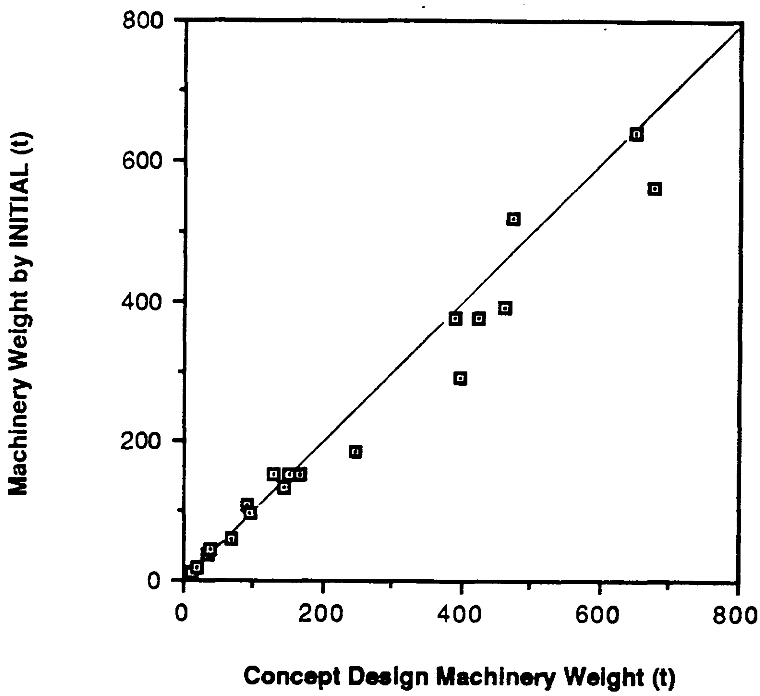


Figure 4.18a Comparison of Published and *INITIAL* Machinery Weights

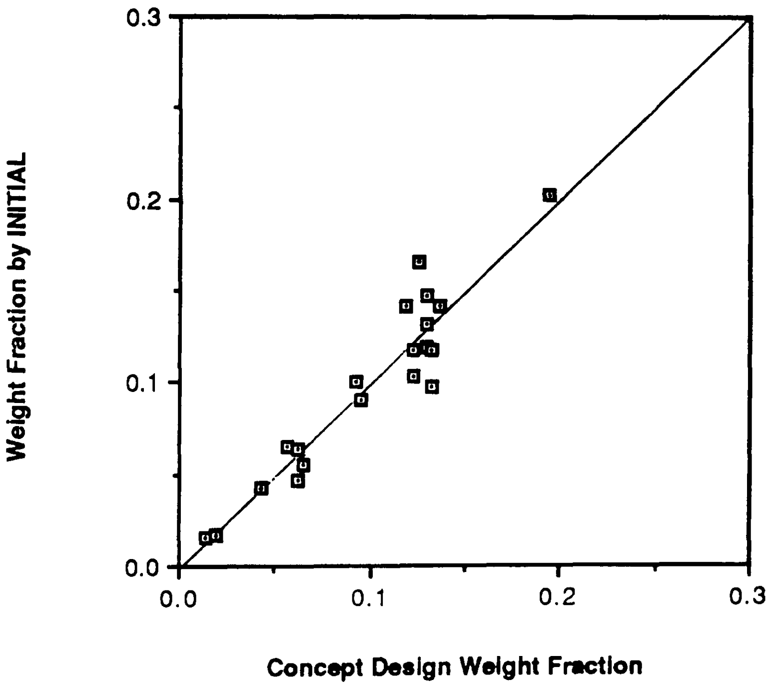


Figure 4.18b Comparison of Published and *INITIAL* Machinery Weight Fractions

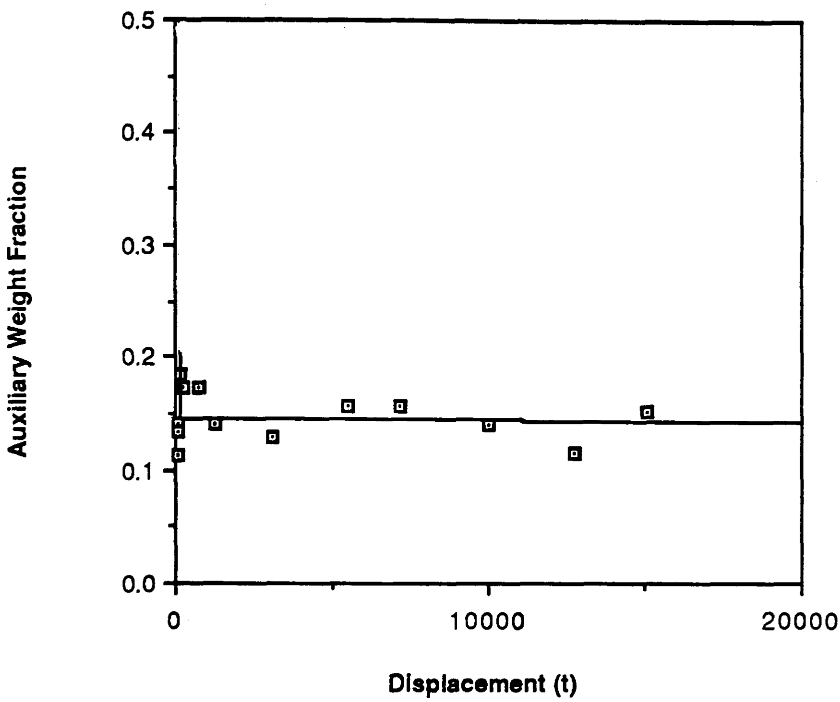


Figure 4.19 SWATH Ship Auxiliary Weight Fractions

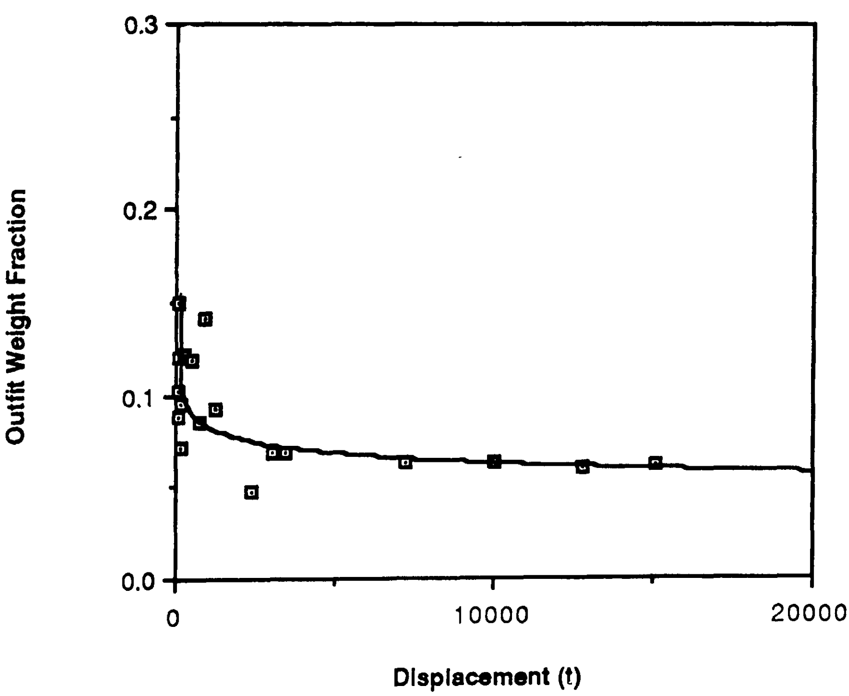


Figure 4.20 SWATH Ship Outfit Weight Fractions

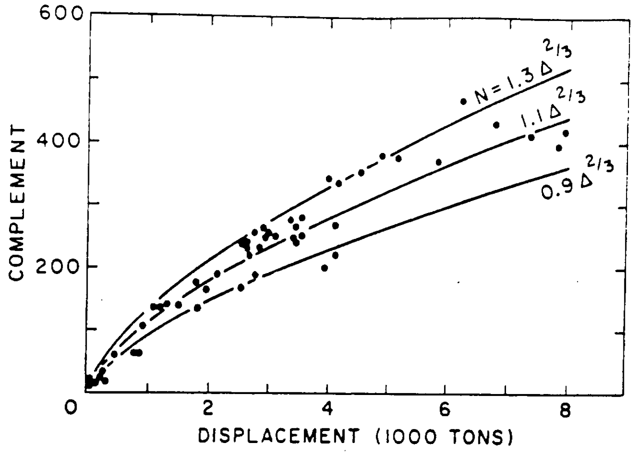


Figure 4.21 Warship Complement as a Function of Size (from [5])

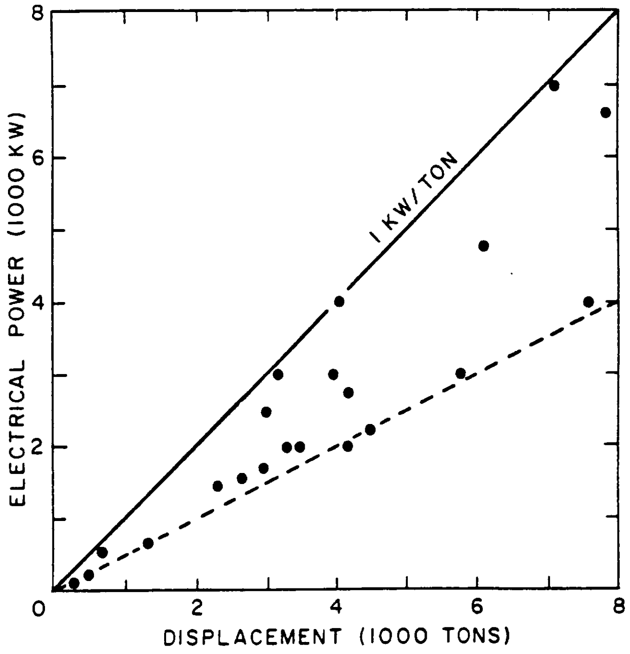


Figure 4.22 Installed Electrical Power for Small Warship (from [5])

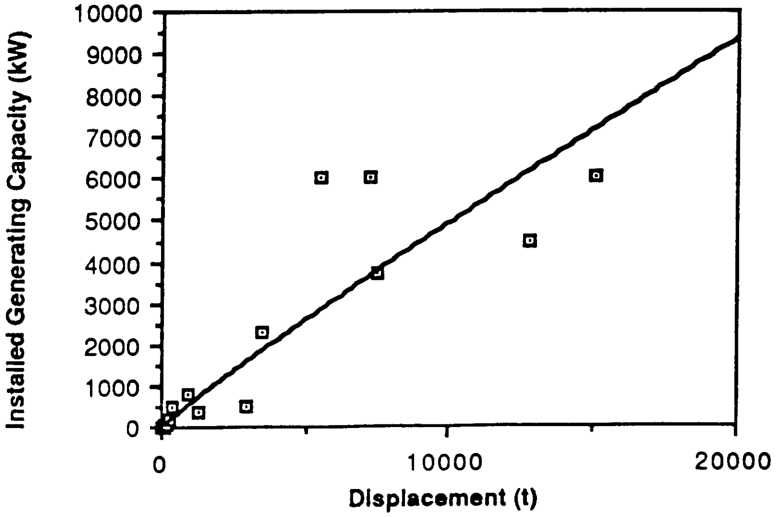


Figure 4.23 Installed Generating Capacity for SWATH Ships

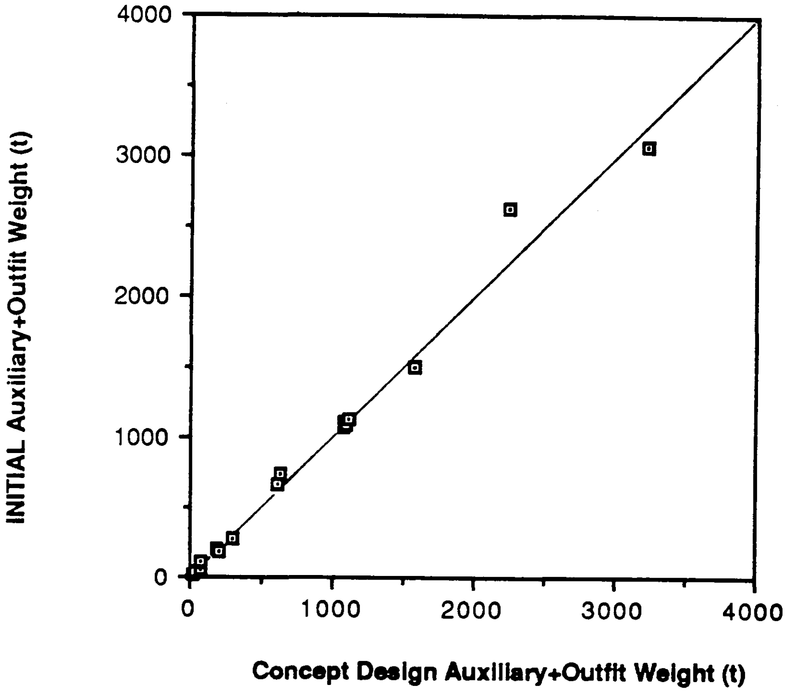


Figure 4.24a Comparison - Published and *INITIAL* Auxiliary & Outfit Weights

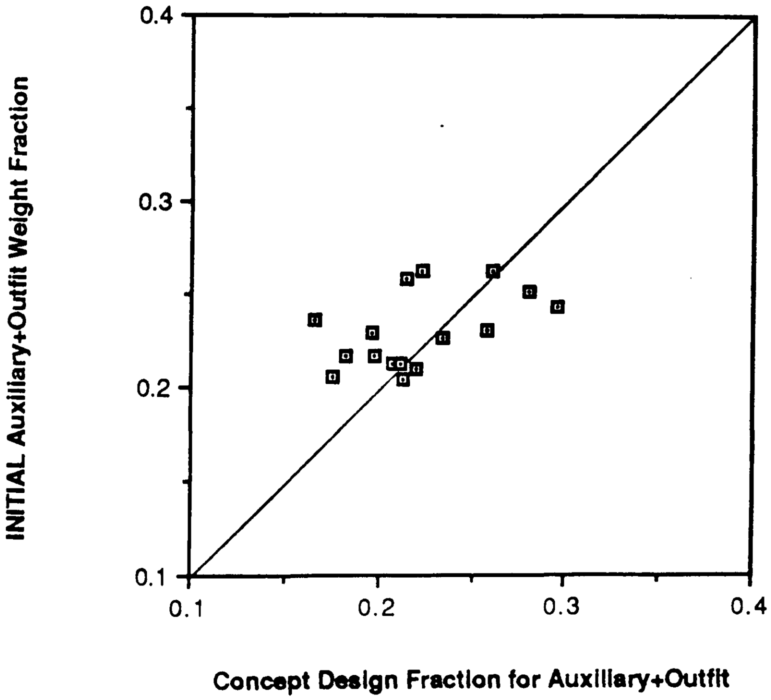


Figure 4.24b Comparison - Published and *INITIAL* Auxiliary & Outfit Weight Fractions

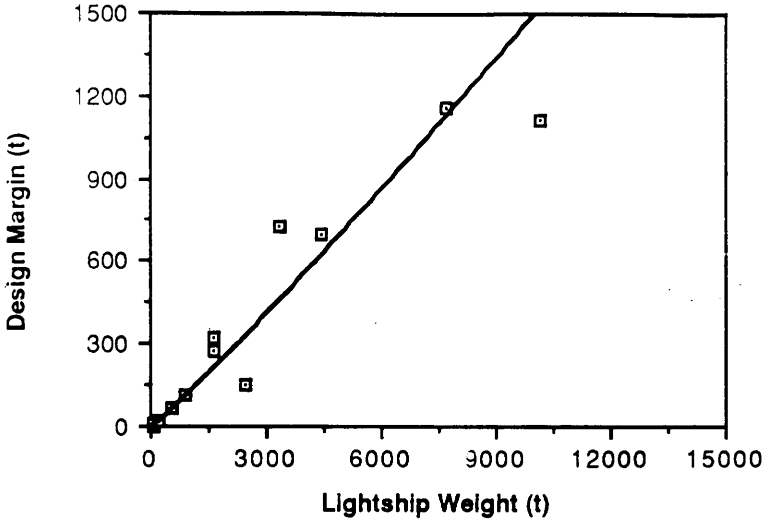


Figure 4.25 Design Margins for SWATH Ships

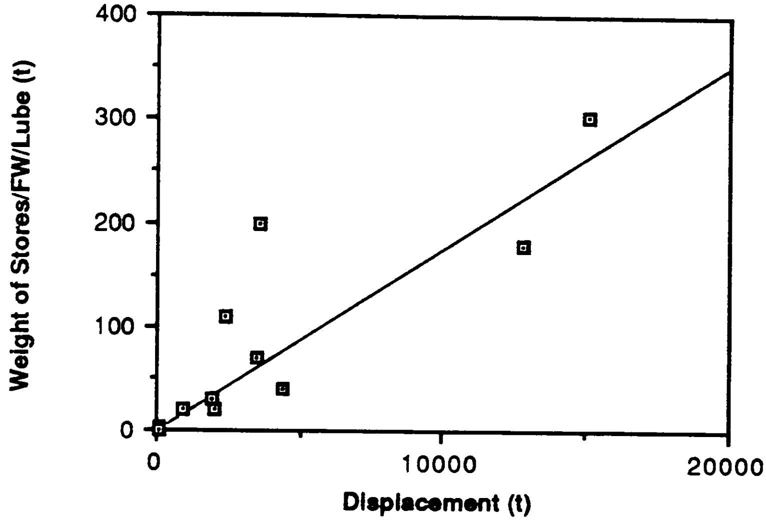


Figure 4.26 Weight of Stores/FW/Lube etc

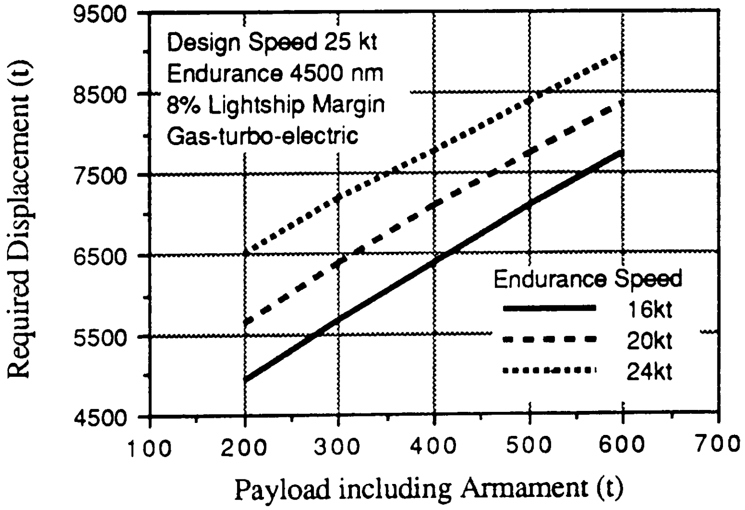


Figure 4.27 Displacement - Speed - Payload Plot for ASW Frigate SWATH

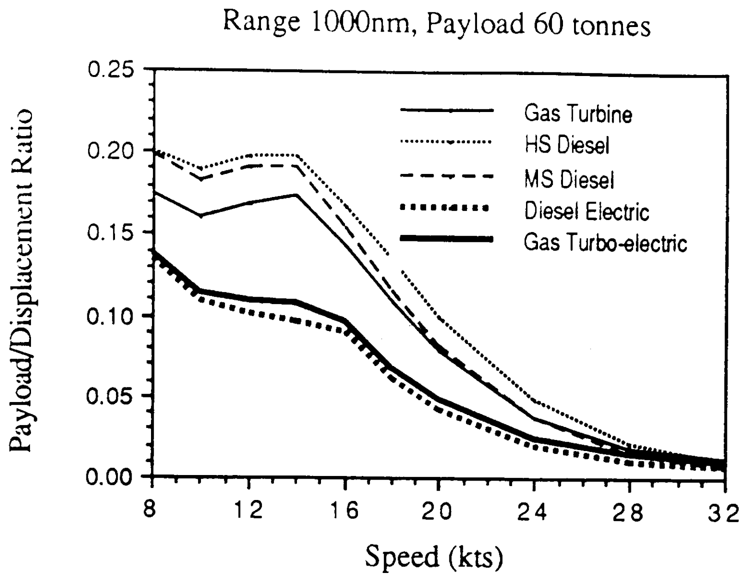


Figure 4.28 Payload/Displacement Ratios versus Power Plant and Design Speed

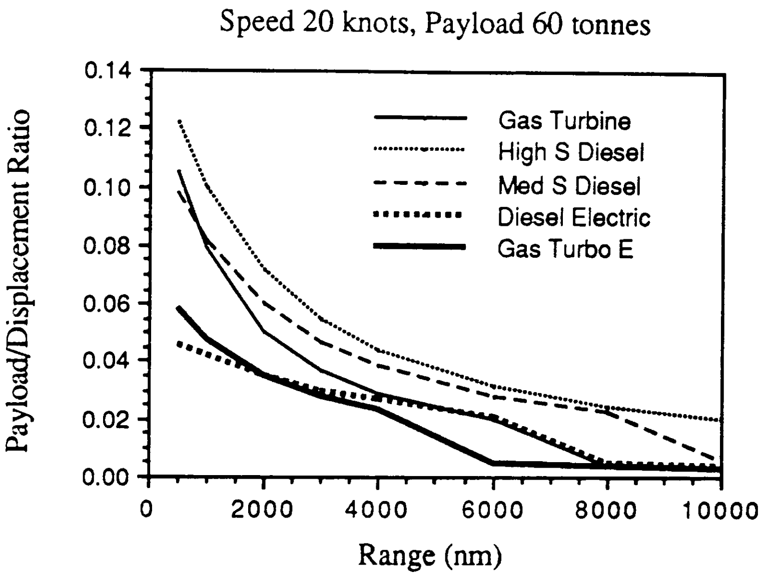


Figure 4.29 Payload/Displacement Ratios versus Power Plant and Endurance

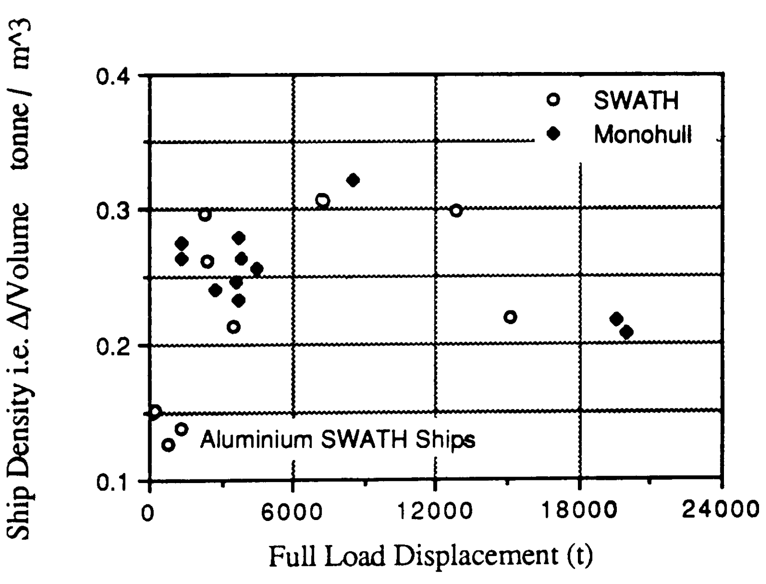


Figure 4.30 Ship Density versus Full Load Displacement

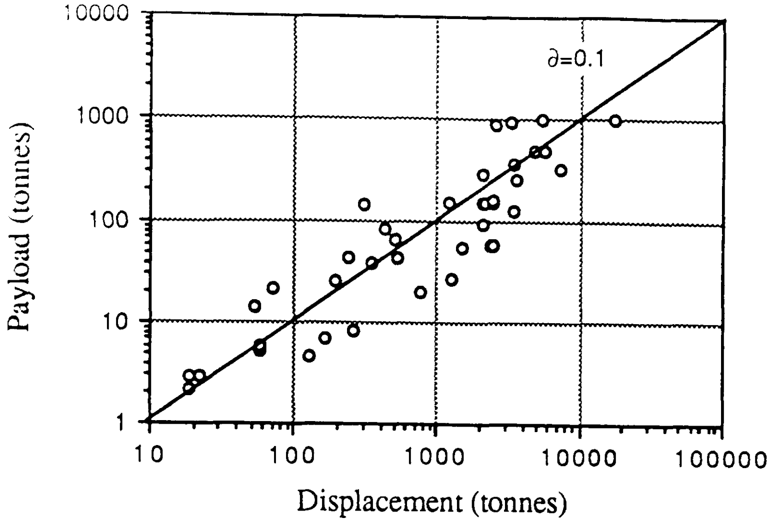


Figure 4.31 SWATH Ship Payload Weight versus Full Load Displacement

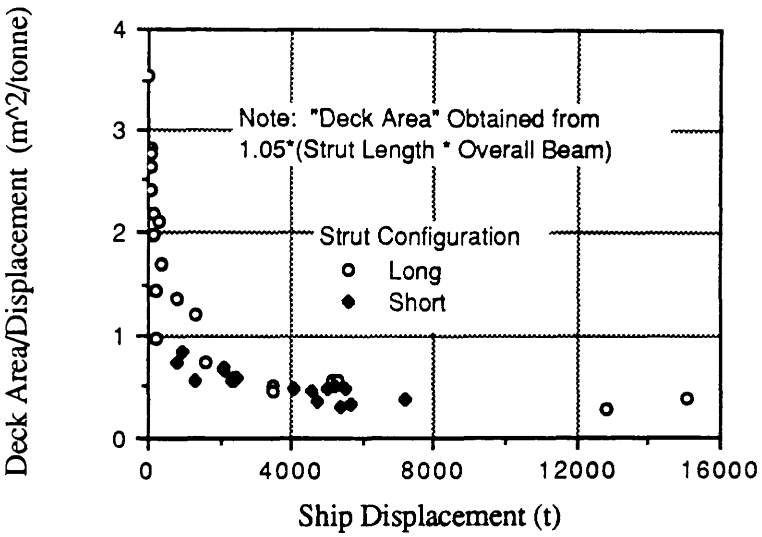


Figure 4.32a Deck Area/Displacement Ratios versus Full Load Displacement

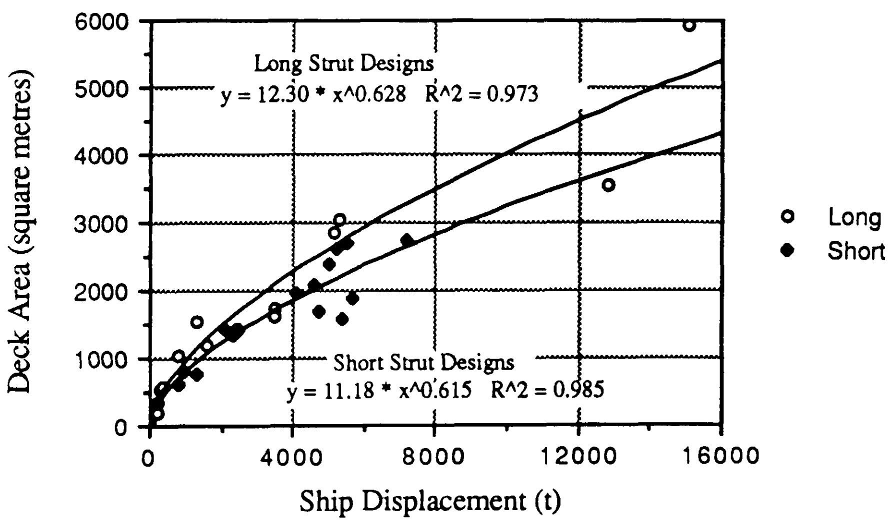


Figure 4.32b Deck Area versus Full Load Displacement and Strut Type

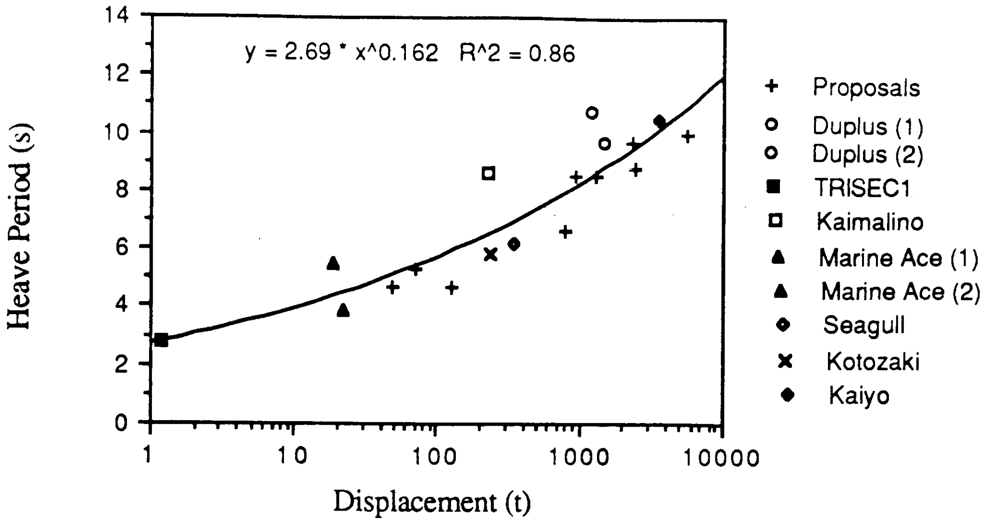


Figure 4.33 SWATH Ship Heave Period versus Full Load Displacement

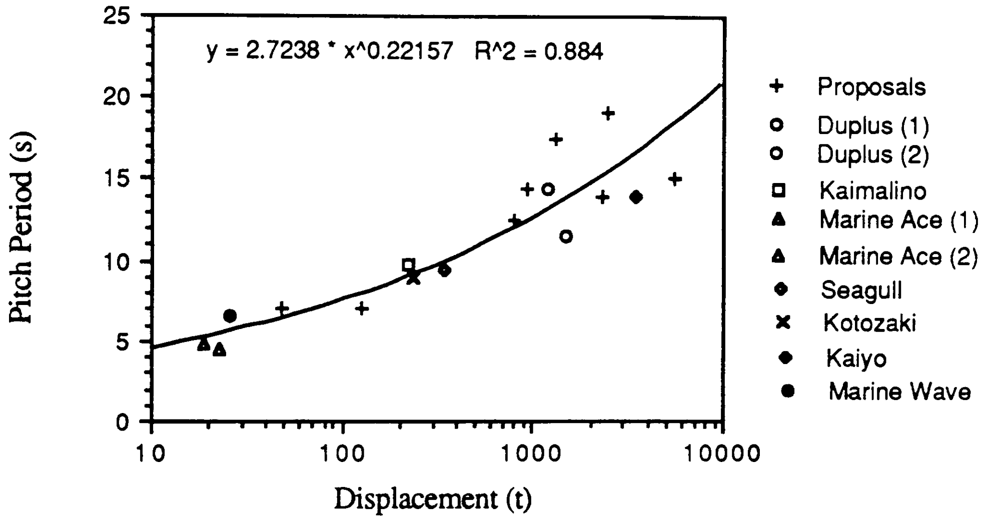


Figure 4.34 SWATH Ship Pitch Period versus Full Load Displacement

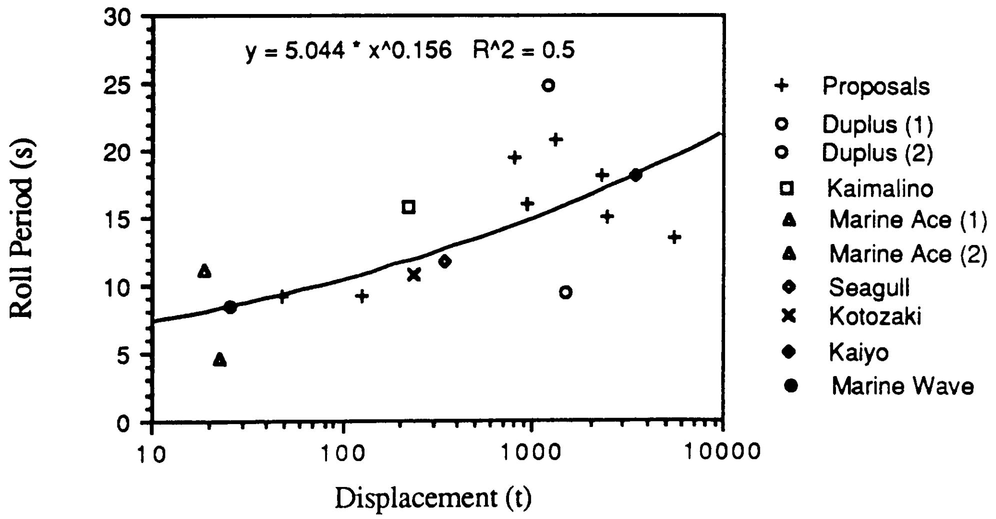


Figure 4.35 SWATH Ship Roll Period versus Full Load Displacement

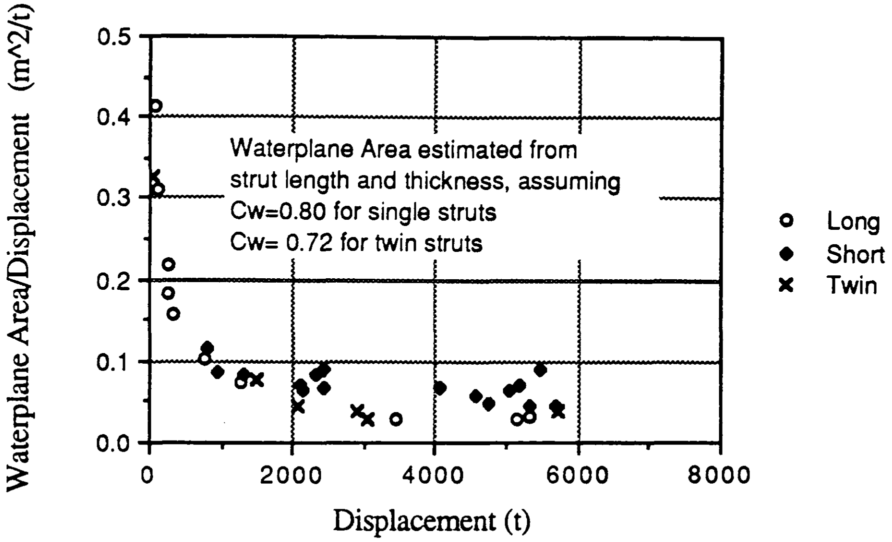


Figure 4.36 Waterplane Area/Displacement Ratios versus Full Load Displacement

CHAPTER 5

HULL DEFINITION

The development and validation of a method for hull definition and associated hydrostatic analysis is described. This is a necessary link between simple 'baseline' definitions and those required for full synthesis including hydrostatics, resistance, seakeeping, and graphics. A family of SWATH designs produced by this tool is introduced as a basis for parametric studies.

5.1 Review of Available Hull Definition Methods for SWATH Ships

Most commercially available ship hull definition packages such as *BLINES* are sufficiently general to be used in defining hullforms as unusual as SWATH [1]. However, dedicated tools of this nature are not necessarily ideal for integration with a conceptual design system, being more suited to final analysis of a synthesised design. Methods for preliminary SWATH hull design need not be so sophisticated.

DTNSRDC/Boeing ASSET/SWATH Program

The US Navy's *ASSET/SWATH* design system [2,3,4] includes a hull definition package in its synthesis sections. This essentially employs non-dimensional geometric parameters to define the lower hull. Most SWATH hullforms, with the exception of '*obround*' section hulls, may be generated and analysed by this tool. Tandem struts are constrained to be of identical length. The analysis sections include a basic graphics facility, and a hydrostatics analysis package. An example of *ASSET* hydrostatics output has been published in [5].

DREA CEM for SWATH Ships

The original version of the DREA *SWACEM* concept exploration tool for SWATH ships [6] was capable of designing only circular section, non-contoured hulls with single struts. Hydrostatics were calculated by a combination of solid geometry and traditional integration techniques. A recent publication [7] indicates that an ability to deal with contoured hulls has been added.

SAI Tool for Hydronumeric SWATH Ship Design

The Science Applications International Corporation's *SWATHGEN* program [8,9] is specifically intended to allow the inclusion of advanced hydrodynamic performance predictions in the early stages of the SWATH design process. The hull definition section accepts input in the form of hull dimensions to develop a mathematically faired hullform using bicubic Hermite spline surface patches. Interactive modifications may be made to the hullform through graphical displays and alteration of the parametric input. Hydrostatic quantities are calculated using Gaussian quadrature. This is a very powerful and versatile tool linked directly to a powering program, but is at present unable to deal with tandem strut or '*obround*' section hulls.

University College London SWATH Hull Definition

Programs developed at UCL for SWATH design include [10] *SWANLY* and *SWATHYD* which produce curves of areas and hydrostatic data for SWATH ships sized by other programs. In addition a program (*SWATHINP*) exists for generating input and control data for the *SWATHMO* motions program and the resistance program *CHAPMAN*. The limits on hull configurations which may be analysed are not published.

University of Glasgow Program for Offshore Structures Hydrostatics (POSH)

This program is part of a suite (*SWATHL*) of programs [11,12] developed for the static and dynamic analysis of offshore vehicles, particularly SWATH ships. *POSH* is concerned only with the definition of the structure geometry, and the calculation of hydrostatic particulars. This part of *SWATHL* has been used to validate the hull definition package developed in the present study. A brief description of the concepts employed by *POSH* for geometry definition is therefore of interest.

POSH defines a structure in terms of members having circular, airfoil, or rectangular/square with/without corner radii cross-section. These members may be of constant or variable section along the principal axis. Variable sections may be defined at up to 9 stations along the member, including the ends. Input takes the form of determining the co-ordinates of the member endpoints (joints) and supplying the sectional definition for each member. The properties of each member at a sufficient number (minimum 3) of stations are determined by exact mathematical formulae. Numerical integration is used only for airfoil sections and for summing sectional data along member principal axes. A three dimensional co-ordinate system is employed and each member contribution to the global system can therefore be accounted for using direction cosines and member lengths. Hydrostatics are determined for each individual member, and summed to give the total at a given waterline.

Limitations of the system include an inability to deal with elliptical hull sections, and the fact that airfoil sections such as struts can be defined at only 9 stations. For design synthesis purposes, the data input scheme is rather inflexible and time consuming. In addition, the geometry definition and output scheme is not designed for use by resistance prediction tools.

5.2 SWATH Ship Hull Definition Requirements

The hull definition section of *DESIN* is intended to transform leading dimensions of a SWATH (as defined by Chapter 4 methods) into a mathematical model of sufficient detail for use by hydrostatics, resistance, and graphics packages. Further, in a computer based synthesis model, a hullform specified initially by the user must be stored in a form permitting automated modification during design iterations.

To be of practical value, such a method must be general in nature. A survey of published SWATH designs (Appendix 1) gave guidance on the range of hull types likely to be required of a synthesis tool. A generalised hydrostatic analysis comparable with commercial packages such as *SIKOB* was considered unNeccessary. However, an ability to generate designs having circular, elliptical or rectangular (with/without corner radius) hull sections was considered desirable. In addition, the ability to arbitrarily position up to two different struts on each hull was specified. Division of the lower hulls into as many as 11 different portions, including nose and tail, was required in anticipation of the need to assess the likely benefits of *contouring*. No publications describe a SWATH hull design method possessing this degree of generality.

5.3 Geometry Definition Procedure

Figure 5.1 illustrates the procedures used in this section of the design program.

5.3.1 Hull Definition

In the baseline sections described in Chapter 4, the lower hull is defined only in terms of length (L_H), maximum breadth (B_H), depth (D_H), corner radius (R_H), and prismatic coefficient C_P. These dimensions may be modified during synthesis iterations.

Full definition of shape is dependent on specifying the primary points of transition in shape (e.g. from nose to PMB). Provision has been made in the current system (module *HYD*) for the user to design hulls with up to m component parts, where $3 \leq m \leq 11$. This provides for the definition of most hull shapes. Figure 5.2 illustrates

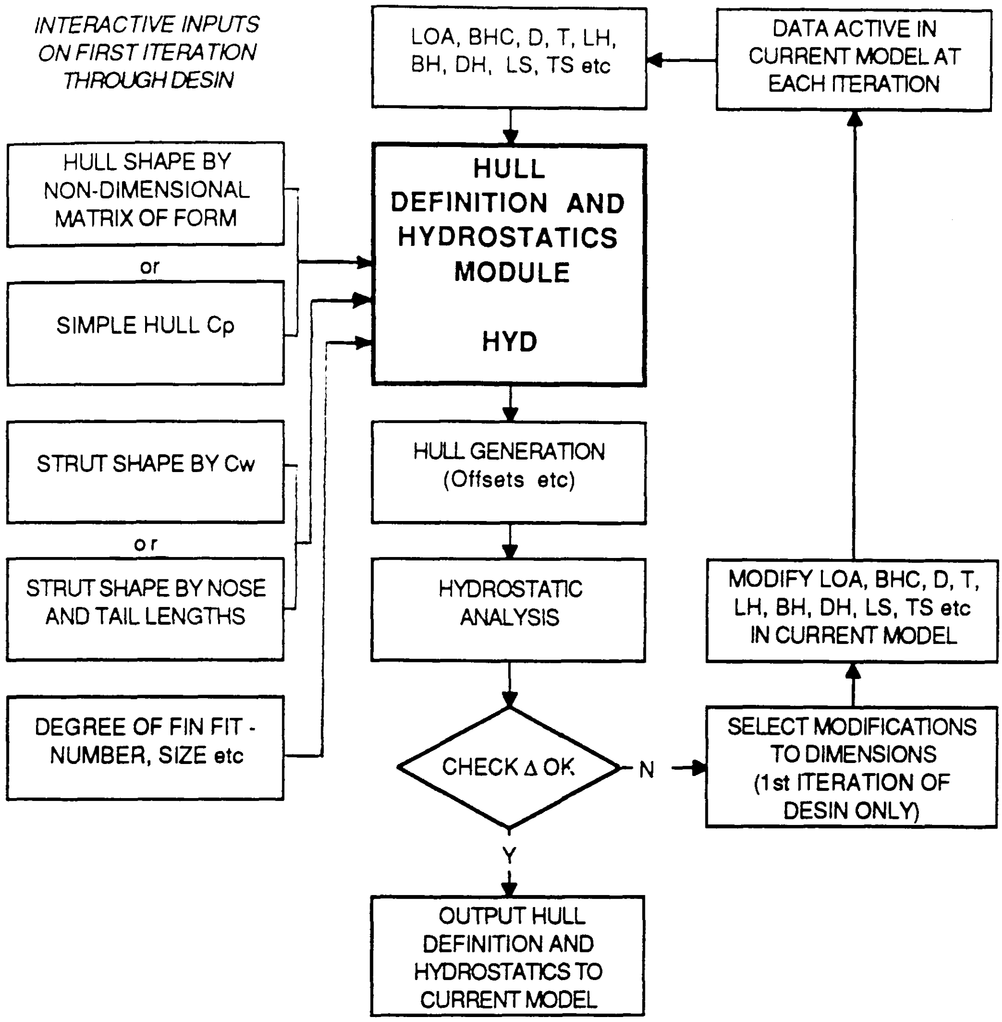
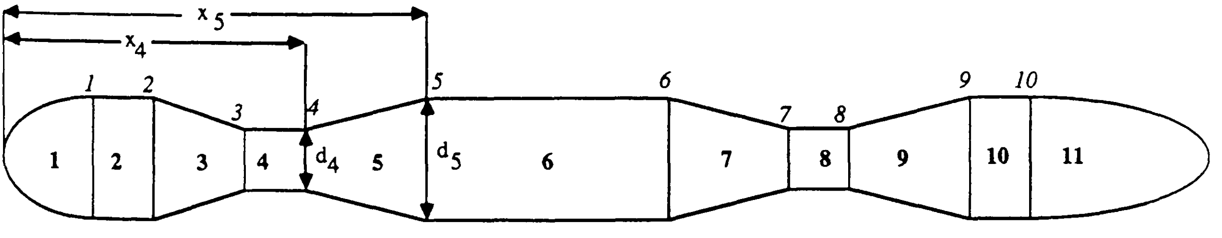


Figure 5.1 Data Flow for Hull Definition and Hydrostatics Module HYD

Hullform illustrated is most complex allowed by DESIN - 11 hull 'components'



N.B. Hull 'components' are numbered in bold type. Component 'endpoints' are numbered in italic type.

Figure 5.2 Illustration of Hull Geometry Definition Convention some of the nomenclature and conventions employed in this chapter using an 11 component hullform as an example. Nose and tail components may have parabolic, elliptical or linear waterlines. Otherwise, linear variation in cross section applies between endpoints.

Hull components are defined in terms of the longitudinal locations (x) and dimensions of n_e endpoints where $n_e = m - 1$. Simple hulls having only a nose, tail and PMB, have only 2 endpoints (at the transitions from nose to PMB and from PMB to tail).

The definitions of locations and dimensions are stored as percentages in order to allow repeated use during synthesis iterations through program *DESIN*. In the first design iteration, a matrix of x_i/L_H, b_i/B_H, and d_i/D_H ratios for $i = 1$ to n_e is defined interactively by the user (Figure 5.1). This allows a wide range of hull shapes to be designed, but in practice well known forms (Figure 5.4) are usually used. It should be noted that this form of input is sufficiently flexible to allow (for example) predominantly elliptical hulls to have a transition to circular sections in the run.

The first iteration of *DESIN* through the hull design package (*HYD*) allows the hydrostatic properties of the designed form to be examined (Figure 5.1). If the hydrostatics of the chosen form prove satisfactory, the basic matrix is stored in the current model and referred to during each synthesis iteration. Otherwise, *DESIN* permits the user to alter any of the hull dimensions in order to achieve the desired properties. Then, during subsequent design iterations, the absolute values of longitudinal locations (x_i) and local particulars of each endpoint (b_i, d_i, and r_i) for a new hull are determined from the selected parent form. This consists of the absolute values of L_H, B_H, D_H, R_H currently active and the non-dimensional definitions.

5.3.2 Strut Definition

A similar approach has been adopted for defining the strut form. At present, *HYD* is limited to consideration of vertical struts positioned centrally on each demihull. Each strut consists of a nose and tail of elliptical, parabolic or lenticular section, with a parallel section of uniform thickness. Within each strut, the points of transition from nose to PMB and from PMB to tail are defined as ratios t_1/L_S and t_2/L_S respectively, where t_i is measured from the strut nose. Once fixed, these ratios define the waterplane area coefficient and are held constant throughout a synthesis sequence. The above assumes that the strut has a constant section vertically, but for structural, hydrodynamic, and electronic warfare reasons it may be desirable to introduce flare into the section.

5.3.3 Stabilising Fin Definition

Fins are required by SWATH ships to counteract the destabilising Munk Moment [21,22] (proportional to the square of the speed times the heave added mass). These surfaces may be fixed or moveable and used to reduce motions and as steering devices. Proper design of these control surfaces is a complex subject [23-25] and is not usually part of the synthesis process. However, provision has been made in *HYD* to account for a typical fin installation in the preliminary hydrostatics of a design.

HYD allows two aft fins (axis usually about $0.8L_H$ from hull nose), with or without two forward canards (about $0.15L_H$ from hull nose) to be considered if required. The exact longitudinal positioning of each set of fins on the hull is an input variable. Fin aspect ratios, and thickness to chord ratios are also user inputs, but values of 1.4 and 14% are suggested. At present there is no provision for inclined fins.

Fin size is a user input, but as a first approximation, fin area may be related to waterplane area. The graphical data published in [26] has been curve fitted and incorporated in *DESIN* for guidance.

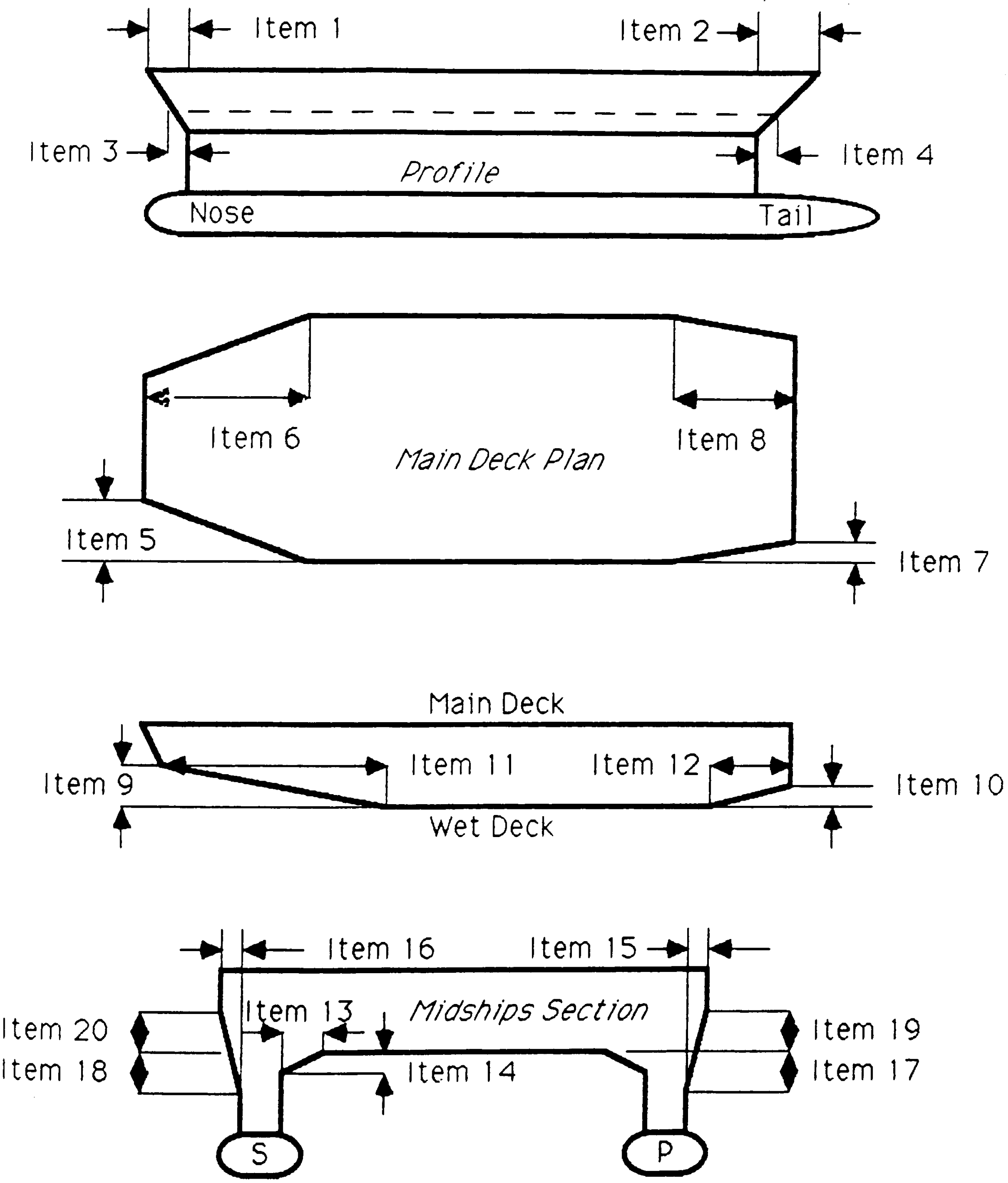
$$\text{Fin Area/Waterplane Area} = 0.366 - 4.78\times10^{-5}\Delta + 2.82\times10^{-9}\Delta^2 \qquad \text{Eqn. 5.1}$$

During synthesis, fin area may be maintained constant, scaled in proportion to waterplane area, or scaled by equation 5.1. Usual distributions of area between forward and aft fins range from 3:7 and 4:6.

5.3.4 Upperworks Definition

The SWATH synthesis program *DESIN* allows the user to define the geometry of the box and superstructures in some detail. These spaces form a major part of the enclosed volume used in performing a space balance, and their definition is also required for certain weight calculations. Up to three levels of superstucture may be defined, simply using lengths, breadths and depths. In defining the box/cross structure, the designer is allowed more freedom in shape. It is possible to specify wet deck sheer (fore and aft), inner and outer haunch geometry, main deck plan, and rake of the forward and after transoms. Figure 5.3 illustrates the 20 items required to define the geometry of the box and haunch structure.

Figure 5.3 Geometry Details Required to Define SWATH Cross Structure in *DESIN*



5.4 Hydrostatic Analysis

The hull and strut geometry described in section 5.3 fully defines the longitudinal (x) variation of strut and hull sections, and allows hull and strut dimensions (b(x), d(x), r(x), t(x)) at any station to be calculated by interpolation. Intersection between the hulls and struts is considered in assessing sectional areas, and allowance is made for up to four control fins. Hydrostatic properties are calculated by employing a 41 ordinate Simpson's integration of sectional areas and strut dimensions to give volumes, areas and associated moments in the normal way. Further details of these calculations may be found in Appendix 4.

5.5 Program Operation

Module *HYD* has been implemented as part of *DESIN* and performs the functions of first generating and then continuously modifying the parent hullform used during synthesis and at the same time producing hydrostatic data. The definition is interfaced with graphics routines (described in Chapter 11) which may be used to visually check the suitability of a designed hullform. It is possible to operate this module independently of *DESIN* (given correctly formatted input). Figure 5.1 illustrates the data flow associated with module *HYD* while Table 5.1 lists input and output variables associated with the program.

Table 5.1 Input and Output Variables for Program *HYD*

Input Variables from Baseline Section
Design draught, hull centreline separation
Hull length, maximum breadth, maximum depth, maximum corner radius
Strut setback, length, maximum thickness
Strut gap, length, maximum thickness for aft strut (in tandem strut design)
Interactive Input Variables
Number of hull 'components' (each having two 'endpoints')

For each component endpoint;	Non-dimensional longitudinal location
	Non-dimensional hull breadth
	Non-dimensional hull depth
For each strut;	Non-dimensional nose length
	Non-dimensional tail length

Number of stabilizing fins (0, 2 or 4)
Ratio of fin area to waterplane area, ratio of aft fin area to fore fin area
Fin aspect ratios, fin thickness/chord ratios
Non-dimensional location of fin axis

Output Variables
Definition of underwater geometry at 41 equally spaced stations
Sectional area curve
Hydrostatic properties at design draught including;
SW displacement, hull volume, C_p, strut volume, waterplane area, C_w, hull/strut intersection volume, fin volume, hull LCB, ship LCB, LCF, VCB, longitudinal and transverse metacentric heights

5.6 Program Validation

As part of the validation process for the methods described in this chapter, a SWATH ship of modern (contoured) form was generated and analysed by the *HYD* package. This vessel has a hull of elliptical section, with proportions as depicted in Figure 5.4c. Table 5.2 further describes the geometry of this vessel, and compares hydrostatic particulars produced by the *ASSET* system and by *HYD*.

It can be seen that there is less than 1% difference between hydrostatics calculated by *HYD* and the comparison method. This is considered an adequate correlation for the purposes of this study. Further validation against independent methods is provided in section 5.8.

5.7 Hull Design

5.7.1 General

Selection of a parent hullform for use in a ship synthesis should be informed by a knowledge of resistance and seakeeping considerations. Program *DESIN* is itself incapable of automated selection of an 'optimum' hullform although many candidate forms may be analysed, allowing informed judgement to be made by the user. In this situation, efficiency in design is related to the suitability of the alternative hullforms considered initially. Some sources of data on underwater configuration may be noted.

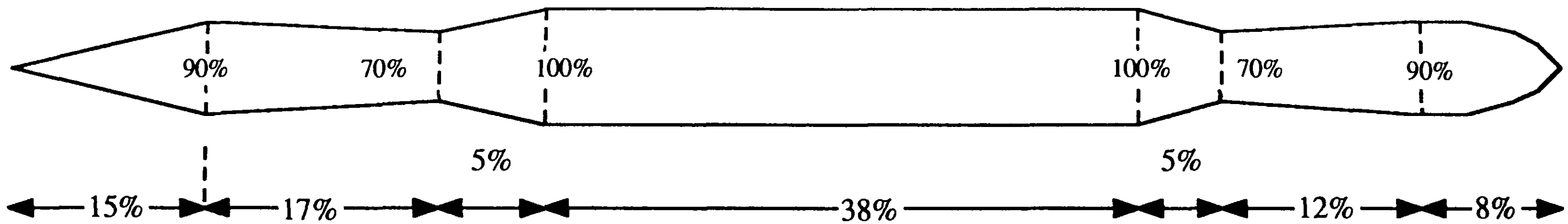
Outline hull definitions at the level required in Chapter 4 may be generated from the regression analysis of Chapter 2. Ideally however, final definition of hullform should be more rationally based. Usually, practical considerations of internal access and draught and length constraints are combined with experiences of previous design studies to provide the parent hullforms for a new synthesis. Some published work also exists to aid the designer in providing good seakeeping or powering characteristics.

For monohulls, Vossers [13] has explored the relationships between hullform and motion characteristics. Despite the importance of the seakeeping objective, no comparable reference exists for SWATH designers. However, many of the conclusions which are true for monohulls are also true for SWATHs [14] although some significant differences exist. At present, the best available guides to SWATH hull design for seakeeping are given by McCreight [14] and Lamb [15]. The work of Chun [16] may be consulted for a discussion of the effects of underwater configuration on resistance.

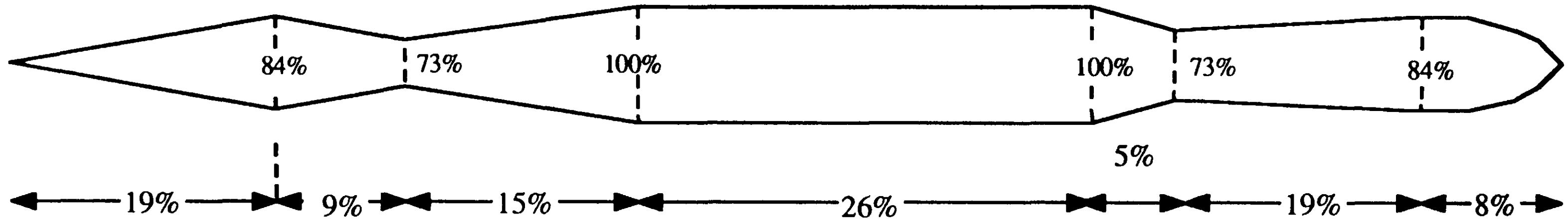
In addition, the contoured hullforms described in section 5.8.4 and Figure 5.4 may provide suitable basis hulls for a number of roles. Subsequent chapters of the thesis describe the relative merits of these hulls in terms of resistance, propulsion, machinery installation and structural design.

Table 5.2 Comparison of Hydrostatics of SWATH Ship by *ASSET* and *HYD*

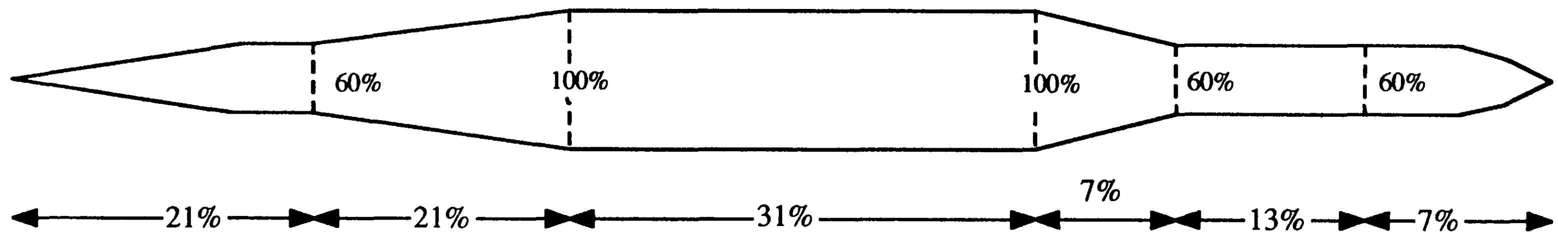
Vessel Geometry		
Hull Length	61.74	
Ellipsoidal Nose Length (m)	4.16	
Forward Cylindrical Portion Length (m)	8.31	
Forward 'Conical' Portion Length (m)	4.47	
Amidships Cylindrical Portion Length (m)	19.22	
After 'Conical' Portion Length (m)	12.70	
After Cylindrical portion Length (m)	5.40	
Paraboloidal Tail Length (m)	7.49	
Maximum Elliptical Hull Breadth (m)	6.72	
Maximum Elliptical Hull Depth (m)	4.45	
Strut Setback (m)	4.25	
Strut Length (m)	50.46	
Elliptical Strut Nose Length (m)	20.10	
Parabolic Strut Tail Length (m)	17.33	
Maximum Strut Thickness (m)	2.44	
Hull Centreline Separation (m)	18.37	
Design Draught (m)	6.65	
Fin Arrangement	*ASSET*	*HYD*
Forward fin axis from hull nose (m)	8.001	8.001
Forward fin chord (m)	2.32	2.36
Forward fin span (m)	3.38	3.305
Forward fin thickness (m)	0.34	0.472
Aft fin axis from hull nose (m)	51.71	51.71
Aft fin chord (m)	4.27	4.2
Aft fin span (m)	5.76	5.88
Aft fin thickness (m)	1.1	0.84
Hydrostatic Particulars	*ASSET*	*HYD*
Hull and strut displacement (t, SW)	2286.9	2298.7
Appendage displacement (t, SW)	41.5	39.3
Hull Prismatic Coefficient	0.592	0.599
Waterplane Area (m^2)	196.9	197.36
VCB from keel (m)	2.898	2.906
LCB aft of hull nose (m)		28.992
LCF aft of hull nose (m)	28.701	28.672
Longitudinal BM (m)	13.26	13.321
Transverse BM (m)	7.35	7.438
Longitudinal KM (m)	16.158	16.227
Transverse KM (m)	10.248	10.344



a) High Speed Hullform A



b) High Speed Hullform B



c) Typical Slow Speed Hullform

N.B. Drawings are not to scale. Entrances are elliptical, runs are parabolic.

5.7.2 SWATH Hull Section Comparison

Although the use of circular, elliptical and rectangular hull sections for SWATH ships has been discussed in general terms, there does not appear to be any published statement quantifying the merits of each type. Because of this, Miller [17] set out to compare each hull type on the basis of equivalent sectional area. Within the limitations of certain assumptions, this can provide useful guidance.

For a circular hull of radius a_c,
Sectional area = πa_c^2
Wetted surface per unit length, $WS_c = 2\pi a_c$
Heave added mass per unit length, $AVM_c = \rho\pi a_c^2$

For an elliptical hull of semi axes a_e, b_e, with B/D ratio $BDR = a_e/b_e$
Sectional area = $\pi a_e b_e$
Wetted surface per unit length, $WS_e = \pi[{}^3/_2(a_e+b_e) - \sqrt{(a_e b_e)}]$, by approximation
Heave added mass per unit length, $AVM_e = \rho\pi a_e^2$

For a rectangular hull of semi axes a_r, b_r, with B/D ratio BDR, and corner radius R_c
Sectional area = $4a_r b_r - 0.858R_c^2$
Wetted surface per unit length, $WS_r = 4(a_r + b_r) - 1.7168R_c$
Heave added mass per unit length, $AVM_r = \rho k\pi a_r^2$
where k depends on BDR and R_c and may be determined from [18]

Relationships between the dimensions of circular, elliptical and rectangular hulls having the same sectional area may be determined for various values of B/D ratio and corner radii. Sectional area is a useful basis for comparison, since, by definition, the volume in the struts of a SWATH is relatively small and (if the hull sectional area distribution remains constant) roughly equivalent designs may be developed on this basis.

For an ellipse having the same section area as a circle, $a_e = a_c\sqrt{BDR}$

For a rectangular hull, $a_r = a_c \sqrt{\{^{\pi}/[^4/_{BDR} - 0.858\,(^c/_{BDR})^2]\}}$ where $c = R_c/b_r$

Using the above relationships, it is possible to indicate equivalent hull dimensions, vessel draught, added mass, heave period, and wetted surface for elliptical and 'obround' hulls, relative to the values for a circular hull. Table 5.3 and Figure 5.5 illustrate some characteristics of circular, elliptical and 'obround' hulls. In this comparison, a number of significant assumptions have been used.

Draught changes have been calculated on the basis of hulls with centrelines submerged to 70% of the total draught (see Chapter 2), and not on the basis of constant strut depth. This means that 'equivalent' designs do not have precisely the same displaced volume.

Added mass values for all sections are those obtained under the assumptions of deep submergence and infinite frequency. This ignores the frequency dependent oscillations present in the hydrodynamic coefficients of SWATH type sections [19,20]. In addition, it has been demonstrated numerically [19,20] that the deeply submerged assumption may only be fully justified for lower hulls with centreline submergences greater than 0.86xDraught. For the rectangular SWATH hulls considered (CS=0.70T), AVM is typically 92% to 86% of the deeply submerged value at infinite frequency of oscillation.

Changes in heave period have been estimated assuming constant waterplane area and ignoring the effect of strut 'masking' on the hull AVM. This effect can be significant [20], and varies for different hulls since a given waterplane area will have a greater influence on hulls of smaller breadth. Similarily, the wetted surface comparisons ignore the effect of the non-wetted area on the hull due to the strut.

Figure 5.5 plots the relative values of heave period, wetted surface, and draught for non-circular hulls relative to the circular baseline. The trade-offs between draught, frictional resistance, and heave period may be gauged for various hull types and B/D ratios. Proportions of a new hullform may be estimated rapidly from Table 5.3 if a change in section is required in mid-design.

The data illustrates the significant reductions in draught which may be obtained with non-circular sections (particularly rectangular hulls with small corner radius). Draught reductions of nearly 40% may be achieved with B/D ratios of 2.0, while increasing heave period by 25% and wetted surface by 15%. The latter figure infers an increase in steel weight since the rectangular section is less efficient structurally as well as involving greater surface area. However, additional steel weight in the hulls is less critical in stability considerations, and the flat stiffened plate arrangement may lead to reduced constructional cost.

Figure 5.5 Comparison of Alternative Lower Hull Section Properties

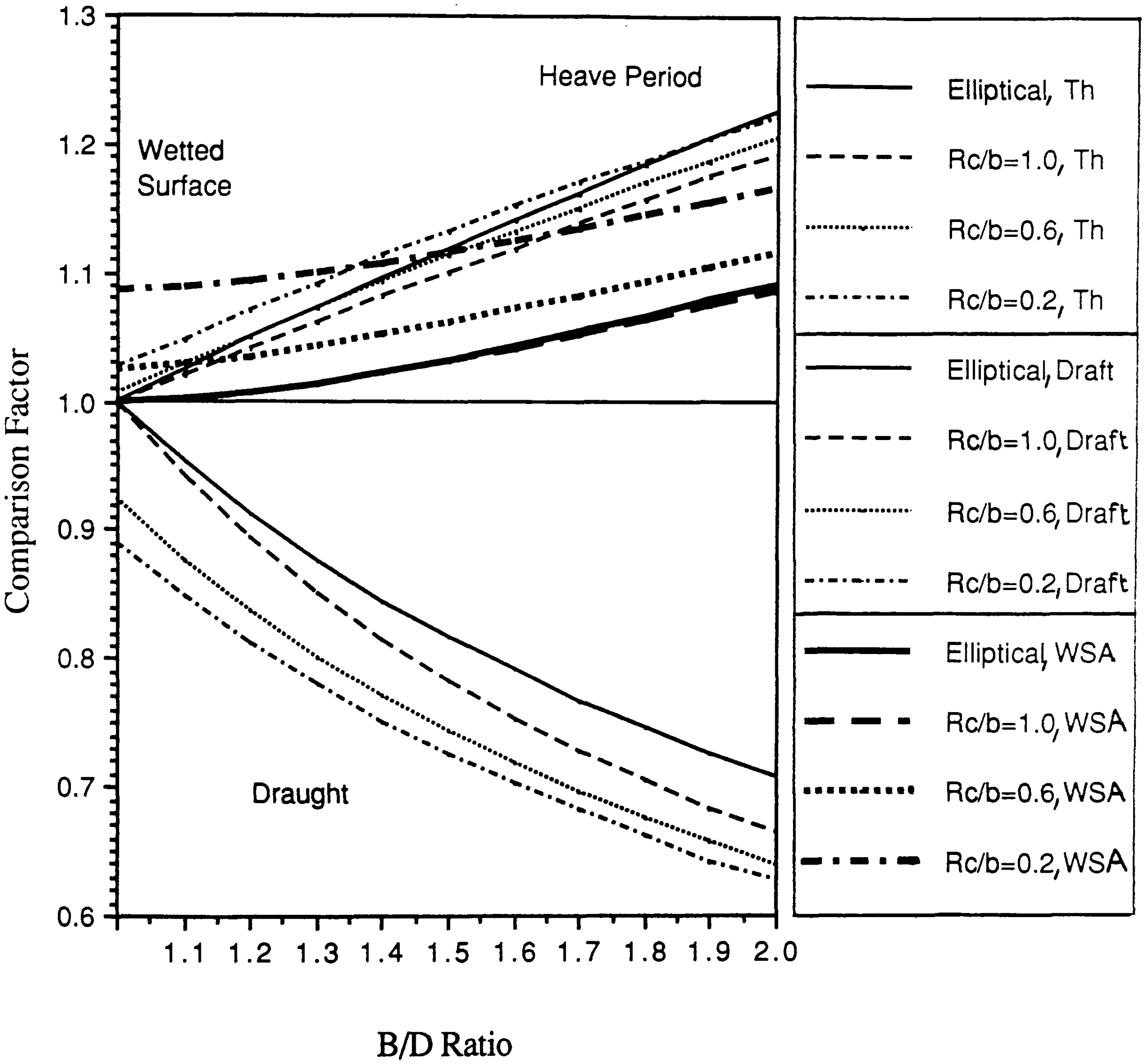


Table 5.3 Comparison of Alternative Lower Hull Section Properties

ELLIPTICAL HULLS

Quantity	*CIRCLE*	*B/D=1.0*	*B/D=1.1*	*B/D=1.2*	*B/D=1.3*	*B/D=1.4*	*B/D=1.5*	*B/D=1.6*	*B/D=1.7*	*B/D=1.8*	*B/D=1.9*	*B/D=2.0*
Hull Breadth	1.000	1.000	1.049	1.095	1.140	1.183	1.224	1.266	1.304	1.342	1.378	1.414
Hull Depth	1.000	1.000	0.953	0.913	0.877	0.845	0.816	0.791	0.767	0.745	0.725	0.707
Heave AVM	1.000	1.000	1.100	1.200	1.300	1.400	1.500	1.600	1.700	1.800	1.900	2.000
Heave Period	1.000	1.000	1.025	1.049	1.072	1.095	1.118	1.140	1.162	1.183	1.204	1.225
Draught	1.000	1.000	0.953	0.913	0.877	0.845	0.816	0.791	0.767	0.745	0.725	0.707
Wetted Surface	1.000	1.000	1.002	1.006	1.013	1.021	1.031	1.042	1.053	1.065	1.078	1.091

RECTANGULAR HULLS - Rc/b =1.0

Quantity	*CIRCLE*	*B/D=1.0*	*B/D=1.1*	*B/D=1.2*	*B/D=1.3*	*B/D=1.4*	*B/D=1.5*	*B/D=1.6*	*B/D=1.7*	*B/D=1.8*	*B/D=1.9*	*B/D=2.0*
Hull Breadth	1.000	1.000	1.036	1.071	1.105	1.140	1.172	1.205	1.236	1.267	1.297	1.326
Hull Depth	1.000	1.000	0.942	0.893	0.851	0.814	0.782	0.753	0.727	0.704	0.683	0.663
AVM k	1.000	1.000	1.007	1.013	1.020	1.025	1.029	1.034	1.039	1.041	1.045	1.044
Heave AVM	1.000	1.000	1.081	1.162	1.247	1.331	1.415	1.501	1.588	1.671	1.758	1.837
Heave Period	1.000	1.000	1.020	1.039	1.060	1.080	1.099	1.118	1.137	1.156	1.174	1.191
Draught	1.000	1.000	0.942	0.893	0.851	0.814	0.782	0.753	0.727	0.704	0.683	0.663
Wetted Surface	1.000	1.000	1.002	1.006	1.013	1.021	1.030	1.041	1.051	1.062	1.074	1.085

RECTANGULAR HULLS - Rc/b = 0.6

Quantity	*CIRCLE*	*B/D=1.0*	*B/D=1.1*	*B/D=1.2*	*B/D=1.3*	*B/D=1.4*	*B/D=1.5*	*B/D=1.6*	*B/D=1.7*	*B/D=1.8*	*B/D=1.9*	*B/D=2.0*
Hull Breadth	1.000	0.923	0.964	1.004	1.042	1.079	1.114	1.149	1.183	1.215	1.247	1.278
Hull Depth	1.000	0.923	0.876	0.836	0.801	0.771	0.743	0.718	0.696	0.675	0.656	0.639
AVM k	1.000	1.205	1.200	1.198	1.193	1.189	1.185	1.180	1.177	1.173	1.168	1.163
Heave AVM	1.000	1.026	1.115	1.207	1.295	1.383	1.472	1.558	1.646	1.733	1.817	1.900
Heave Period	1.000	1.006	1.028	1.050	1.071	1.092	1.112	1.131	1.150	1.169	1.187	1.204
Draught	1.000	0.923	0.876	0.836	0.801	0.771	0.743	0.718	0.696	0.675	0.656	0.639
Wetted Surface	1.000	1.023	1.028	1.034	1.042	1.051	1.061	1.071	1.082	1.093	1.104	1.116

RECTANGULAR HULLS - Rc/b = 0.2

Quantity	*CIRCLE*	*B/D=1.0*	*B/D=1.1*	*B/D=1.2*	*B/D=1.3*	*B/D=1.4*	*B/D=1.5*	*B/D=1.6*	*B/D=1.7*	*B/D=1.8*	*B/D=1.9*	*B/D=2.0*
Hull Breadth	1.000	0.890	0.933	0.974	1.014	1.052	1.089	1.124	1.158	1.192	1.224	1.256
Hull Depth	1.000	0.890	0.848	0.812	0.780	0.751	0.726	0.703	0.681	0.662	0.640	0.628
AVM k	1.000	1.394	1.373	1.359	1.343	1.330	1.317	1.305	1.291	1.280	1.269	1.257
Heave AVM	1.000	1.104	1.196	1.290	1.380	1.471	1.561	1.649	1.732	1.818	1.902	1.983
Heave Period	1.000	1.026	1.048	1.070	1.091	1.112	1.132	1.151	1.169	1.187	1.205	1.221
Draught	1.000	0.8[illegible]0	0.848	0.812	0.780	0.751	0.726	0.703	0.681	0.662	0.640	0.628
Wetted Surface	1.000	1.085	1.088	1.093	1.099	1.107	1.115	1.124	1.134	1.144	1.154	1.165

5.8 A Family of SWATH ships

5.8.1 General

This section presents the hydrostatic particulars of a family of SWATH ships generated by the *HYD* routines. These results provide further validation of the system, as they compare favourably with results from *POSH*. They also illustrate the capability which the *HYD* method offers of generating a hullform with specified characteristics. In addition, these geometries provide the foundation for parametric studies detailed in later chapters of the thesis.

5.8.2 Simple Hullforms

Five designs were produced initially. These nominally cover the 1000, 2000, 3000, 4000 and 5000 tonne displacements. Simple, circular hulls with ellipsoidal noses ($0.3L_H$) and paraboloidal tails ($0.25L_H$) were used for all 5 designs. Short struts ($0.8L_H$) with elliptical noses ($0.35L_H$) and parabolic tails ($0.35L_H$) are setback $0.1L_H$ from the hull nose. Leading dimensions of these vessels are listed in the first section of Table 5.4, and enclosed volume particulars given in Table 5.5 for nominal arrangements of superstructure. Two values of box clearance are indicated for each vessel, these being the upper and lower values suggested by Lamb [15] for these displacements.

Such simple hulls are the most basic SWATH forms likely to be considered in practice. Their main attribute is simplicity of construction, and the coincidence of LCB-LCF afforded by the single short strut arrangement. This is desirable in reducing coupled heave and pitch motions.

5.8.3 Validation of Program *HYD*

The five simple hull designs were employed in validating the hydrostatics calculation procedures. Table 5.4 shows that *HYD* gives a close agreement with analytical geometry in the calculation of prismatic coefficient and waterplane area. By contrast, *POSH* is seen to be less accurate in its handling of strut waterplane area. This is felt to be due to the poorer definition of strut shape in *POSH*.

There is about 1% difference in displacements calculated by *POSH* and *HYD*, while LCB is calculated to within 0.1% of LOA. These agreements are considered satisfactory.

Table 5.4 Hydrostatics of a Family of Simple SWATH Ships

DESIGN	*1000*	*2000*	*3000*	*4000*	*5000*
Vessel Geometry					
Hull Length (m)	71.747	78.964	83.558	86.97	89.78
Ellipsoidal Nose Length (m)	21.524	23.689	25.067	26.091	26.934
Paraboloidal Tail Length (m)	17.937	19.74	20.889	21.743	22.445
Diameter (m)	3.116	4.151	4.897	5.5	6.016
Strut Setback (m)	7.175	7.896	8.356	8.697	8.978
Strut Length (m)	57.398	63.171	66.846	69.58	71.824
Elliptical Nose Length (m)	20.089	22.11	23.396	24.353	25.138
Parabolic Tail Length (m)	20.089	22.11	23.396	24.353	25.138
Strut Thickness (m)	0.917	1.481	1.964	2.399	2.798
Design Draught (m)	4.674	6.227	7.346	8.25	9.024
Hull Centreline Spacing (m)	21.244	22.68	23.92	24.4	25.484
Displacement (t, SW)					
HYD	1018.6	2049.4	3081.5	4112.7	5148.3
POSH	1012.5	2033.4	3052.7	4069.2	5087.1
CHUN	969.4	1931.4	2880.3	3825.5	4761.7
Hull Prismatic Coefficient					
By Solid Geometry	0.7833	0.7833	0.7833	0.7833	0.7833
HYD	0.7834	0.7834	0.7834	0.7834	0.7834
Waterplane Area (m^2)					
By Geometry	85.08	151.22	212.21	269.81	324.84
HYD	84.97	151.05	211.94	269.47	324.42
POSH	83.99	149.34	209.65	266.54	320.98
Wetted Surface Area (m^2)					
POSH	1469.2	2129.2	2636.1	3061.7	3438.4
Lin-Day-Reed	1467.5	2127.5	2632.9	3058.4	3433.7
CHUN	1494.6	2174.7	2698.1	3140.4	3533.1
LCB from Hull Nose (m)					
HYD	35.127	38.645	40.884	42.545	43.912
POSH	35.167	38.699	40.946	42.614	43.988
LCF from Hull Nose (m)					
HYD	34.744	38.233	40.462	42.117	43.475
POSH	35.011	38.527	40.772	42.438	43.807
LCB-LCF Separation (m)					
HYD	0.383	0.412	0.382	0.428	0.437
POSH	0.156	0.172	0.174	0.176	0.181
VCB from Keel (m)					
HYD	1.874	2.573	3.097	3.531	3.909
POSH	1.868	2.562	3.082	3.512	3.886
Longitudinal BM (m)					
HYD	16.985	18.186	18.994	19.605	20.09
POSH	16.319	17.495	18.318	18.936	19.433
Transverse BM (m)					
HYD	9.667	9.761	10.158	10.102	10.625
POSH	9.598	9.692	10.088	10.02	10.535
Longitudinal KM (m)					
HYD	18.859	20.759	22.091	23.136	23.999
POSH	18.187	20.058	21.399	22.448	23.319
Transverse KM (m)					
HYD	11.541	12.334	13.255	13.633	14.534
POSH	11.466	12.254	13.17	13.531	14.421

Table 5.5 Enclosed Volume Characteristics of a Family of SWATH Ships

Design	1000	2000	3000	4000	5000
Leading Particulars					
SW Displacement (HYD)	1018.6	2049.4	3081.5	4112.7	5148.3
Hull length (m)	71.75	78.96	83.56	86.97	89.78
Hull radius (m)	1.56	2.08	2.45	2.75	3.01
Strut length (m)	57.40	63.17	66.85	69.58	71.82
Strut thickness (m)	0.92	1.48	1.96	2.40	2.80
Waterplane area (m^2)	85.0	151.1	211.9	269.5	324.4
45° haunch depth (m)	0.92	1.48	1.96	2.40	2.80
Box length (m)	57.40	63.17	66.85	69.58	71.82
Box beam (m)	22.16	24.16	25.88	26.80	28.28
Box depth (m)	3.20	3.20	3.20	3.20	3.20
Superstructure 1 length (m)	28.70	31.59	33.42	34.79	35.91
Superstructure 1 beam (m)	18.49	18.24	18.03	17.20	17.09
Superstructure 1 depth (m)	2.70	2.70	2.70	2.70	2.70
Superstructure 2 length (m)	11.48	12.63	13.37	13.92	14.36
Superstructure 2 beam (m)	14.79	14.59	14.42	13.76	13.67
Superstructure 2 depth (m)	2.70	2.70	2.70	2.70	2.70
(High box clearance designs)					
Box clearance (m)	3.40	4.27	4.91	5.38	5.94
Abovewater strut depth (m)	2.48	2.79	2.95	2.98	3.14
(Low box clearance designs)					
Box clearance (m)	2.21	2.77	3.17	3.48	3.88
Abovewater strut depth (m)	1.29	1.29	1.21	1.08	1.08
Volume of components					
Underwater volume (m^3)	994	1999	3006	4012	5023
Hull volume (m^3)	857	1674	2466	3237	3998
Submerged strut volume (m^3)	137	325	541	775	1024
Haunch volume (m^3)	131	376	699	1085	1524
Box volume (m^3)	4070	4884	5537	5967	6500
Superstructure 1 volume (m^3)	1433	1555	1627	1616	1657
Superstructure 2 volume (m^3)	459	498	521	517	530
(High box clearance designs)					
Abovewater strut volume (m^3)	211	421	624	803	1019
Total volume (m^3)	**7297**	**9733**	**12014**	**14001**	**16254**
(Low box clearance designs)					
Abovewater strut volume (m^3)	110	195	256	291	351
Total volume (m^3)	**7197**	**9507**	**11646**	**13489**	**15586**

Estimates of transverse stiffness (KM_T) are also within 1%, but this can still permit an error of 10 cm in metacentric height. The potential for this kind of error must be borne in mind, especially if combined with the uncertainty which will inevitably be associated with estimating KG in the early design stages. Larger discrepancies occur in the LCF and KM_L results, but this is considered to arise from the inaccuracy of *POSH* in dealing with the ends of the struts.

The wetted surface calculation employed by Lin-Day-Reed (Chapter 6) is confirmed by *POSH*, and the L-D-R method has been employed in *DESIN*.

5.8.4 Contoured Hullforms

Modern SWATH designs tend to employ longitudinally varying non-circular sections in order to reduce resistance and draught and improve motions. Figure 5.4 illustrates three such hullforms of current interest. Experience with practical designs (Chapter 12) has led to the development of these hulls. Designs 5.4a and (particularly) 5.4b are forms intended for maximum speeds near a lower hull Froude number of 0.45, but capable of economic operation at Froude number 0.30. A slow speed role with a maximum Froude number of 0.3 is suited to design 5.4c.

'Equivalent' contoured hull designs displacing the same volume and having the same draught as the 'simple' hulls of section 5.8.2 were developed using *HYD*. These were a 'cokebottle' design with the form of Figure 5.4c and a 'dogbone' design similar to Figure 5.4a.

It was decided to replace the circular section of the simple hulls with elliptical sections of B/D=1.4. Because the use of non-circular sections may be expected to allow reductions in draught, 'shallow' versions of the contoured hulls were also derived. In this case, the geometries were manipulated to give 75% of the draught of the 'deep' versions. This distortion results in abnormal SWATH ships with an excessive proportion of volume in the lower hulls, and very shallow struts. As shown in Figure 5.5, draught reductions of 15% (compared to circular hulls) may be expected in a 'normal' elliptical hull design with B/D=1.4. Resistance and seakeeping qualities of these 'shallow' hulls may be expected to be poor, although the larger hulls and reduced draught may find uses.

Table 5.6 contains the particulars of the simple 'baseline' hulls and the alternative contoured forms.

Table 5.6 Hydrostatic Particulars of Five Alternative SWATH Hullforms

Hullform	*Baseline Hull*	*"Coke" Deep*	*"Coke" Shallow*	*"Dogbone" Deep*	*"Dogbone" Shallow*
DESIGN 1000					
Displacement (t, SW)	1018.6	1008.9	1006.4	1015.86	1019.1
Hull Prismatic Coefficient	0.7834	0.5974	0.5974	0.7479	0.7479
Draught (m)	4.674	4.597	3.505	4.427	3.573
Hull Breadth (m)	3.116	4.149	4.404	3.712	3.902
Hull Depth (m)	3.116	2.963	3.145	2.652	2.787
LCB from Amidships	0.747	2.341	2.505	1.667	1.726
LCF from Amidships	1.13	1.13	1.13	1.13	1.13
VCB from Keel	1.874	1.823	1.646	1.672	1.523
Transverse KM	11.541	11.583	11.43	11.365	11.186
Longitudinal KM	18.859	18.972	18.838	18.703	18.501
DESIGN 2000					
Displacement (t, SW)	2049.4	2029.9	2046.22	2023.9	2030.2
Hull Prismatic Coefficient	0.7834	0.5974	0.5974	0.7479	0.7479
Draught (m)	6.227	6.227	4.832	6.227	4.632
Hull Breadth (m)	4.151	5.477	5.929	4.799	5.239
Hull Depth (m)	4.151	3.912	4.235	3.428	3.742
LCB from Amidships	0.837	2.5	2.977	1.778	1.888
LCF from Amidships	1.244	1.244	1.244	1.244	1.244
VCB from Keel	2.573	2.533	2.257	2.396	2.046
Transverse KM	12.334	12.386	12.032	12.278	11.897
Longitudinal KM	20.759	20.882	20.461	20.801	20.393
DESIGN 3000					
Displacement (t, SW)	3081.5	3064.9	3103.9	3053.4	3045.5
Hull Prismatic Coefficient	0.7834	0.5974	0.5974	0.7479	0.7479
Draught (m)	7.346	7.346	5.559	7.284	5.364
Hull Breadth (m)	4.897	6.461	7.135	5.66	6.241
Hull Depth (m)	4.897	4.615	5.096	4.043	4.458
LCB from Amidships	0.895	2.602	2.88	1.861	1.993
LCF from Amidships	1.317	1.317	1.317	1.317	1.317
VCB from Keel	3.097	3.055	2.681	2.883	2.427
Transverse KM	13.225	13.269	12.766	13.135	12.706
Longitudinal KM	22.091	22.152	21.538	22.051	21.645
DESIGN 4000					
Displacement (t, SW)	4112.69	4102.1	4083.1	4117.8	4072.2
Hull Prismatic Coefficient	0.7834	0.5974	0.5974	0.7479	0.7479
Draught (m)	8.25	8.25	6.188	8.25	6.188
Hull Breadth (m)	5.5	7.254	8.014	6.358	7.007
Hull Depth (m)	5.5	5.182	5.724	4.541	5.005
LCB from Amidships	0.94	3.279	2.986	1.916	2.055
LCF from Amidships	1.368	1.368	1.368	1.368	1.368
VCB from Keel	3.531	3.489	3.013	3.324	2.781
Transverse KM	13.633	13.617	13.188	13.413	12.984
Longitudinal KM	23.136	23.145	22.76	22.905	22.581
DESIGN 5000					
Displacement (t, SW)	5148.33	5147.8	5065.9	5199.1	5071.2
Hull Prismatic Coefficient	0.7834	0.5974	0.5974	0.7479	0.7479
Draught (m)	9.024	9.024	6.768	9.024	6.768
Hull Breadth (m)	6.016	7.935	8.765	6.979	7.67
Hull Depth (m)	6.016	5.668	6.261	4.985	5.479
LCB from Amidships	0.978	2.733	3.069	1.965	2.112
LCF from Amidships	1.415	1.415	1.415	1.415	1.415
VCB from Keel	3.909	3.866	3.307	3.69	3.063
Transverse KM	14.534	14.453	14.106	14.212	13.85
Longitudinal KM	23.999	23.959	23.724	23.585	23.459

5.9 Conclusions

A generalised hull definition method for SWATH ships has been developed. This is a necessary component of any synthesis tool employing analytical methods requiring accurate knowledge of the hull form. Hydrostatic calculations using this tool are in good agreement with results obtained by other methods. The approach described is suitable for design and analysis of a wide range of SWATH configurations, and has been used to generate a family of SWATH designs for use in parametric studies of various design features.

References to Chapter 5

1. Catley, D. and Whittle, C., "Exploitation of an Advanced Surface Definition Capability for Hull Form Design and Analysis", *Proceedings*, PRADS, Trondheim, June 1987

2. Mulligan, R.D. and Edkins, J.N., "ASSET/SWATH - A Computer Based Model for SWATH Ships", *Proceedings*, International Conference on SWATH Ships and Advanced Multi-Hulled Vessels, RINA, London, April 1985

3. Mulligan, R.D. and Edkins, J.N., *Small Waterplane Area Twin Hull Advanced Surface Ship Evaluation Tool - Preliminary Theory Manual*, DTNSRDC Advanced Concepts Office, April 1983

4. Devine, M.D., "ASSET - A Computer-Aided Engineering Tool for the Early Stage Design of Advanced Marine Vehicles", Paper No. 78-725, AIAA/SNAME Advanced Marine Vehicles Conference, April 1978

5. Betts, C.V., Ferreiro, L.D., Grzeskowiak, S.R., McDonald, N.A. and Parlett, P.J., "Design Study for an ASW SWATH Frigate", *Proceedings*, International Symposium on Anti Submarine Warfare, RINA, London, May 1987

6. Nethercote, W.C.E., and Schmitke, R.T., "A Concept Exploration Model for SWATH Ships", *Transactions*, RINA, Vol. 124, 1982

7. Koops, A. and Nethercote, W.C.E., "An Extended SWATH Concept Exploration Model", *Proceedings*, International Conference on SWATH Ships and Advanced Multi-Hulled Vessels II, RINA, London, November 1988

8. Cressy, C. and Meinhold, M.J., "*SWATHGEN* Computer Aided Design Program Users Manual", Science Applications International Corporation, Report No. SAI-84/3051, February 1985

9. Salvesen, N., Kerczek, C.H., Scragg, C.A., Cressy, C.P. and Meinhold, M.J., "Hydro-numeric Design of SWATH Ships", SNAME *Transactions*, Vol. 93, 1985, pp. 325-346

10. Betts, C.V., "Some UK Developments in SWATH Design Research", *Proceedings*, International High Performance Vehicle Conference, Shanghai, November 1988

11. Seren, D.B., Leitch, E. and Miller, N.S., "The SWATH Wave Load Program - Progress Report No. 4 - Program for Offshore Structure Hydrostatics (POSH)", University of Glasgow, Department of Naval Architecture and Ocean Engineering Report NAOE-HL-83-35c, 1983

12. Seren, D.B., Miller, N.S., Ferguson, A.M. and McGregor, R.C., "Some Motion and Resistance Aspects of SWATH Ship Design", *Proceedings*, International Conference on SWATH Ships and Advanced Multi-Hulled Vessels, RINA, London, 17-19 April 1985

13. Vossers, G., *Resistance, Propulsion and Steering of Ships - Behaviour of Ships in Waves*, The Technical Publishing Company, Netherlands, 1962

14. McCreight, K.K., "Assessing the Seaworthiness of SWATH Ships", SNAME Annual Meeting, November 1987

15. Lamb, G.R., "Influence of Seakeeping Requirements on SWATH Ship Design", SNAME Local Section (Chesapeake), Paper, June 1987

16. Chun, H.H., "Theoretical and Experimental Studies on the Resistance of SWATH Ships", *Ph.D. Thesis*, University of Glasgow, 1988

17. Miller, N.S., "Some Design Notes for SWATH", YARD Internal Memorandum, 28/1/88

18. Validakis, J., and MacEachen, C., "Computer Program and Examination of Infinite Frequency Added Mass Coefficients of Submerged 2-D Sections", University of Glasgow, Department of Naval Architecture and Ocean Engineering, Report NAOE-84-54, September 1984

19. Validakis, J., Seren, D.B. and Leitch, E., "Frequency Dependent Hydrodynamic Coefficient Data for the Heave, Sway and Roll Modes - Part I - Submerged, Symmetrical Single-Hull Sections", University of Glasgow, Department of Naval Architecture and Ocean Engineering, Report NAOE-84-02, February 1984

20. Validakis, J., and Percival, D.J., "Frequency Dependent Hydrodynamic Coefficient Data for the Heave, Sway and Roll Modes - Part II - Surface Piercing, Single-Hull-Strut Combinations", University of Glasgow, Department of Naval Architecture and Ocean Engineering, Report NAOE-85-45, July 1985

21. Munk, M.M., "The Aerodynamic Forces on Airship Hulls", Report No. 184, National Advisory Committee for Aeronautics, 1924

22. Chapman, R.B., "Sinkage and Trim of SWATH Demihulls", AIAA Paper 74-327, AIAA/SNAME/USN Advanced Marine Vehicles Conference, San Diego, Ca., February 25-27 1974

23. Santos, R. and Sartori, G., "On the Vertical Plane Stability of Small Waterplane Area Twin Hull Ships", *Proceedings*, International Congress on Marine Technology, Athens, May-June 1984

24. Ware, J.R., Best, J.F., Scott, V.A. and McCreight, K.K., "SWATH Control Design Using Optimal Techniques", *Proceedings*, 6th Ship Control Systems Symposium, October 1981

25. Caldeira-Saraiva, F., Clarke, D. and Nicholson, K., "SWATH Vertical Motion Control Using a Frequency Domain Multivariable Approach", *Proceedings*, 7th Ship Control Systems Symposium, 1984

26. Gore, J.L. (editor), "SWATH Ships", *Naval Engineers Journal*, February 1985

CHAPTER 6

RESISTANCE ESTIMATION

A short review is made of methods available for predicting the resistance of SWATH ships. The integration of these techniques with the synthesis model is described and results of some comparative and parametric studies presented.

6.1 SWATH Resistance Prediction Tools

The computer model described in this thesis has not required the development of any techniques for predicting the resistance of SWATH ships. This important function has been provided by tools developed by other researchers. This chapter briefly discusses some aspects of these methods with respect to their integration with the overall design system.

The ability to predict resistance and powering characteristics is a fundamental technological requirement for any type of marine vehicle. Monohull geometry is such that theoretical prediction of resistance is usually impracticable. Instead, 'standard series' based on experimental data are used to estimate powering requirements. For SWATH ships, the regular geometric shapes lend themselves to theoretical drag prediction. This is fortunate, in view of the current lack of any reliable alternative method (other than experiments).

A number of researchers have now obtained satisfactory correlation between experimental data and theoretical predictions of SWATH resistance. These studies have employed potential theory to predict wavemaking, and standard naval architectural practices for estimating frictional drag. Table 6.1 lists the most well known methods for predicting SWATH resistance.

Table 6.1 Principal SWATH Resistance Prediction Programs

Program	Developer	Date	Ref	Comments
SWATHRP	Chapman (NUC)	1972	[4]	line sources, simple input
-	Anderson (DREA)	1980	[5]	closely based on Chapman
SYNTHESIS	Lin, Day, Reed (DTNSRDC)	1974	[1,2,3]	line sources, simple input
CLOSEFIT	Lin, Day, Reed (DTNSRDC)	1974	[1,2,3]	line sources, offset input
OSWATH	Chun (University of Glasgow)	1988	[6,7]	plane sources, offset input
MSWATH	Chun (University of Glasgow)	1988	[6,7]	plane sources, simple input
-	Bertram, Jensen (Hamburg)	1988	[8]	3D panel method
-	Huang (Dalian Inst of Technology)	1987	[9]	wavemaking drag only
SWATHGEN	Salvesen et al (SAI Corp.)	1985	[10,11]	linked to hull definition tool
-	Gadd (BMT)	1981	[13]	generalised 3D potential flow
RESON1	Chilo, Stefano (CETENA)	1980	[12]	closely based on Lin-Day

With the exception of the generalised panel methods [8,13], the above tools introduce the assumptions of slenderness or thinness and linearised wave theory. The three dimensional methods solve the non-linear problem and allow bodies of almost arbitrary shape to be modelled, but data input is time consuming and they are computationally expensive.

By utilising a line distribution of singularities on the longitudinal centreline of the lower hulls and a plane source distribution over the centreplane of the struts, Chapman [4] devised a solution to the wave making drag of SWATH ships. Most subsequent developments have followed this approach. His computer program (*SWTHRP*) employs a geometry definition using simple mathematical formulae.

Based on the same theory as Chapman, but using Chebyshev coefficients and a cubic spline curve fitting procedure, Lin and Day [1] developed another program [2,3] for predicting the drag of SWATH ship hulls and struts defined by offsets.

Salvesen et al [10,11] developed a technique generally similar to Chapman's, but employed a correction term accounting for the outflow between strut and hull. They also identified the importance of a geometry definition system which automatically ties the hullform to the hydrodynamic computations, and provided such a capability with *SWATHGEN*.

Instead of using two sets of Chebyshev coefficients, as employed by Lin and Day, Huang [9] concluded that he had significantly reduced the computational effort involved in the former method by employing the first kind of Chebyshev polynomial (one set of Chebyshev coefficients).

The line source distribution is strictly only suitable for hulls of circular cross section and semi-empirical correction factors are required to model non-circular hulls. In recognition of this limitation, Chun [6,7] developed a method of distributing a number of sources on each cross section. This technique allows the drag of non-circular SWATH hulls to be predicted with greater accuracy than the earlier methods.

Reference [6] contain a discussion of these methods. The present synthesis tool makes use of *CLOSEFIT*, *OSWATH*, *MSWATH* and the DREA version of the Chapman program.

6.2 SWATH Resistance Programs Employed in *DESIN*

References [3] and [5] contain FORTRAN listings of the Lin-Day-Reed and Chapman programs and the Glasgow University programs *OSWATH* and *MSWATH* also became available for the present study. An option to select any of these programs forms part of the *DESIN* synthesis program. Automated links with the hull definition procedures of Chapter 5 are included to provide an integrated design capability. In this way it is possible for a SWATH geometry to be defined rapidly and its resistance characteristics obtained automatically. This is especially useful in the final manipulation of a design to suit operational requirements.

Because of their greater flexibility, the programs developed by Chun are almost always selected when using *DESIN*. The two available options differ only in their geometry input format. *MSWATH* is designed for SWATH ships defined by mathematical formulae and, on a DEC *VAX11/730*, requires only 2.5% of the CPU time of *OSWATH*. This version of the program is therefore suited to use in a computer aided design model, but is restricted in terms of the geometries which can be handled. Therefore, in order to maintain the flexibility in geometry permitted by the hull definition procedures, it was decided to employ *OSWATH* as the principal design tool.

In general. the total resistance of a surface ship is treated as an additive sum of a number of components. One possible definition of the components of resistance is described in Chapter 4. Table 6.2 lists the definitions employed by the three tools available in *DESIN*.

Table 6.2 Structure of SWATH Resistance Programs

Method	Resistance Components		Calculation method
Lin-Day-Reed	Wavemaking	R_W	Linear wave theory
	Frictional	R_F	Schoenherr 1947 Mean Line
	Form	R_{FF}	Derived from experiments
Chapman	Wavemaking	R_W	Linear wave theory
	Frictional	R_F	Schoenherr 1947 Mean Line
	Eddymaking	R_E	Scaled from hull R_F and strut R_F
	Spray drag	R_S	From model data
	Appendage	R_{AP}	Scaled as 10% R_F
	Aerodynamic	R_A	Using frontal area and C_D of 0.5
Chun	Wavemaking	R_W	Linear wave theory
	Frictional	R_F	ITTC 1957 Line
	Form	R_{FF}	Derived from experiments
	Appendage	R_{AP}	Empirical formulae for aerofoil sections

The details of these calculations have been covered elsewhere [1-6] and are not discussed here. A good comparison of the Chapman and Lin-Day approaches is available in reference [14].

Figure 6.1 compares predictions by these methods of the naked hull effective power of the contoured elliptical hulled SWATH of Table 5.2. The empirical approach described in section 4.3.5.3 of Chapter 4 is also included and seen to perform well. The three theoretical approaches are within engineering accuracy of one another, except between speeds of 8 and 12 knots, where the Chun method gives significantly higher predictions than the others. It should be noted that Chun's approach is the only one directly suited to predicting the resistance of non-circular hulls.

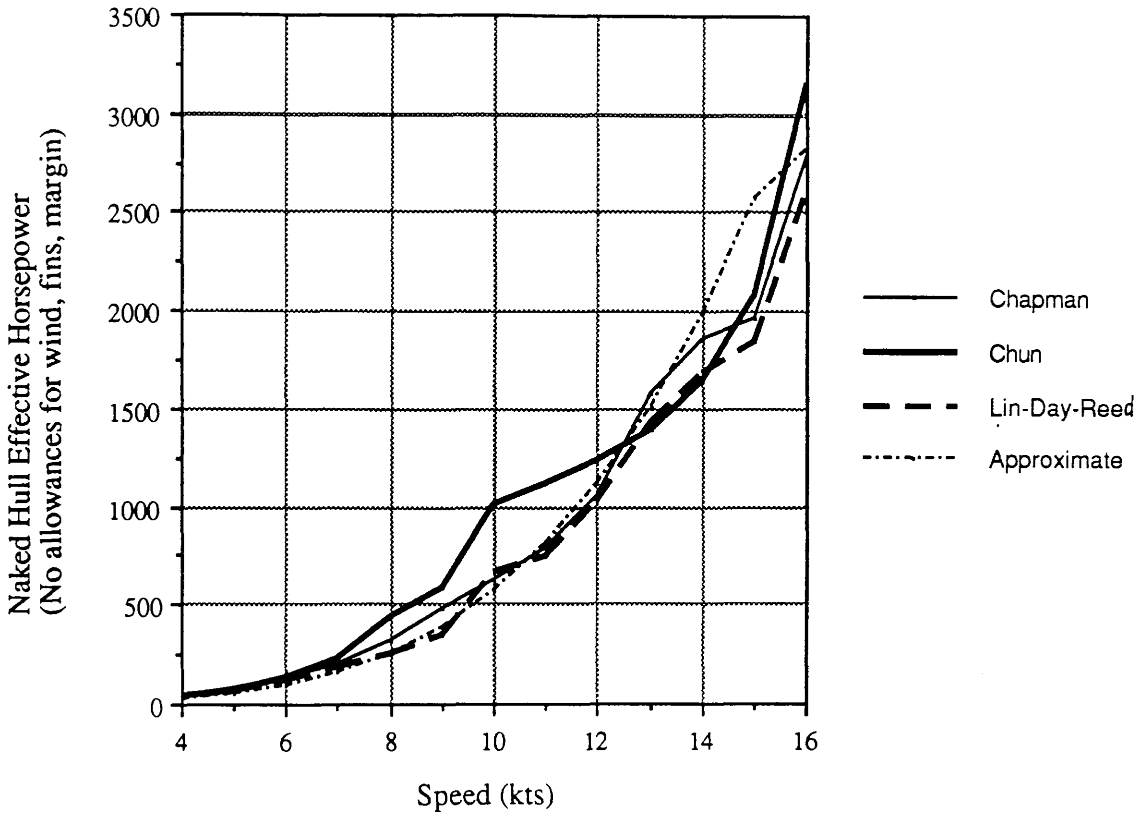


Figure 6.1 Comparison of Effective Power Predictions for Contoured Hull SWATH

DESIN has been provided with the ability to apply fouling and assurance margins to the basic effective power predictions of the programs, depending on the policies being adopted for a given design project. Choice of design or uncertainty margins for use in SWATH powering estimates within the current project has been guided by comparing calculated resistances from the three programs for a set of standard hulls.

6.3 Resistance of a Family of SWATH Hullforms

6.3.1 Simple Hullforms

The alternative resistance prediction packages were used to predict the naked hull effective powers of the five simple SWATH ships defined in Table 5.4. Since these vessels are circular hulled, all three methods are theoretically suitable for predicting the wavemaking of the lower hulls. A comparison of estimated naked hull effective powers at three potential design speeds is shown in Table 6.3.

Table 6.3 Comparison of Effective Power Predictions for a Family of SWATH Ships

Powers are quoted in metric HP

Displacement (t)	1000			2000			3000			4000			5000		
Speed (kts)	15	20	25	15	20	25	15	20	25	15	20	25	15	20	25
Chapman	1782	3686	8124	2873	5476	14589	3457	6495	20522	3782	7427	26820	4352	8478	32231
L-D-R	1829	3968	8454	2918	5588	15052	3574	6692	21346	3996	7670	27478	4274	8974	33236
Chun	1722	3974	8418	2582	5518	14616	3128	6488	20384	3576	7270	25954	4064	8246	31094

For a given design condition, the different methods disagree by an average of 6%. A margin of at least this magnitude should therefore be applied in preliminary SWATH powering calculations. Larger margins are recommended for vessels of more complex form. This level of agreement is acceptable in preliminary phases of design, and is comparable to the accuracy which would be expected in equivalent monohull power estimates.

An important feature of SWATH design, not immediately evident in the above, but illustrated in Figures 6.2 to 6.6, is the prominent 'hump' in the wavemaking resistance at Froude Numbers close to 0.3 (and 0.5). It is often worthwhile to arrange the submerged geometry in such a way that both the magnitude and location of these resistance peaks are altered. Bulges amidships are useful in reducing wavemaking at Fn=0.3, while bulges at the hull extremities can reduce the resistance peak near Fn=0.5. The so-called 'contoured' hullforms introduced in Chapters 2 and 5 offer these advantages at the expense of increased constructional difficulty.

6.3.2 Resistance of Contoured Elliptical Hulls

In order to illustrate the potential benefits of such forms, resistance characteristics of the contoured hulls described in Table 5.6 and Figure 5.4 were studied. These are two amidships bulged or 'cokebottle' designs intended for operation near Froude Numbers of 0.3 and two complex or 'dogbone' designs intended for Froude Numbers close to 0.5. The former are approximately similar in profile to the *TAGOS-19* hull design, whilst the latter are closer to modern SWATH frigate hullforms.

These four hulls are all of elliptical cross section with B/D ratios of 1.4. 'Deep' draught (100% of simple baseline hull) and 'shallow' draught (75% of baseline value) versions are considered. The latter options offer greater internal area in the hull, but are less slender and bring the submerged body closer to the free surface, increasing residuary resistance. For these reasons they are hydrodynamically unattractive forms.

In Table 6.4, the lower hull dimensions of the ten deep draught variants are listed, together with the changes in resistance relative to the simple options of Table 6.3. These increases or reductions in drag are expressed as positive or negative percentages of the values provided in Table 6.3 by the Chun method (Chapman and Lin-Day-Reed methods require empirical correction factors for non-circular hulls). Reductions in resistance from the baseline are indicated in **bold** type.

Table 6.4 Changes in Effective Power Obtained with 'Deep' Draught Contoured Hulls

			Hull Dimensions (m)		% change in baseline EHP			
Δ (t)	Hullform	*Code*	Breadth	Depth	15 kt	17 kt	20 kt	25 kt
1000	Midships bulge	*Cokebottle*	4.149	2.963	**-22.60**	**-0.74**	15.20	7.90
	Complex hull	*Dogbone*	3.712	2.652	**-6.04**	11.10	**-1.79**	**-2.28**
2000	Midships bulge	*Cokebottle*	5.477	3.912	**-23.30**	**-5.60**	28.38	15.12
	Complex hull	*Dogbone*	4.799	3.428	**-6.43**	10.32	2.28	**-4.48**
3000	Midships bulge	*Cokebottle*	6.461	4.615	**-19.63**	**-25.97**	36.89	21.26
	Complex hull	*Dogbone*	5.660	4.043	5.82	**-10.36**	4.41	**-6.08**
4000	Midship bulge	*Cokebottle*	7.254	5.182	**-15.88**	**-32.31**	42.42	26.77
	Complex hull	*Dogbone*	6.358	4.541	20.47	**-16.67**	7.53	**-5.90**
5000	Midships bulge	*Cokebottle*	7.935	5.668	**-14.02**	**-36.54**	42.76	31.39
	Complex hull	*Dogbone*	6.979	4.985	32.78	**-20.85**	8.85	**-5.57**

It may be seen that the midships bulges provide significant percentage reductions in power in the lower speed regime, but increase high speed power requirements. The complex forms provide somewhat lower percentage reductions at the 25 knot speed but at these higher powers the savings in absolute terms are still significant. Large increases in power at 15 knots are associated with the complex hull, although the resistance peak near 17 knots is reduced for the larger vessels.

Better performance would be expected from hulls designed with more attention to individual size-speed conditions, rather than the ad hoc philosophy used in deriving the above dimensions. For instance, the hullform depicted in Figure 5.3b is expected to give a better high speed performance than that of Figure 5.3a. Some guidance on choice of SWATH geometry to minimise drag is available in reference [6].

Using this information and the computer programs described in Chapters 5 and 6 in a systematic manner, it is relatively simple to develop hullforms suited for a particular role. It is demonstrated in Chapter 8, however, that the constraint of hull dimensions on installed machinery is as important as hydrodynamics in determining maximum sustained speed for family of SWATH ships discussed in this thesis. This is particularly evident in the performance of the shallow draught designs.

Table 6.5 shows that at most of the speeds and sizes considered, the low values of slenderness and centreline submergence associated with these distorted geometries lead to considerable increases in effective power. However, Chapter 8 shows that these penalties may be offset by the ability to fit more powerful engines in the larger hulls. In practice, of course, one wishes to minimise installed power for a given speed.

Table 6.5 Changes in Effective Power Obtained with 'Shallow' Draught Contoured Hulls

Δ (t)	Hullform	*Code*	Hull Dimensions (m) Breadth	Depth	% change in baseline EHP 15 kt	17 kt	20 kt	25 kt
1000	Midships bulge	*Cokebottle*	4.404	3.145	**-12.54**	6.02	18.27	10.14
	Complex hull	*Dogbone*	3.902	2.787	14.10	27.92	**-2.67**	**-4.13**
2000	Midships bulge	*Cokebottle*	5.929	4.235	**-6.89**	4.28	37.08	25.05
	Complex hull	*Dogbone*	5.239	3.742	28.22	60.82	7.21	**-2.60**
3000	Midships bulge	*Cokebottle*	7.135	5.096	45.91	23.13	89.95	56.06
	Complex hull	*Dogbone*	6.241	4.458	69.50	54.39	26.20	0.32
4000	Midship bulge	*Cokebottle*	8.014	5.724	111.41	60.38	167.84	86.57
	Complex hull	*Dogbone*	7.007	5.005	97.87	35.39	31.47	**-3.35**
5000	Midships bulge	*Cokebottle*	8.765	6.261	157.04	78.89	213.22	108.11
	Complex hull	*Dogbone*	7.670	5.479	136.86	28.72	41.45	**-4.37**

Figures 6.2 to 6.6 contain curves of EHP for the five hullform variants on each displacement, which illustrate the poor drag characteristics of the shallow draught designs more graphically.

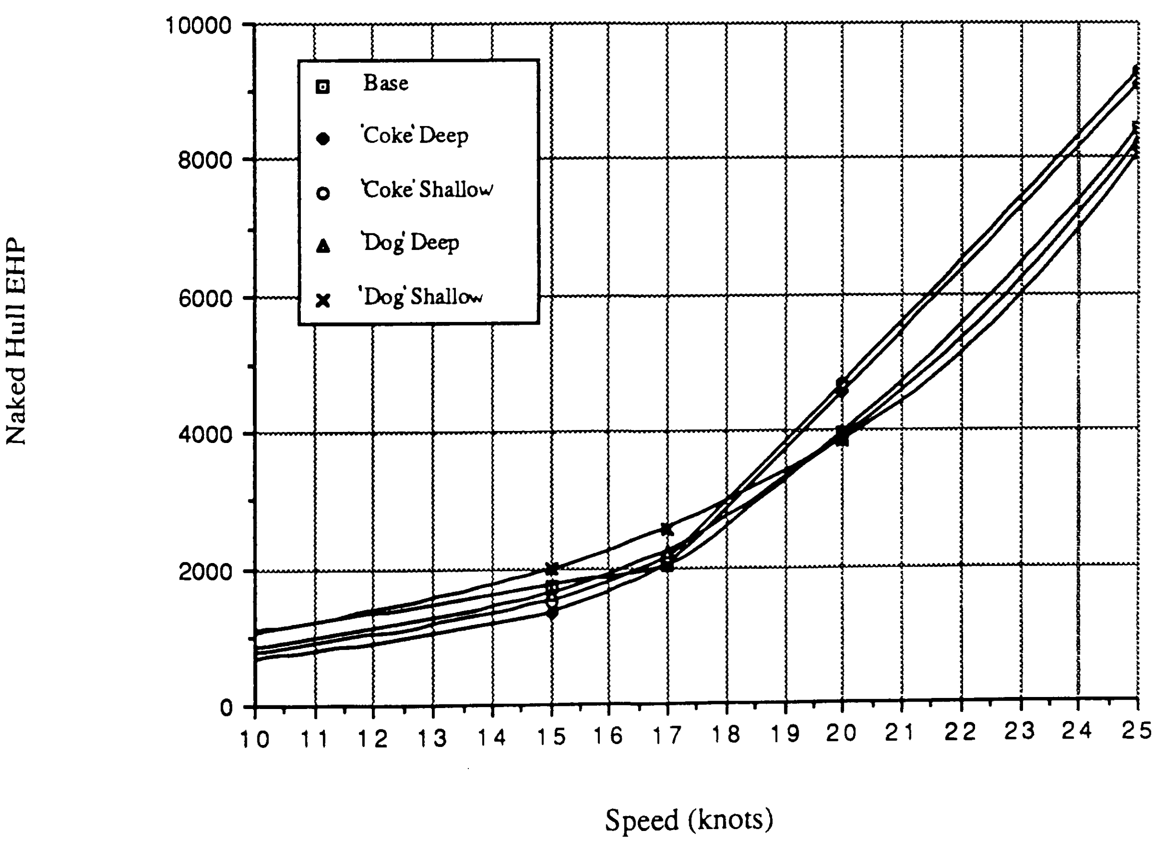


Figure 6.2 Effective Powers - 5 Alternative 1000 tonne SWATH Hullforms

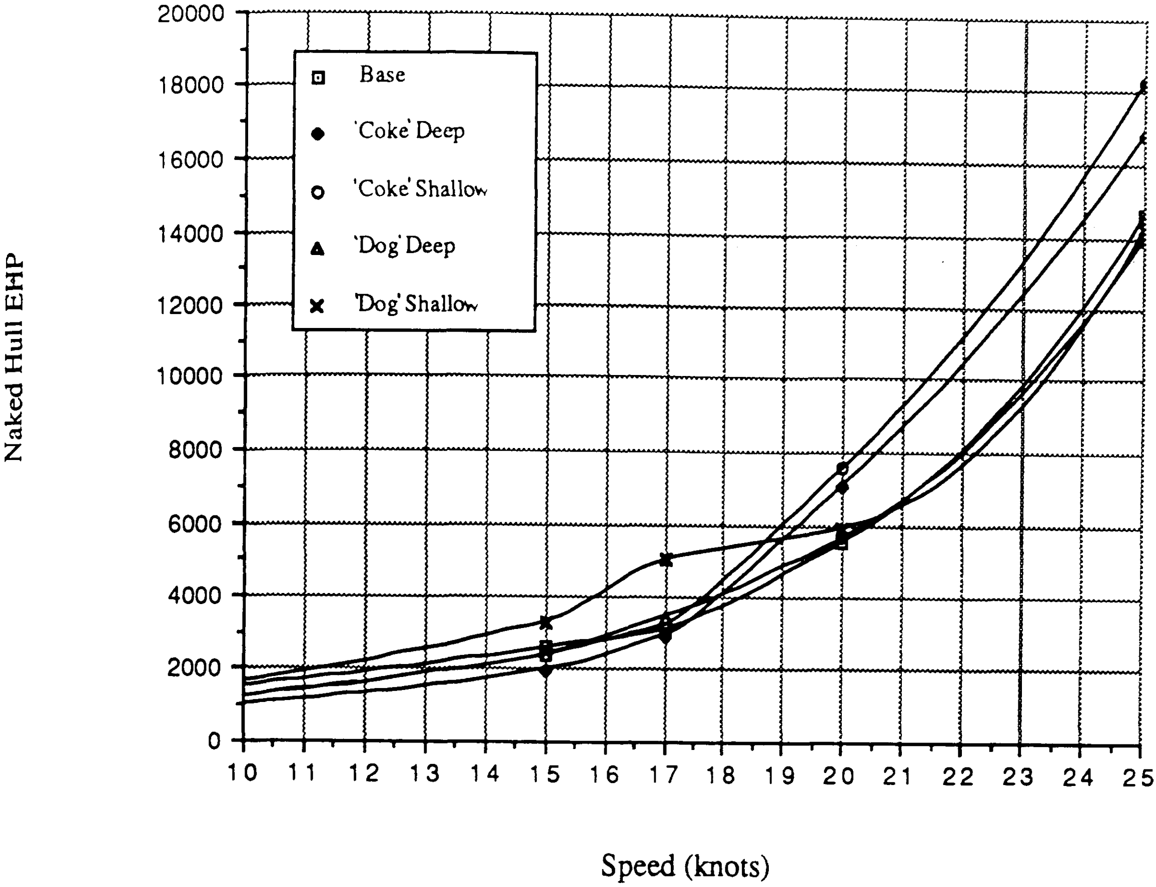


Figure 6.3 Effective Powers - 5 Alternative 2000 tonne SWATH Hullforms

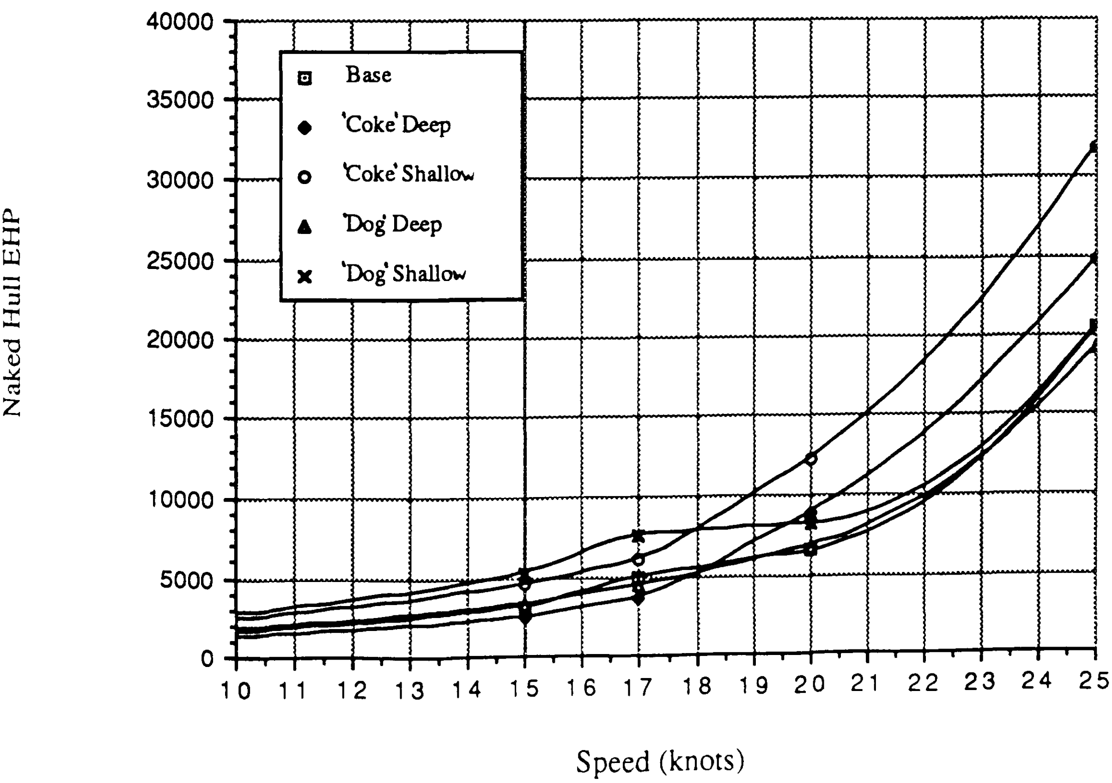


Figure 6.4 Effective Powers - 5 Alternative 3000 tonne SWATH Hullforms

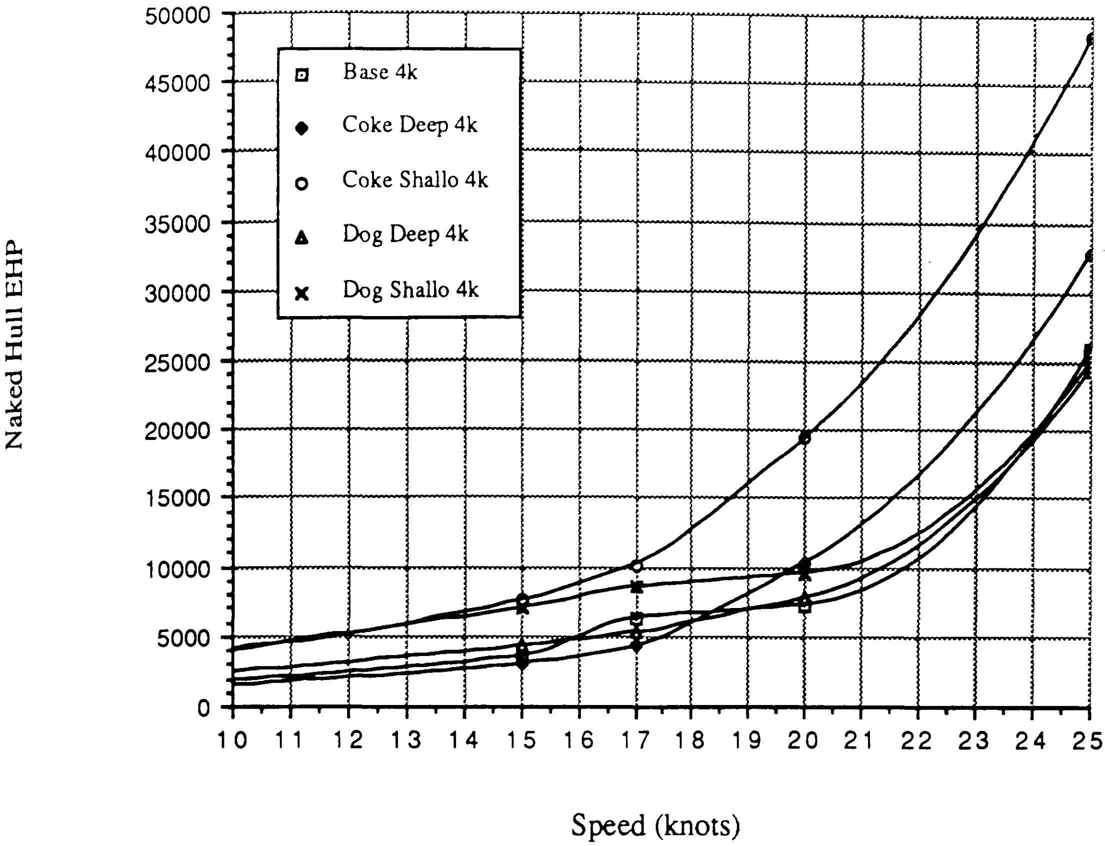


Figure 6.5 Effective Powers - 5 Alternative 4000 tonne SWATH Hullforms

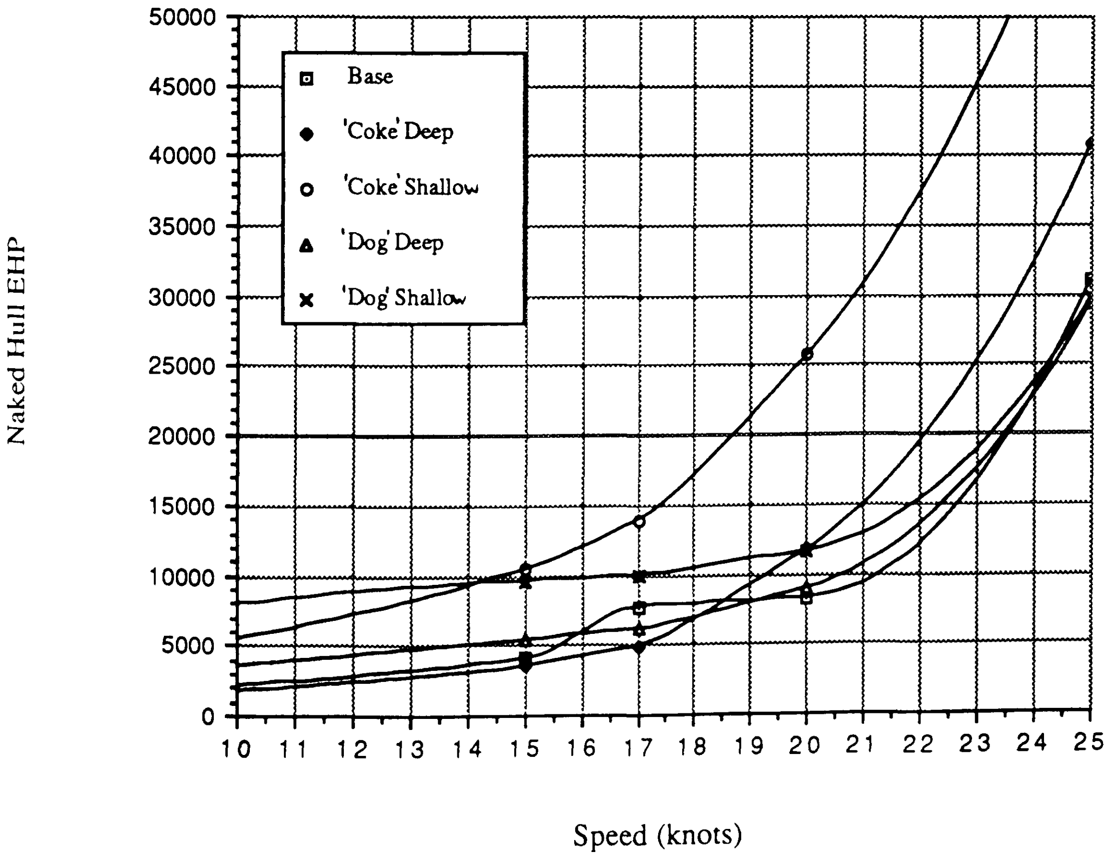


Figure 6.6 Effective Powers - 5 Alternative 5000 tonne SWATH Hullforms

6.4 Resistance Module Operation

6.4.1 Input and Output Associated with Resistance Modules

In the first iteration through the synthesis program *DESIN*, the user has to specify the preferred calculation method, and the percentage fouling and design margins to be applied. Small algorithms automatically convert the hull definition in the current model into the format required by the chosen numerical method. Operating speeds and the sea states required for calculating power augment are obtained from the current model, having being provided earlier in the run of *DESIN*. Table 6.6 lists the principal input and output variables. Documentation of the Chun [15] and Lin-Day-Reed [16] programs has been completed as part of the current project.

Table 6.6 Input and Output Data for Resistance Module

Input Data

Interactive input

Select calculation method from; Lin-Day-Reed theory
Chapman theory
Chun theory

or make use of previously prepared file of Speed-EHP data
Fouling margin, as percentage of frictional resistance
Design (uncertainty) margin on EHP estimate

Input from Current Model

Hull definition (defined by module *HYD*)
Operating speeds (previously defined as principal design requirements)
Sea states (wave heights) defined as user requirements

Output Data

Echo of vessel geometry as idealised by resistance tool
Estimated wetted surface
For each speed, the following data is provided:
Components of resistance (strut, hull, hull-strut interference, demi-hull interferences, frictional, form, appendage, fouling, margins, weather allowances). These are presented as absolute values, and as coefficients.
Total estimated EHP

6.4.2 Choice of Hullform

The choice of 'optimum' proportions for SWATH ships is a complex problem involving many factors in addition to resistance. Even neglecting those other considerations, and attempting to optimise drag characteristics alone, is a complicated process. The large number of hull design variables makes a systematic study of all the contributing factors a difficult matter, and one which has yet to be dealt with.

In the synthesis model described in this thesis, the hullform is determined using the methods described in Chapters 2, 4 and 5. The resistance prediction sections do not themselves allow for modification of geometry, and merely calculate the drag of the form with which they are presented. However, some appreciation of the factors important in SWATH resistance is of interest to potential users. The following paragraphs contain some simple guidelines abstracted from reference [6]. These were derived from analysis of a computational study using the program developed by Chun.

The speed regime(s) in which a vessel is to operate are of prime importance in determining suitable dimensions and attention should be paid to the possibilities of obtaining favourable interference effects between different wavemaking sources. However, a SWATH arrangement which will give favourable interference characteristics at all speeds cannot be obtained.

Proper apportioning of the volume between hulls and struts is essential and depends on the draught and speeds of interest. It is also important to keep the struts as slender as possible.

Changes in draught alter the magnitude of the various resistance components, while their pattern with respect to Froude Number remains virtually constant. In the speed range where viscosity dominates, lighter draughts offer the lowest resistance. In the wavemaking regime, two possibilities exist. SWATH ships with slender hulls ($L/D \geq 15$) do not benefit from increased draught because their wavemaking component is small compared to the frictional drag which increases with increasing wetted surface. On the other hand, a draught at which the resistance is a minimum will exist for vessels with hull slenderness ratios lower than about 12.

The wave interference system produced between the two demihulls can be favourable or unfavourable depending on speed. At higher speeds (above $Fn=0.5$), a wide spacing is necessary to avoid unfavourable interference. At moderate speeds ($Fn=0.35$-0.45), well chosen spacings <u>can</u> reduce resistance by as much as 40% of the drag of two infinitely spaced hulls.

The peaks and hollows in the resistance curves are significantly affected by the position of the strut(s) on the demihull. A 'short' strut located centrally on the hull gives favourable hull-strut interference at moderate speeds, but is unfavourable at high speeds. For an overhanging strut, the situation with regard to hull-strut interference is reversed. In general, a 'short' strut design produces less total drag at moderate to high speeds than the overhanging strut option, which is best at slow speeds.

References to Chapter 6

1. Lin, W.C., "The Force and Moment on a Twin Hull Ship in Steady Potential Flow", *Proceedings*, 10th Symposium on Naval Hydrodynamics, Cambridge, Mass., 1974, pp 493-516

2. Reed, A.M., "Documentation for SWATH Ship Resistance and Propulsion Prediction Programs (*Closefit* and *Synthesis*) Users Manual", DTNSRDC Report SPD-0927-02, 1981

3. Reed, A.M., "Documentation for SWATH Ship Resistance and Propulsion Prediction Programs (*Closefit* and *Synthesis*) Maintenance Manual", (includes FORTRAN program listing), DTNSRDC Report SPD-0927-02, 1981

4. Chapman, R.B., "Hydrodynamic Drag of Semisubmerged Ships", *Transactions*, ASME, vol. 4, 1972

5. Anderson, R.J., "A Computer Program for SWATH Ship Resistance and Power Estimation", DREA Technical Memorandum 80/C, (includes FORTRAN program listing), April 1980

6. Chun, H.H., "Theoretical and Experimental Studies on the Resistance of SWATH Ships", *Ph.D Thesis*, University of Glasgow, March 1988

7. Chun, H.H., Ferguson, A.M. and McGregor, R.C., "A New Computational Tool to Estimate the Resistance of SWATH Ships", *Proceedings*, International High Performance Vehicle Conference, Shanghai, November 1988

8. Bertram, V. and Jensen, G., "A Practical Method for Wave Resistance Prediction for SWATH Ships", *Proceedings*, International High Performance Vehicle Conference, Shanghai, November 1988

9. Huang, D.L., "A Modified Method for Calculating the Wave Resistance of SWATH Ships", *International Shipbuilding Progress*, vol.34, April 1987

10. Salvesen, N., et al, "Hydronumeric Design of SWATH Ships", *Transactions*, SNAME, vol. 93, 1985

11. Cressy, C.P. and Meinhold, M.J., "SWATHGEN Computer Aided Design Program User's Manual", United States Coast Guard Report CG-D-8-85, February 1985

12. Chilo, B. and de Stefano, D., "Programma *RESON1* (HD05) - Istruzioni per l'uso", CETENA Report No. 1087, October 1980

13. Gadd, G.E., "A Convenient Method for Estimating Wave Resistance and its Variation with Small Changes of Hull Shape for a Wide Range of Ship Types", *Marine Technology*, vol. 28, 1981

14. "An Analysis of Two Resistance Prediction Programs for SWATH Ships", extract from MARIN Report No. 43755-4-DR

15. MacGregor, J.R., "Program *OSWATH3* - Calculation of Resistance of SWATH Ships", SWATH User Guide YM5670/003/00A, SWATH User Guides Volume 1, YARD, 1988

16. MacGregor, J.R., "Program *RESIST* - Calculation of Resistance of SWATH Ships", SWATH User Guide YM5670/002/00A, SWATH User Guides Volume 1, YARD, 1988

17. Lin, W.C. and Day, W.G., "The Still Water Resistance and Propulsion Characteristics of Small Waterplane Area Twin Hull (SWATH) Ships", AIAA Paper 74-325, AIAA/SNAME Advanced Marine Vehicles Conference, San Diego, February 1974

CHAPTER 7

PROPELLER DESIGN

Methods currently used in the preliminary design of SWATH propellers are reviewed and a collection of model test data is presented. The available data is used to develop expressions relating self propulsion factors to basic design parameters. These are integrated with the open water characteristics of Troost B-series propellers in a computer program. A parametric study of propulsion aspects of a family of typical SWATH designs is presented.

7.1 Introduction

In recent years, several advanced techniques (discussed in Chapter 6) have been developed to calculate the resistance of SWATH ships. These tools allow the systematic variation of hull proportions in order to minimise drag.

However, vessel geometry must balance resistance characteristics with requirements for access, adequate hydrostatics and seakeeping and efficient structural design. These more 'obvious' aspects receive consideration in any SWATH design and compromises in hullform usually result. In contrast, little attention has been paid to studying the relationships between hullform and propulsive efficiency.

Since the hull proportions which influence resistance can be expected to have a first order effect on the hull efficiency elements, this is a potentially important area in SWATH design. As high propulsive efficiency is widely claimed to be one of the advantages of the SWATH configuration, it is important to develop some means whereby the influence of hullform on resistance *and* propulsion can be determined. It is also important to be able to examine the significance of other factors, such as design RPM, diameter constraints, allowable cavitation.

7. 2 Current SWATH Propulsive Design Practice

7.2.1 General

This section reviews some methods currently used in preliminary design of propellers for SWATH ships. The techniques employed in the computer aided design programs of the US and Royal Canadian Navies are described. This is followed by brief notes on the propulsion aspects of several SWATH designs.

7.2.2 DREA Concept Exploration Model

In its original form, the DREA concept exploration model for SWATH ships [37] calculated QPC by referring to results from self propulsion tests of the SWATH 6A model at DTNSRDC [15]. Effectively this meant that a single curve (Fig. 7.1) of QPC versus Froude Number was used to predict the propulsive efficiency of all designs produced by this program.

A recent publication [49] indicates that this part of the program has been altered to incorporate self propulsion factors from model tests of the Netherlands-Canada SWATH project with Wageningen B Series data.

A constant relative rotative efficiency of 0.99 is employed. Thrust deduction was found to be dependent only on propeller diameter d (in metres).

$$t = 4.3/d^2 \qquad \text{Eqn. 7.1}$$

An expression exhibiting speed and diameter dependencies was derived for Taylor wake fraction. (D is hull diameter in metres, V is ship speed in knots)

$$w_T = B - A \qquad \text{Eqn. 7.2}$$

where $B = 0.7528 / [e^{1.58(d/D)}]$

and $A = 0.158 - 0.158 \cos [(V - 23)\, 6.923\, \pi / 180]$ for $V \geq 17$ knots

$A = 0.058$ for $v < 17$ knots

7.2.3 USN Synthesis Tool *ASSET-SWATH*

The USN synthesis program *ASSET-SWATH* [38] has a dedicated *Propeller Module* intended to characterise a 'feasible' propeller within the constraints of cavitation, RPM and other considerations. In this program, maximum propeller efficiency is calculated at maximum ship speed at a propeller diameter or RPM fixed by the user. Cavitation is considered by reference to Burrill's criteria. Three types of propeller are considered; fixed pitch, controllable pitch, and contra-rotating.

Wake, thrust deduction, and relative rotative efficiency are user inputs, and are assumed constant over the full ship speed range, although these factors are known to vary with speed.

Three alternative methods are provided for calculating propeller open water characteristics.

Analytic uses equations derived from results of a series of lifting line calculations for optimum 5 bladed single propellers. A similar calculation option is provided for 5/4 bladed contra-rotating propellers. This calculation method permits the designer to vary thrust loading coefficient, and blade area ratio.

The *Troost* method can search for the optimum Wageningen B series propeller while varying number of blades, blade area and P/D ratios.

The *Model* method operates on open water propeller data supplied by the user in terms of thrust coefficient (k_T) and torque coefficient (k_Q) as functions of P/d ratio and advance coefficient J.

7.2.4 Existing SWATH Vessels

Since descriptions of SWATH vessels do not always include information on the propulsion system, this section contains supplementary data. General descriptions (with data sources) of the vessels may be found in Appendix 1.

The SSP *Kaimalino* is fitted [39] with two 4 bladed *Wilkinson* CRP propellers with a maximum rotational speed of 345 RPM. These are 78" (1.98m) diameter, with an expanded area ratio of 0.575 and Troost B4.70 series blade sections of 0.045 blade thickness ratio. Calculations incorporating boundary layer inflow determined a wake fraction of 0.24 and thrust deduction of 0.10, and an overall propulsive efficiency of 77%. With this arrangement, predicted speed at 3130 kW shaft power is 25 knots.

Details of the propellers fitted to *Kaiyo* may be found in ref. [11]. The diesel electric propulsion system has two fixed RPM settings; 75 RPM for slow speed and DP operations and 150 RPM for transit conditions. Controllable pitch propellers are therefore necessary. The propellers are highly skewed, 4 bladed, 3.8m diameter *Kamome* CPC-95BF. On trials, *Kaiyo* attained a speed of 14.1 knots with a shaft power of 3350 kW (both shafts).

The propellers fitted to *Halcyon* have been documented by Luedeke et al [12]. This vessel can attain 22.4 knots using two 4 bladed *Hundested* VP9 FR-H 45" (1.143m) diameter CRP screws operating at 660 RPM at MCR of 380 kW per shaft.

A description of the propeller design process for the USS *Victorious* (TAGOS-19) may be found in [50]. Initial self propulsion tests using stock propellers indicated constant t of 0.17, with w_T and η_{rr} ranging from 0.19 to 0.165 and 0.975 to 0.99 respectively, at speeds between 3 and 12 knots. The final design specified 5 bladed, 3.05m diameter screws with expanded area ratio 0.4276 and P/d of 0.6471 at 0.7R. Model tests using the design propeller indicated t of 0.18 and w_T of 0.245 at full power (10.5 knots, 180 RPM, P_D 1193 kW)

7.2.5 SWATH Design Studies

A study by UCL (Appendix 1 No. 90) for a 5470t ASW SWATH [27] contains some propulsion data. CODLAG drive and 5 bladed fixed pitch propellers of 6m diameter, with a pitch ratio of 1.2 are used. Open water screw characteristics were taken from a 20" AEW methodical series [30]. Hull efficiency elements were determined by making reference to submarine data [31]. This apparently presents wake fraction and thrust deduction as functions of the ratio of propeller diameter to hull diameter. At maximum ship speed of 28 knots (c. 30570 kW effective power), a rotational speed of 140 RPM and QPC of 73% are indicated. A propulsive efficiency of 76% was used for lower powers.

A concept design study (Appendix 1 No. 103) of a 2415t sonar support SWATH [41,46] specified diesel electric propulsion and FPP propellers of 3.05m diameter and 200 RPM at MCR. A QPC of 70% was assumed at the design speeds of 8 and 14 knots. These efficiencies were considered pessimistic by experienced US SWATH designers.

A design to similar requirements produced a 2330t SWATH [40] configuration (Appendix 1 No. 104). A diesel electric propulsion system drives two 3.42m diameter, 5 bladed FPP propellers at 150 RPM at MCR. EHP of the design (including appendages and design margins) is 385kW at 8 knots and 2210kW at 14 knots. It should be noted that both this and the previous vessel are intended for towing submerged objects having a drag of 20kN at 3 knots.

A comprehensive South Korean study [45] for a SWATH passenger ferry (Appendix 1 No. 98) included self propulsion tests at $^{1}/_{7}$th scale. Although the full results are not available, it is possible to deduce from the published power curves that the QPC is 70% at the design speed of 21.8 knots. This speed is attained at an effective power of 1010 kW and propeller RPM of 586. From the general arrangement drawing, the propellers appear to have a diameter of 1.1m on a hull diameter of 1.6m.

As part of the investigations at CETENA into SWATH passenger ferries (Appendix 1 No. 96) for Mediterranean routes, a propeller design study was carried out [18]. Hull mounted gas turbines were considered as prime movers for these vessels. Two 4 bladed CP propellers of NACA 66 section were specified, having an open water efficiency of 76% at a speed of 195 RPM. Propeller geometry details are; developed area ratio of 0.70, diameter of 3.45m, and pitch ratio of 1.9. This arrangement is designed for a vessel with an effective power of 9695 kW at 35 knots. Implicit in the calculations were a wake fraction of 0.01, thrust deduction factor of 0.06 (giving a hull efficiency of 0.949) and allowable back cavitation of 25%. The self propulsion figures are reported to have been derived from results presented in ref. [14], but it is in fact impossible to determine values of wake and thrust deduction from this source (hull efficiency alone is presented).

In his report [10] of a study (Appendix 1 No. 92) for a large diesel-electric auxiliary vessel, Kaysen proposed the use of a contra-rotating (fixed pitch) propeller system for each hull. He suggested that this arrangement could provide a QPC of 85%. The design has an effective power of 8950 kW at 20 knots.

The *SWATH83* design study (Appendix 1 No. 88) carried out by Pieroth and Lamb of Grumman and DTNSRDC [26] also specifies the use of twin contra-rotating propellers. At cruise speed (20 knots, shaft power 16780 kW) these are intended to have a nominal rotational speed of 85 RPM. Scaling from arrangement drawings suggests that the propellers are of 4.5m and 3.2m diameter. From the curves of effective and shaft power presented in the paper, it is possible to identify the use of a QPC of 70% throughout the speed range.

Other data may be obtained from an extensive study by the US Coast Guard [28,29] into small (125t to 1270t) offshore patrol SWATH ships (Appendix 1 Designs No. 5-8). These designs employ 5 bladed CRP propellers (Gawn Series data). Hull efficiency elements were obtained from model tests [15]. Initially, several design speeds were examined for each ship size, although *25 knots* was selected as the final speed. It can be seen from Table 7.1 that the USCG study assumes the same self propulsion factors for different vessels. A propeller diameter/hull diameter ratio of 91% was employed throughout for consistency with ref. [15]. Figure 7.2 illustrates QPC versus Froude Number for each vessel.

Table 7.1 Propulsive Characteristics Assumed for USCG Designs (taken from ref. [28])

Vessel	Speed (kts)	n_{rre}	(1-t)	(1-w)	n_h	n_o	QPC
	10	0.950	0.910	0.875	1.040	0.667	0.666
	15	1.020	0.900	0.850	1.059	0.649	0.701
125 LT	20	1.025	0.930	0.920	1.011	0.712	0.738
	25	*1.010*	*0.900*	*0.945*	*0.952*	*0.742*	*0.714*
	30	1.015	0.915	0.970	0.943	0.762	0.729
	10	0.950	0.910	0.875	1.040	0.694	0.693
	15	1.020	0.900	0.850	1.059	0.680	0.734
250 LT	20	1.025	0.930	0.920	1.011	0.705	0.730
	25	*1.010*	*0.900*	*0.945*	*0.952*	*0.733*	*0.705*
	30	1.015	0.915	0.970	0.943	0.753	0.721
	10	0.950	0.910	0.875	1.040	0.720	0.719
	15	1.020	0.900	0.850	1.059	0.718	0.775
750 LT	20	1.025	0.930	0.920	1.011	0.695	0.720
	25	*1.010*	*0.900*	*0.945*	*0.952*	*0.715*	*0.688*
	30	1.015	0.915	0.970	0.943	0.743	0.711
	10	0.950	0.910	0.875	1.040	0.709	0.708
	15	1.020	0.900	0.850	1.059	0.718	0.775
1250 LT	20	1.025	0.930	0.920	1.011	0.706	0.731
	25	*1.010*	*0.900*	*0.945*	*0.952*	*0.709*	*0.682*
	30	1.015	0.915	0.970	0.943	0.737	0.705

7.3 SWATH Model Propulsion Test Results

Even within the US Navy's extensive SWATH research programme only 6 propulsion experiments were completed by 1985, and only two of these included a wake survey. Furthermore, these employed stock propellers which were not evolved from realistic design constraints. Consequently, it is difficult to draw firm conclusions about the propulsive characteristics of SWATH ships.

This section brings together results from propulsion tests in the US, Japan, Canada and the UK, and presents a broad database. If similarities exist between a new SWATH hullform and one of the test forms, then manual use of the appropriate data is recommended. This is more likely to produce realistic results than the approximations developed in section 7.5. This section does not contain any significant data analysis.

7.3.1 Speed Dependency of Self Propulsion Factors

A number of self propulsion tests have been carried out on SWATH models. These are documented in Table 7.2 and plotted in Figures 7.3 to 7.6. It can be seen from the figures that the self propulsion results exhibit the large oscillations typical of a propelled body of revolution with propeller axis close to the free surface.

A simple regression analysis (ignoring speed dependent oscillations) provides the following straight line approximations,

n_{rre}	=	1.012+0.141[Froude Number]	Eqn. 7.3
$(1-w_T)$	=	0.681+0.377[Froude Number]	Eqn. 7.4
$(1-t)$	=	0.813+0.125[Froude Number]	Eqn. 7.5

NB Froude Number based on submerged body length

It is possible to detect patterns in the speed dependent oscillations of the self propulsion factors. Some general and approximate observations may be made;

a) $(1-w_T)$ and $(1-t)$ generally possess a peak at Froude Numbers of 0.3 and 0.5 and a trough at a Froude Number of 0.38.
b) although less distinct, the curves of hull efficiency follow a general pattern of peaks or troughs at the above Froude numbers.
c) the pattern of relative rotative efficiencies is too confused to permit similar observations.
d) all the self propulsion factors appear stable at Froude Numbers above 0.6
d) the trends for $(1-w_T)$ and $(1-t)$ are similar to that of the total wavemaking resistance coefficient of SWATH vessels [42].

Table 7.2 Particulars of SWATH Model Propulsion Experiments

IDENTIFICATION		SWATH MODEL DETAILS				HULL DETAILS				STRUT DETAILS			PROPELLER DETAILS					
Codename	Source	Form	$V(m^3)$	LOA(m)	T(m)	L(m)	D(m)	L/D	C_p	L(m)	t(m)	C_w	RPM	NoB	d(m)	d/D	P/d	BAR
JAP1 1.00	[13]	A	0.4012	3.000	0.450	3.000	0.300	10.00		0.940	0.135			6	0.184	0.613	1.500	0.700
JAP1 0.75	[13]	A	0.3768	3.000	0.375	3.000	0.300	10.00		0.940	0.135			6	0.184	0.613	1.500	0.700
DREA 329	[17]	B	0.2615		0.360	3.298	0.204	16.17	0.850	3.277	0.975							
AMTE	[16]	C				3.529	0.310	11.38		3.373								
5276	[14]	D	0.4433	4.288	0.418	4.288	0.258	16.62	0.758	3.377	0.120	0.709	60-200	5	0.245	0.950	1.226	0.844
5287	[14]	D	0.4624	4.303	0.418	4.303	0.269	16.00	0.758	3.392	0.120	0.740	50-190	5	0.245	0.910	1.226	0.844
5337-A	[15]	D	0.2500	3.300	0.360	3.300	0.200	16.50	0.851	2.360	0.100	0.818	25-225	5	0.193	0.965	1.147	0.634
JAP2 1.31	[6]	B	0.1493		0.363	2.000	0.200	10.00		2.070				4	0.157	0.785	1.000	1.100
JAP2 1.01	[6]	B	0.1310		0.302	2.000	0.200	10.00		2.070				4	0.157	0.785	1.000	1.100

KEY TO SWATH MODEL HULLFORMS

A Circular *simple* hull, tandem strut, with no aft overhang

B Circular *simple* hull, single strut, with overhang aft

C Circular *contoured* hull, single strut, with overhang aft

D Circular *simple* hull, single strut, with no aft overhang

Thus

i) at local maxima of the wavemaking resistance coefficient (@ Froude Numbers 0.3, 0.5), the wake fraction and thrust deduction possess local minima, and
ii) at the local minima of the wavemaking resistance coefficient (@ Froude Number 0.38), the wake fraction and thrust deduction possess a local maxima.

Reference will be made to these observations in section 7.5.2.

7.3.2 Wake Distribution

Wake distributions are available [6,13] for two of the vessels (*JAP1 0.75* at Froude No. 0.408 and *JAP2 1.31* at Froude No. 0.407). The original results are presented in Figures 7.7 and 7.8 in the form of contours of nominal wake fraction $w_n = (V - V_{an})/V$ where V_{an} is the nominal speed of advance of the propeller, or the mean of the measured local velocities in the place of the propeller when the propeller is absent.

The presence of an overhanging strut in *JAP2 1.31* introduces a significant asymmetry into the wake distribution on that model while *JAP1 0.75* has a more uniform distribution.

The graphical presentation was converted into numerical form by first measuring the nominal wake at the intersections of a matrix of radial axes and concentric circles. A mean nominal wake was then calculated for concentric circles of differing radii (from the propeller axis). These are plotted in Fig. 7.9. It can be seen that despite the asymmetry of *JAP2 1.31* the two tests reveal similar patterns in the decrease of wake with distance from the screw axis. It is possible to approximate the results of *both* tests by a logarithmic expression of the form

$$w_n = 0.0881[r/R]^{-1.372} \qquad \text{Eqn. 7.6}$$

where r and R are the radii of the concentric circle at which the wake is desired, and the hull, respectively.

Scaling full scale propulsion characteristics from model data is a complex problem which has not been fully resolved [5] for monohull ships. There is no guidance available for SWATH designers so Lin and Day [14] assume that their model results for w, t will scale directly to full size. Similar views have been expressed [33] in relation to submarine data.

7.4 Submarine Propulsion Data

The effects of the free surface on propulsion factors which are evident in SWATH results are not present in submarine test data. However, the lower hull sections of SWATH ships are similar in form to the hulls of modern submarines, and it is therefore interesting to examine the data available on submarine propulsion.

Because of the secrecy which has always been associated with submarines, publications on submarine design are rare. Much of the research and development work in this field remains unpublished.

7.4.1 Pre 1960 US Submarine Design

In an important paper published in 1960, Arentzen and Mandel [2] discussed some aspects of the propulsive efficiency of submarines.

The single propeller mounted axially behind a body of revolution is in an ideal position to recover some of the energy imparted to the boundary layer by the passage of the hull through the water. Thus, the ratio of propeller diameter to hull diameter must be important in governing hull efficiency. Fig 7.10 from ref. [2] presents model test results indicating the variation of self propulsion factors with this ratio. These tests are concerned with rather old hullforms, and propeller diameter/hull diameter ratios between 35% and 70%. It can be seen that:

a) both wake and thrust deduction decrease with increasing propeller diameter, and
b) hull efficiency decreases for screw/hull diameter ratios above 35%

It is also interesting to note that the hull appendages increase thrust deduction, wake and hull efficiency. This is presumably due to their increasing the wake velocity w_V=(V-Va) at a rate greater than the increase in thrust deduction (t=T-R_t).

Since hull efficiency decreases with propeller diameter and propeller efficiency increases, there probably exists a value of diameter and RPM which yields an optimum QPC for each design.

Arentzen and Mandel stated that there is some doubt that these model test results can be scaled to full size because the relative boundary layer (BL) thickness is greater on the model than on the full scale. This would tend to increase interaction effects and reduce appendage drag on the model. However, Hadler, in discussion [33] to this paper, noted that full scale measurements on a submarine do not support the above hypothesis (classical in model-full scale correlation work). Boundary layer experiments have shown that the BL thickness and velocity distribution are quite similar on model and ship. It is probable that the full size hull roughness counteracts the effect of Reynolds number on BL thickness. This convention has been accepted in the present study.

7.4.2 US Submarine Tanker Designs

Another publication from this era [1] presents QPC values for a series of large submarine tankers. In these cases the hull efficiency elements were derived [36] from plots of wake fraction and thrust deduction against propeller diameter over the square root of the wetted surface for a series of circular hulled models. These designs employed propellers with diameters between 28% and 32% of the hull diameter. It has proved impossible to isolate the hull efficiency elements used, but the published QPC information has been incorporated in Table 7.3 and Figure 7.16.

7.4.3 UK Attack (SSN) Submarine Tests

This section contains the conclusions of tests at ARE(Haslar) [9] on submarine forms. This information should be treated with care because of some unexplained trends which they contain. The propeller sizes ranged between 40% and 70% of the hull diameter.

Observations which can be made from the results are set out below.

a) There is a weak relationship between wake and propeller size. For tail half angles up to 25° wake decreases with increasing propeller size. This is in agreement with Arentzen/Mandel (section 7.4.1)
b) Wake fraction increases (non linearly) with increasing fullness of run. This is in qualitative agreement with SSPA (section 7.4.4)
c) Thrust deduction decreases with increasing propeller size. This is in agreement with Arentzen/Mandel (section 7.4.1)
d) Thrust deduction increases (approximately linearly) with increasing fullness
e) There is a weak relationship between hull efficiency and increasing propeller size. For all but the fullest forms tested, a small increase in η_h may be observed. This is in contrast to Arentzen/Mandel data (section 7.4.1)
f) Hull efficiency increases rapidly (in a non linear manner) with increasing fullness, is in excess of 100% and may reach as much as 170%
g) Relative rotative efficiency (usually) increases with increasing propeller size, and is generally in excess of 100%
h) Relative rotative efficiency exhibits a confused relationship with fullness
i) QPC increases moderately with increasing fullness
j) QPC increases with increasing propeller size, and may exceed 100%

Items f) and b) are the most controversial of the above observations. To the author's knowledge, the very high hull efficiencies observed with full forms have not been adequately justified. The *rate* of increase is governed by the *non linear* increase in wake fraction with increasing fullness. This latter phenomenon in particular is worthy of further study. The difficulty of conducting submarine propulsion tests must be considered if using these results.

7.4.4 Modern Submarine Data

The hydrodynamics of modern submarines are discussed in a publication [8] from SSPA. Mean Taylor wake is claimed to be about 33% for a *full form* submarine and 26% for a *slender* vessel. These descriptions of form are not defined in greater detail.

SSPA also refer to the risk of flow separation aft in connection with (primarily) the need for low noise and undisturbed flow to propeller. Fig. 7.11 indicates that separation free flow can be maintained in the pure ahead condition with a tail cone half angle of up to 25 degrees. Above 25° one may assume that the flow into the propeller deteriorates and its behaviour becomes non linear. This is a more reasonable assumption than that employed in the analysis of the ARE(H) results.

7.5. Prediction of Self Propulsion Factors

The previous sections have presented information which may be used manually to estimate self propulsion factors for particular SWATH (and submarine) designs. Generalised approximations are more suitable for use in parametric studies and computer programs. In this section the data of sections 7.3 and 7.4 is used to derive parametric approximations for the self propulsion factors. It is appreciated that because of the small size and inconsistency of the available database these results must be treated with discretion.

7.5.1 *Emerson* Type Formulae for QPC

QPC is the product of open water efficiency, hull efficiency and relative rotative efficiency. Ideally, in estimating QPC each of these quantities should be developed separately. However, in cases where only a small amount of data is available, it is sometimes effective to construct an approximation to a quantity directly. This is because larger errors may be introduced by 'piecewise' estimates.

Attempts were made to develop simple equations for the prediction of QPC for propelled bodies of revolution. Correlation of known data with functions involving propeller/hull size ratios proved unsuccessful, despite the importance of this parameter in other approximations. However, submarine data exhibits (Figure 7.12) a good relationship with RPM x √Body Length.

$$QPC = 26.44 \, [\, N\sqrt{L} \,]^{-0.479} \qquad \text{Eqn. 7.7}$$

The SWATH points do not follow this trend closely. In particular, for high values of $N\sqrt{L}$ (high speed propellers) equation 7.7 is pessimistic. The SWATH data is as well approximated by a simple

$$QPC = 72.6\% \qquad \text{Eqn. 7.8}$$

Table 7.3 contains the data used to construct Figure 7.12 and equation 7.7.

Table 7.3 QPC Figures for SWATH and Submarine Designs

Design	Source	Propeller Diameter (m)	Hull Depth (m)	Hull Length (m)	RPM	QPC (%)
Kaimalino	[39]	1.98	1.98	22.0	345	77.0
CETENA	[18]	3.45	3.00	42.8	195	72.0
UCL ASW	[27]	6.00	4.40	107.0	140	73.0
5337-A‡	[15]	4.36	4.57	74.2	224	73.5
5276¤	[14]	5.00	5.26	87.5	190	73.0
5287¤	[14]	5.00	5.49	87.8	190	72.5
YSL SSV	[41]	3.05	3.60	66.0	200	70.0
HHI/KIMM	[45]	1.10*	1.60	17.2	586	70.0
Sub-tanker	[1]	7.25	23.00	160.0	100	84.6
Sub-tanker	[1]	7.71	26.06	182.9	100	83.0
Sub-tanker	[1]	7.78	24.38	193.5	100	82.0
Sub-tanker	[1]	8.08	28.50	201.2	100	81.3
Sub-tanker	[1]	8.23	24.38	233.0	100	80.0
Trafalgar class	[9]	5.88	9.80	85.4	108	97.4

NB ‡ Results for full scale speed of 28 knots
¤ Results for full scale speed of 30 knots
* Estimated from General Arrangement

7.5.2 Piecewise Estimation of Self Propulsion Factors

7.5.2.1 Theoretical Background

The Taylor wake fraction w_T = (V-Va)/V provides a measure of the difference between the velocity (Va) of the water entering the screw and the speed of the vessel (V). The wake fraction can be conceived of as having three components [24].

Potential Wake: This is the wake of a body moving without wavemaking in an ideal (frictionless) fluid. The increased pressure of the close streamline flow near the stern of a body reduces the relative velocity of the water past the hull. This can be calculated mathematically [3] and increases with the fullness and breadth/length ratio of the body.

Wave Wake: This is the wake resulting from the movement of water particles in waves adjacent to the screw. If a propeller is located so that the water particles in the stern wave are moving in the direction of the ship (as in a crest), energy may be regained. Ship speed is thus an important factor.

Frictional Wake: This is the wake due to frictional effects on the water close to the ships hull. This is often the largest component of wake. It is difficult to predict because of the lack of a mathematical model to describe the flow in the boundary layer at the aft end of ship's hulls. However, the thickness of the BL is nearly proportional to the length of the body and the frictional wake decreases with increasing d/L since this ratio determines how much of the propeller is working in the boundary layer. Also, the thickness of the friction belt and consequently the frictional wake increases with the breadth of the body.

Many researchers have assumed a close relationship between thrust deduction and wake fraction. This has not been clearly demonstrated, although it is likely that both quantities are dependent on much the same parameters.

Thrust deduction t = (T - R_T)/T measures the difference between the resistance (R_T) of a vessel when towed and the thrust (T) required to propel a vessel at the same speed.

Potential Thrust Deduction: In true potential flow it can be shown that the potential thrust deduction is equal to the potential wake.

Wave Thrust Deduction: The stern wave system will be influenced by the screw action, and therefore the wavemaking resistance and thrust deduction will change.

Frictional Thrust Deduction: Friction with the hull induces a forward velocity in water which is then accelerated in the opposite direction by the propeller. This increases the resistance which means that the propulsion thrust has to be increased, giving a positive thrust deduction.

For a typical body, the thrust deduction increases with increasing D/L ratio, but at a lower rate than the wake fraction. Hull efficiency will therefore follow the same trend. This is in agreement with the observation by Mitsui [32] that propulsive efficiency tends to decrease with increasing lower hull slenderness.

None of the above deals with the question of what shape of lines should be adopted in the aft body of the hulls. With the current interest in SWATHs with contoured hulls, the need to determine the effect of hull shape on propulsion factors becomes important. No data describing these effects has been located in the present study, and this is a significant limitation of the propeller design procedure described in the following sections. However, there is some evidence [9] that tails which are truncated (within limits) offer greater hull efficiency than more slender forms, while Figure 7.11 indicates the tail cone angles which permit separation free flow. This aspect of hull design is also important from the point of view of installing shafting.

7.5.2.2 Construction of Approximations

With the limited data to hand, it is not considered possible to develop empirical expressions for SWATH ships containing all the factors discussed in section 7.5.2.1. In particular, it has not proved possible to correlate wake and thrust deduction with hull slenderness. Further theoretical and experimental study of this relationship would be of value. However it was considered important to include the influence of certain basic design parameters. An analysis of the available data led to the conclusion that ship speed and propeller size could be presented in a reasonable empiricism. It has proved impossible to isolate the influence of hull L/D ratio. This is however considered to be an important parameter, whose influence on self propulsion factors should be studied.

Speed Dependence of Wake and Thrust Deduction

It was decided first of all to represent the available thrust deduction and wake data in terms of lower hull Froude Number. This employed the observations of section 7.3.1 and led to the following simple approximations to the data.

Table 7.4 Baseline Approximations to Taylor Wake Fraction and Thrust Deduction

Speed Range (Fn)	$f_1(1-w_T)$	$f_2(1-t)$
0.00 - 0.30	0.70+0.15[Fn/0.30]	0.90
0.30 - 0.38	0.85-0.05[(Fn-0.30)/0.08]	0.90-0.05[(Fn-0.30)/0.08]
0.38 - 0.50	0.80+0.09[(Fn-0.38)/0.12]	0.85+0.07[(Fn-0.38)/0.12]
0.50 -	0.89	0.92

Diameter Dependence of Wake and Thrust Deduction

The above idealisations are based on a nominal d/D ratio of 0.85. It was considered important that the effect of screw size be added because of its influence on open water efficiency, and the possibility of tradeoffs on screw size.

A US Navy resistance and propulsion program for SWATH ships [43] uses approximations for wake and thrust deduction which are solely dependent on the ratio of propeller diameter to hull diameter. These equations were originally used in a study [44] of air cushion vehicle propulsion.

Taylor wake fraction, $$w_T = \frac{0.71}{\exp\,[1.58\,(d/D)\,]} \qquad \text{Eqn.7.9}$$

Thrust deduction fraction, $$t = \frac{0.05}{(d/D)^{1.26}} \qquad \text{Eqn. 7.10}$$

where d/D is the ratio of propeller diameter to hull diameter. These relationships are illustrated in Figure 7.13 and 7.14,with the associated hull efficiency curve in Figure 7.15. It can be seen that the hull efficiency follows the same trend as that noted by Arentzen and Mandel, i.e. after an initial rise, a drop in n_h may be observed for screw/hull diameter ratios above 30% or so.

These relationship between self propulsion elements and propeller/hull size ratio were compared with propeller data and hull efficiency elements for several SWATH designs. i.e. *Kaimalino* and models *5276, 5287, 5337-A, JAP1,* and *JAP2*. This information is plotted in Figures 7.13 - 7.15, together with the curves of equations 7.9 and 7.10.

Apart from the thrust deduction results from *JAP1*, it can be seen that the SWATH points and the curves are in fairly good agreement. The influence of speed on the self propulsion factors is at least of the same order as the effect of different propeller/hull diameter ratios.

In order to deal with screw size ratios other than 0.85, the form of equations 7.9 and 7.10 was used to provide correction factors to the approximations of Table 7.4. The final expressions for the self propulsion factors are;

$$(1-w_T) = f_1(1-w_T) + 0.1854 - 0.71 \exp[-1.58\,(d/D)] \qquad \text{Eqn. 7.11}$$

$$(1-t) = f_2(1-t) + 0.0614 - 0.05\,[\,(d/D)^{-1.26}\,] \qquad \text{Eqn. 7.12}$$

Relative Rotative Efficiency

No improvement on the straight line approximation (Equation 7.3) to relative rotative efficiency could be derived.

7.5.2.3 Testing of Approximations

The expressions derived in section 7.5.2.2 were compared with experimental hull efficiencies for models *5276* and *5287*. These models did not form part of the data used to construct the thrust deduction and wake approximations and so are independent checks of the method.

It can be seen from Figure 7.16 that the correlation between experimental and predicted hull efficiencies is good for these models. Figure 7.17 compares hull efficiency data for models *JAP1, JAP2, 5276, 5287, 5337-A* with the values predicted by the empirical methods.

The approximate methods produce curves which show hull efficiency decreasing with increasing screw diameter/hull diameter ratio. This is the relationship reported for submarines by Arentzen [2] and for air cushion vehicles by Roddy and Strom-Tejsen [44]. It is felt that it is important to account for this effect in SWATH design, either manually or in a synthesis program.

7.6. *TROOST* Propeller Design

This section contains a description of an automated method for propeller design which uses the self propulsion approximations of section 7.5, and open water performance characteristics from the Wageningen B series of propellers.

7.6.1 Propeller Design Variables

Some of the variables which have been incorporated in an automated propeller design program [47] for SWATH ships (program *SWATHPROP*) will be discussed.

For a high open water propeller efficiency, the speed of rotation of the screw should be low. However, in cases where screw diameter is restricted, it is sometimes necessary to increase the RPM. The present method requires an initial input of RPM from the main ship design system/user, but this may (if desired) be incremented automatically to optimise efficiency in the case of restricted diameter.

Diameter

Typically, SWATH propeller diameter is only about 83% of the hull depth. Figure 7.18 illustrates this relationship, using data obtained from several SWATH designs, including *Kaimalino, Kotozaki, Kaiyo and Halcyon.* It is interesting that it is unusual for the full diameter of the lower hulls to be exploited by the propeller diameter, probably due to operational considerations.

Propeller diameter $d = 0.83$ [Hull Depth] Eqn. 7.13

Propeller diameter is is an output of the program, but its optimisation is subject to practical constraints. It was considered reasonable to set an upper limit of 100% on the propeller diameter/hull diameter ratio. Primarily, this is in order to minimise the typically large draught of SWATH vessels. Also, diameter ratios beyond 100% are outwith the range of the empirical expressions for self propulsion factors derived in section 7.5. With this limitation manufacturing limits on the maximum diameter of propeller are unlikely to concern SWATH designers. However, in the present study, an upper limit of 11m has been set on propeller diameter.

Blade Area Ratio (BAR)

Open water efficiency increases with decreasing blade area ratio but the minimum BAR is governed by cavitation considerations. BAR is therefore initially selected by the designer, but may be over ridden by the program. In the present study, an upper limit of $7^1/_2$% on back cavitation is used. This is achieved by using a curve fit to the cavitation criteria published by Burrill [25,24]. Alteration of subroutine CAVITSWA will permit design for lower noise conditions, or for cases where higher cavitation is permissible.

7.6.2 Open Water Efficiency

The most comprehensive source of open water data for screw propellers is that published by NSMB [20, 21]. This is the Wageningen/Troost B series, and is presented in several formats. The Bp-δ form of presentation is suited to selection of the optimum efficiency for given RPM, speed of advance and delivered power.

The well known parameters Bp and δ are reproduced in equations 7.14 and 7.15, where P_D is delivered horsepower at propeller, d is propeller diameter in feet, and V_a is speed of advance in knots.

$$B_p = \frac{\text{RPM}\,[\,(P_D/1.025)^{0.5}\,]}{V_a^{\,2.5}} \qquad \text{Eqn. 7.14}$$

$$\delta = \frac{\text{RPM}\,[\,d\,]}{V_a} \qquad \text{Eqn. 7.15}$$

Sabit [19] presented equations derived from regression on the B series results. These are in a form suitable for use in computer aided design systems. For predetermined Bp and BAR; δ, P/d, and n_{opt} may be determined by regression equations of the form

$$\begin{aligned} &a_0 + a_1 \ln Bp + a_2 (\ln Bp)^2 + a_3 (\ln Bp)^3 \\ &\quad + a_4 (BAR) + a_5 (BAR)^2 + a_6 (BAR)^3 \\ &\qquad + a_7 (\ln Bp)(BAR) + a_8 (\ln Bp)(BAR)^2 + a_9 (\ln Bp)^2 BAR \qquad \text{Equn. 7.16} \end{aligned}$$

The coefficients a_0 to a_9 depend upon the number of blades (4 or 5) and whether it is δ, P/d or n_{opt} that is being calculated.

Field Efficiency

The equations of Sabit refer to the optimum efficiency lines (n_{opt}) of the Bp-δ charts. In cases where diameter is restricted, or RPM is altered, the propeller efficiency may depart from the optimum efficiency line. An empirical method due to Cameron [22,23] has been used to determine the field efficiency (n_o) using n_{opt}.

By erecting an ordinate at a given Bp on the charts, and reading off the value of δ_{opt} corresponding to n_{opt}, the values of 0.95δ, 0.90δ , 0.85δ etc may be determined, and the corresponding n_o values plotted on the ordinate. Repetition of this process for other values of Bp allows curves of n_o to be constructed. These have the same characteristics as the optimum efficiency line.

Table 7. 5 Comparisons of Propeller Efficiency (by Bp-δ charts and equation 7.17)

δ		120	140	160	180	200	220	240	260
BAR = 0.60									
δ x 1.00	n_{opt}	0.700	0.665	0.634	0.601	0.571	0.543	0.518	0.492
δ x 0.95	n_{charts}	0.696	0.660	0.627	0.595	0.563	0.535	0.510	0.486
δ x 0.95	$n_{eqn.}$	0.694	0.659	0.627	0.594	0.564	0.536		
δ x 0.90	n_{charts}		0.648	0.614	0.580	0.549	0.520	0.495	0.470
δ x 0.90	$n_{eqn.}$		0.645	0.614	0.581	0.551	0.522		
δ x 0.85	n_{charts}		0.629	0.592	0.558	0.525	0.500	0.474	0.450
δ x 0.85	$n_{eqn.}$		0.625	0.593	0.560	0.529	0.501		
BAR = 0.75									
δ x 1.00	n_{opt}	0.671	0.642	0.612	0.584	0.555	0.526	0.500	
δ x 0.95	n_{charts}	0.666	0.636	0.605	0.577	0.545	0.521	0.495	
δ x 0.95	$n_{eqn.}$	0.665	0.636	0.605	0.577	0.548	0.519		
δ x 0.90	n_{charts}	0.658	0.620	0.590	0.560	0.532	0.505	0.480	
δ x 0.90	$n_{eqn.}$		0.622	0.592	0.564	0.535	0.505		
δ x 0.85	n_{charts}			0.565	0.538	0.510	0.484	0.460	
δ x 0.85	$n_{eqn.}$		0.602	0.571	0.543	0.514	0.484		
BAR = 1.05									
δ x 1.00	n_{opt}	0.645	0.615	0.585	0.553	0.523	0.495	0.469	0.445
δ x 0.95	n_{charts}	0.639	0.610	0.580	0.549	0.517	0.490	0.464	0.440
δ x 0.95	$n_{eqn.}$	0.639	0.609	0.578	0.546	0.516	0.488		
δ x 0.90	n_{charts}	0.621	0.591	0.562	0.532	0.503	0.476	0.450	0.426
δ x 0.90	$n_{eqn.}$		0.595	0.565	0.533	0.503	0.474		
δ x 0.85	n_{charts}			0.538	0.511	0.484	0.457	0.432	0.410
δ x 0.85	$n_{eqn.}$		0.575	0.544	0.512	0.482	0.453		

This procedure can be represented by equations which, for known δ_{opt}, n_{opt} and δ, give the field efficiency.

$$n_o = n_{opt} - [1.5\,(1.0 - \delta/\delta_{opt}) + 0.065] \times [1.0 - \delta/\delta_{opt}] \times [\,\delta/(\delta_{opt} + 10)\,] \qquad \text{Eqn. 7.17}$$

Table 7.5 compares open water efficiencies calculated by this method with values lifted manually from charts. The comparison shows satisfactory agreement.

7.6.3 Design Method

The iterative automated design procedure is illustrated in Figure 7.19. Primary inputs are the ship speed V, effective power (including margins and appendage allowances), hull length (L) and diameter (D), preferred RPM, BAR and number of blades. The design problem may be idealised as; the selection of a propeller giving the highest QPC and smallest blade area with constraints on diameter, RPM and cavitation. This neglects the effect of hull geometry, and assumes hulls of 'normal' shape. Abnormally bluff or slender tail sections would invalidate the procedure.

An iterative solution procedure is used to determine the propeller diameter which will yield maximum QPC. This calculates the efficiency elements for a series of propeller/hull diameter ratios (0.1 to 1.0) in the following manner.

Delivered power is arbitrarily set to 150% of EHP in the first iteration for each propeller size. Relative rotative efficiency, thrust deduction and wake fraction are calculated using equations 7.3, 7.11 and 7.12. The speed of advance (Va) is then calculated from $V[1-w_T]$. This information is sufficient to calculate B_p. The program is suitable for B_p values between 5 and 155.

Using equation 7.16 and the appropriate coefficients, the values of n_{opt}, δ and P/d at the optimum efficiency line may be calculated. A value of δ is calculated for the current diameter and the corresponding field efficiency is then determined from equation 7.17.

At this stage, the QPC may be calculated using the propeller, hull, and relative rotative efficiencies. W..n the known EHP, a new P_D may be derived. A check is then made between the input and output values of P_D. Differences above 3% trigger further design cycles, beginning with new values of P_D and diameter and continuing until the assumptions used to determine Bp are satisfactory.

When this criterion is satisfied, the *optimum* and *actual* open water efficiencies are compared. For differences above 3% (which may be caused by the unsatisfactory diameter being investigated), the program will (if desired) increase RPM in steps of 5% to bring the design point closer to the optimum.

A final check using Burrill's criteria is performed to ensure that BAR is adequate to keep back cavitation below 7.5%. If the initial value of BAR is insufficient, the complete design procedure is restarted with a new value. The acceptable range of BAR is from 0.45 to 1.05.

A loss of 2% of open water efficiency is assumed for CP propellers.

This procedure provides QPC values for a range of propeller diameters, from which the optimum screw is determined. Final output includes; diameter, RPM, pitch/diameter ratio, BAR, QPC, and components thereof. This enables the designer to estimate required propulsive powers, and associated fuel requirements.

Table 7.6 lists the input and output variables of the propeller design module (*SWATHPROP*) of the SWATH synthesis package.

Table 7.6 Input and Output Variables for Propeller Design Software

Input Variables	Output Variables
Ship Speeds and EHP Data	Relative Rotative Efficiency
Desired Margins (Service, Fouling)	Taylor Wake Fraction
Lower Hull Length	Thrust Deduction Factor
Lower Hull Depth	Propeller Diameter
Vessel Draught	Blade Area Ratio (if altered from input)
Propeller Type (Fixed or Controllable Pitch)	Propeller RPM (if altered from input)
Propeller RPM	Screw Open Water Efficiency
Number of Blades	Quasi Propulsive Coefficient
Blade Area Ratio (BAR)	Required Delivered Power
	B_p
	δ

7.7 Program Validation

The methods described in sections 7.5 and 7.6 have been checked by comparison with known SWATH propulsive data. Complete sets of propulsive design parameters for SWATH ships are rare in the open literature. It is unusual to encounter all of P_D, EHP, ship speed, vessel dimensions, and propeller details. At present it is only possible to prove that predictions of QPC and propeller diameter are in the right 'ballpark'.

Several SWATH propeller designs were carried out using the method described. The initial data used, and the propeller details derived using the program are presented in Table 7.7.

Table 7.7 Data Used to Check Propeller Design Program

Vessel	Speed/Power		Hull Details		Propeller			Design		*Program*	
Name	EHP	V(kts)	L(m)	D(m)	RPM	Type∞		d(m)	QPC(%)	*d(m)*	*QPC(%)*
Kaimalino	3234	25.0	22.0	1.98	345	4	CP	1.98	77	*1.80*	*80*
YSL SSV	2500	14.0	66.0	4.7/3.6	200	4‡	FP	3.05	70	*2.74*	*70*
MoD SSV	2388	14.0	61.8	4.40	150	5	FP	3.42	70	*3.26*	*71*
Kaiyo	2790‡	14.1	55.2	5.81	150	4	CP	3.80		*3.37*	*67*
Halcyon	800‡	22.4	16.1	1.52	660	4	CP	1.14‡		*0.95*	*77*
HHI/KIMM	1350	21.8	17.2	1.60	586	4‡	CP‡	1.10‡	70	*1.17*	*72*
UCL ASW	41000	28.0	107.0	6.6/4.4	140	5	FP	6.00	73	*5.61*	*74*
CETENA	13000	35.0	42.8	4.5/3.0	195	4	CP	3.45	72	*Not Feasible*	

Note - ‡ refers to estimated value
∞ refers to number of blades and CP/FP

The program tends to underestimate propeller size compared to the known data. However, this supports the earlier observation that SWATH propeller diameter is unlikely to exceed hull diameter. Figure 7.20 shows that the program derived diameters follow the same trend with √[EHP/Speed] as the known values. The mean error in the estimates of diameter is less than 10%.

Differences in allowable cavitation figures and the effects of CP installations are the most likely causes of differences in particulars. The *Kaimalino* propellers are of unusual form and do not conform to the B series data. The CETENA propeller allows 25% back cavitation, but cannot be designed by the program to less than 7.5% cavitation.

Published and predicted QPC values are shown in Figure 7.21 as a function of RPM√L. The mean error in the estimates of QPC is under 2%, and this performance is considered adequate for the present purposes.

7.8 Parametric Study

The propeller design methods described in the previous sections were used to study the effect of diameter variations on a typical family of SWATH ships. The *'baseline'* or simple hulled SWATH vessels developed in Chapter 5 were used in the study. These ships have circular, uncontoured hulls, and single struts (without aft overhang) and are described in Table 7.8.

Table 7.8 Basis Data for Family of SWATH Ship Designs

	Hull Details			Effective Powers (kW)		
Disp(t)	L (m)	D (m)	T (m)	15kt	20kt	25kt
1000	71.747	3.116	4.674	1550	3283	7208
2000	78.964	4.151	6.227	2571	4929	12857
3000	83.558	4.897	7.346	3173	5961	17981
4000	86.970	5.500	8.250	3590	6923	23077
5000	89.780	6.016	9.024	4057	8019	27830

7.8.1 Terms of Reference

A design RPM of 200 was employed in the study. Normally, some freedom in RPM is available to the designer and variable RPM is a more realistic design situation. However, many SWATH ships will employ electric drive, including the option of fixed speed AC motors. These offer the possibility of an integrated electrical system at the expense of a CP propeller for speed control. It is therefore considered that the assumption of fixed RPM is reasonable.

The Bp-δ results corresponding to the B4.55 screw were employed, unless cavitation dictated an increase in BAR.

Results were generated for each of the vessels at speeds of 15, 20 and 25 knots. These conditions are referred to as *1.15, 1.20, 1.25,......, 5.20, 5.25*, denoting both size (in 1000t units) and speed (in knots).

For each of these conditions, the open water, hull and relative rotative efficiencies and QPC were calculated at hull diameter/propeller diameter ratios of 0.1, 0.2,...., 1.0. Inevitably many of these design points lie well above the optimum efficiency line of the B-δ diagrams, and without the option to increase RPM, remain so. Some fall below the optimum efficiency line.

7.8.2 Results

These effects are illustrated in Figures 7.22 to 7.26 for each of the five vessel sizes. Figures 7.27 to 7.29 present virtually the same results in terms of the three design speeds considered. For this family of SWATH ships the following results can be recognised.

a) Increasing the screw diameter above a given fraction of the hull diameter leads to a fall-off in open water efficiency. This is seen to be more significant in determining optimum QPC than the decrease in hull efficiency with this ratio.
b) The optimum screw size ratio increases with increasing speed/power, but decreases with increasing ship size (figures 7.30 to 7.32).
c) The curves of QPC versus d/D ratio become closer for different ship sizes with increasing speed (cf 25 knots).

Analyzing the optimum values of QPC and diameter (Table 7.9) reveals some further details.

Table 7.9 - Optimum QPC and Propeller Diameter/Hull Diameter Ratios

	Optimum QPC at			Optimum d/D Ratio at		
Δ (tonnes)	15knots	20knots	25knots	15knots	20knots	25knots
1000	74.2%	77.3%	79.5%#	0.920	0.990	1.000#
2000	72.1%	76.2%	77.4%	0.710	0.800	0.940
3000	70.6%	75.8%	75.7%	0.630	0.720	0.880
4000	69.8%	75.2%	74.2%	0.580	0.670	0.840
5000	69.0%	74.5%	73.0%	0.550	0.640	0.800

Constrained

Figure 7.30 shows the optimum QPC for each of the design speeds/design displacement conditions considered. It can be seen that despite the constraint on RPM which existed, virtually all of the 15 design points may have a QPC in excess of 70%. The most inefficient propulsion occurs with the 15 knot conditions.

The relationship between propulsive efficiency and Froude Number is illustrated in Figure 7.34. The data suggests that there exists a local maximum in QPC at Froude Numbers around 0.36. This corresponds to the position of the well known hollow in the residuary resistance curves of SWATH ships. This phenomena is due to the fact that the propeller thrust loading varies with the residuary resistance, while the propulsive efficiency varies inversely. Thus there should exist peaks in propulsive efficiency at hollows in the residuary resistance curve.

Significant improvements in efficiency may be observed for the 5000t vessel between speeds of 15 and 20 knots. At the exact locations of the wavemaking peaks (near 17 knots), the QPC would be expected to be even lower than at 15 knots. This finding is important in that it reinforces the desirability of avoiding the area of the local hump in the residuary resistance curve.

Figure 7.31 shows that the optimum *physical* propeller diameter does increase with increasing ship size, although its *ratio* to the hull diameter decreases (Figure 7.32). Most design points show an optimum screw/hull diameter ratio less than unity. Hence, constraining propeller diameter to less than hull diameter is not significant for these vessels. Significant increases in diameter result from increasing speed/power.

Figure 7.33 presents the optimum propeller diameter for all 15 design points as a function of the square root of EHP/Speed. For this family of SWATH vessels, optimum propeller diameter may be approximated by the straight line equation

Optimum Diameter (m) = $1.865 + 0.09 \sqrt{[EHP/Speed]}$ Eqn. 7.18

where EHP is in kW and Speed is in knots.

7.9 Conclusions

A study has been made of the propulsive performance of SWATH ships and, less intensively, submarines. This has created a database of experimentally derived self propulsion factors which may be employed in the design of these vehicles. There are some contradictions in the available data which indicate the need for more study of the fluid flow at the after end of these vessels.

In the absence of other approximations, empirical expressions have been derived to predict the self propulsion factors of SWATH ships. These incorporate the effects of propeller diameter/hull diameter ratio and ship speed. These expressions are not sophisticated enough to fully represent the experimental data and are incapable of accounting for the effects of different lower hull shapes. This further illustrates the need for better techniques for predicting the hull efficiency elements of SWATH ships.

A one to one correlation has had to be assumed between the experimentally derived hull efficiency elements and full size vessel data.

A method for estimating propeller dimensions and performance has been developed for use in the SWATH synthesis program. This algorithm is designed to determine the required shaft power for any SWATH design, given the effective power and geometrical details of the vessel. It provides an estimate of QPC, making reference to physical constraints, with the secondary aim of defining a suitable propeller geometry. For a selected range of published designs, the program was found to estimate QPC to within 2% of published values and diameter to within 10%.

This tool has been used in parametric studies of the effects on propulsive performance of variations in major design parameters. These indicate that for a typical family of SWATH vessels, a QPC in excess of 70% may be achieved. It is demonstrated that at Froude Numbers near 0.36 which correspond to hollows in the residuary resistance curves, a local maximum exists for QPC. This reinforces the desirability of operating in this regime. Also, for this series of vessels, the optimum ratio of propeller diameter to hull diameter is typically less than unity.

References to Chapter 7

1. Russo, L., Turner, H. and Wood, F.W., "Submarine Tankers", *Transactions* SNAME, Vol. 68, 1960

2. Arentzen, E.S. and Mandel, P., "Naval Architectural Aspects of Submarine Design", *Transactions* SNAME, Vol. 68, 1960

3. Tsakonas, S. and Jacobs, W.R., "Potential and Viscous Parts of the Thrust Deduction and Wake Fraction for an Ellipsoid of Revolution", *Journal of Ship Research*, Vol. 4, no. 2, November 1960

4. Wislicenus, G.F., "Hydrodynamics and Propulsion of Submerged Bodies", ARS Semi-Annual Meeting, Los Angeles, May 9-12, 1960, *ARS Journal*, December 1960

5. Benedek, Z., "An Investigation of the Scale Effect on Self-Propulsion Factors", *International Shipbuilding Progress*, V[illegible]. 15, no. 163, March 1968

6. Nakai, Y. and Tamai, H., "On the Resistance and Propulsion Performance of a Small Waterplane Area Twin Hull (SWATH) Ship" (in Japanese), *Journal Kansai Society of Naval Architects*, No. 185, June 1982

7. O'Reilly, J.D., "Trailing Shaft Operations on a SWATH Ship", *M.Sc Dissertation*, University College London, Department of Mechanical Engineering, 1986

8. Hellstrom, S.A., "Submarine Design - Hydrodynamic Aspects", *Proceedings*, Warship'88 International Symposium on Conventional Naval Submarines, RINA, London, 3-4 May, 1988

9. Rydill, L., "Submarine Propeller Design", lecture delivered at YARD offices, Glasgow, 11th May 1988

10. Kaysen, H.D., "SWATH AGS Deep Ocean Survey Ship", Chesapeake Section, SNAME, October 1985

11. Ozawa, H., "The Design and Operation of Catamaran Vessels", *Transactions*, NECIES, Vol. 103, 1986-87

12. Luedeke, G., Montague, J., Posnansky, H., and Lewis, Q., "The RMI SD-60 SWATH Demonstration Project", *Proceedings*, International Symposium on SWATH Ships and Advanced Multihulled Vessels, RINA, London, 1985

13. Tanaka, H., Takeshi, H., Sugai, N., and Araj, C., "Studies on Propulsive Performance of Semi Submerged Ship and it's Model Testing Method" (in Japanese), Society of Japanese Shipbuilders, Autumn Conference, November 1982

14. Lin, W.C. and Day, W.G., "The Still Water Resistance and Propulsion Characteristics of SWATH Ships", AIAA Paper No. 74-325, AIAA Advanced Marine Vehicles Conference, 1974

15. Yeh, H.Y.H. and Neal, E., "Powering Characteristics of SWATH 6A in Calm Water and Head Seas Represented by Model 5337-A and Using Propellers 4415-4416", DTNSRDC Report SPD-396-20, March 1977

16. "SWATH Ship Concept - Propulsion Characteristics of Modified SWATH 9 Form", AMTE(H) Report R83024

17. Report by Canadian Defence Research Establishment Atlantic (DREA), Report LTR-SH-312

18. L. Grossi, "Progetto preliminaire dell'elica di un mezzo navale tipo SWATH" (in Italian), CETENA Report no. 1488, Genoa, August 1982

19. Sabit, A.S., "Optimum Efficiency Equations of the NSMB Propeller Series 4 and 5 Blades", *International Shipbuilding Progress*, vol. 23, 1976

20. Yosifov, K., Zlatev, Z. and Staneva, A., "Optimum Characteristics Equations for the 'K-J' Propeller Design Charts Based on the Wageningen B-Screw Series", *International Shipbuilding Progress*, vol. 23, 1976

21. Oosterveld, M.W.C., and van Oossanen, P., "Further Computer-Analysed Data of the Wageningen B-Screw Series", *International Shipbuilding Progress*, Vol. 22, pp. 251-262, 1975

22. Cameron, R.M., *Economic Ship Design*, Ph.D Thesis, University of Glasgow, 1970

23. Chatterjee, A.K., *A Computer Model for Preliminary Design and Economics of Container Ships*, Ph.D Thesis, University of Glasgow, 1982

24. Comstock, P.J., *Principles of Naval Architecture,* SNAME Publications, New York, 1967

25. Burrill, L.C. and Emerson, A., "Propeller Cavitation: Further Tests on 16" Propeller Models in the King's College Cavitation Tunnel', *Transactions*, NECIES, 1962-63

26. Pieroth, C.G. and Lamb, G.R., "The SWATH Option as a V/STOL Aircraft Carrier", 7th AIAA/SNAME/ASNE Marine Systems Conference, New Orleans, 23-25 February 1983

27. Betts, C.V., Ferreiro, L.D., Grzeskowiak, S.R., McDonald, N.A. and Parlett, P.J., "Design Study for an Anti-Submarine Warfare SWATH Frigate", *Proceedings*, International Symposium on Anti Submarine Warfare, RINA, London, May 1987

28. Allen, R.G. and Holcomb, R.S., "The Application of Small SWATH Ships to Coastal and Offshore Patrol Missions", *Proceedings*, 2nd Symposium on Small Fast Warships and Security Vessels, RINA, London, May 18-21 1982

29. Holcomb, R.S. and Allen, R.G., "Investigation of the Characteristics of Small SWATH Ships Configured for United States Coast Guard Missions", DTNSRDC Report No. SDD-83-3, June 1983

30. "Methodical Series Propeller Data", AEW Report No. L6/51

31. *Post-MSc Submarine Design Exercise Notes*, University College London, 1986

32. Narita, H., Mabuchi, T., Kunitake, Y., Nakamura, H. and Matsushima, M., "Design and Full Scale Test Results of Semi-Submerged Catamaran (SSC) Vessels", 1st International Marine Systems Design Conference, London, April 1982

33. Hadler, J.B., Discussion to [2], 1960

34. Costeletos, M.S., Discussion to [1], 1960

35. Bustard, E.E., Discussion to [1], 1960

36. Russo, L., Turner, H. and Wood, F.W., Author's reply to [34] and [35], 1960

37. Nethercote, W.C.E. and Schmitke, R.T., "A Concept Exploration Model for SWATH Ships", *Transactions*, RINA, 1982

38. Mulligan, R.D. and Edkins, J.N., "ASSET-SWATH - A Computer Based Model for SWATH Ships", *Proceedings*, International Symposium on SWATH Ships and Advanced Multihulled Vessels, RINA, London, 1985

39. Stenson, J.J., "Full Scale Powering Trials of the Stable Semi-Submerged Platform, *SSP Kaimalino*", DTNSRDC Report SPD-650-01, April 1976

40. Pattison, D.R. and Rose, P.H.A., "SWATH - The UK MoD Design and Assessment Programme", *Proceedings*, International Conference on SWATH Ships and Advanced Multi-hulled Vessels, RINA, London, November 1988

41. *SWATH SSV Concept Study Report*, Yarrow Shipbuilders Limited, July 1987

42. Numata, E., "Predicting Hydrodynamic Behaviour of SWATH Ships", *Marine Technology*, SNAME, January 1981

43. Reed, A.M., "Documentation for SWATH Ship Resistance and Propulsion Prediction Programs (*Closefit* and *Synthesis*) Maintenance Manual, DTNSRDC Report SPD-0927-02, April 1981

44. Roddy, R.F. and Strom-Tejsen, J., "Study of ACV Propulsion Systems - Propulsor Design and Performance", DTNSRDC Report SPD-378-09

45. Lee, K.Y, Lee, D.K., Kim, E.S., Kim, J.G. and Kim, J.H., "On the Design Technology of SWATH Ship for High Speed Coastal Passenger Vessel", *Proceedings*, High Speed Surface Craft Conference, January 1988

46. Smith, D.L., Cuthbertson, W., MacGregor, J.R. and McGregor, R.C., "SWATH Design - A Shipbuilders View and a Practical Example", *Proceedings*, International Conference on SWATH Ships and Advanced Multi-hulled Vessels, RINA, London, November 1988

47. MacGregor, J.R., "SWATH User Guide - Program *SWATHPROP*", SWATH Program User Guides Vol. 1, YARD Ltd, YM5670/006/00A

48. "Semi Submerged Catamaran Survey Ship *Kotozaki*", High Speed Surface Craft, April 1982

49. Koops, A and Nethercote, W.C.E, "An Extended SWATH Concept Exploration Model", *Proceedings*, International Conference on SWATH Ships and Advanced Multi-hulled Vessels, RINA, London, November 1988

50. Kim, K.H. and Reed, A.M., "Propeller Design of US Navy's SWATH, TAGOS-19", *Proceedings*, PRADS'87, Trondheim, June 1987

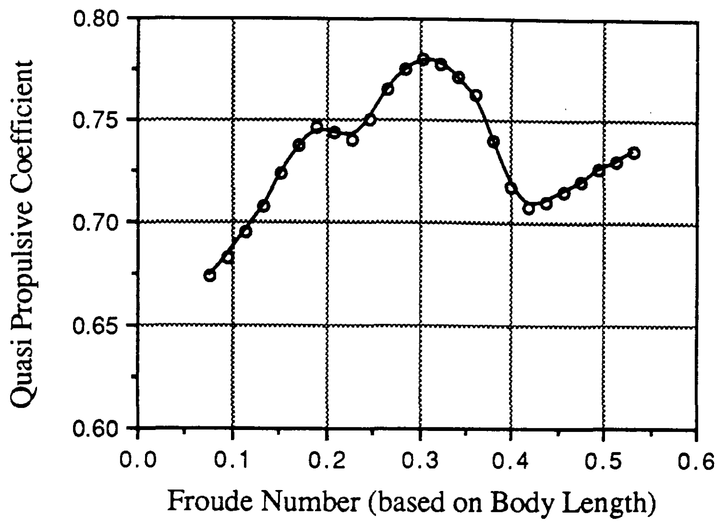


Figure 7.1 OPC Curve Used by Original DREA CEM for SWATH Ships

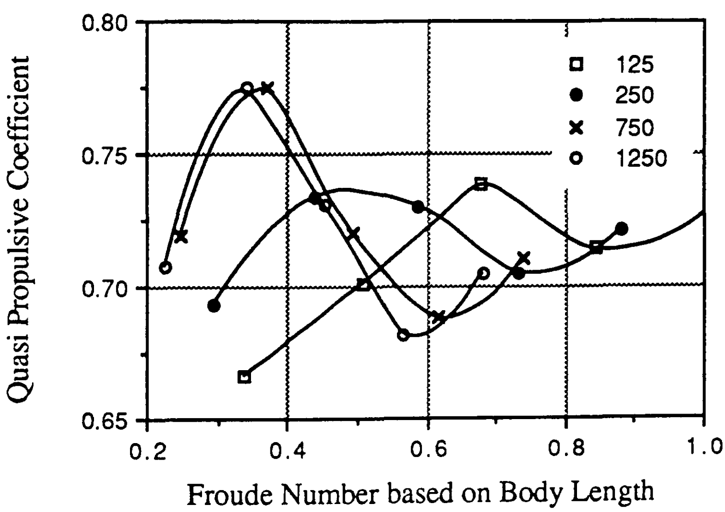


Figure 7.2 OPC Data for USCG SWATH Designs

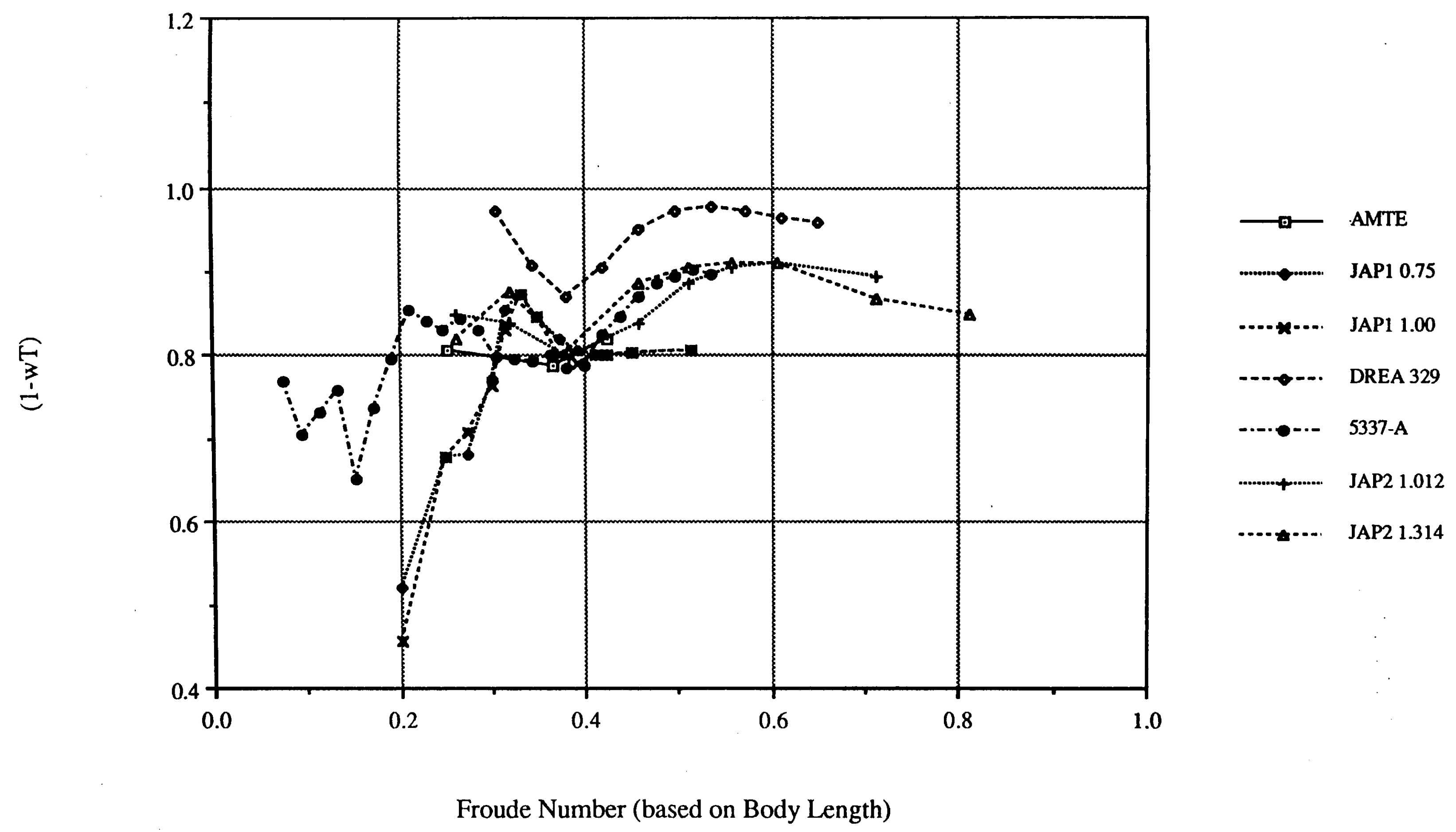


Figure 7.3 Taylor Wake Fraction fro[illegible] WATH Model Experiments

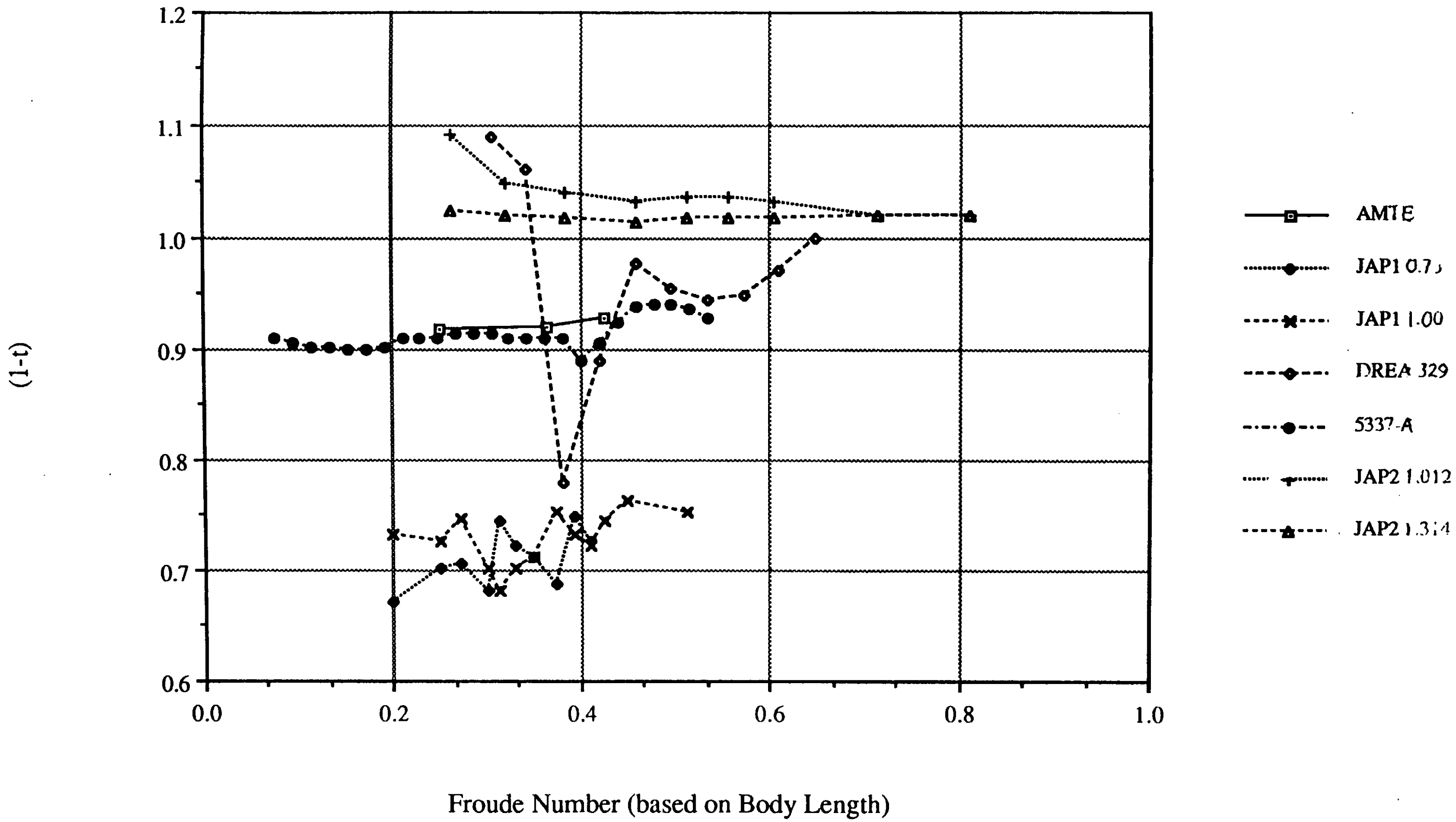


Figure 7.4 Thrust Deduction Factors from SWATH Model Experiments

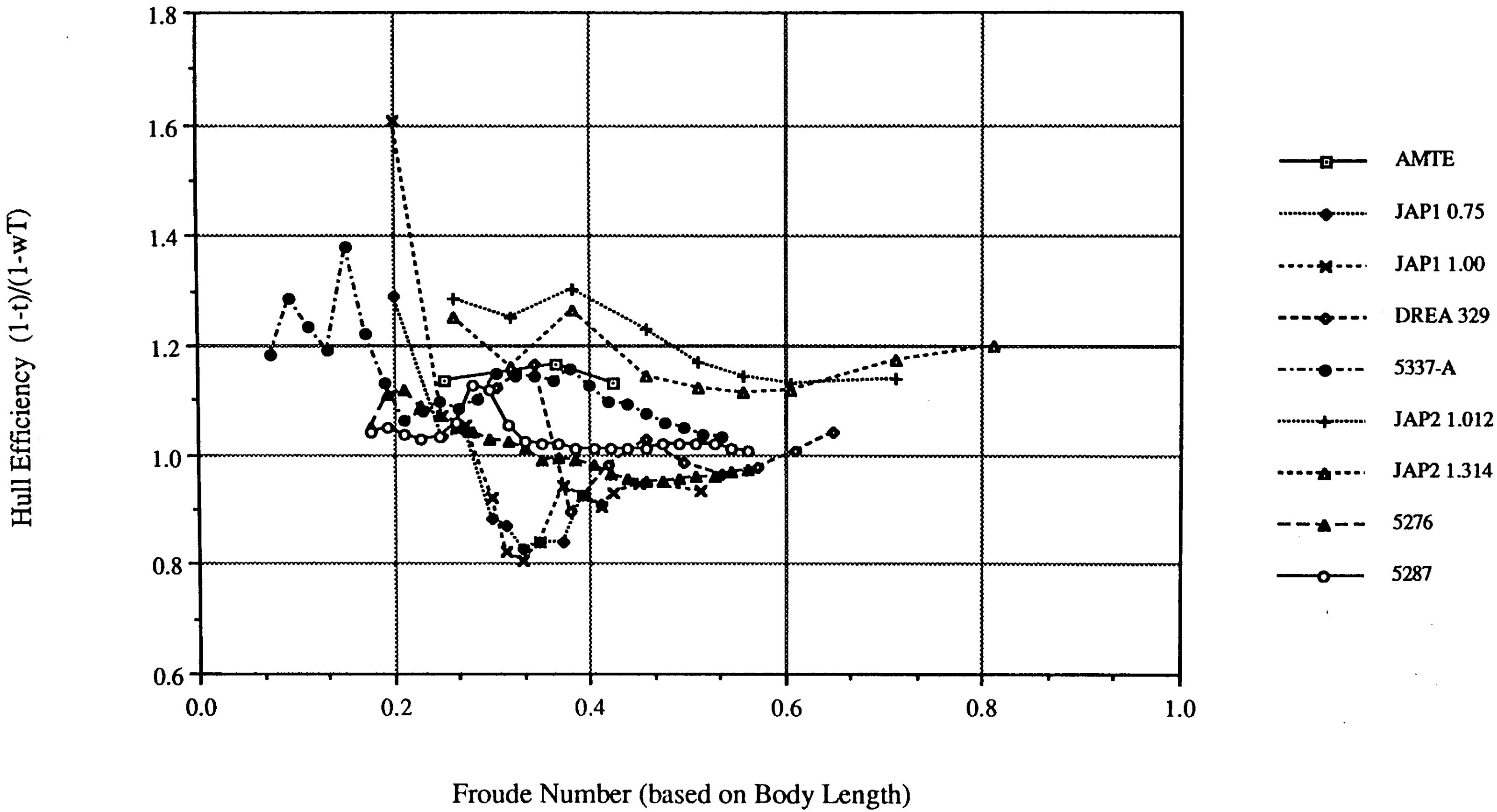


Figure 7.5 Hull Efficiencies from SWATH Model Experiments

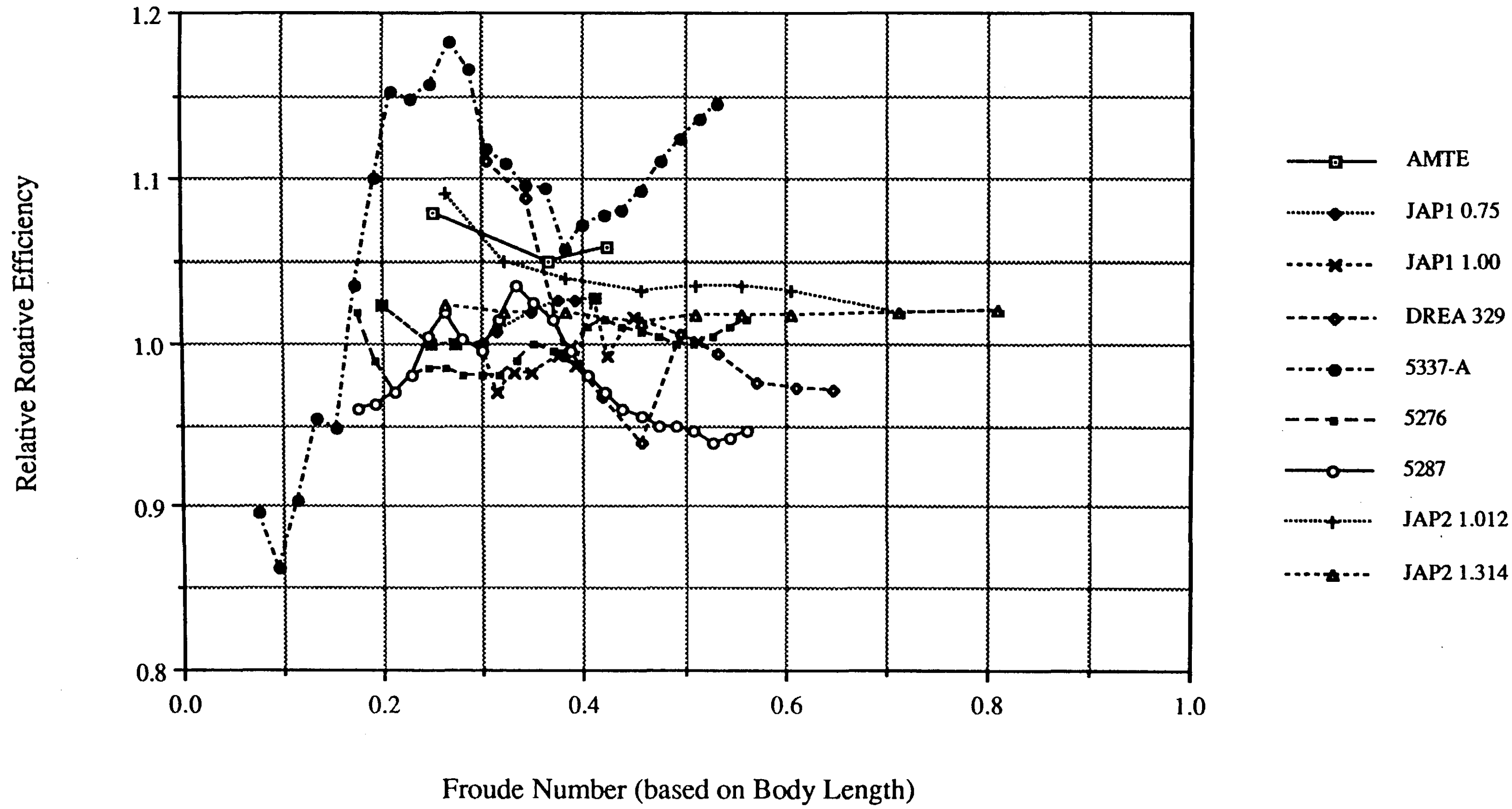


Figure 7.6 Relative Rotative Efficiencies from SWATH Model Experiments

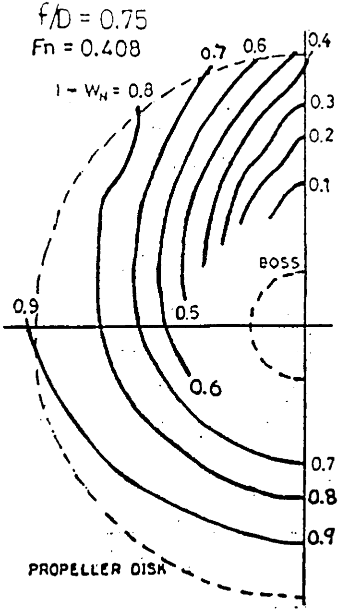


Figure 7.7 Radial Wake Distribution for Model *JAP1 0.75* - from ref. [6]

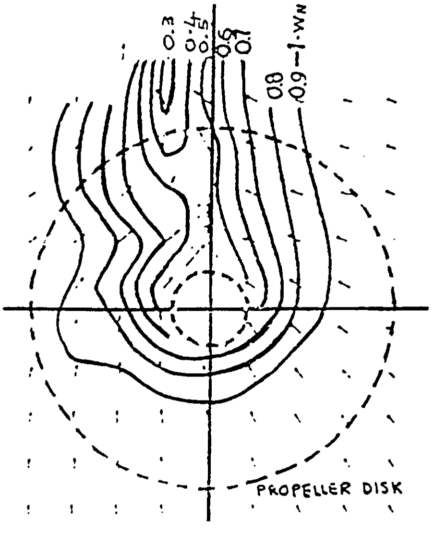


Figure 7.8 Radial Wake Distribution for Model *JAP2 1.31* - from ref. [13]

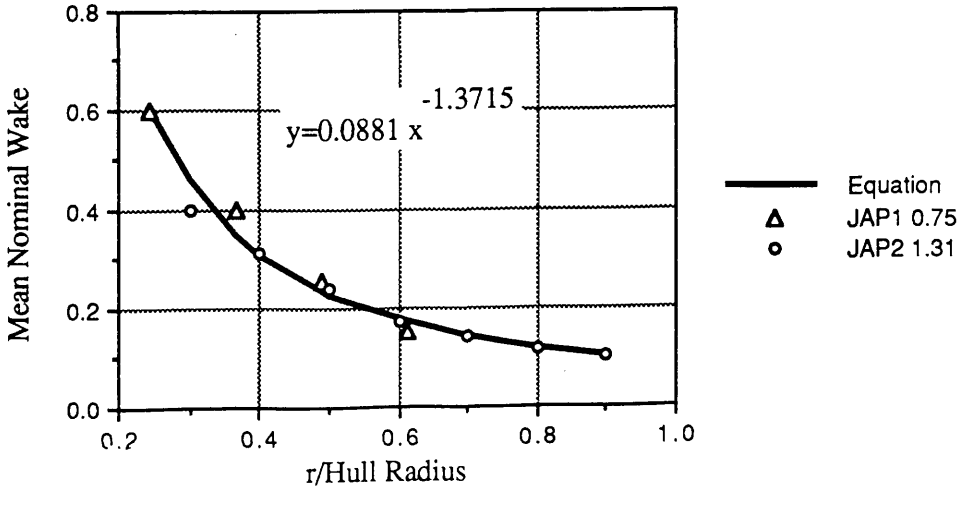


Figure 7.9 Radial Variation of Wake with Distance from Screw Axis

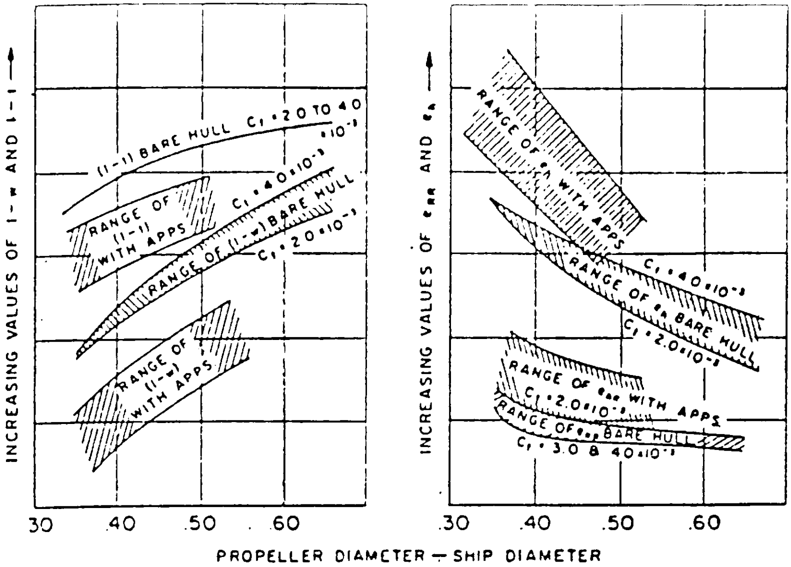


Figure 7.10 Variation of Propulsive Factors with Screw/Hull Size Ratio - from ref. [2]

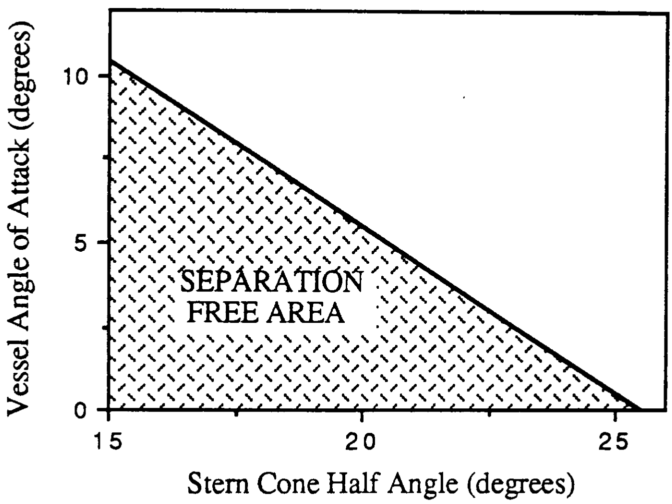


Figure 7.11 Relation Between Aft Cone Angle & Flow Separation - from ref. [8]

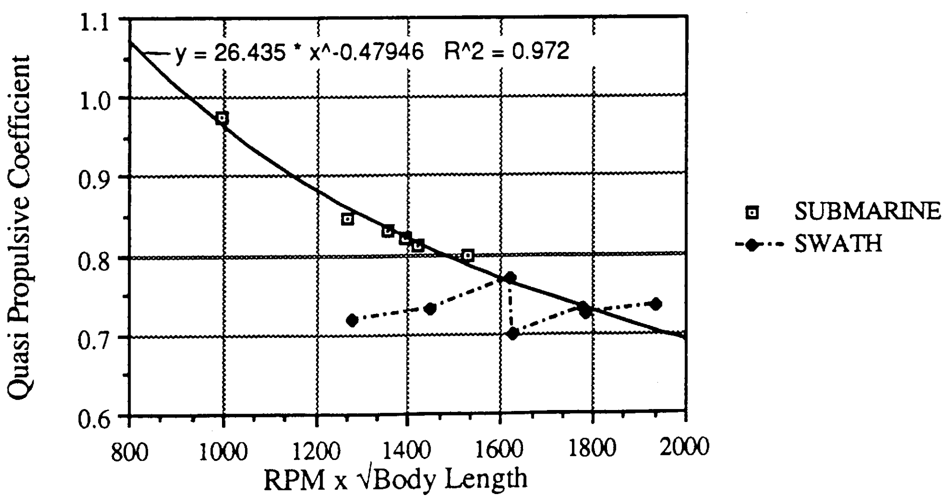


Figure 7.12 *Emerson* Type OPC Relationship for Submarines

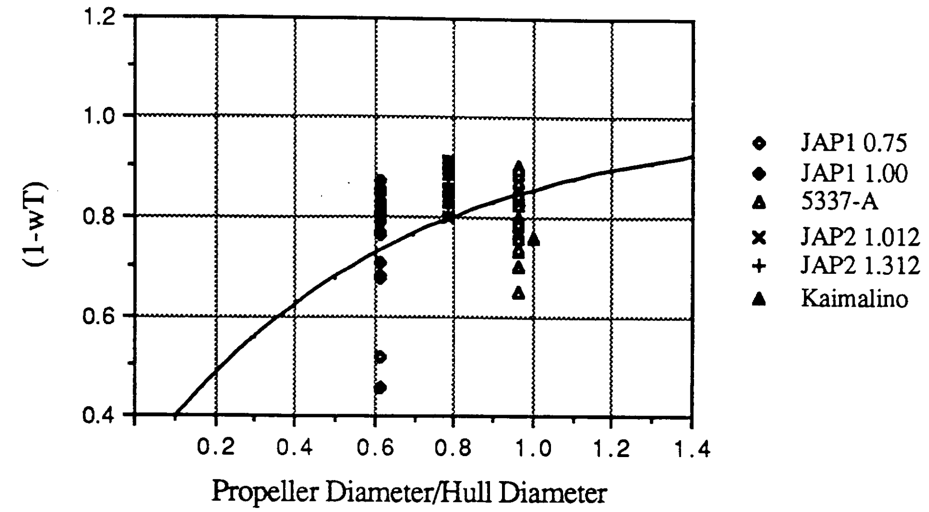


Figure 7.13 Taylor Wake Fraction by DTNSRDC Equation & SWATH Model Results

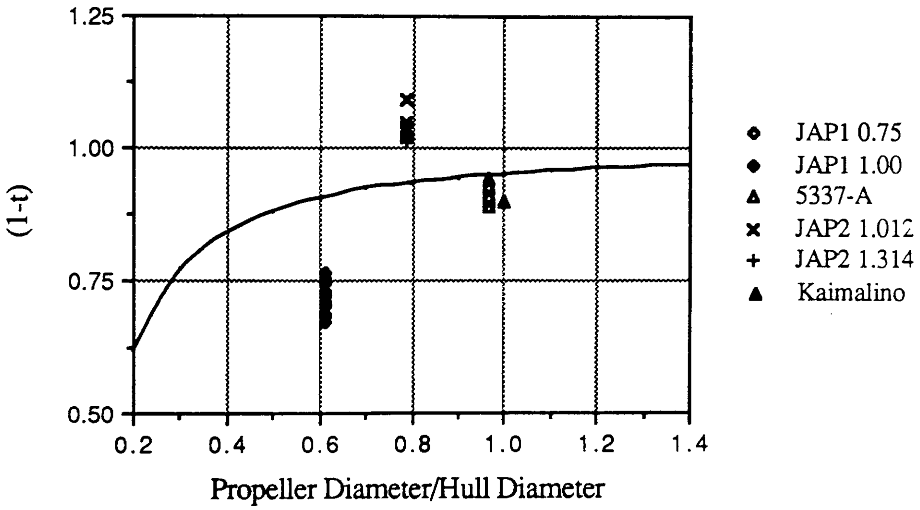


Figure 7.14 Thrust Deduction by DTNSRDC Equation & SWATH Model Results

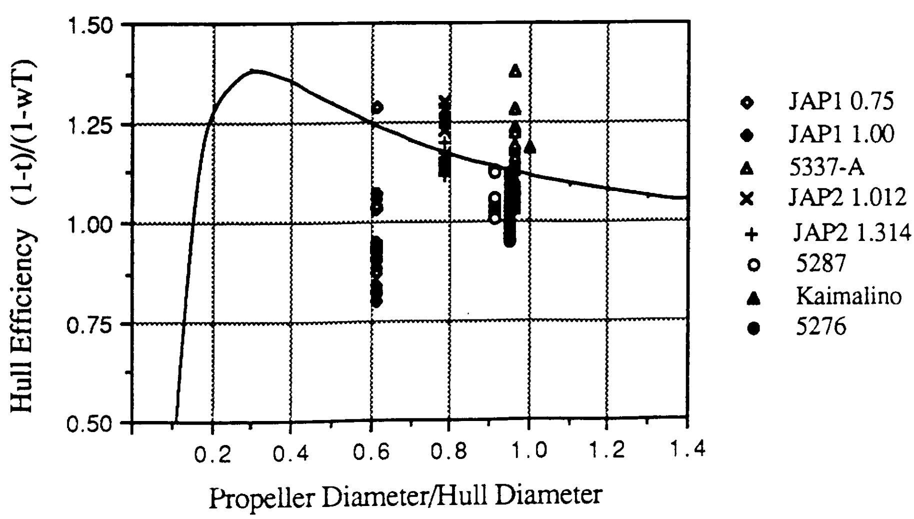


Figure 7.15 Hull Efficiency by DTNSRDC Equation & SWATH Model Results

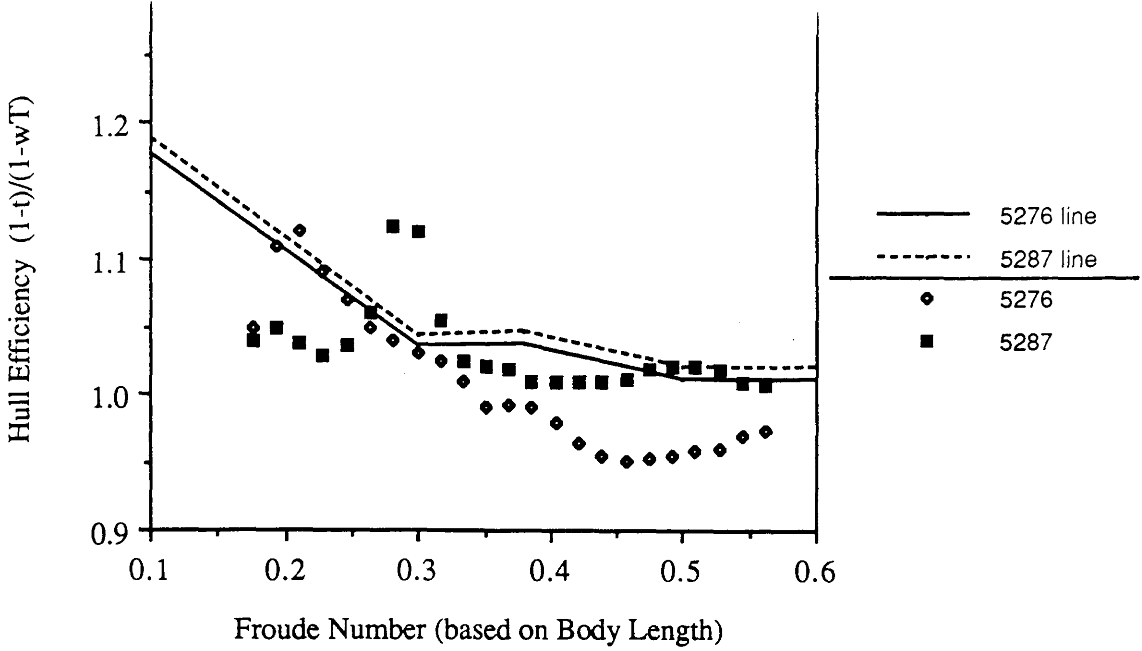


Figure 7.16 Independent Comparison of Hull Efficiency Equations with Model Data

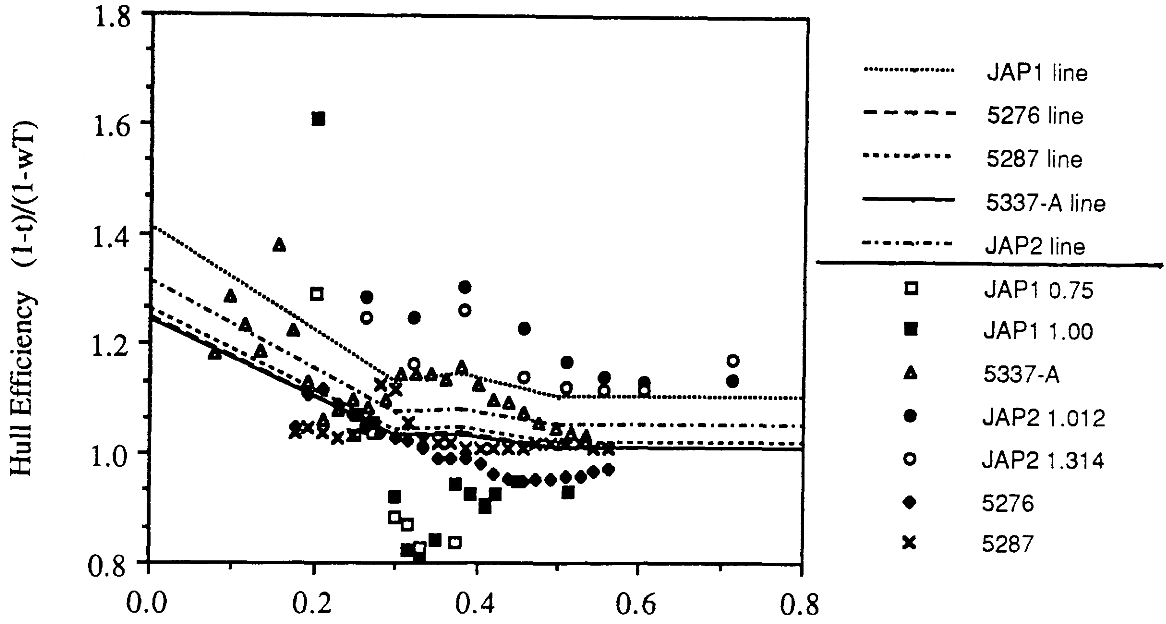


Figure 7.17 Comparison of Hull Efficiency Approximations with All Model Data

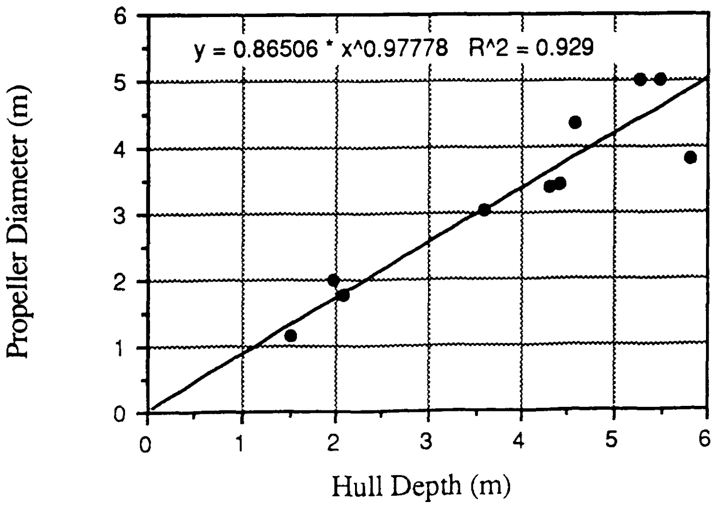


Figure 7.18 Typical Propeller Diameters for SWATH Ships

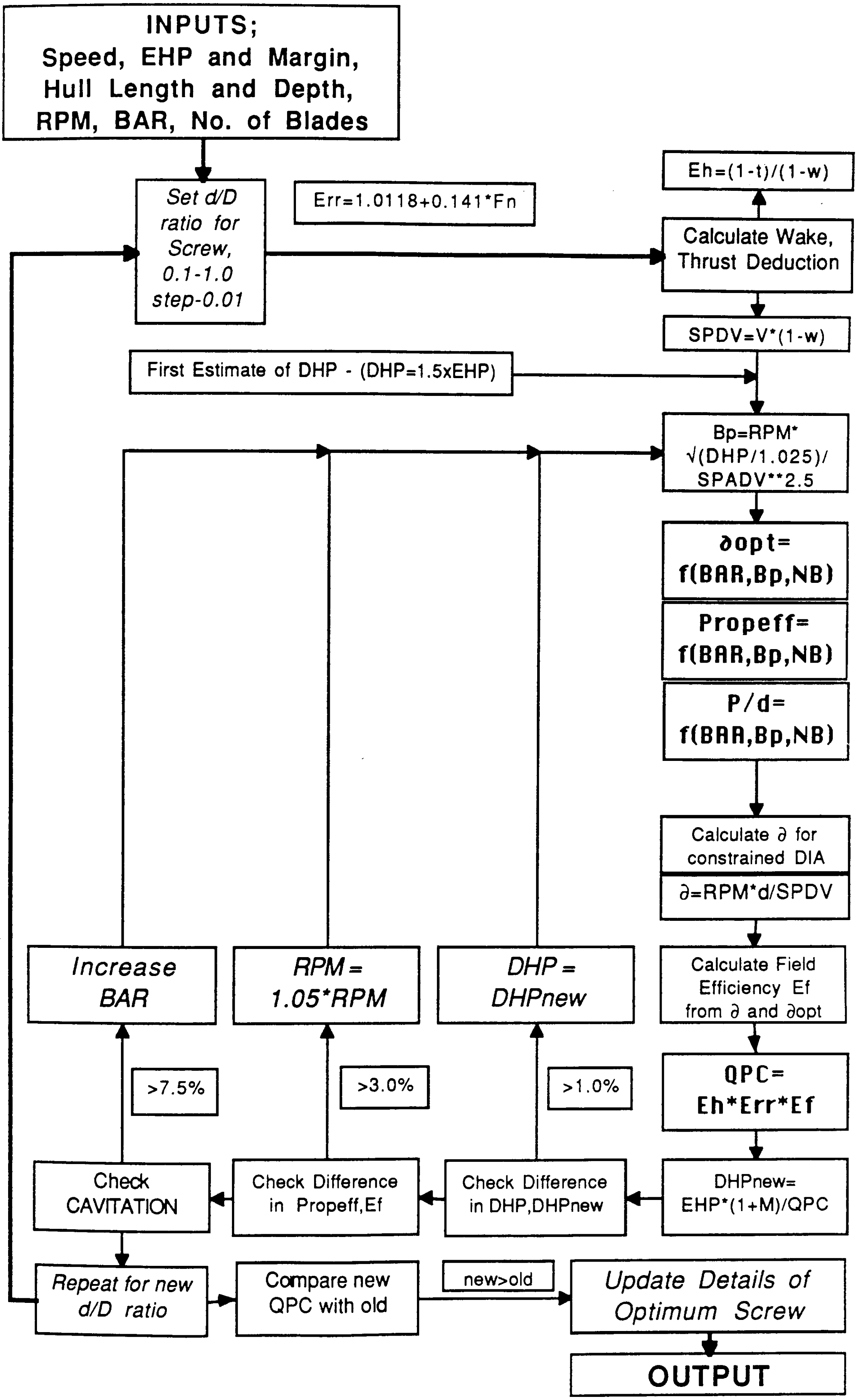


Figure 7.19 Flowchart of Automated Propeller Design Method

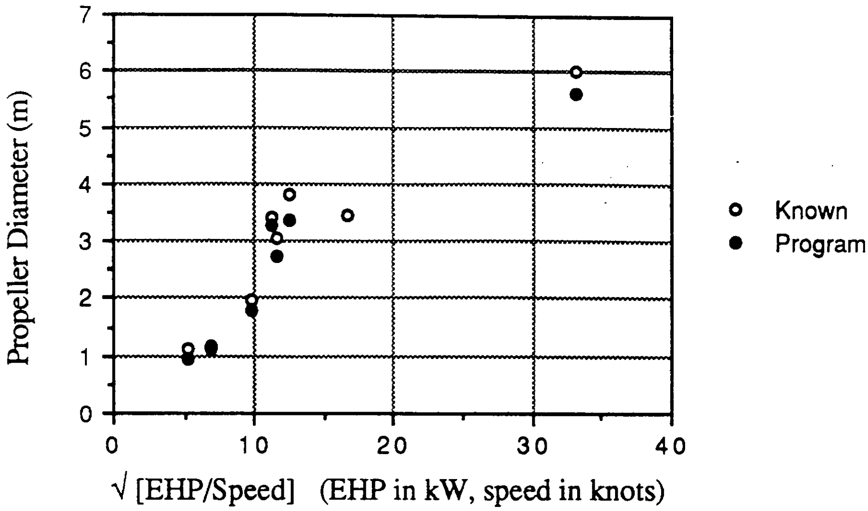


Figure 7.20 Comparison of Propeller Diameters by Program with SWATH Data

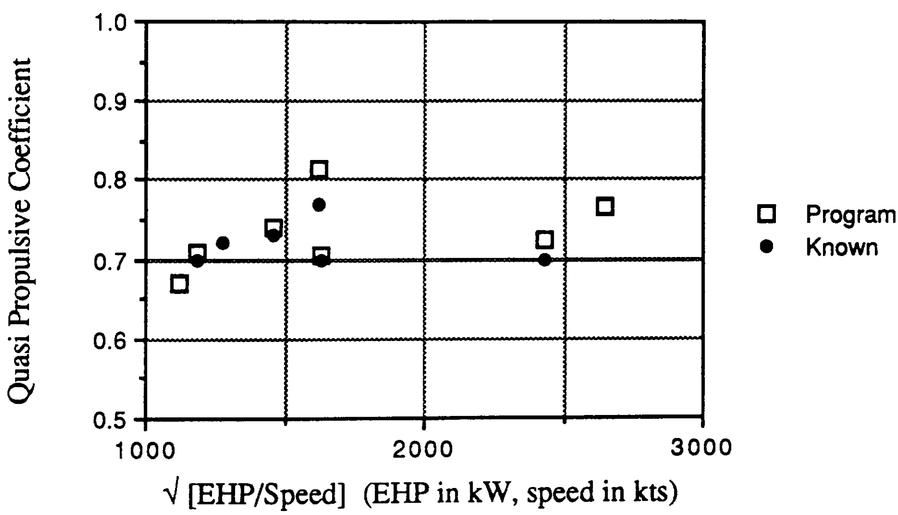


Figure 7.21 Comparison of QPCs derived by Program with SWATH Data

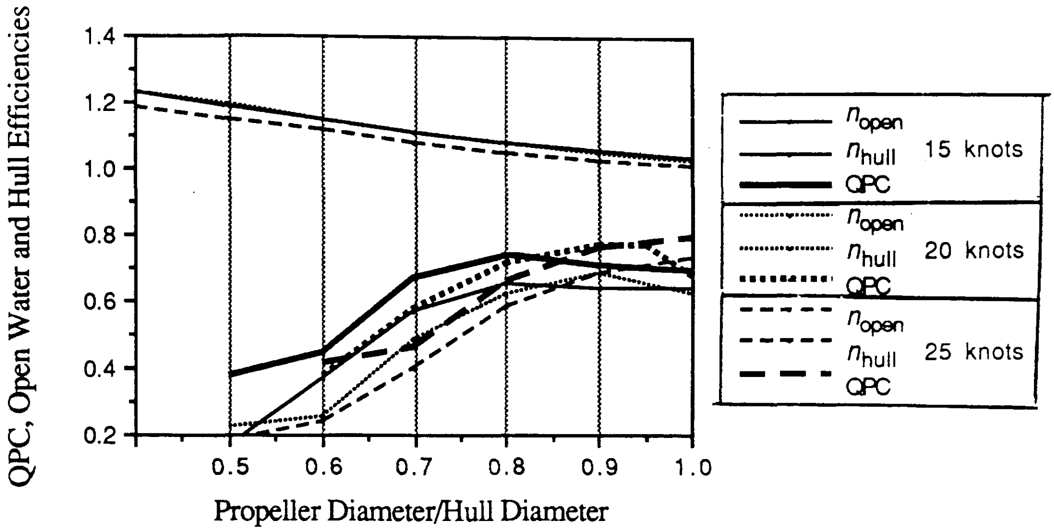


Figure 7.22 Propulsive Efficiencies versus d/D Ratio & Speed - 1000t SWATH

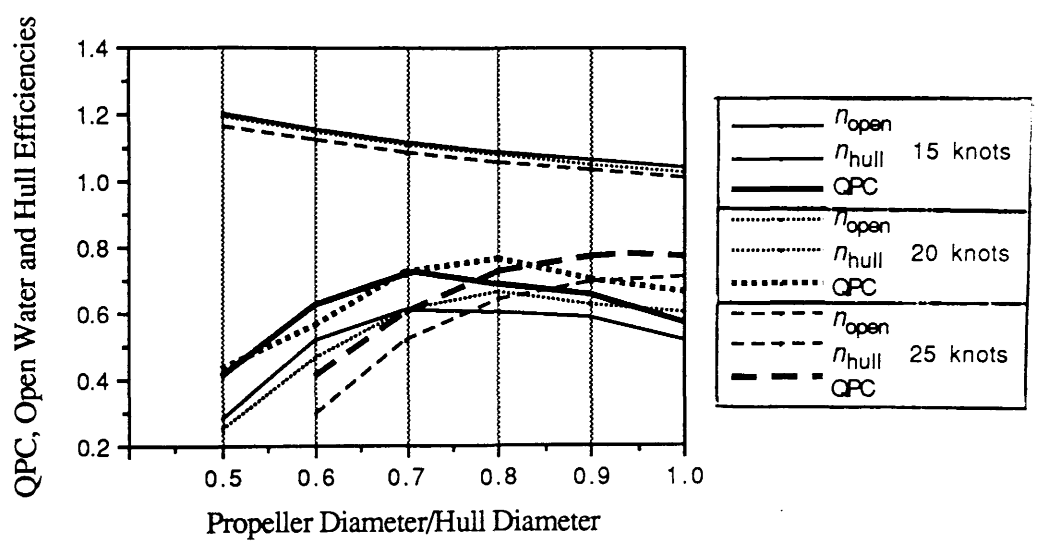


Figure 7.23 Propulsive Efficiencies versus d/D Ratio & Speed - 2000t SWATH

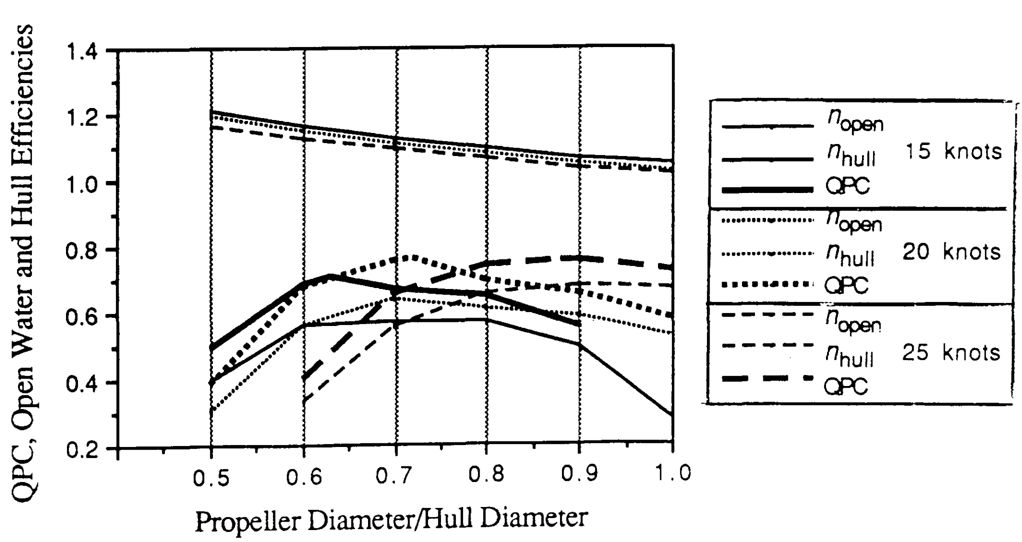


Figure 7.24 Propulsive Efficiencies versus d/D Ratio & Speed - 3000t SWATH

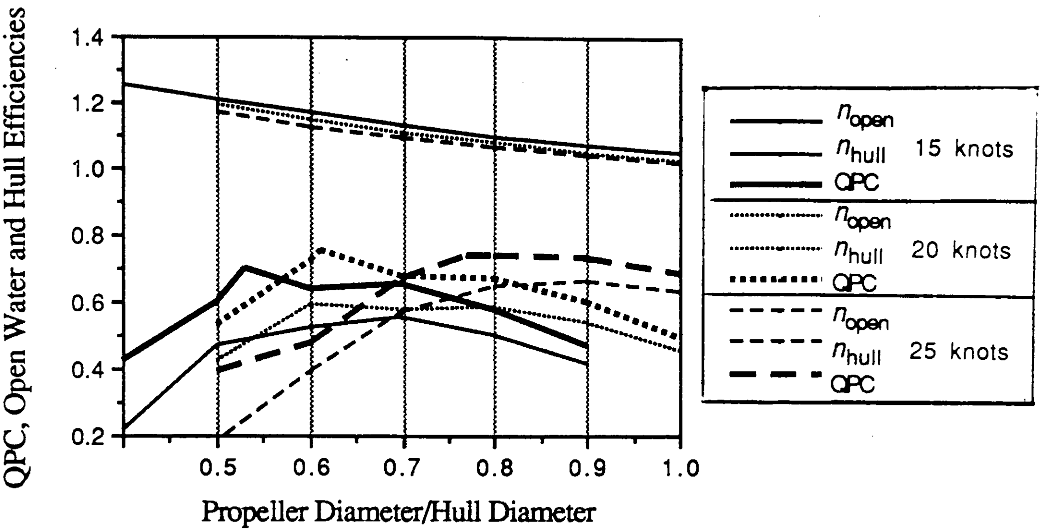


Figure 7.25 Propulsive Efficiencies versus d/D Ratio & Speed - 4000t SWATH

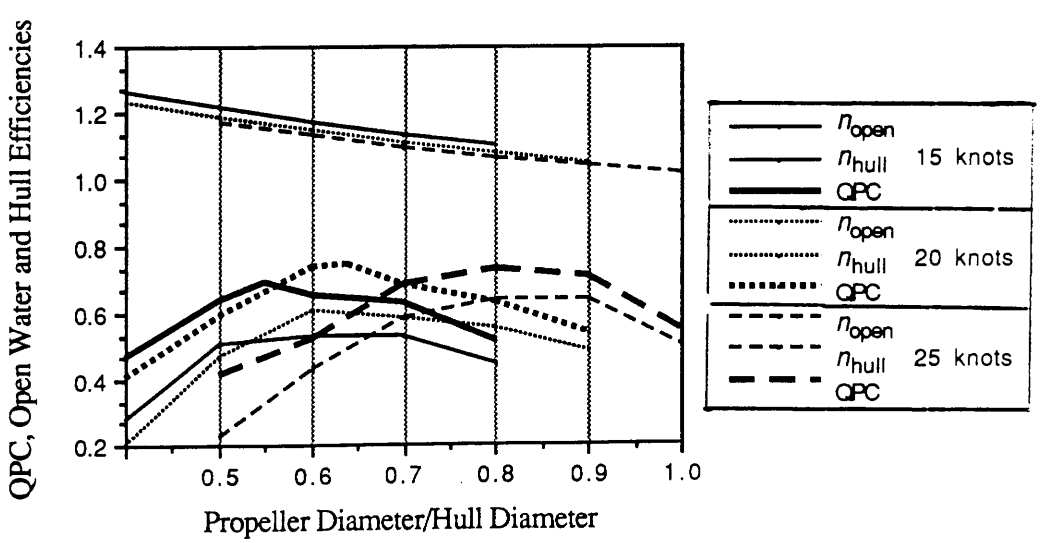


Figure 7.26 Propulsive Efficiencies versus d/D Ratio & Speed - 5000t SWATH

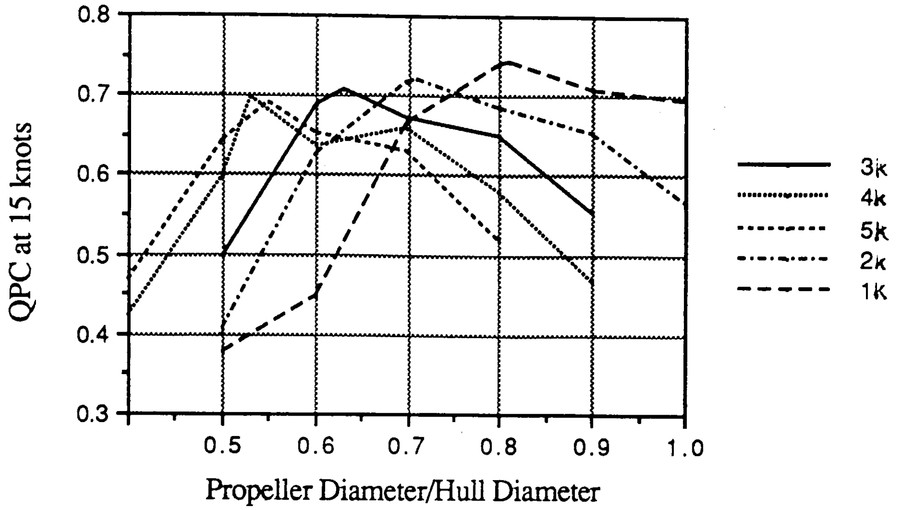


Figure 7.27 Propulsive Efficiencies versus d/D Ratio & SWATH Size - 15 knots

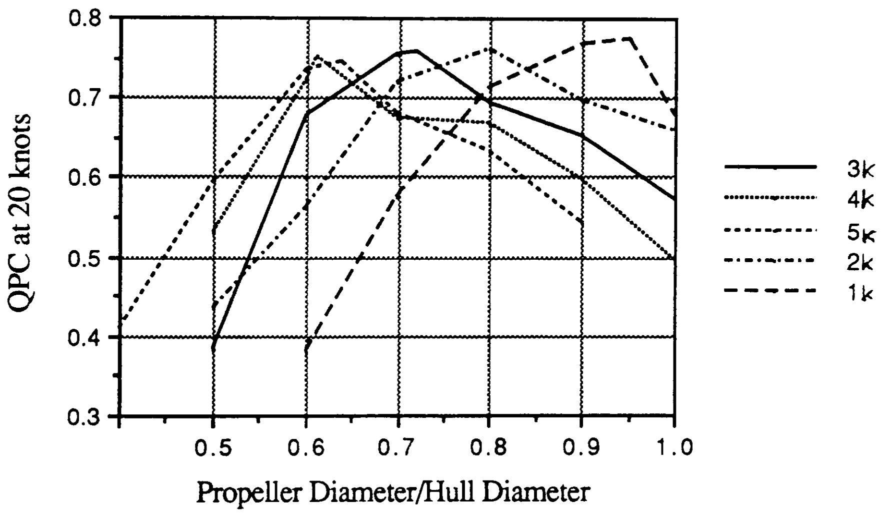


Figure 7.28 Propulsive Efficiencies versus d/D Ratio & SWATH Size - 20 knots

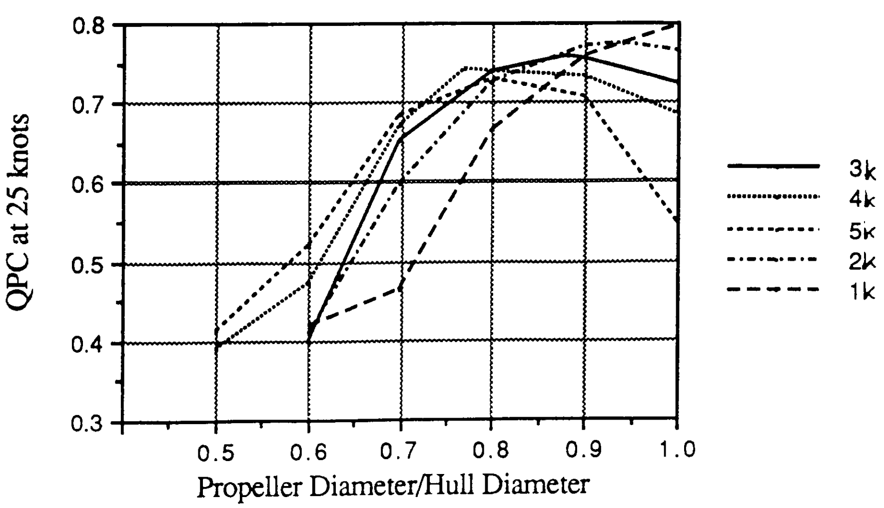


Figure 7.29 Propulsive Efficiencies versus d/D Ratio & SWATH Size - 25 knots

8.2.6 High Speed Diesels

Engines operating at speeds above 1000 RPM are considered to be 'high speed'. Strictly speaking this group should be divided into three subsections, as presented in Table 8.1, taken from [9].

Table 8.1 High Speed Diesel Characteristics from ref. [9]

Engine Type	Power (kW)	Speed (RPM)	Spec. Wt. (kg/kW)	Rel. Cost (%)	(g/kWhr) Fuel	Lube	Overhaul Intervals (hours) 'Top'	Complete
Special Purpose#	4000	1800+	2.5-3.5	75-100	225-240	2-4	2000	4000
Very High Speed#	5000	1500-1800	3.5-5.0	60-85	210-235	1-3	3000-4000	6000-12000
High Speed§	7000	1000-1500	5.0	40-75	210-220	1-2	6000-12000	16000-24000

NB # with gearbox, § no gearbox

The wartime success of the diesel engined German E-Boats encouraged the post-war development of Special Purpose engines for MTB type craft. Unconventional techniques, often based on aero engine practice, were used to achieve high power to weight ratios, at the expense of a short overhaul life. Steady technical advances are constantly made by the leading diesel manufacturers. This type of engine now competes with the marine gas turbine as the power plant for fast attack craft, and the two devices are similar in several respects.

Special Purpose diesels are removed for frequent overhauls, as are gas turbines, and need careful attention. Running for long periods at small fractions of rated output can be particularly troublesome. One approach to this problem has been marketed by MTU, who developed a cylinder cut out system to reduce smoke emission from locomotive engines idling in stations. This technique of shutting off the fuel to one bank of engines permits the reduced powers required for maneuvering to be generated more comfortably. It is possible for diesel engines to compete with gas turbines because the weight differential between the two systems (including fuel), need not be great for lower power installations. This is because of the better SFC of the diesels, and the weights of ductwork, gearing, and acoustic enclosures associated with a turbine, as well as any machinery for low speed operations. Table 8.2, taken from [30], illustrates this effect.

Table 8.2 Weights of Twin Screw Machinery & Fuel for 12 hours at 3000 HP per shaft

	Valenta Diesel	*Deltic* Diesel	Gas Turbine (with cruise diesel)
Machinery	23,500	18,860	13,625
Fuel	12,210	13,600	24,720
Total	*35,710*	*32,460*	*38,345*

NB Weights are in kg

Very High Speed engines have been developed from lower powered models, by uprating through use of turbocharging and moderate increases in piston speeds (made possible by improved materials and lubricants). Three to four-fold increases in power have been obtained in this way. High Speed engines place emphasis on durability and are relatively heavy, but have low fuel consumption.

When one considers the number of cylinders (80 is not unusual) which may be involved in a multiple diesel installation, and the injectors, valves and pistons implied by this number, the sheer volume of maintenance work becomes apparent. The highly rated models are especially demanding in this respect, and this is one of the main drawbacks of diesel engines.

Tables A5.3 and A5.4 in Appendix 5 contain details of inline and vee engines operating above 1000 RPM. This data forms part of the basis for the machinery design program described in section 8.7. No explicit distinction is made between the three subgroups, but analysis of the RPM column indicates the nature of the machine. To allow manual use of the data, the information has been plotted in Figures 8.11 to 8.20.

Because the vee is the lightest and most compact configuration, relatively few high speed inline engines are marketed and are only available in powers up to 3500 HP (2.6 MW). Inline engines have power to weight ratios of about 9kg/kw (6.7kg/HP), and have lengths from 1000mm to 4500mm. Breadths range from 750mm to 1900mm, and depths from 1000mm to 2800mm. Fuel consumption for these engines ranges from 245 g/kWhr in the lower powers to 200 g/kWhr, for the larger units.

A large number of vee engines are marketed in sizes up to 10000 HP (7.45 MW), with typical power to weight ratios of 3.6 kg/kw (2.7 kg/kw). Lengths are from 1000mm to 6000mm. Breadths are dependent on the angle of the vee, and two distinct trends may be observed in the data. At the lower powers, engines have breadths starting from about 800mm and rising to 1600mm at 2000HP. From 2000HP,the remainder of the power range is available at a breadth around 1600mm. From 3500HP, the power range is also covered by engines around 2300mm wide. The majority of vee engines have depths between 900mm and 2900mm. The trend of fuel consumption with engine power is roughly similar to that of the inline engines.

8.2.7 Marine Gas Turbines

In the late 1950s, the Royal Navy introduced the *Brave* class FPB, fitted with three *Proteus* engines. These units were developed for turboprop aircraft rather than jets, and were built with a power turbine which could be used to drive a marine gearbox. Subsequent development of the marine gas turbine has been rapid, with subsequent 'generations' revolutionizing the state of the art.

Advantages of the gas turbine include its quick start from cold, ability to develop full power immediately after start up, and very low maintenance needs between overhauls [31]. The main attraction of the gas turbine is its large power output in relation to its weight and volume. In practice this is not always as dramatic as the manufacturers information initially suggests. Quoted performance often takes no account of losses in the intake ducts, and weights refer to the engine package only. Weight and space taken up by extra gearing, acoustic enclosures, and ducting may be significant.

High fuel consumption, especially at part load, is the main drawback of a gas turbine. Recent developments have improved this situation, and the performance of some gas turbines is close to that of lightweight diesels. Gas turbines have a short overhaul life, and are generally removed to base or the manufacturer for overhaul. A repair by replacement policy may be maintained. This means that removal routes and handling equipment must be provided at the design stage, generally through the ducting.

Other negative aspects of gas turbines are high initial cost, and intake and emission of large volumes of air. High infra red signature is a problem with gas turbine exhausts, but 'cheesegraters' have been developed to reduce this problem. Gas turbines require a salt free supply of combustion air and this requires the fitting of a large deck structure containing filter elements and large intake ducts. Similarily, ducting must be provided to exhaust the burnt gases. With lower hull mounted engines, SWATH ships require longer duct lengths than a monohull of the same displacement because of their greater draught and freeboard. Gas turbine performance is very sensitive to duct losses which depend on duct length, diameter and number of bends.

Salt free fuel for gas turbines may be achieved by supplying clean fuel to the ship or by providing fuel handling equipment. Smaller craft may choose the first option as it avoids extra weight associated with handling gear, and eliminates the need for coated fuel tanks. Larger vessels usually filter fuel aboard, as the speed at which their large quantities of fuel are received means that a salt free supply is not guaranteed. This means that fuel centrifuges will be part of the fuel system, and tank coating becomes desirable. Coating of tanks places certain restraints on the shape and depth of fuel tanks, as periodic maintenance is necessary.

IDENTIFICATION		CRUISE RATING			CONTINUOUS RATING			INTERMITTENT RATING			PHYSICAL CHARACTERISTICS				COST
Manufacturer	*Model*	*BHP*	*RPM*	*g/kwhr*	*BHP*	*RPM*	*g/kwhr*	*BHP*	*RPM*	*g/kwhr*	*Weight (kg)*	*L (mm)*	*B (mm)*	*D (mm)*	*£m*
Bare Engines															
Rolls Royce	*Gnome*							1420	19500	363		1667	462	527	
Rolls Royce	*Proteus*				4500	5500	343	5000	5500		1414	2870	1067	1067	
Rolls Royce	*RB211*				36210	5200	231				12000	5400	3750	3330	2.5
Rolls Royce	*SM2A*	14750	4970	245	17100	5270	240	18800	5390	235	15960	6096	2286	2794	1.7
Rolls Royce	*SM3A*	14750	4970	245	17100	5270	240	18800	5390	235	8300	6620	2060	2352	1.6
Rolls Royce	*SM2C*				24161	5200					15960	6096	2286	2794	1.8
Rolls Royce	*SM3C*				24161	5200					8300	6620	2060	2352	1.7
Avco Lycoming	*TF25*				2500		337	3000			600	1270	870	1110	
Avco Lycoming	*TF15*				1500	3000					1137	1685	991	846	
Avco Lycoming	*TF40*				4000		271	4600			526	1320	880	1111	
Avco Lycoming	*TF40B*				3955	15400	285	4400	16100	345	544				
Avco Lycoming	*TF35*				2800		339	3100			529	1310	770	1080	
Avco Lycoming	*TF12A*				1150		367	1275			417	1300	720	1080	
Avco Lycoming	*TF14B*				1400		359	1600			417	1300	720	1080	
Allison	*501-K*							5396	14500		1130	2677	1300	1300	
Allison	*570-KF*				6445	11500	280	7170	11500	282	612	1830			
Allison	*571-KF*				7694	11500	249	8288	11500	247	733	1870			
Garrett	*GTPF 990*				5600	7200	279	6250		274	2449	2740			
Garrett	*IM 831-800*				713			800			794	1651	1016	889	
General Electric	*LM 100*				1100		371					1924	508	864	
General Electric	*LM 500*				5000						1031	3307	1179		
General Electric	*LM 1500*				15000	5300	335				3674	7620	2000	2111	
General Electric	*LM 2500*				21500	2800	255	30000	3600	229	11657	6530	2240	2600	4.1
General Electric	*LM 5000*							52970		213					
Pratt & Whitney	*FT9*	35960	3600	240	37720	3600	240	41800	3600	243	6078				
Pratt & Whitney	*FT4A-12*				24400	3600	316	31000	3600		6441				
Pratt & Whitney	*FT12*				2500	9000	483	3770	9000		5216				
Modules															
Rolls Royce	*Tyne*	5340	3425	286	5800	14500	280				14060	5560	2120	2620	
Rolls Royce	*SM1A*	14750	4970	245	17100	5220	240	18800	5390	235	24460	7502	2286	3390	
Rolls Royce	*SM1C*				24161						24460	7502	2286	3390	
Rolls Royce	*Olympus*				28000	5556	290	29600	5660	287	30870	9170	2640	3710	
Rolls Royce	*RB211*				36210	5200	231				42290	7040	4200	3900	
Garrett	*GTPF 990*				5600	7200	279	6250		274	2835	3040	1600	1210	
Pratt & Whitney	*FT9*	35960	3600	240	37720	3600	240	41800	3600	243	22119	8077	2896	3277	
General Electric	*LM2500*					3600					20900	8250	2640	2950	

Table 8.3 Particulars of US and UK Gas Turbines

Only a limited number of gas turbines exist owing to the small size of the market, and the expense in developing and proving a new model. This means that the ship designer does not have complete freedom in matching ship size and speed with power. Information on the models which are available has been obtained from a number of sources (references [11] to]20]) and summarised in Table 8.3. Table 8.3 has also been formatted as a data file for the SWATH machinery design module. The powers quoted do not take account of losses due to ducting, for which a 5% deduction may be assumed. Losses due to internal gearing may be taken as 3%.

Gas turbines are often marketed with at least two different ratings, the most usual being *Continuous* and *Intermittent*. *Continuous* power is the output which can be provided by the machine for long periods of time, and is the rating most useful for ship design purposes. The *Intermittent* rating is a sprint power which can be developed for short duration (say 1 hour). Some engines are also marketed as suitable for operation in *Cruise* mode for extended periods. Analysis of the data in Table 8.3 allows approximations to be derived.

Cruise BHP	= 0.925 [Continuous BHP]	Eqn. 8.1
Intermittent BHP	= 1.167 [Continuous BHP]	Eqn. 8.2

There is a wide variation in weight for a given power owing to differing degrees of engine modularisation. Most engines are marketed as *'bare'* turbines, but some are available in box shaped acoustic enclosures which are large enough to permit access for maintenance. As an example, the Rolls Royce *Spey* engine is marketed in fully modularised form (SM1), with a baseplate (SM2) or 'bare' (SM3). Further complication arises from the fact that uprated versions of this engine (the C variants) are now being marketed. For a fully modularised large engine, the power to weight ratio may be 1.6kg/kW (1.2 kg/HP), while a small 'bare' engine may have a value of 0.7kg/kW (0.5 kg/HP). Linear dimensions are not so affected by the degree of modularisation, and the following regression equations illustrate the typical range of engine dimensions.

Length (mm)	= 34.6 [Continuous Rating (HP)]$^{0.518}$	Eqn. 8.3
Breadth (mm)	= 38.7 [Continuous Rating (HP)]$^{0.414}$	Eqn. 8.4
Depth (mm)	= 53.4 [Continuous Rating (HP)]$^{0.395}$	Eqn. 8.5
Engine L*B*D (m^3)	= 0.002[Engine Weight (kg)]$^{1.067}$	Eqn. 8.6

Fuel efficiency for turbines operating at their intended rating improves with increasing power. The data in Table 8.3 shows values of 380g/kWhr for low power units, decreasing to 230 g/kWhr for the most powerful engines.

Duct work associated with gas turbines is significant, and must be considered early, especially in SWATH design. Sizing of intake ducting is often governed by the requirement that the gas generator be withdrawn by this route, with a clearance of perhaps 100mm on either side. Information presented in [31] gives equation 8.7 which may be used to relate duct area to engine power. Exhaust ducting area should strictly be estimated separately but the same equation may be used without significant error.

Duct Sectional Area (m^2) = $0.000777[\text{No Loss BHP}]^{0.848}$ Eqn. 8.7

Reference [31] also provides guidance on the required size of deck mounted air filtration units. These are generally supplied in modular form (1.77m long, 0.99m high, 0.2m deep) and simple multiples fitted for different installations. *Tyne* engines require two, while an *Olympus* requires eight. The weight of these units may be estimated at 292 kg per m^3.

By making reference to the data in Table 8.3, and the information presented in the above equations, the weight and volume of gas turbine plant may be determined.

8.2.8 Petrol Engines

Petrol engines were used by British and American fast coastal craft during the Second World War but are no longer used in warships. The inflammability of the fuel, and the development of reliable high performance diesel engines has led to the virtual disappearance of the marine petrol engine. They have been fitted in *Marine Ace*, the experimental Japanese SWATH, but other SWATH applications of petrol engines are extremely unlikely except at demonstrator (manned model) scale.

8.3 Mechanical Transmission

8.3.1 Reduction Gearing

There are two main types of marine gearing in use for reducing engine revolutions to propeller revolutions. These are the parallel shaft and less common epicyclic or planetary gears. Parallel shaft gears can be built, with little risk, in any reasonable size, and the built-in offset can be advantageous, particularly for SWATH ships. Planetary gears involve more risk, but are lighter and more compact and hence suited to installation in SWATH ship lower hulls. Planetary gear diameter is approximately equal to that of the gas turbine, making for compact in-line installation.

Equations 8.8 and 8.9 from [25] may be used to develop weights for reduction gears.

Parallel Shaft Gear Weight (kg) $= 25\ Q^{0.91}$ Eqn. 8.8

Planetary Gear Weight (kg) $= 9.5\ Q^{0.95}$ Eqn. 8.9

$$\text{where } Q = \frac{\text{BHP}}{\text{Input RPM}} \frac{(R_G+1)^3}{R_G} \qquad \text{Eqn. 8.10}$$

and R_G is the ratio of input to output RPM.

Figure 8.21 compares weights developed assuming input RPM of 4000, output RPM 200 and heavily loaded teeth (K factor 500) with typical bands of power/weight ratio for US and European parallel shaft and planetary gears [15] and points for specific US planetary gear units [15].

8.3.2 Combining Gears

Transmitting power from more than one prime mover to the propeller requires sophisticated, often purpose-built gearing. Gears such as CODAG, CODOG have been operated successfully in naval vessels. Mechanical drive for high speeds combined with electrical transmission for silent slow speed operation may be fitted in SWATH ships designed for military roles. Other types of *and/or* propulsion schemes will be difficult to install in the limited space available in SWATH ship lower hulls. However, Table 8.4 contains weights of combining gears for some recent naval ships [24], and is included for reference purposes.

8.3.3 Right Angle Drive

Excluding electric transmission, four methods exist for transmitting power from the box structure of a SWATH to the lower hulls. These are bevel gearing, chain drive, belt drive and hydraulic drive.

Bevel gearing, has the advantage of being the most popular choice of transmission among the existing SWATHs, and has a proven reputation. *Marine Ace, Seagull, Ohtori, Kotozaki, Betsy* (ex *Suave Lino*) are fitted with right angle drives. The widespread use of thruster devices which employ bevel gears to transmit power from a single vertical shaft to a horizontal propeller has helped to establish this technology. Single bevel gears transmitting 5.0 MW (6700 HP) have been manufactured for the largest thrusters.

Table 8.4 Particulars of Combining Gear Weights for Naval Vessels

Ship	Gearing	Power (kW)	Weight (t)	Remarks
USN *FFG-7* class GM frigate	COGAG	29.8 2x*LM2500*	51.0	Twin input, single output. CP propeller
USN *Spruance* class GM destroyer	COGAG	29.0 x 2 4 x *LM2500*	76.0 (2 off)	Twin screw, with 2 GTs per shaft. CP propellers
RN *Invincible* class V/STOL cruiser	COGAG	36.8 x 2 4 x *Olympus TM3B*	150.0 (2 off)	Twin screw, with 2 GTs per shaft. FP propellers
RN *Type 22* class (Batch 3) frigate	COGAG	15.5 x 2 2 x *SM1A+RM3C*	36.5 (2 off)	Twin screw, with 2 GTs per shaft. CP propellers
RN *Type 22-07* ASW frigate	COGOG	11.8 x 2 2 x *SM1A/RM1C*	36.5 (2 off)	Twin screw, with 2 GTs per shaft. CP propellers
RN *Type 42* class GM destroyer	COGOG	18.75 x 2 2 x *TM3B/RM1C*	33.5 (2 off)	Twin screw, with 2 GTs per shaft. CP propellers
RN *Island* class OPV	CODAD	3.15 2 x *12RK3CM*	10.0	Single screw, with 1 or 2 diesels running. CP prop
RN *Type 23* class frigate	CODLAG	13.4 x 2	36.6 (2 off)	Twin screw, 1 GT, 1 motor per shaft. FP propellers
Italian Navy *Lupo* class frigate	CODOG	17.25 x 2 2 x *LM2500*	35.0 (2 off)	Twin screw, 1 GT, 1 DC motor per shaft. CP props
Danish Navy *KV72* corvette	CODOG (splitter)	18.7 *LM2500, 20V956*	48.0 (1 off)	Twin screw, 1 GT, 1 diesel in total. CP propeller

It is possible to reduce the weight and risk involved in the gears and shafts by using twin torque paths (two sets of gears and shafts), which can double the transmission capacity, and/or gearing up the speed of the vertical shafts to reduce the torque.

The Japanese SWATH ferry *Seagull* employs two vertical shafts operating between two sets of bevel gears, arranged in a 'back to back' fashion. This installation transmits 4050 HP (3.0 MW) to each propeller, but Mitsui [35] are confident that similar devices transmitting 17500 HP (13.0 MW) can be constructed.

Hydrofoils have also been built with bevel gearing, but the techniques used have resulted in extremely lightweight and specialised systems which may not be acceptable in SWATH design. The US Navy experimental *AGEH-1 Plainview* has two 'Z-drive' units each transmitting 15000 HP (11.2 MW) and the major elements of the gearing are claimed to have given trouble free operation [23], although the ship has suffered from several operational problems. The weight of the gearing was held to the order of 10 to 20 percent of that of conventional marine gearing. The Canadian hydrofoil *Bras d'Or* employs twin torque paths and stepped up vertical shaft speed to transmit 15000 HP (11.2 MW) to each of it's two propellers. The two hydrofoil installations operate at very high revolutions, driving very high speed supercavitating propellers, and the torque loadings are therefore relatively low.

A technology does exist for manufacture of proven bevel gear drives up to powers of 6700 HP (5.0 MW) and for the purposes of this study it is assumed that systems up to 17500 HP (13 MW) are feasible, although probably expensive. However, with bevel gearboxes of this capacity, there may be a risk of unacceptably high noise levels for naval or scientific applications.

Angled shafts transmitting power from engines mounted forward in the box to propellers in the lower hulls are fitted in the small Japanese SWATHs *Marine Wave* and *Sun Marina*. Systems of this type have been employed for years in some fast patrol boats and harbour tugs. It is intended to fit a transmission of this type in the *FDC400* ferry [38] under construction by FBM for a Madeira service.

High torque belt drive (as fitted in the *Halcyon*) provides another option for transmission of power between two widely separated parallel shafts. A manufacturing base for this type of equipment is present in the form of suppliers of heavy duty industrial belt drives. A simplified design method for SWATH belt drives may be derived from material prepared by one such manufacturer [36].

In a study of possible transmission systems for a 400 tonne SWATH, which eventually became the *Seagull,* Mitsui [35] considered chain (as used in *Kaimalino*) bevel, and hydraulic drives. Their conclusions are summarised in Table 8.5, and have been adopted as the standards for use in the machinery design program.

Table 8.5 Comparison of Transmission Systems by Mitsui [35]

Transmission Type	Bevel Gear	Chain Drive	Hydraulic Drive
Efficiency (%)	97-98	97-98	75-80
Maximum Power 'off the shelf' (HP)	10,000	3,700	2000
Casing Diameter at 2000 HP (mm)	800	1200	1500
Reversing Capability	No	No	Yes
Noise	Low	Medium	High
Vibration	Low	Medium	High

8.4 Survey of Mechanical Drive Studies for SWATH Ships

The data presented in the previous sections may be used manually to develop an estimate of the weight and space requirements of diesel or gas turbine machinery schemes employing mechanical transmission. This process has also been automated, as described in section 8.7. Additional guidance may be obtained from the results of previous studies. Table 8.6 is extracted from a US Navy study [1] and presents the limiting vessel dimensions for a matrix of prime mover and transmission types. These dimensions were developed from machinery arrangement sketches. A similar study sponsored by the Royal Navy [32] produced the results summarised in Table 8.7.

Table 8.6 Required SWATH Dimensions for Installing US Gas Turbines - from [1]

Transmission System	Prime Mover (*bare* GTs)	Number per ship	Total Installed Power (HP)	Required Strut Thickness (m)	Required Hull Diameter (m)
Hull mounted with double reduction gearing	LM2500	2	45,000	2.44	5.18
	LM2500	4	90,000	3.51	7.01
	FT9	2	70,000	3.35	6.01
	FT9	4	140,000	5.03	8.08
	LM5000	2	90,000	3.81	7.01
	LM5000	4	180,000	6.10	9.75
Hull mounted with planetary (epicyclic) gearing	LM2500	2	45,000	2.44	5.03
	LM2500	4	90,000	3.51	6.40
	FT9	2	70,000	3.35	5.33
	FT9	4	140,000	4.27	6.01
	LM5000	2	90,000	3.81	5.79
	LM5000	4	180,000	4.42	8.23
Z-drive with planetary gearing in lower hulls	LM2500	2	45,000	1.98	3.66
	LM2500	4	90,000	1.98	4.57
	FT9	2	70,000	1.98	4.57
	FT9	4	140,000	1.98	4.88
	LM5000	2	90,000	1.98	4.57
	LM5000	4	180,000	1.98	5.79
Waterjet propulsion	LM2500	2	45,000	1.98	3.26
	LM2500	4	90,000	2.04	3.44
	FT9	2	70,000	2.01	3.35
	FT9	4	140,000	2.16	3.66
	LM5000	2	90,000	2.04	3.44
	LM5000	4	180,000	2.29	3.81

NB Strut thickness and hull diameter are extreme dimensions. Hulls are <u>circular</u> section.

Table 8.7 Particulars of Mechanical Drive Schemes for UK SWATH Ships

Machinery Scheme Details	Total Shaft Power (MW)	Clear Hull Diameter (metres)	Clear Strut Width (metres)	Engines/Gensets Weight (tonnes)	Engines/Gensets Cost (£m)	Electric Motors Weight (tonnes)	Electric Motors Cost (£m)	Electrical Control Weight (tonnes)	Electrical Control Cost (£m)	Gearboxes Weight (tonnes)	Gearboxes Cost (£m)	Props/Shafts Weight (tonnes)	Props/Shafts Cost (£m)	Total Weight (tonnes)	Total Cost (£m)
Hull fitted HSD 18cyl Valenta Parallel shaft gbx	5.33	3.75	1.80	18.50	0.83					4.20	.0.07	14.00	0.20	37.00	1.10
Hull fitted MSD 18RK270 Ruston Parallel shaft gbx	10.20	4.40	1.90	55.00	0.90					15.00	0.25	30.00	0.30	100.00	1.45
Hull fitted GT RM1C module Parallel shaft gbx	7.40	3.60	1.40	25.20	2.34					36.00	0.50	30.00	0.30	91.00	3.14
Hull fitted GT SM1A module Parallel shaft gbx	23.50	4.60	2.30	50.00	3.40					73.00	0.91	57.00	0.76	180.00	5.07
Hull fitted GT SM3A 'bare' Epicyclic gbx	23.50	4.00	1.60	16.60	3.20					18.00		57.00	0.76	92.00	
Hull fitted GT SM1C module Parallel shaft gbx	33.20	4.60	2.30	50.00	3.60					73.00	0.91	77.00	1.10	247.00	5.66
Hull fitted GT SM3C 'bare' Epicyclic gbx	33.20	4.00	1.60	16.60	3.40					18.00		77.00	1.10	112.00	
Hull fitted GT LM2500 module Epicyclic gbx	43.60	4.80	2.20	42.00	6.00					18.00		77.00	1.10	137.00	
Hull fitted GT RB211 'bare' Epicyclic gbx	44.40	5.00	2.20	27.60	5.00					18.00		77.00	1.10	123.00	
Bevel drive HSD 18cyl. Valenta Red. gbx in hull	5.18	2.20	0.60	18.50	0.83					4.20 *plus bevel gears*	0.07	14.00	0.20		
Bevel Drive GT SM1A module Epicyclic gbx hull	22.40	3.20	0.90	50.00	3.40					18.00 *plus bevel gears*		57.00	0.76		

8.5 Electrical Drive

8.5.1 General

Traditionally, the appeal of electrical propulsion has been it's unrivalled ability in meeting a widely varying power demand. The low noise and vibration signatures are also desirable for certain applications. For SWATHs, the complete freedom in siting the prime movers relative to the propeller is especially attractive. However, there are penalties to be paid for such advantages, notably in the high weight, volume, and cost associated with electric drive. Reference [40] is an extremely useful source of data for estimating weight and volume requirements of AC electric propulsion equipment. For a given power at the propeller shaft, the prime movers must also produce more power than an equivalent direct drive arrangement because of the losses in the electrical cables and machines. For these reasons, electric propulsion installations are relatively uncommon.

The character of an electric propulsion system may vary considerably within the terms of the above definition. The prime movers may be any of the items discussed in section 8.2, while the generating machines may produce AC or DC power. Electric motors may be DC, or fixed or variable speed AC, and the control gear may convert DC power into AC, or vice versa.

In this thesis, the use of superconducting equipment has not been considered, except to note in passing that by operating at temperatures approaching absolute zero, winding resistance may be significantly reduced and savings of as much as 75 - 90% of generator weight and volume are claimed [37].

8.5.2 Generating Sets

Diesel powered generating sets are usually marketed as integrated packages, while large prime movers such as gas turbines must be matched to available generating machines. For naval applications, the consideration of 'rafting' the machinery may influence the weights and dimensions of the installation. In this investigation, only AC alternators have been considered because of the weight, size and cost penalties associated with DC generators, and because of the current preference for this arrangement, even where DC motors are employed. DC generators are currently limited to speeds between 300 and 1000 RPM, while AC generators are not RPM limited and are often used with turbine drives

8.5.3 Cabling and Control Gear

The control gear for electric propulsion systems demands considerable volume, especially if frequency converter equipment is needed to supply variable frequency power to variable speed motors. If variable speed motors are to be used, then Cyclo-Converters or Load Commutated Inverters must be employed for frequency conversion. Load Commutated Inverter equipment employs a thyristor bridge to convert generated AC line frequency to DC current, which is then smoothed and thyristor inverted back to AC output frequency, typically higher than the input frequency. The high frequencies obtained from this equipment are ideal for high speed geared motors, but the efficiency is only about 95%. Table 8.8 (from [32]) contains details of such equipment from which approximations 8.11 and 8.12 have been derived.

Table 8.8 Particulars of Control Gear for Variable Speed Motors from [32]

Motor Power (MW)	Transformer L(m)	Transformer B(m)	Transformer D(m)	Transformer W(t)	Choke L(m)	Choke B(m)	Choke D(m)	Choke W(t)	Inverter L(m)	Inverter B(m)	Inverter D(m)	Inverter W(t)	Total Weight (tonnes)
2.00	2.50	2.50	0.81	5.00	1.90	1.90	2.25	0.75	7.60	1.00	2.50	4.00	9.75
10.0	3.30	3.10	2.38	19.0	2.75	2.75	2.50	1.50	5.60	1.80	2.50	6.00	26.5
20.0	4.00	4.00	2.50	30.0	3.00	3.00	2.50	3.00	8.00	2.70	2.40	8.00	41.0

Variable Speed Control Gear Weight (t) $= 6.32[\text{Power (MW)}]^{0.62}$ Eqn. 8.11

Variable Speed Control Gear Volume (m^3) $= 21.6[\text{Power (MW)}]^{0.54}$ Eqn. 8.12

8.5.4 Propulsion Motors

Three basic types of electric propulsion motor are available. They are
a) DC motors (variable speed), which do not require reduction gearing/CP propellers,
b) constant speed AC motors (direct or geared drive), which require CP propellers,
c) variable speed AC motors (direct or geared drive), which do not require CPP.

Direct drive DC motors are large and heavy, but are used extensively in submarines and icebreakers because of the simplicity of speed control, and the high torque available at low revolutions. The state of the art in this technology is currently 8.5 MW (11,400 HP) per motor. However, the low power to weight ratio and high cost of such motors means that AC motors are generally a more attractive solution. This lack of demand means that development activity is rather low key and dramatic improvements in design are rare. It is therefore only in large and slow SWATHs that DC motors are likely to be fitted. Table 8.9 contains details [32] of large DC motors.

Table 8.9 DC Motors Particulars from [32]

Power (MW)	RPM	Voltage (V)	Length (m)	Breadth (m)	Height (m)	Weight (t)
1.50	193	600	3.50	3.00	3.90	45
4.00						85
5.40	100/200	800				
6.60			6.00	3.50	3.60	
8.90	105/180	1200				

With all AC motors, the developed power will vary as the square of the diameter and linearly with the length. It is therefore possible to design motors for particular applications, although with SWATH ships the constraint on diameter will lead to less optimised design than normal. Synchronous machines may be used in variable or constant speed drives, while asynchronous (induction) motors are intended for constant speed drives. Synchronous machines are heavier, and roughly twice as expensive as the induction type for the same power, but involve the lowest power losses (2%).

Constant speed AC motors operate on a fixed frequency supply similar to that demanded by the ship services and so offer the possibility of an integrated system. The obvious drawbacks are the cost and complexity of the CPP needed to control propulsive power, and the underwater noise and inefficiency associated with off-pitch operation of the propeller.

Variable speed AC motors are operated on variable frequency supply from variable frequency generators or thyristor frequency converters. Variable frequency generated power is not suitable for use by shipboard services and is not ideal for vessels which have a wide speed range.

Details [32] of direct drive AC motors are presented in Table 8.10. These motors tend to be large and heavy, and are not automatic choices for SWATH ships.

Table 8.10 Direct Drive AC Motors Particulars from [32]

Power (MW)	RPM	Voltage (kV)	Length (m)	Breadth (m)	Depth (m)	Weight (t)
2.00	250	6	2.74	2.30	3.45	16
3.00	250	6	2.97	3.90	4.02	21
5.00	250	6	3.33	3.90	4.04	28
8.00	250	6	3.93	5.00	5.13	41
10.0	250	6	4.04	5.00	5.13	48

Weight of Direct Drive AC Motors (t) $= 9.85\ (\text{Power in MW})^{0.680}$ Eqn. 8.13

Volume of Direct Drive AC Motors (m^3) $= 13.2\ (\text{Power in MW})^{0.931}$ Eqn. 8.14

Breadth of Direct Drive AC Motors (m) $= 1.98\ (\text{Power in MW})^{0.431}$ Eqn. 8.15

Geared electric motors achieve their low weight and cost as a consequence of the high operating speeds. The associated gearboxes do imply losses in transmission, and also increase cost and underwater noise signature. Table 8.11 illustrates details of high speed AC motors [32]. Equations which may be used for estimating weights and spatial requirements are derived from this data.

Weight of Geared AC Motors (t) $= 4.38\ (\text{Power in MW})^{0.79}$ Eqn. 8.16

Volume of Geared AC Motors (m3) $= 4.89\ (\text{Power in MW})^{0.40}$ Eqn. 8.17

Breadth of Geared AC Motors (m) $= 1.44\ (\text{Power in MW})^{0.26}$ Eqn. 8.18

Table 8.11 Geared Drive AC Motors Particulars from [32]

Power (MW)	RPM	Voltage (kV)	Length (m)	Diameter (m)	Weight (t)	Cost (£k)
0.50	1800	3.3	2.50	1.20	2.50	20
0.50	1800	3.3	2.00	1.20	2.75	40
1.00	1800	3.3	3.25	1.35	4.00	22
2.00	1800	3.3	3.25	1.65	6.50	30
2.00	1800	3.3	3.50	1.65	9.25	60
3.00	1800	3.3	3.50	1.95	9.50	60
4.00	1800	3.3	3.70	2.25	12.00	100
5.00	1800	3.3	4.00	2.50	15.50	135
6.00	1800	3.3	4.25	2.50	19.00	175
8.00	1800	3.3	5.30	2.50	25.00	185
10.0	1800	3.3	6.00	2.50	30.00	200
15.0	1800	3.3	6.10	2.75	37.50	250
20.0	1800	3.3	6.50	3.00	42.00	300

Dimensions and weights exclude coolers and ducting

The weights and volumes of air coolers for the motors, and the associated ducting, are not included in the above collection of data. Normal practice is to mount the closed air circuit watercooled units on top of the motors but it should be possible to site them remotely, if, as is the case with SWATH, vertical dimensions are to be minimised.

8.5.5 Electrical Transmission Efficiencies

Table 8.12 lists the transmission efficiencies which have been adopted in the current study for the various components of electrical plant. These figures are taken from [32].

Table 8.12 Electrical Transmission Efficiencies from [32]

Component	Conventional DC	Conventional AC
Generator	94.00 - 96.00	97.50 - 98.50
Motor	94.00 - 96.00	97.00 - 98.00
Cable System	93.00 - 97.00	98.5 - 99.75
Efficiency Subtotal	*82.20 - 89.40*	*93.10 - 96.20*
Excitation Power	2.50 - 4.00	2.50 - 4.00
Range of Efficiency	*78.70 - 85.40*	*89.10 - 93.70*

8.6 Survey of Electrical Drive Studies for SWATH Ships

The data presented in the previous sections may be used manually to develop an estimate of the weight and space requirements of SWATH electrical machinery schemes. This process has also been automated, as described in section 8.7. However, additional guidance may be obtained from previous studies. Table 8.13 is extracted from a US Navy study [1] and presents the limiting vessel dimensions for a matrix of prime mover and transmission types. These dimensions were developed from machinery arrangement sketches. A similar study by Simpson [32] (sponsored by the Royal Navy) produced the results summarised in Table 8.14.

Table 8.13 Required Hull Dimensions for Installing US GT-Electric Drive - from [1]

Transmission System	Prime Mover (*bare* GTs)	Number per ship	Total Installed Power (HP)	Required Strut Thickness (m)	Required Hull Diameter (m)
High speed electric motors with double reduction gears in hulls	LM2500	2	45,000	1.98	5.18
	LM2500	4	90,000	2.13	6.71
	FT9	2	70,000	2.13	6.01
	FT9	4	140,000	2.13	7.62
	LM5000	2	90,000	2.13	6.71
	LM5000	4	180,000	2.13	8.61
Cryogenic transmission	LM2500	2	45,000	1.98	3.66
	LM2500	4	90,000	1.98	4.57
	FT9	2	70,000	1.98	4.57
	FT9	4	140,000	1.98	4.88
	LM5000	2	90,000	1.98	4.57
	LM5000	4	180,000	1.98	5.79

NB Strut thickness and hull diameter are extreme dimensions. Hulls are circular section.

Table 8.14 Particulars of Electrical Drive Schemes for UK SWATH Ships

Machinery Scheme Details	Total Shaft Power (MW)	Clear Hull Diameter (metres)	Clear Strut Width (metres)	Engines/Gensets Weight (tonnes)	Engines/Gensets Cost (£m)	Electric Motors Weight (tonnes)	Electric Motors Cost (£m)	Electrical Control Weight (tonnes)	Electrical Control Cost (£m)	Gearboxes Weight (tonnes)	Gearboxes Cost (£m)	Props/Shafts Weight (tonnes)	Props/Shafts Cost (£m)	Total Weight (tonnes)	Total Cost (£m)
4x8RK270Z DGs 2x2MW variable speed AC motors	3.88	2.75	0.80	136.00	1.12	18.50	0.12	20.00	0.10	9.20	0.10	14.00	0.17	198.00	1.61
5xValenta DGs 2x2MW variable speed AC motors	3.64	2.75	0.80	80.00	1.71	18.50	0.12	20.00	0.10	9.20	0.10	14.00	0.17	143.00	2.20
5x16RK270Z DG 2x6MW variable speed AC motors	11.64	4.00	1.00	280.00	2.20	38.00	0.35	52.00	0.50	15.00	0.30	26.00	0.45	411.00	3.80
6x12RK270Z DG 2x6MW variable speed AC motors	11.64	4.00	1.00	264.00	1.93	38.00	0.35	52.00	0.50	15.00	0.30	26.00	0.45	395.00	[illegible]
5x12RK270Z DG 2x6MW variable speed AC motors	9.70	3.80	1.00	220.00	1.61	38.00	0.35	52.00	0.50	15.00	0.30	26.00	0.45	351.00	3.21
Above schemes are 'integrated', i.e. one additional DG is included to ensure that ship's services are maintained with one DG 'down' *Schemes below supply only propulsive power*															
3xSM1A GT gen 2x15MW constant speed AC motors	29.10	4.10	1.10	120.00	7.10	75.00	0.50			120.00	0.96	74.00	0.74	389.00	9.30
3xSM1A GT gen 2x15MW variable speed AC motors	29.10	4.10	1.10	120.00	7.10	75.00	0.50	70.00	1.00	120.00	0.96	37.00	0.37	422.00	9.40

8.7 Machinery Design Software

8.7.1 Introduction

A machinery design method has been developed for use in the SWATH synthesis model. This has two options which allow a machinery scheme to be specified by;

a) interrogation of prime mover datafiles, or

b) use of predesigned specification, stored on file

Option b) is made available simply by the computerisation of the data in tables 8.7 and 8.13. Option a) is more involved, and is discussed in the following section.

8.7.2 Automated Interrogation of Machinery Data Files

As mentioned previously, datafiles of medium and high speed diesels (inline and vee), and gas turbines (bare and modularised) form the basis for this method. A computer program (*MACHY*) has been developed to interrogate this information under the guidance of the SWATH designer.

The software assumes that the total power requirements are met by two identical power trains (one per shaft). The program is designed to allow the user to specify *AND* or *OR* systems for cruise and sprint power, or to choose one power plant for all speed requirements. In the latter case, one, two, three or four (identical) prime movers may be used. In the case of an *AND/OR* scheme, up to two cruise units may be used in conjunction with one or two larger engines. Prime movers may be medium speed diesels (inline or vee), high speed diesel (inline or vee), or bare or modularised gas turbines. The large number of permutations which this permits is illustrated in Figure 8.23. Because of space constraints within SWATH hulls most of the combined systems illustrated are unlikely to be practical.

Further control over the final design is provided by an option to specify a particular feature for optimisation, provided that the power requirements are satisfied. This allows the user to restrict his search for a suitable prime mover to those of a particular manufacturer or country (Appendix 5 lists the 17 countries and 61 manufacturers included in the diesel engine database). Alternatively, he may choose to search for the engine which delivers the required power with the minimum weight or length or breadth or depth or specific fuel consumption.

Table 8.15 lists the input and output variables for the machinery design module.

Table 8.15 Input & Output Variables - Machinery Module (Mechanical Transmission)

Input Variables

Required shaft power and RPM at *maximum* and *cruise* conditions (these may be identical)
Propulsion system from; simple, AND or OR
Location of prime movers from; hulls, box or superstructure
Number of main engines (maximum of 4 for a simple system, otherwise maximum of 2)
Type of main engines from; gas turbines (bare or modularised), high speed diesels (inline or vee), medium speed diesels (inline or vee)
Number of cruise engines (if any)
Type of cruise engines from; gas turbines (bare or modularised), high speed diesels (inline or vee), medium speed diesels (inline or vee)
Optimising variable from; weight, length, breadth, depth, SFC, manufacturer, country of origin

Output Variables

Main engine particulars; power, RPM, weight, length, breadth, depth, SFC, cost, manufacturer, country
Cruise engine particulars; power, RPM, weight, length, breadth, depth, SFC, cost, manufacturer, country
Gearbox particulars; weight, length, breadth, depth
Total system particulars; weight, length, breadth, depth

8.7.3 Limiting Effect of Lower Hull Dimensions on Installed Power

The data collected for the above system has been used to examine the effects of physical restrictions on the power which can be installed in the lower hulls of SWATH ships. The logical location for electric motors is in the hulls. With mechanical drive, siting of the prime movers in the lower hulls is desirable because of the straightforward power train this provides. Despite this obvious advantage, none of the SWATH ships at sea employ this arrangement, largely due to their small size. It should also be noted that lower hull mounted machinery involves more hullborne noise and ducting losses than box mounted prime movers. However, the demands of the latter option on box volume and transmission weight may lead to larger ship size.

In order to assess the feasibility of lower hull mounted machinery, studies were carried out for elliptical hulls with B/D ratios of 1.0 (circular), 1.3 and 1.5. The maximum power which could be delivered by a single item of machinery was calculated for a range of hull dimensions and the motors indicated below. In addition, a distinction was made between UK produced units and those available worldwide.

Machinery Items Considered	Identifying Codes
Medium Speed Diesel - Inline	MSL
Medium Speed Diesel - Vee	MSV
High Speed Diesel - Inline	HSL
High Speed Diesel - Vee	HSV
Gas Turbines - Modules	GTM
Gas Turbines - Bare	GTB
AC Motors - Geared	ACgear
AC Motors - Direct Drive	ACdir
DC Motors - Direct Drive	DCdir

Because of the potential for wide variations in structural arrangements, internal hull breadth and depth were used as reference dimensions. However, from Chapter 9, internal hull dimensions are approximately 86% of the external values, and this ratio was used in conjunction with equations 2.19 and 2.21 from Chapter 2 to indicate a typical SWATH displacement associated with each hull. It was assumed that each item of machinery may be positioned centrally in the hull as shown in Figure 8.22. The use of reduction gearboxes with a shaft offset should allow this to be the case in practice. Machinery items were idealised as rectangular in section, and considered in association with maintenance spaces of 2.0m by 0.6m on either side as illustrated in Figure 8.22.

Under the above assumptions, the machinery datafiles were searched to determine the most powerful motor which could be fitted in hulls between 2 and 12 metres internal breadth (in steps of 0.1m). The results are contained in Tables 8.16 to 8.18 and figures 8.24 to 8.38. The tables in particular may readily be used manually as design aids.

The nominal ship sizes at which it becomes possible to install given machinery types are summarised in Table 8.19.

Clear Hull Diameter (metres)	Nominal Ship Displacement (tonnes)	High Speed Diesel				Medium Speed Diesel				Gas Turbines				Electric Motors		
		Inline configuration		'Vee' configuration		Inline configuration		'Vee' configuration		GT modules		Bare engines		AC Geared	AC Direct	DC Direct
		UK	World	UK	World	UK	World	UK	World	UK	World	UK	World			
2.40	605															
2.70	862												2200			
2.80	961	120	648		1500								2960			
2.90	1068	500	1680		1500							5000	8000			
3.00	1182	700	3600		1500		2000					5000	8000			
3.10	1304	1000	3600		1500		2600					9000	9000			
3.20	1434	1000	3600	1600	2750	3988	3988					11600	11600	1340		
3.30	1573	2880	4800	2500	4200	6160	6160					11600	11600	2680		
3.40	1720	2880	4800	2500	4200	6160	6400		4900			11600	11600	2680		
3.50	1877	2880	4800	6080	16650	6160	6400		4900		11200	11600	11600	5360		
3.60	2042	2880	6600	6080	16650	6160	6400	4080	5600		11200	11600	11600	5360		
3.70	2217	2880	6600	9120	16650	6160	7800	12320	12320		11200	11600	11600	5360		
3.80	2402	2880	6600	9120	16650	6160	7800	12320	12320		11200	11600	30000	8046		
3.90	2597	2880	6600	9120	16650	6160	8000	12320	12320	11600	11600	34200	34200	8046		
4.00	2801	2880	6600	9120	16650	7920	8000	12320	12320	11600	11600	34200	43000	10728		
4.10	3017	2880	6600	9120	19800	7920	9000	12320	12320	34200	34200	34200	43000	10728		
4.20	3243	2880	6600	9120	19800	7920	9000	12320	12886	34200	34200	56000	56000	10728	5360	
4.30	3480	2880	6600	9120	19800	7920	9000	12320	12886	34200	34200	56000	56000	26820	5360	
4.40	3729	2880	6600	9120	19800	7920	9240	12320	12886	34200	43000	56000	56000	26820	5360	
4.50	3989	2880	6600	9120	19800	7920	9900	12320	12886	34200	43000	56000	56000	40200	5360	
4.60	4261	2880	6600	9120	19800	13410	13140	12320	12886	56000	75440	56000	56000	40200	5360	
4.70	4545	2880	6600	9120	19800	13410	13140	12320	12886	56000	75440	56000	56000	53600	5360	
4.80	4841	2880	6600	9120	19800	13410	13400	12320	12886	56000	75440	56000	56000	53600	5360	
4.90	5150	2880	6600	9120	19800	13410	19800	14080	18360	56000	75440	56000	56000	53600	5360	
5.00	5472	2880	6600	9120	19800	13410	19800	23000	23000	56000	75440	56000	56000	53600	5360	4020
5.20	6155	2880	6600	9120	19800	13410	19800	23000	23000	56000	75440	56000	56000	53600	5360	17700
5.40	6893	2880	6600	9120	19800	13410	19800	23000	23000	56000	75440	72420	72420	53600	5360	17700
5.50	7283	2880	6600	9120	19800	13410	19800	23000	23000	56000	75440	72420	72420	53600	5360	17700
5.60	7687	2880	6600	9120	19800	13410	21600	23000	23000	56000	75440	72420	72420	53600	5360	17700
5.70	8106	2880	6600	9120	19800	13410	21600	23000	29700	56000	75440	72420	72420	53600	13410	17700
5.80	8540	2880	6600	9120	19800	13410	21600	23000	29700	72420	75440	72420	72420	53600	13410	17700
5.90	8990	2880	6600	9120	19800	13410	21600	21120	29700	72420	75440	72420	72420	53600	13410	17700
6.10	9935	2880	6600	9120	19800	13410	21600	21120	30400	72420	75440	72420	72420	53600	13410	17700
6.30	10945	2880	6600	9120	19800	13410	29700	21120	30400	72420	75440	72420	72420	53600	13410	17700
6.50	12021	2880	6600	9120	19800	13410	29700	23360	30400	72420	75440	72420	72420	53600	13410	17700
6.90	14380	2880	6600	9120	19800	13410	29700	23360	37980	72420	75440	72420	72420	53600	13410	17700
7.20	16338	2880	6600	9120	19800	13410	29700	23360	37980	72420	75440	72420	72420	53600	21440	17700
7.80	20772	2880	6600	9120	19800	13410	34600	23360	37980	72420	75440	72420	72420	53600	21440	17700
10.00	43772	2880	6600	9120	19800	13410	34600	23360	37980	72420	75440	72420	72420	53600	21440	17700

Table 8.16 Maximum Installed Powers for Lower Hulls - B/D=1.0

Clear Hull Breadth (metres)	Nominal Ship Displacement (tonnes)	High Speed Diesel Inline configuration UK		High Speed Diesel 'Vee' configuration UK		Medium Speed Diesel Inline configuration UK		Medium Speed Diesel 'Vee' configuration UK		Gas Turbines GT modules UK		Gas Turbines Bare engines UK		Electric Motors AC Geared	Electric Motors AC Direct	Electric Motors DC Direct
		UK	World	UK	World	UK	World	UK	World	UK	World	UK	World			
2.00	176															
3.20	721												2200			
3.30	791	400	1680		1500								5600			
3.40	865	700	3600		1500		480					5000	8000			
3.50	943	1000	3600		1500		2600					9000	9000			
3.60	1026	1000	3600	1600	2750	3988	3988					11600	11600	1340		
3.70	1114	2880	4800	2500	4200	6160	6160					11600	11600	2680		
3.80	1207	2880	4800	2500	4200	6160	6160		4900			11600	11600	2680		
3.90	1305	2880	6660	6080	16650	6160	6160		4900		11200	11600	11600	5360		
4.00	1408	2880	6660	9120	16650	6160	6400	12320	12320		11200	11600	11600	5360		
4.10	1516	2880	6660	9120	16650	6160	7800	12320	12320		11200	11600	11600	8046		
4.20	1630	2880	6660	9120	16650	6160	7800	12320	12320		11200	34200	34200	8046		
4.30	1749	2880	6660	9120	16650	6160	7800	12320	12320	11600	11600	34200	34200	8046		
4.40	1874	2880	6660	9120	19800	7920	7920	12320	12320	11600	11600	34200	34200	10728		
4.50	2004	2880	6660	9120	19800	7920	8000	12320	12320	34200	34200	56000	56000	10728		
4.60	2141	2880	6660	9120	19800	7920	9000	12320	12320	34200	34200	56000	56000	26820	5360	
4.70	2284	2880	6660	9120	19800	7920	9000	12332	12332	34200	43000	56000	56000	26820	5360	
4.80	2433	2880	6660	9120	19800	7920	9240	12332	12332	34200	43000	56000	56000	40200	5360	
4.90	2588	2880	6660	9120	19800	7920	9240	12332	12332	34200	75440	56000	56000	40200	5360	
5.00	2750	2880	6660	9120	19800	13140	13140	12332	12332	56000	75440	56000	56000	53640	5360	
5.20	3093	2880	6660	9120	19800	13140	19800	12332	16320	56000	75440	56000	56000	53640	5360	
5.40	3464	2880	6660	9120	19800	13140	19800	12332	18360	56000	75440	56000	56000	53640	5360	17700
5.50	3660	2880	6660	9120	19800	13140	19800	14080	19800	56000	75440	56000	56000	53640	5360	17700
5.60	3863	2880	6660	9120	19800	13140	19800	14080	19800	56000	75440	72420	72420	53640	5360	17700
6.00	4751	2880	6660	9120	19800	13140	19800	14080	23000	72420	75440	72420	72420	53640	13410	17700
6.20	5242	2880	6660	9120	19800	13140	21600	14080	23000	72420	75440	72420	72420	53640	13410	17700
6.30	5500	2880	6660	9120	19800	13140	21600	14080	30400	72420	75440	72420	72420	53640	13410	17700
6.40	5766	2880	6660	9120	19800	13140	21600	21120	30400	72420	75440	72420	72420	53640	13410	17700
6.70	6616	2880	6660	9120	19800	13140	21600	23360	30400	72420	75440	72420	72420	53640	13410	17700
7.20	8210	2880	6660	9120	19800	13140	29700	23360	30400	72420	75440	72420	72420	53640	13410	17700
7.80	10439	2880	6660	9120	19800	13140	29700	23360	37980	72420	75440	72420	72420	53640	21440	17700
9.20	17129	2880	6660	9120	19800	13140	34600	23360	37980	72420	75440	72420	72420	53640	21440	17700
10.00	21997	2880	6660	9120	19800	13140	34600	23360	37980	72420	75440	72420	72420	53640	21440	17700
12.00	38011	2880	6660	9120	19800	13140	34600	23360	37980	72420	75440	72420	72420	53640	21440	17700

Table 8.17 Maximum Installed Powers for Lower Hulls - B/D=1.3

Clear Hull Breadth (metres)	Nominal Ship Displacement (tonnes)	High Speed Diesel Inline configuration UK	High Speed Diesel Inline configuration World	High Speed Diesel 'Vee' configuration UK	High Speed Diesel 'Vee' configuration World	Medium Speed Diesel Inline configuration UK	Medium Speed Diesel Inline configuration World	Medium Speed Diesel 'Vee' configuration UK	Medium Speed Diesel 'Vee' configuration World	Gas Turbines GT modules UK	Gas Turbines GT modules World	Gas Turbines Bare engines UK	Gas Turbines Bare engines World	Electric Motors AC Geared	Electric Motors AC Direct	Electric Motors DC Direct
2.00	176															
3.50	943												2200			
3.60	1026	124	648		1500								5600			
3.70	1114	700	3600		1500							5000	8000			
3.80	1207	880	3600		1500		2000					9000	9000			
3.90	1305	1000	3600	1600	2750	3988	3988					11600	11600	1340		
4.00	1408	2880	3808	2500	4200	6160	6160					11600	11600	2680		
4.10	1516	2880	4800	2500	4360	6160	6160		3260			11600	11600	2680		
4.20	1630	2880	6660	6080	13200	6160	6160		5600	11200	11200	11600	11600	5360		
4.30	1749	2880	6660	9120	13310	6160	6160	12320	12320	11200	11200	11600	11600	5360		
4.40	1874	2880	6660	9120	16650	6160	6160	12320	12320	11200	11200	11600	30000	8046		
4.50	2004	2880	6660	9120	16650	6160	6610	12320	12320	11600	11600	34200	34200	8046		
4.60	2141	2880	6660	9120	16650	6160	7800	12320	12320	11600	11600	34200	43000	10728		
4.70	2284	2880	6660	9120	19800	6160	7800	12320	12320	11600	11600	56000	56000	10728		
4.80	2433	2880	6660	9120	19800	6160	9000	12320	12320	11600	11600	56000	56000	26820		
4.90	2588	2880	6660	9120	19800	6160	9000	12320	12320	11600	43000	56000	56000	26820		
5.00	2750	2880	6660	9120	19800	6160	9000	12320	12320	11600	43000	56000	56000	40200		
5.10	2918	2880	6660	9120	19800	7920	9000	12320	12320	34200	75440	56000	56000	40200		
5.20	3093	2880	6660	9120	19800	7920	9000	12332	12332	34200	75440	56000	56000	53640	5360	
5.30	3275	2880	6660	9120	19800	7920	9000	12332	12332	34200	75440	56000	56000	53640	5360	
5.40	3464	2880	6660	9120	19800	7920	19800	12332	12332	34200	75440	56000	56000	53640	5360	
5.60	3863	2880	6660	9120	19800	13140	19800	12332	12886	56000	75440	56000	56000	53640	5360	17700
5.80	4292	2880	6660	9120	19800	13140	19800	12332	16320	56000	75440	72420	72420	53640	5360	17700
6.00	4751	2880	6660	9120	19800	13140	19800	12332	19800	56000	75440	72420	72420	53640	5360	17700
6.10	4993	2880	6660	9120	19800	13140	19800	14080	19800	56000	75440	72420	72420	53640	5360	17700
6.20	5242	2880	6660	9120	19800	13140	19800	14080	19800	72420	75440	72420	72420	53640	13410	17700
6.30	5500	2880	6660	9120	19800	13140	19800	14080	22800	72420	75440	72420	72420	53640	13410	17700
6.50	6041	2880	6660	9120	19800	13140	19800	14080	30400	72420	75440	72420	72420	53640	13410	17700
6.60	6324	2880	6660	9120	19800	13140	19800	14080	30400	72420	75440	72420	72420	53640	13410	17700
6.80	6917	2880	6660	9120	19800	13140	21600	23360	30400	72420	75440	72420	72420	53640	13410	17700
7.80	10439	2880	6660	9120	19800	13140	29700	23360	30400	72420	75440	72420	72420	53640	13410	17700
8.20	12128	2880	6660	9120	19800	13140	29700	23360	30400	72420	75440	72420	72420	53640	21440	17700
8.40	13038	2880	6660	9120	19800	13140	29700	23360	37980	72420	75440	72420	72420	53640	21440	17700
10.20	23343	2880	6660	9120	19800	13140	34600	23360	37980	72420	75440	72420	72420	53640	21440	17700
12.00	38011	2880	6660	9120	19800	13140	34600	23360	37980	72420	75440	72420	72420	53640	21440	17700

Table 8.18 Maximum Installed Powers for Lower Hulls - B/D=1.5

Table 8.19 Minimum Size of SWATH Vessel Associated with Machinery Types

Machinery Type	Displacement (t) for Various Hulls Circular	B/D=1.3	B/D=1.5
High speed diesel - inline - UK only	960	790	1030
High speed diesel - inline - worldwide	960	790	1030
High speed diesel - vee - UK only	1430	1030	1300
High speed diesel - vee - worldwide	960	790	1030
Medium speed diesel - inline - UK only	1430	1030	1300
Medium speed diesel - inline - worldwide	1180	860	1200
Medium speed diesel - vee - UK only	2040	1400	1750
Medium speed diesel - vee - worldwide	1720	1200	1520
Gas turbine - module - UK only	2600	1750	1630
Gas turbine - module - worldwide	1880	1300	1630
Gas turbine - bare - UK only	1070	870	1110
Gas turbine - bare - worldwide	860	720	940
AC geared	1430	1030	1300
AC direct	3240	2140	3090
DC direct	5470	3460	3860

Above data refers only to single-motor-per-shaft lower hull installations

It should be noted that the SWATH displacements quoted above are typical values only. For a given displacement, the SWATH geometry may vary considerably to suit particular ends, and the hull breadth and depth (Tables 8.16 to 8.18) are truer guides to the limits on machinery installation. High speed diesels and bare gas turbines may be installed at displacements below 1000 tonnes. Lower hull mounted medium speed diesels are possible in vessels between 1000 and 2000 tonnes displacement. Geared AC motors become feasible about 1500 tonnes while modularised gas turbines may be fitted in SWATHs of 2000 tonnes. It appears that in the majority of cases, the smallest displacement at which machinery may practically be installed in the lower hulls is offered by elliptical hulls with a B/D ratio of 1.3.

It is clear from Tables 8.16 to 8.18 that where internal combustion engines are concerned, UK manufactured models offer considerably less power for a given hull size than their European competitors. This is particularly true of high speed vee engines (Figures 8.24, 8.28. 8.32), where the difference may be of the order of 100%. Insistence on the use of UK builders for prime movers is a significant penalty for the Royal Navy SWATH designer.

Gas turbines provide the most power for a given hull size. Bare gas turbines are the smallest prime movers but it is not possible to fit modularised gas turbines in some smaller SWATHs where compact diesels may be fitted.

Maximum installed power also varies depending on the shape of hull section. A study compared the data in Tables 8.16 to 8.18 on the basis of power per demihull sectional area for each machinery type. Figure 8.46 illustrates maximum installed powers for high speed vee diesels dependent on hull shape. For demihulls with a sectional area below $10m^2$, circular hulls allow the greatest powers and elliptical hulls with B/D=1.5 the lowest. For larger hulls, the situation is reversed, and B/D=1.5 hulls are the most efficient in terms of attainable power density. The difference in power/area values for the two hullforms is not great, and is equivalent to a 10 to 30% difference in sectional area, depending on machinery type.

8.7.4 Parametric Studies of SWATH Designs

The results of the study described in section 8.7.3 were applied to the 25 SWATH hullforms described in Table 5.6 to determine the limiting values of SHP for each hull-machinery combination. The results of this study are presented in Table 8.20 where the weights of the most powerful machinery items suitable for each hull are also listed. It should again be noted that these results refer to lower hull installations only.

The speed-power curves presented in Chapter 6 were employed to estimate the sustained speed attainable by each hull-machinery combination. Naked hull EHP was multiplied by a factor of 1.15 to allow for appendage drag, and a margin of 15% was allowed for design uncertainty and service conditions. An overall propulsive coefficient of 70% (72% QPC and 97% transmission efficiency) was used to estimate shaft horsepower requirements for each hull.

Under the above assumptions, none of the propulsion schemes are capable of providing a sustained speed of 30 knots in any of the 25 hullforms studied. Figures 8.39 to 8.45 illustrate the sustained speeds available with each hullform from the different propulsion options. It is apparent from Table 8.20 and Figures 8.39 to 8.45 that different hullforms influence sustained speed as much by their effect on the size of propulsion unit as by their resistance characteristics. In particular, higher speeds may be attained using medium speed vee diesels with the arbitrarily designed but capacious 'dogbone' (shallow) hull (Figure 8.42) than with more optimised forms.

These factors indicate that in the sizes considered, maximum speed becomes limited by lower hull volume rather than machinery weight. It is recognised that maximising sustained speed is not always a design objective, especially where this involves very large powers. Choosing spacious hulls merely to install powerful motors is an expensive design solution.

Table 8.20 Installed Powers and Sustained Speeds for 25 SWATH Designs

Hullform	*Baseline Hull*			*'Coke' (deep)*			*'Coke' (shallow)*			*'Dogbone' (deep)*			*'Dogbone' (shallow)*		
Ship Size - Machinery Fit	*SHP*	*Weight*	*Speed*	*SHP*	*Weight*	*Speed*	*SHP*	*Weight*	*Speed*	*SHP*	*Weight*	*Speed*	*SHP*	*Weight*	*Speed*
DESIGN 1000															
High Speed Inline (UK)				1000	3.0	*9.6*	2880	9.2	*15.0*				700	2.0	*6.0*
High Speed Inline (all)				3600	10.5	*16.8*	4800	11.7	*17.5*				3600	10.5	*15.0*
High Speed Vee (UK)				1600	2.0	*11.0*	2500	6.3	*14.4*						
High Speed Vee (all)				2750	1.5	*16.0*	4200	3.4	*16.9*				1500	0.8	*8.0*
Medium Speed Inline (UK)				3988	13.0	*17.2*	6160	17.2	*18.4*						
Medium Speed Inline (all)				3988	13.0	*17.2*	6160	17.2	*18.4*				480	6.0	*3.0*
Medium Speed Vee (UK)															
Medium Speed Vee (all)							4900	15.2	*17.6*						
Gas Turbine Modules (UK)															
Gas Turbine Modules (all)															
Bare Gas Turbines (UK)				11600	4.4	*21.7*	11600	4.4	*21.7*				5000	0.6	*17.0*
Bare Gas Turbines (all)	2200	0.4	*10.0*	11600	4.4	*21.7*	11600	4.4	*21.7*	5600	0.5	*18.5*	8000	0.5	*20.5*
Geared AC Motors				1340	2.8	*10.0*	2680	4.0	*14.5*						
Direct Drive AC Motors															
Direct Drive DC Motors															
DESIGN 2000															
High Speed Inline (UK)	2880	9.2	*10.0*	2880	9.2	*12.4*	2880	9.2	*10.0*	2880	9.2	*11.0*	2880	9.2	*9.0*
High Speed Inline (all)	6600	19.0	*17.5*	6660	19.0	*17.6*	6660	19.0	*17.3*	6660	19.0	*16.8*	6660	19.0	*15.0*
High Speed Vee (UK)	6080	9.2	*17.2*	9120	21.2	*18.6*	9120	21.2	*18.3*	9120	21.2	*18.6*	9120	21.2	*16.2*
High Speed Vee (all)	16650	20.5	*22.4*	19800	26.0	*22.0*	19800	26.0	*21.6*	16650	20.5	*22.5*	19800	26.0	*23.0*
Medium Speed Inline (UK)	6160	17.2	*17.3*	7920	39.7	*18.0*	13140	59.1	*19.8*	6160	17.2	*16.5*	7920	39.7	*15.5*
Medium Speed Inline (all)	6400	43.0	*17.4*	9000	50.0	*18.6*	13140	59.1	*19.8*	7800	34.7	*18.0*	8000	66.0	*15.5*
Medium Speed Vee (UK)	4080	12.0	*12.5*	12332	38.6	*19.6*	12332	38.6	*19.4*	12320	25.8	*20.6*	12320	25.8	*20.6*
Medium Speed Vee (all)	5600	17.0	*16.9*	12332	38.6	*19.6*	12332	38.6	*19.4*	12320	25.8	*20.6*	12320	25.8	*20.6*
Gas Turbine Modules (UK)				34200	24.7	*25.5*	56000	30.9	*27.2*				34200	24.5	*26.2*
Gas Turbine Modules (all)	11200	22.8	*20.4*	43000	20.9	*26.5*	75440	22.1	*28.2*	11200	2.8	*20.3*	34200	24.5	*26.2*
Bare Gas Turbines (UK)	11600	4.4	*20.5*	56000	10.5	*27.8*	56000	10.5	*27.2*	11600	4.4	*20.4*	56000	10.5	*29.7*
Bare Gas Turbines (all)	11600	4.4	*20.5*	56000	10.5	*27.8*	56000	10.5	*27.2*	11600	4.4	*20.4*	56000	10.5	*29.7*
Geared AC Motors	5360	9.3	*16.4*	26820	30.0	*23.9*	53640	42.0	*26.9*	8046	9.5	*18.0*	10728	12.0	*18.4*
Direct Drive AC Motors				5360	16.0	*17.0*	5360	16.0	*16.6*						
Direct Drive DC Motors															
DESIGN 3000															
High Speed Inline (UK)	2880	9.2	*10.0*	2880	9.2	*10.8*	2880	9.2		2880	9.2	*10.0*	2880	9.2	
High Speed Inline (all)	6600	19.0	*15.4*	6660	19.0	*16.7*	6660	19.0	*12.7*	6660	19.0	*15.4*	6660	19.0	*11.7*
High Speed Vee (UK)	9120	21.2	*16.6*	9120	21.2	*17.7*	9120	21.2	*15.2*	9120	21.2	*17.2*	9120	21.2	*14.0*
High Speed Vee (all)	19800	26.0	*22.2*	19800	26.0	*20.7*	19800	26.0	*19.1*	19800	26.0	*22.4*	19800	26.0	*22.0*
Medium Speed Inline (UK)	7920	39.7	*16.4*	13140	59.1	*19.1*	13140	59.1	*17.5*	7920	39.7	*16.6*	13140	59.1	*16.4*
Medium Speed Inline (all)	9000	50.0	*16.6*	19800	149.0	*20.7*	19800	149.0	*19.1*	9240	49.0	*17.3*	19800	149.0	*22.0*
Medium Speed Vee (UK)	12320	23.8	*19.5*	14080	54.5	*19.2*	14080	54.5	*17.9*	12332	38.6	*19.5*	12332	38.6	*19.5*
Medium Speed Vee (all)	12886	32.7	*20.0*	19800	72.0	*20.7*	23000	218.0	*20.0*	12332	38.0	*19.5*	16320	50.0	*21.5*
Gas Turbine Modules (UK)	34200	24.5	*24.5*	56000	30.9	*26.0*	72420	42.3	*25.2*	34200	24.5	*24.7*	56000	30.9	*26.9*
Gas Turbine Modules (all)	34200	24.5	*24.5*	75440	21.1	*27.5*	75440	21.1	*26.3*	43000	20.9	*25.7*	75440	21.2	*28.2*
Bare Gas Turbines (UK)	56000	10.5	*27.0*	56000	10.5	*26.0*	72420	12.0	*25.2*	56000	10.5	*27.0*	56000	10.5	*26.9*
Bare Gas Turbines (all)	56000	10.5	*27.0*	56000	10.5	*26.0*	72420	12.0	*25.2*	56000	10.5	*27.0*	56000	10.5	*26.9*
Geared AC Motors	10728	12.0	*18.3*	53640	42.0	*25.7*	53640	42.0	*24.4*	40200	37.5	*25.4*	53640	42.0	*26.6*
Direct Drive AC Motors	5360	16.0	*14.0*	5360	16.0	*15.5*	13410	28.0	*17.5*	5360	16.0	*13.7*	5360	16.0	*10.0*
Direct Drive DC Motors				17700	140.0	*20.4*	17700	140.0	*18.6*						
DESIGN 4000															
High Speed Inline (UK)	2880	9.2		2880	9.2	*10.0*	2880	9.2		2880	9.2		2880	9.2	
High Speed Inline (all)	6600	19.0	*15.0*	6660	19.0	*16.0*	6660	19.0	*8.0*	6660	19.0	*13.0*	6660	19.0	*8.0*
High Speed Vee (UK)	9120	21.2	*16.0*	9120	21.2	*17.5*	9120	21.2	*11.2*	9120	21.2	*16.0*	9120	21.2	*11.2*
High Speed Vee (all)	19800	26.0	*21.7*	19800	26.0	*20.0*	19800	26.0	*17.3*	19800	26.0	*21.5*	19800	26.0	*21.0*
Medium Speed Inline (UK)	13410	59.1	*19.1*	13140	59.1	*18.5*	13140	59.1	*14.4*	13140	59.1	*19.1*	13140	59.1	*15.0*
Medium Speed Inline (all)	13410	59.1	*19.1*	21600	144.0	*20.5*	21600	144.0	*17.6*	19800	149.0	*21.5*	19800	149.0	*21.0*
Medium Speed Vee (UK)	12320	25.8	*17.0*	14080	54.5	*18.6*	23360	125.7	*17.7*	12332	38.6	*18.5*	14080	54.5	*15.6*
Medium Speed Vee (all)	12886	32.7	*17.3*	23000	218.0	*20.7*	30400	140.0	*19.2*	18360	58.0	*21.2*	23000	218.0	*21.8*
Gas Turbine Modules (UK)	56000	30.9	*25.5*	72420	42.3	*25.8*	72420	42.3	*23.5*	56000	30.9	*26.0*	72420	42.3	*26.8*
Gas Turbine Modules (all)	75440	21.1	*26.6*	75440	21.1	*26.0*	75440	21.1	*23.5*	75440	21.1	*27.4*	75440	21.2	*27.0*
Bare Gas Turbines (UK)	56000	10.5	*25.5*	72420	12.0	*25.8*	72420	12.0	*23.5*	56000	10.5	*26.0*	72420	12.0	*26.8*
Bare Gas Turbines (all)	56000	10.5	*25.5*	72420	12.0	*25.8*	72420	12.0	*23.5*	56000	10.5	*26.0*	72420	12.0	*26.8*
Geared AC Motors	53600	42.0	*25.3*	53640	42.0	*24.2*	53640	42.0	*22.1*	53640	42.0	*25.8*	53640	42.0	*25.5*
Direct Drive AC Motors	5360	16.0	*14.0*	13410	28.0	*18.5*	13410	28.0	*14.4*	5360	10.0	*25.8*	13410	28.0	*15.0*
Direct Drive DC Motors				17700	140.0	*19.7*	17700	140.0	*17.1*	17700	140.0	*21.1*	17700	140.0	*20.8*
DESIGN 5000															
High Speed Inline (UK)	2880	9.2		2880	9.2		2880	9.2		2880	9.2		2880	9.2	
High Speed Inline (all)	6600	19.0	*14.0*	6660	19.0	*15.0*	6660	19.0		6660	19.0	*10.0*	6660	19.0	
High Speed Vee (UK)	9120	21.2	*15.6*	9120	21.2	*17.0*	9120	21.2	*9.2*	9120	21.2	*14.0*	9120	21.2	
High Speed Vee (all)	19800	26.0	*21.6*	19800	26.0	*19.3*	19800	26.0	*15.0*	19800	26.0	*21.0*	19800	26.0	*18.0*
Medium Speed Inline (UK)	13410	59.1	*16.5*	13140	59.1	*18.2*	13140	59.1	*8.0*	13140	59.1	*18.2*	13140	59.1	*12.0*
Medium Speed Inline (all)	19800	149.0	*21.6*	21600	144.0	*20.7*	29700	205.0	*17.5*	19800	149.0	*21.0*	21600	144.0	*18.2*
Medium Speed Vee (UK)	23000	218.0	*22.0*	23360	125.7	*21.0*	23360	125.7	*16.0*	14080	54.5	*18.3*	21120	102.5	*18.2*
Medium Speed Vee (all)	23000	218.0	*22.0*	30400	140.0	*21.4*	30400	140.0	*17.6*	23000	218.0	*21.6*	30400	140.0	*22.6*
Gas Turbine Modules (UK)	56000	30.9	*24.7*	72420	42.3	*23.8*	72420	42.3	*21.2*	72420	42.3	*25.5*	72420	42.3	*25.5*
Gas Turbine Modules (all)	75440	21.1	*25.6*	75440	21.1	*24.7*	75440	21.1	*22.2*	75440	21.1	*26.0*	75440	21.1	*26.0*
Bare Gas Turbines (UK)	56000	10.5	*24.7*	72420	12.0	*23.8*	72420	12.0	*21.2*	72420	12.0	*25.5*	72420	12.0	*25.5*
Bare Gas Turbines (all)	56000	10.5	*24.7*	72420	12.0	*23.8*	72420	12.0	*21.2*	72420	12.0	*25.5*	72420	12.0	*25.5*
Geared AC Motors	53600	42.0	*24.5*	53640	42.0	*20.0*	53640	42.0	*20.5*	53640	42.0	*24.7*	53640	42.0	*24.7*
Direct Drive AC Motors	5360	16.0	*12.8*	13410	28.0	*18.2*	13410	28.0	*8.0*	13410	28.0	*18.2*	13410	28.0	*12.0*
Direct Drive DC Motors	17700	140.0	*21.2*	17700	140.0	*19.1*	17700	140.0	*14.0*	17700	140.0	*20.5*	17700	140.0	*14.0*

NB SHP is TOTAL installed metric HP; Weight (tonnes) is that of 1 motor only; Speed (knots) is that attained at 1.3(Naked EHP) and 70% OPC

It may also be seen that the values of sustained speed obtained in this study are rather low, and no machinery-ship combination is capable of speeds in excess of 30 knots. Speeds of this order are not unusual in certain roles for which SWATH ships are competing platforms. By combining output from more than one lower hull mounted prime mover, the top speeds of the larger vessels may be improved. For the smaller sizes, the required power can only be provided by employing box mounted machinery and bevel drives or (extending the discussion beyond its present constraints) advanced electrical motors.

Greater maximum SWATH speeds could be achieved by more radically contoured 'dogbone' hullforms, but in general it appears that single machinery installations in the lower hulls of SWATH ships are not suited for high speed applications. These conclusions are in agreement with the evidence provided by the machinery systems actually used to provide high speeds in the SWATH ships at sea.

Bare gas turbines offer the only possibilty of propelling a 1000 tonne hull above 20 knots. Various combinations of hullform and machinery exist to allow sustained speeds above 20 knots for the larger vessels, with upper values between 25 and 29 knots.

Not surprisingly, gas turbines offer the highest sustained speeds for all hulls. For the SWATH designs examined, a speed advantage of 6 knots over internal combustion engines is common. For the larger SWATHs, geared AC motors are the closest competitors, while high speed diesels are the best alternative in the smaller vessels. For the larger SWATHs, medium speed diesels offer higher speeds than high speed diesels because the latter are not marketed in very large powers. The medium speed engines are extremely heavy, and a lighter solution may be to combine two or more high speed units to provide the required power and utilise the space available in the larger hulls.

There appears to be a 4 or 5 knot difference in sustained speed available from UK produced high speed diesels and their international competitors. UK built medium speed diesels are competitive in the smaller vessel sizes, but show a speed disadvantage of about 3 knots at 5000 tonnes.

8.8 Conclusions

There is an extremely complex interaction between the design of a SWATH hullform and that of the machinery installation which requires careful attention. The study reported in this chapter has included a collection of machinery data at a level of detail sufficient for use by the SWATH designer. This data has been incorporated in a software tool to allow design of a machinery system for SWATH vessels.

The use of this tool has allowed the maximum powers which may be installed in the lower hulls of SWATH ships to be identified for a range of hull sections and machinery types. This study has shown that high speed diesels and bare gas turbines may be installed in normal SWATH hulls with displacements below 1000 tonnes. Lower hull mounted medium speed diesels are possible in vessels between 1000 and 2000 tonnes displacement. Geared AC motors become feasible about 1500 tonnes while modularised gas turbines may be fitted in SWATHs of 2000 tonnes.

Circular hulls allow greater powers for a given cross-sectional area than elliptical hulls for demihulls with sectional area below $10m^2$. For larger hulls, the situation is reversed, and non-circular hulls are most efficient in terms of attainable power density.

It has been shown that UK manufactured diesel engines offer considerably less power for a given hull size than their European competitors. For high speed vee engines the difference is of the order of 100% and restrictions on country of origin thus impose a significant penalty in the design of SWATH vessels for the Royal Navy .

Where they may be fitted, gas turbines provide the most power for a given hull size. It is not possible to fit modularised gas turbines in some smaller SWATHs where compact diesels may be fitted.

In a parametric study of 25 SWATH hullforms it was found impossible to provide a sustained speed of 30 knots with one prime mover per shaft in any of the designs studied. This particular study indicates that different hullforms can influence sustained speed as much by their effect on the size of propulsion unit as by their resistance characteristics. These factors indicate that in the 1000 to 5000 tonne size range considered, maximum speed becomes limited by lower hull volume rather than machinery weight.

Bare gas turbines are the only propulsion type to allow speeds in excess of 20 knots for the 1000 tonne hullforms considered. More conventional machinery types may be used to propel the larger vessels at speeds above 20 knots. Gas turbines offer the highest sustained speeds (between 25 and 29 knots), showing a speed advantage of about 6 knots over internal combustion engines for a given hullform. For larger SWATHs, geared AC motors are the closest competitors, while high speed diesels are the best alternative in the smaller vessels. UK produced high speed diesels give sustained speeds some 4 or 5 knots below those attained with European diesels.

Within the assumptions and limits of size of the present study it appears that three design decisions are necessary if SWATH ships are to attain speeds in excess of 30 knots; more than one motor may be fitted in each of the lower hulls, prime movers may be fitted in the box and more slender hulls employed, and/or radically contoured hullform designs may be used.

The data and software described in this chapter provide a basis for further study of the design of SWATH machinery. Further work is necessary to quantify the strut dimensions associated with different machinery schemes. Aspects of mechanical and electrical drive from box mounted prime movers should also be studied to determine the parameters of importance to the overall synthesis.

References to Chapter 8

1. Kennell, C.G. "Small Waterplane Area Twin Hull (SWATH) Combatant Ship Parametric Study", ASNE *Naval Engineers Journal*, October 1979

2. Gore, J.L. (editor), "SWATH Ships", *Naval Engineers Journal*, February 1985

3. Betts, C.V., Ferreiro, L.D., Grzeskowiak, S.R., McDonald, N.A. and Parlett, P.J., "Design Study for an Anti-Submarine Warfare SWATH Frigate", *Proceedings*, International Symposium on Anti-Submarine Warfare, RINA, London, May 1987

4. "Machinery in Ships Completed in 1985", *The Motor Ship*, February 1986

5. Palmer, S.J. "The Impact of the Gas Turbine on the Design of Major Surface Warships",*Transactions* RINA 1974

6. "Directory of World Propulsion and Auxiliary Machinery", Supplement to *The Motor Ship*, November 1985

7. "1986 Guide to Marine Engine Selection" Supplement to *Marine Propulsion and Small Boat International*, December 1985/January 1986

8. Various Marine Engine Manufacturer's Catalogues, 1985 and 1986

9. Bowes, J. and McNeill, D. "Machinery for Small Fast Warships", *Proceedings*, Symposium on Small Fast Warships and Security Vessels, RINA, 1978

10. Dawson, C. "Power for Fast Attack Craft", *Combat Craft*, September 1983

11. McLeavy, R. (editor) "Powerplants", *Jane's Surface Skimmers 1985*, Jane's Yearbooks

12. McLeavy, R. (editor) "Air Cushion Vehicle and Hydrofoil Powerplants", *Jane's Surface Skimmers, Hovercraft and Hydrofoils 1973-74*, Jane's Yearbooks

13. Rolls-Royce Ltd, Various Documents including - MGT 5413/A (September 1984), MGT 5458 (April 1985), TJ 420 (1985), MGT 5444 (September 1985)

14. "The Spey Gas Turbine", Special Supplement to *Naval Forces* No. 1, 1986, Vol. VII

15. Rains, D.A. "Prospects in Naval Gas Turbine Power Plant Machinery", ASNE *Naval Engineers Journal*, April 1975

16. Leopold, R. "Gas Turbines in the US Navy: Analysis of an Innovation and it's Future Prospects as Viewed by a Ship Designer", ASNE *Naval Engineers Journal*, April 1975

17. Kordenbrock, J.U. and Harry, C.W. "The Arctic Surface Effect Vehicle Program", ASNE *Naval Engineers Journal*, April 1976

18. Conway, D.H. "The Marine Gas Turbine Reliability Data Program", ASNE *Naval Engineers Journal*, April 1976

19. Silver, S. and Lauriat, T.B. "The Avco Lycoming TF40B Marine Gas Turbine for the US Navy LCAC", *Proceedings*, High Speed Surface Craft Conference, London, 1983

20. Baskerville, J.E. and Quandt. E.R. "Future Propulsion Machinery Technology for Gas Turbine Powered Frigates, Destroyers and Cruisers", ASNE *Naval Engineers Journal*, March 1984

21. Sammis, G.G., Gaylo, C.M. and Toth, J. "Power Transmission Options for Large Naval Hydrofoil Ships", Paper 78-758, AIAA/SNAME Advanced Marine Vehicles Conference, San Diego, 1978

22. Harrington, R.L. (editor), *Marine Engineering*, SNAME, New York, 1971

23. Johnston, R.J. and O'Neill, W.C. "A Ship Whose Time Has Come and Gone-*Plainview* (AGEH-1)", Paper 79-2020, AIAA/SNAME Advanced Marine Vehicles Conference, Baltimore, Md., 1979

24. Private Communication from YARD Ltd Surface Ship Machinery Group, YARD ref. Y86/DRMcK/JMcG/MD, May 1986

25. Barr, R.A. and Etter. R.J. "Selection of Propulsion Systems for High Speed Advanced Marine Vehicles", Paper 74-334, AIAA/SNAME Advanced Marine Vehicles Conference, San Diego, 1974

26. "Naval Propulsion Systems", Special Supplement - *Naval Forces* no.1, 1986, Vol. VII

27. "Propulsion Gears", Special Supplement to *Naval Forces* no.1, 1986, Vol. VII

28. "Lay-Out Options for Vessels with Wide Speed Ranges", *Marine Engineering/LOG*, April 1986

29. Private Communication from Richard Simpson, YARD Ltd Surface Ship Machinery Group, May 1987

30. Wadley, N.J. "The Diesel Engine for Powering High Speed Craft", *Proceedings*, Symposium on Small Fast Warships and Security Vessels, RINA, 1978

31. Ballantine, N.J.H. "The Compact Gas Turbine for Powering Small Fast Ships", *Proceedings*, Symposium on Small Fast Warships And Security Vessels, RINA, 1978

32. Simpson, R.R., "SWATH Machinery Installation Study", YARD Report 3236, 1987

33. Holcomb, R.S. and Allen, R.G., "Investigation of the Characteristics of Small SWATH Ships Configured for United States Coast Guard Missions", DTNSRDC Report Number SDD-83-3, June 1983

34. Plumb, C.M., "Propulsion of ASW Vessels", *Proceedings*, International Symposium on Anti-Submarine Warfare, RINA, London, May 1987

35. Narita, H et al "Design and Full Scale Test Results of Semi Submerged Catamaran (SSC) Vessels", *Proceedings*, 1st International Marine Systems Design Conference, London, 1982

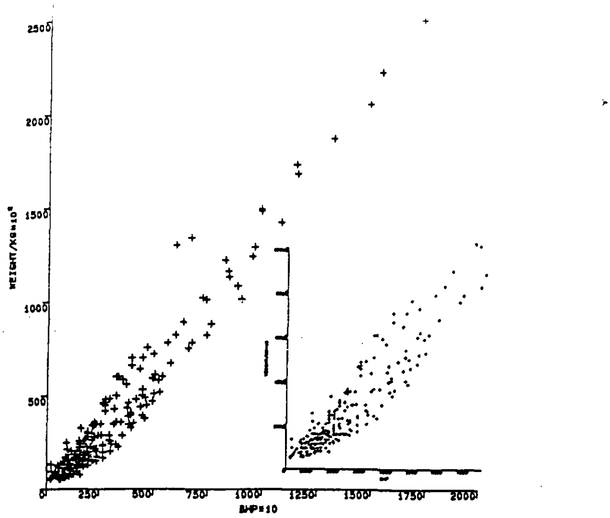
36. Fenner Wedge Belt Drives, J. H. Fenner & Co., Hull, 1987

37. Parsons, M "Informal Notes for NA330 Ship Power Systems 1", Department of Naval Architecture and Marine Engineering, University of Michigan, 1977

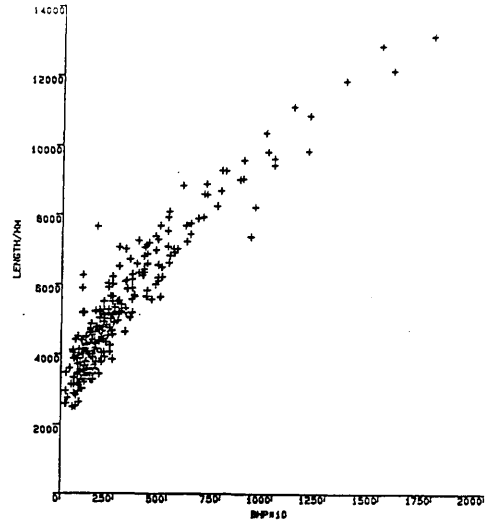
38. "Fast Displacement Catamaran 400", FBM Ltd, Cowes, November 1988

39. McCann, Mole "Superconducting Electric Propulsion Systems for Merchant and Naval Ship Concepts", *Transactions* SNAME, 1973

40. Acker, F.E., Greene, D.L. and Jolliff, J.V., "Modelling of Weight and Volume for Advanced Alternating Current Electric Drive Machinery", ASNE *Naval Engineers Journal*, May 1983



WEIGHT VERSUS BHP
MEDIUM SPEED DIESELS
INLINE CONFIGURATION



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MEDIUM SPEED DIESELS
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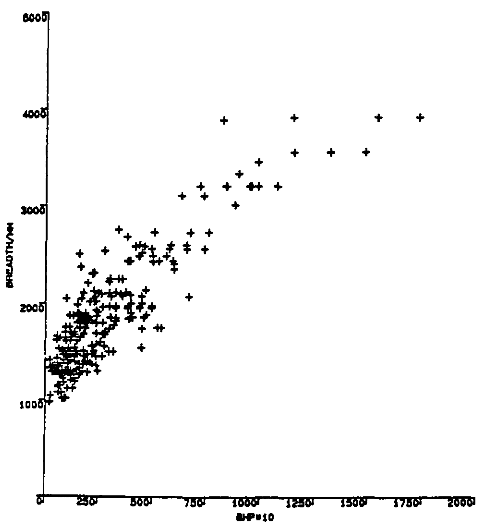

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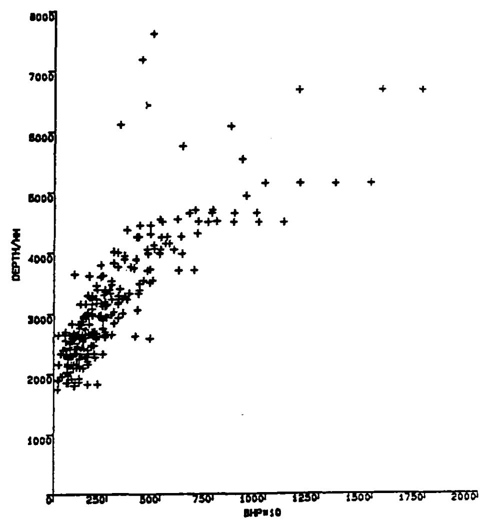
MEDIUM SPEED DIESELS
INLINE CONFIGURATION



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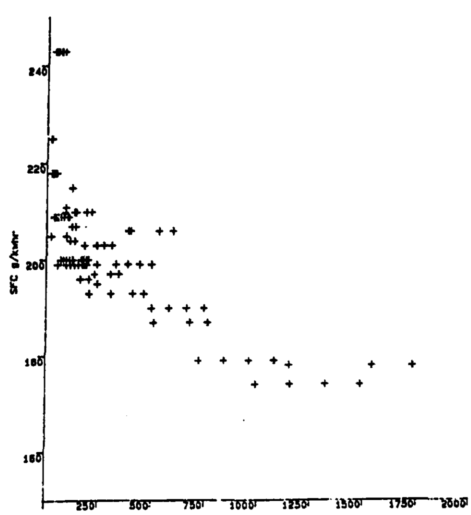
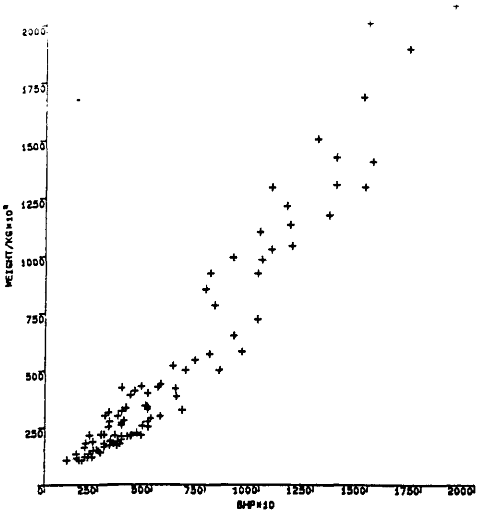


SFC VERSUS BHP
MEDIUM SPEED DIESELS
INLINE CONFIGURATION

Figures 8.1 to 8.5 Particulars of Medium Speed Inline Motors



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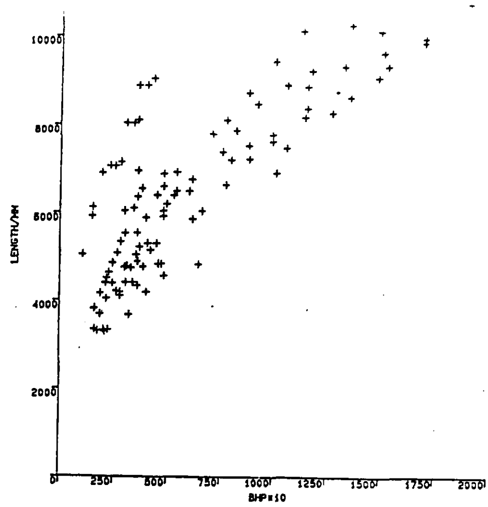
MEDIUM SPEED DIESELS
VEE CONFIGURATION



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MEDIUM SPEED DIESELS
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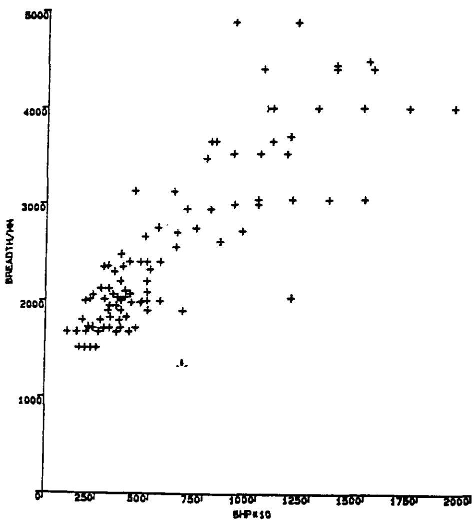

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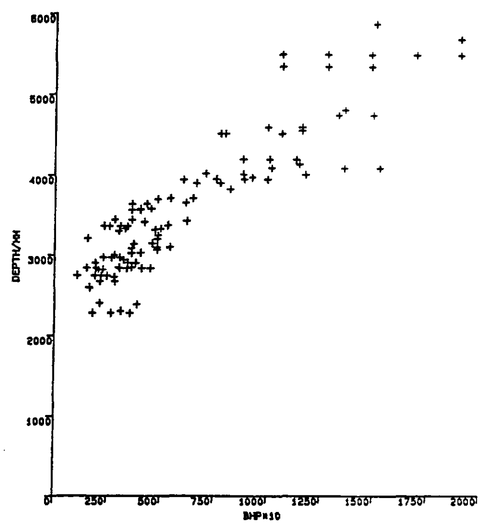

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MEDIUM SPEED DIESELS
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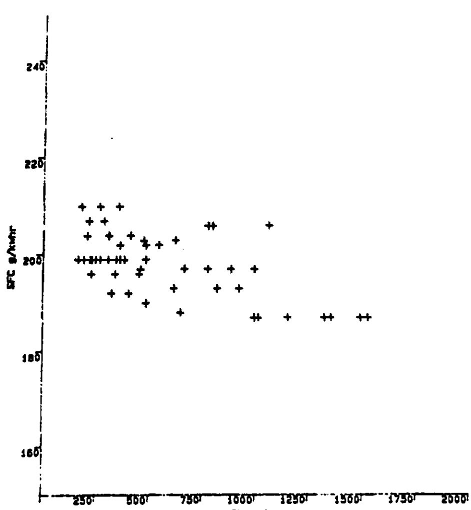
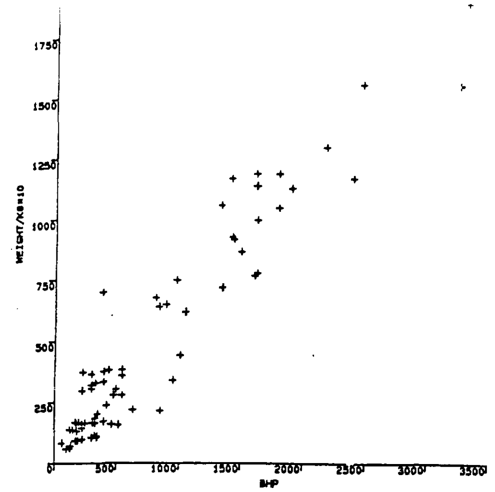
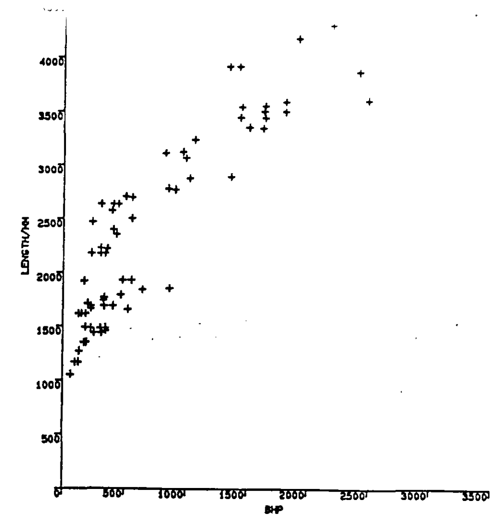


SFC VERSUS BHP
MEDIUM SPEED DIESELS
VEE CONFIGURATION

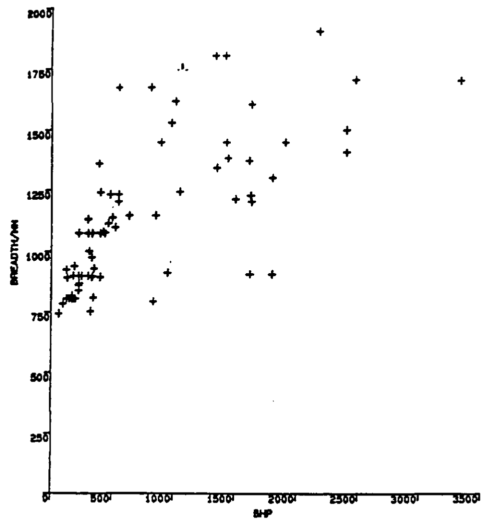
Figures 8.6 to 8.10 Particulars of Medium Speed Vee Motors



WEIGHT VERSUS BHP
HIGH SPEED DIESELS
INLINE CONFIGURATION



LENGTH VERSUS BHP
HIGH SPEED DIESELS
INLINE CONFIGURATION



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HIGH SPEED DIESELS
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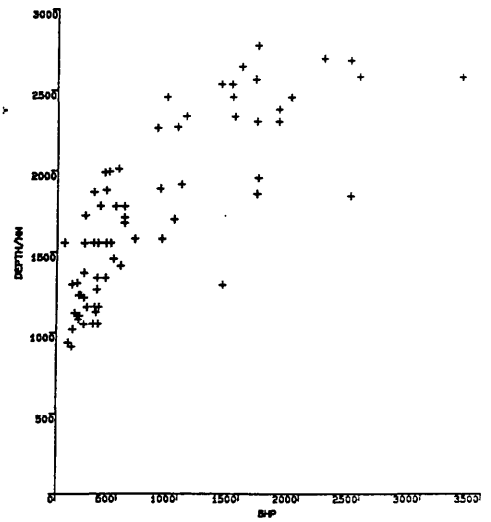

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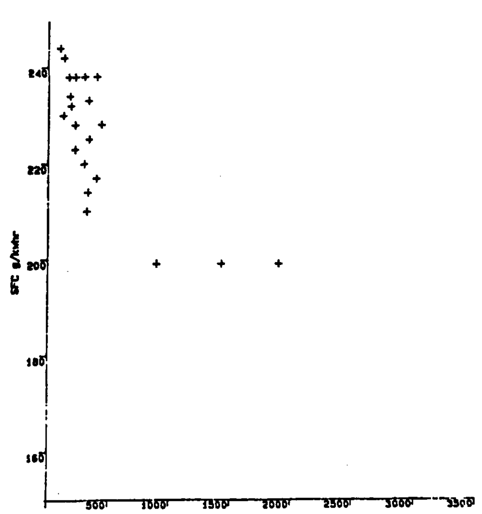

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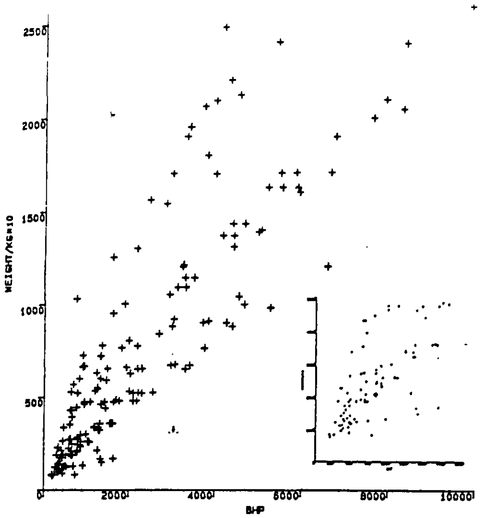
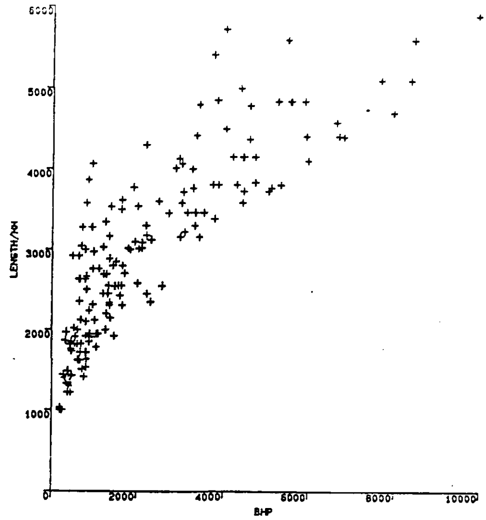
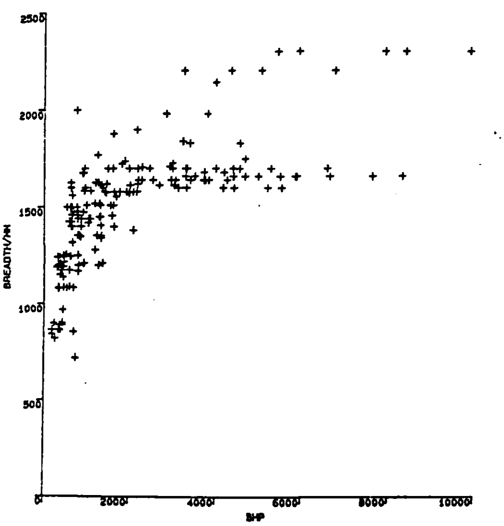
Figures 8.11 to 8.15 Particulars of High Speed Inline Motors



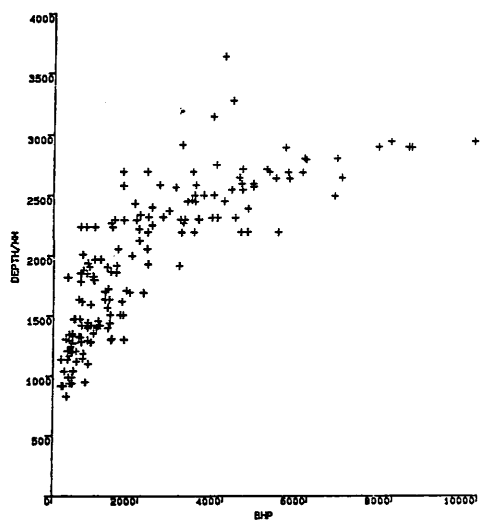
WEIGHT VERSUS BHP
HIGH SPEED DIESELS
VEE CONFIGURATION



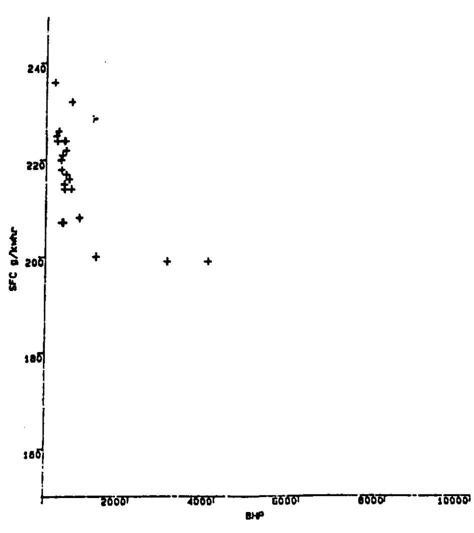
LENGTH VERSUS BHP
HIGH SPEED DIESELS
VEE CONFIGURATION



BREADTH VERSUS BHP
HIGH SPEED DIESELS
VEE CONFIGURATION



DEPTH VERSUS BHP
HIGH SPEED DIESELS
VEE CONFIGURATION



SFC VERSUS BHP
HIGH SPEED DIESELS
VEE CONFIGURATION

Figures 8.16 to 8.20 Particulars of High Speed Vee Motors

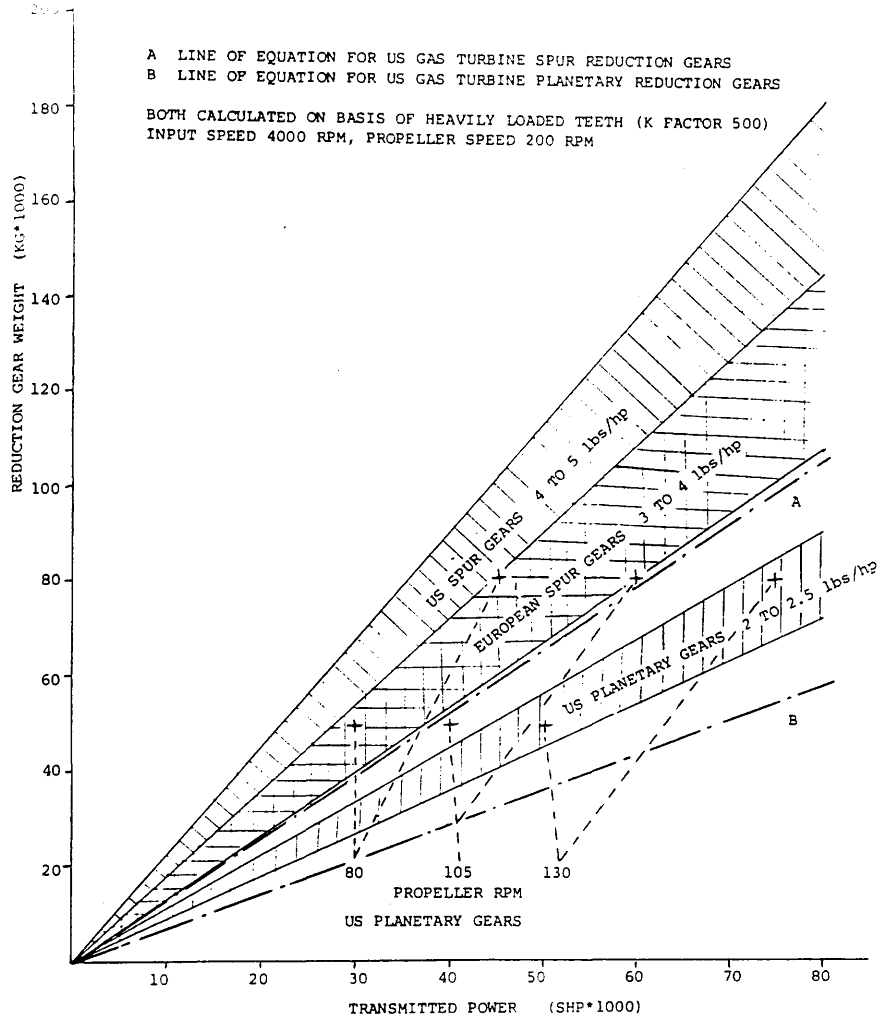


Figure 8.21 Comparison of Reduction Gearbox Weight Estimates

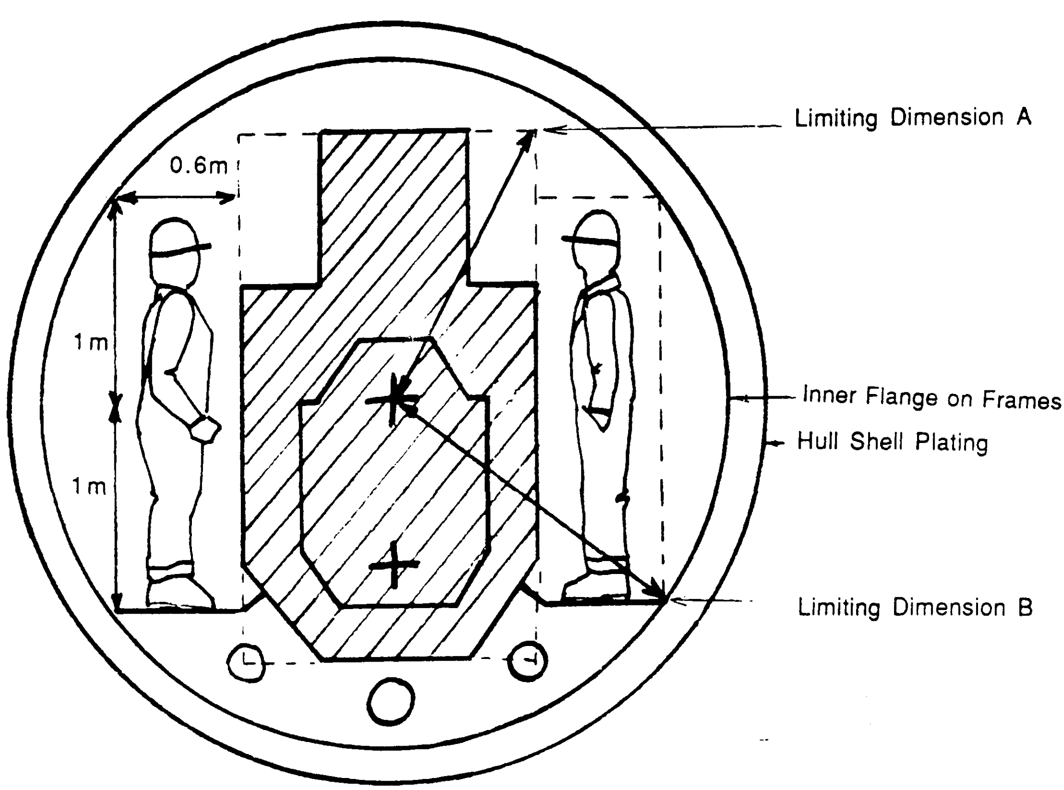
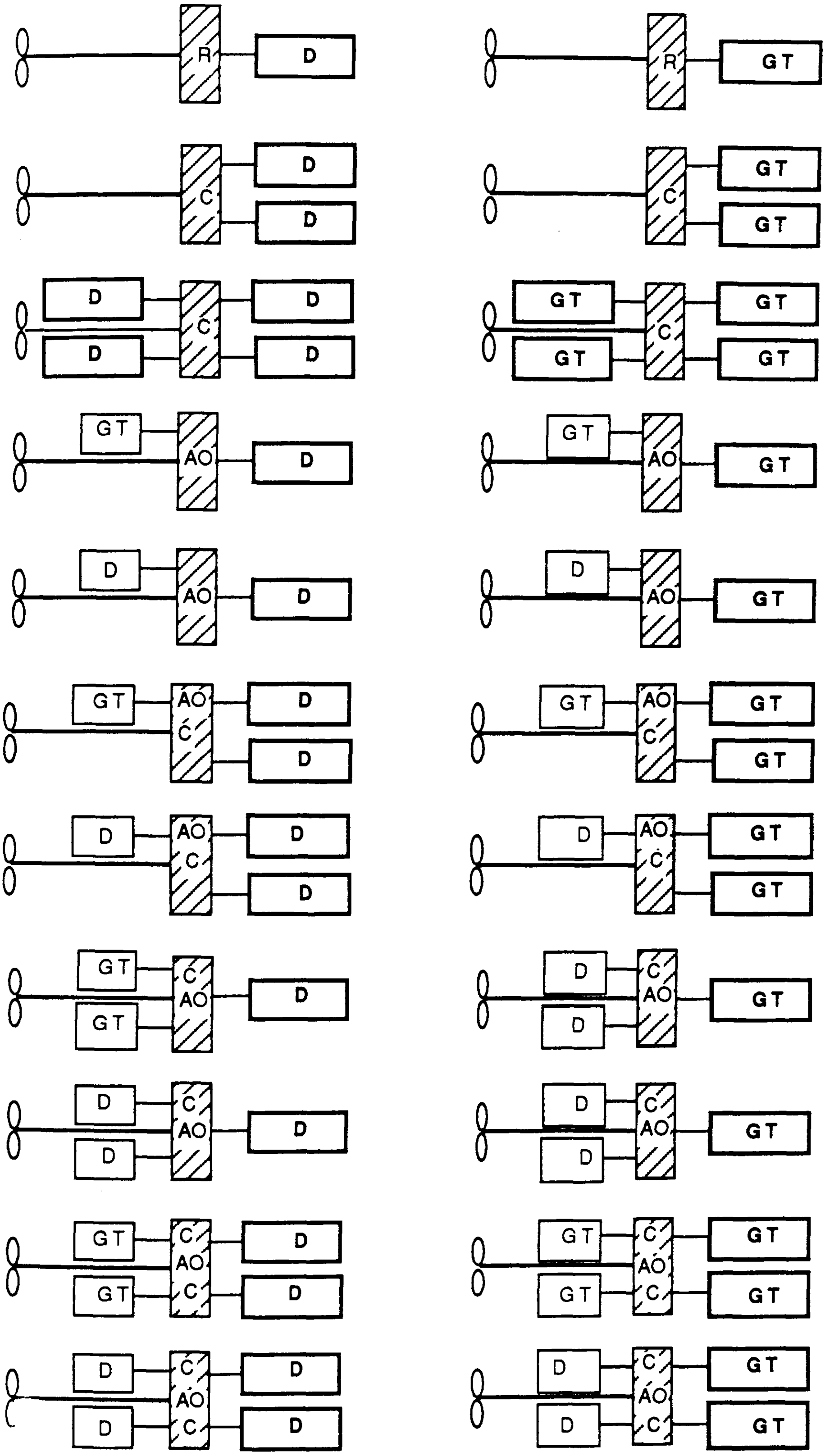


Figure 8.22 Critical Dimensions in Machinery Installation Study



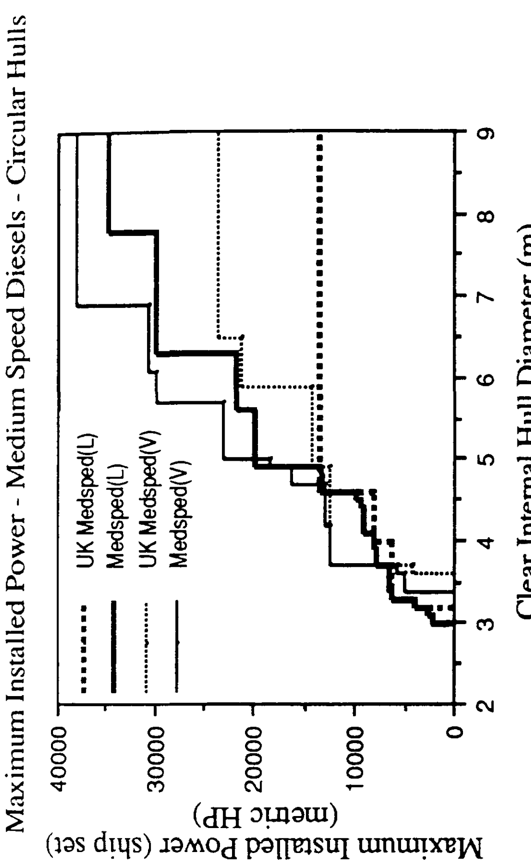
N.B. [box] indicates a main engine, which may be diesel (D) or gas turbine (GT).

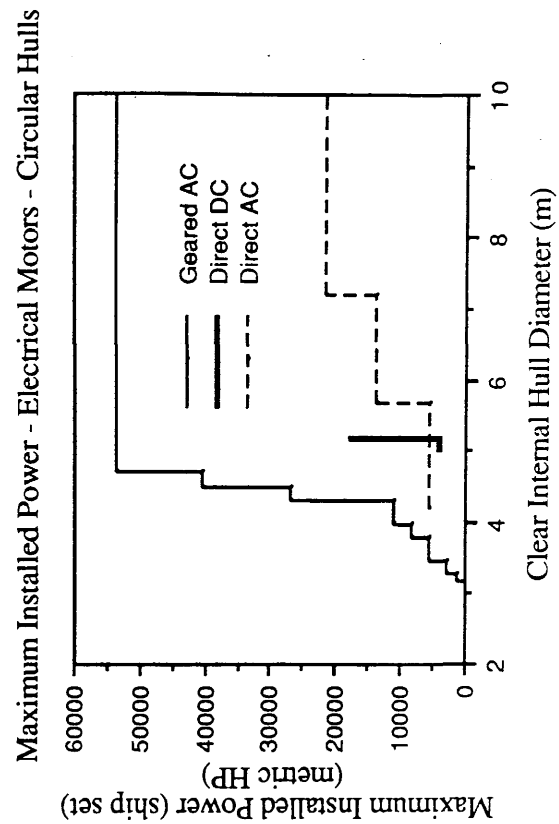
[box] indicates a cruise and/or boost engine, which may be diesel (D) or gas turbine (GT).

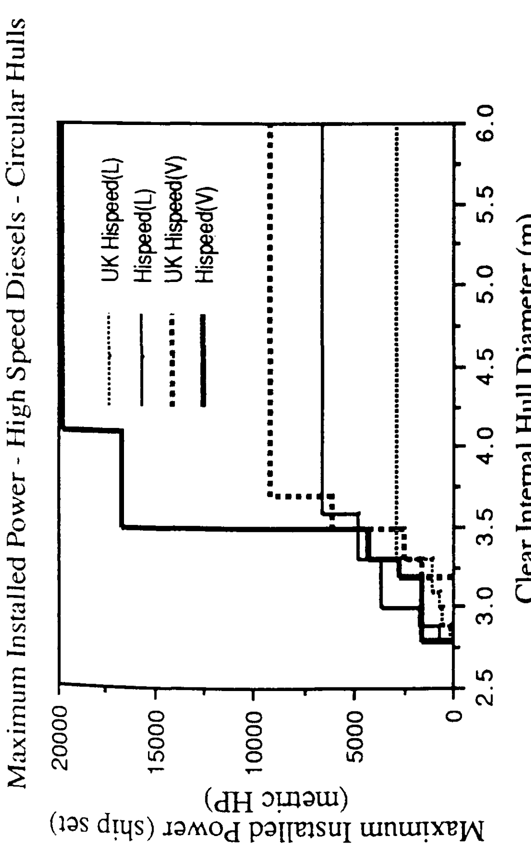
[hatched box] indicates a gearbox, which may be simple reduction (R), combining (C), an AND/OR unit (AO), or a system which combines (C) and also allows cruise or boost power (AO)

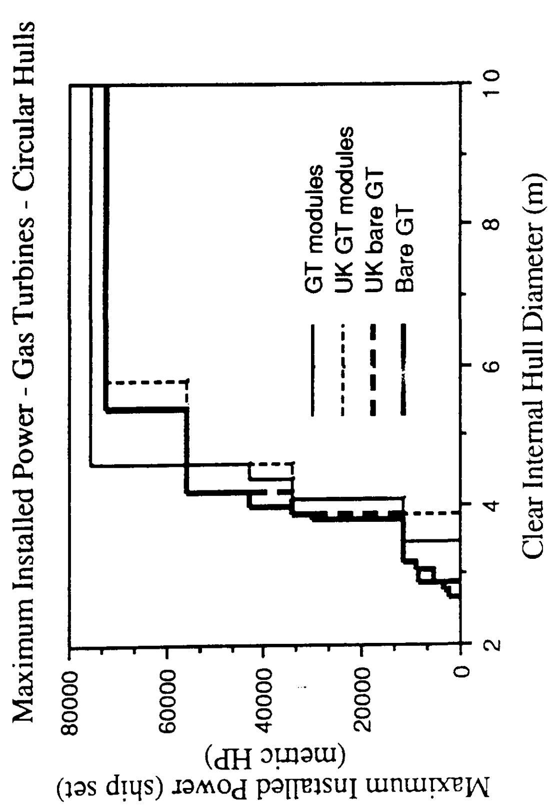
Figure 8. 23 Machinery Installations Permitted by Design Software

Figures 8.24 to 8.27 Maximum Installed Powers - Circular Hulls

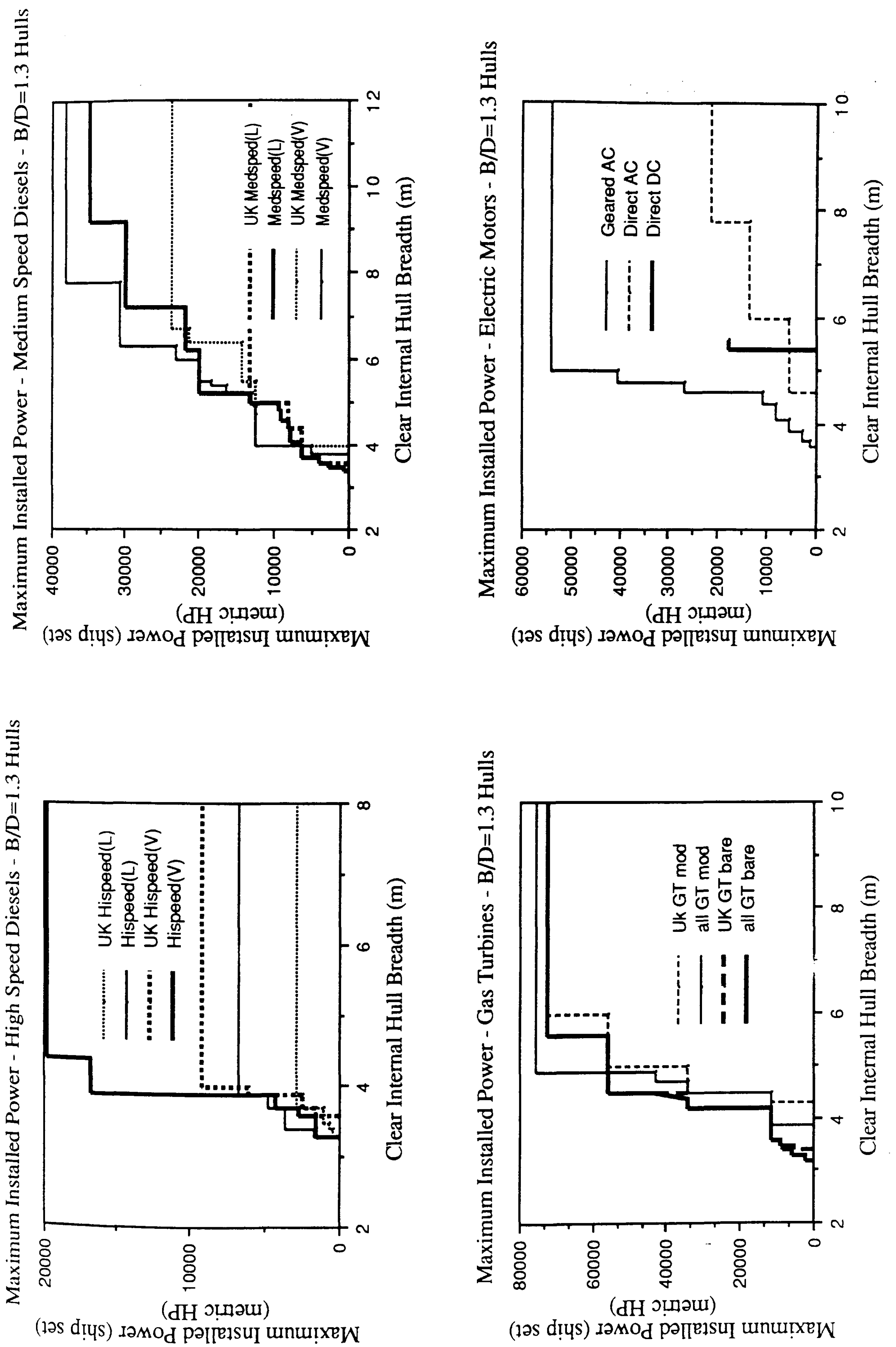




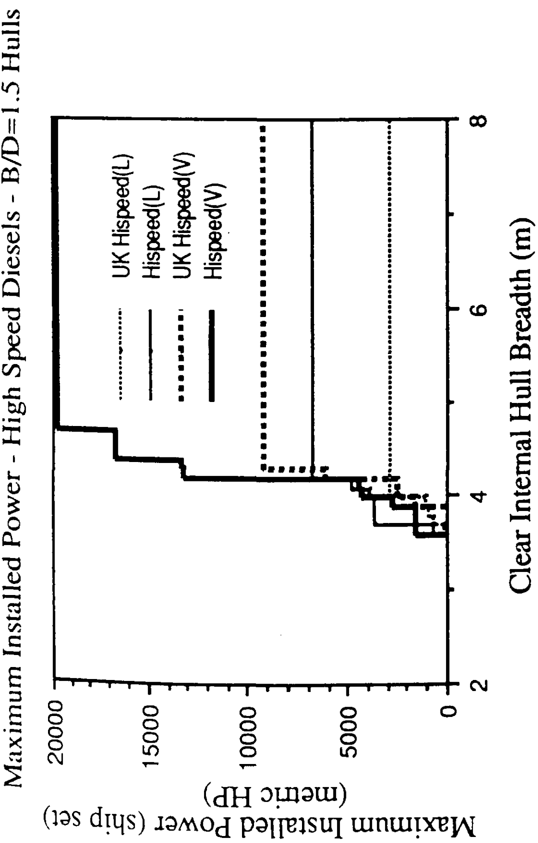


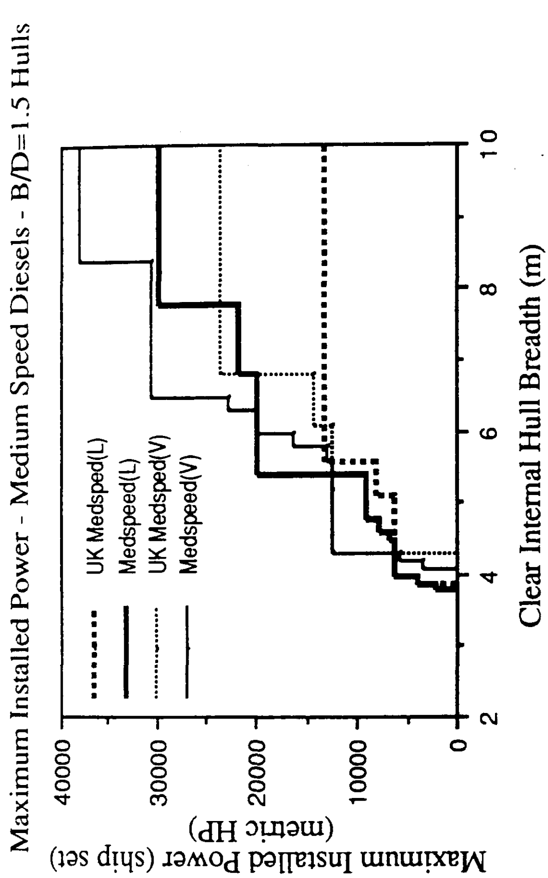


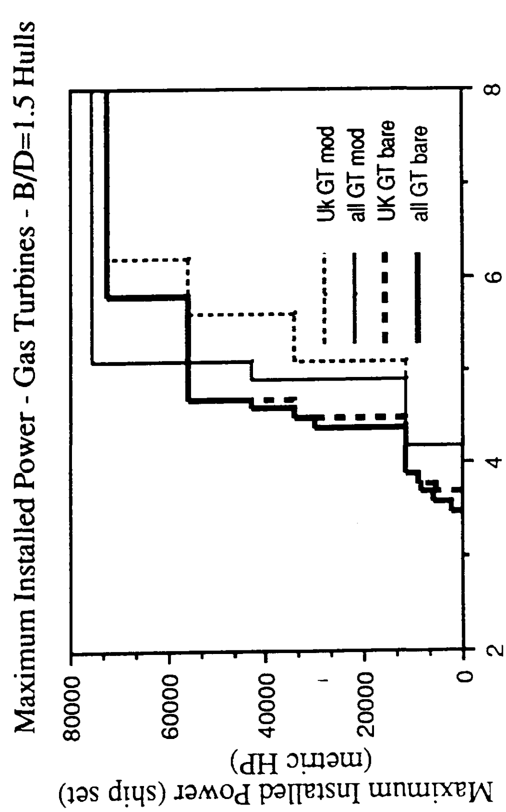
Figures 8.28 to 8.31 Maximum Installed Powers - B/D=1.3 Hulls

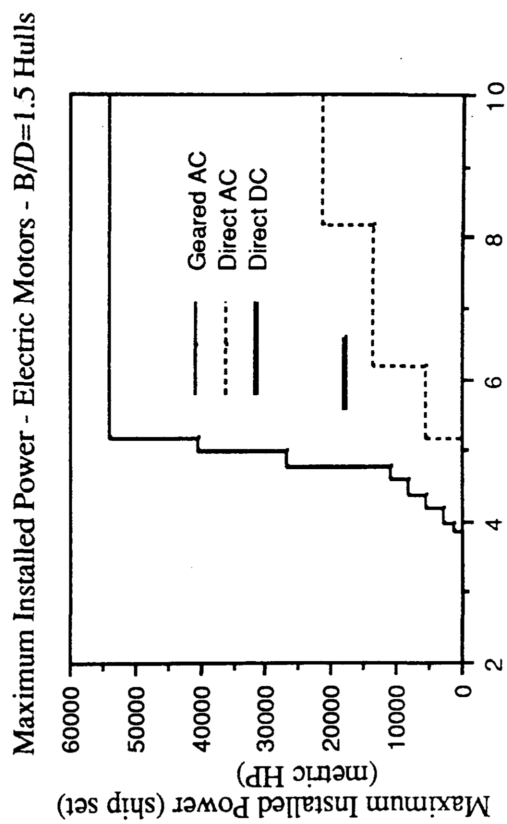


Figures 8.32 to 8.35 Maximum Installed Powers - B/D=1.5 Hulls









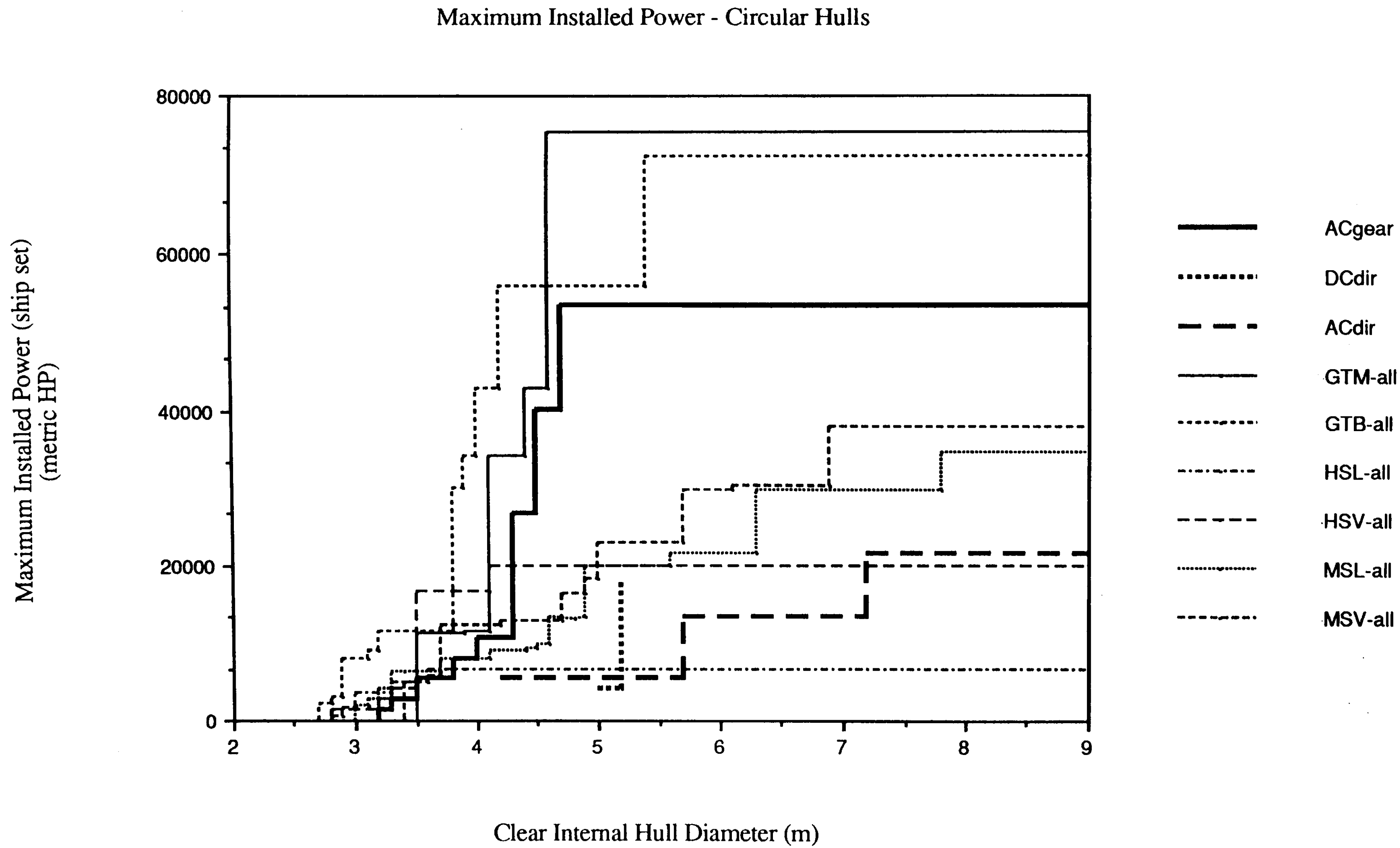


Figure 8.36 Comparison of Installed Powers by Machinery Type - Circular Hulls

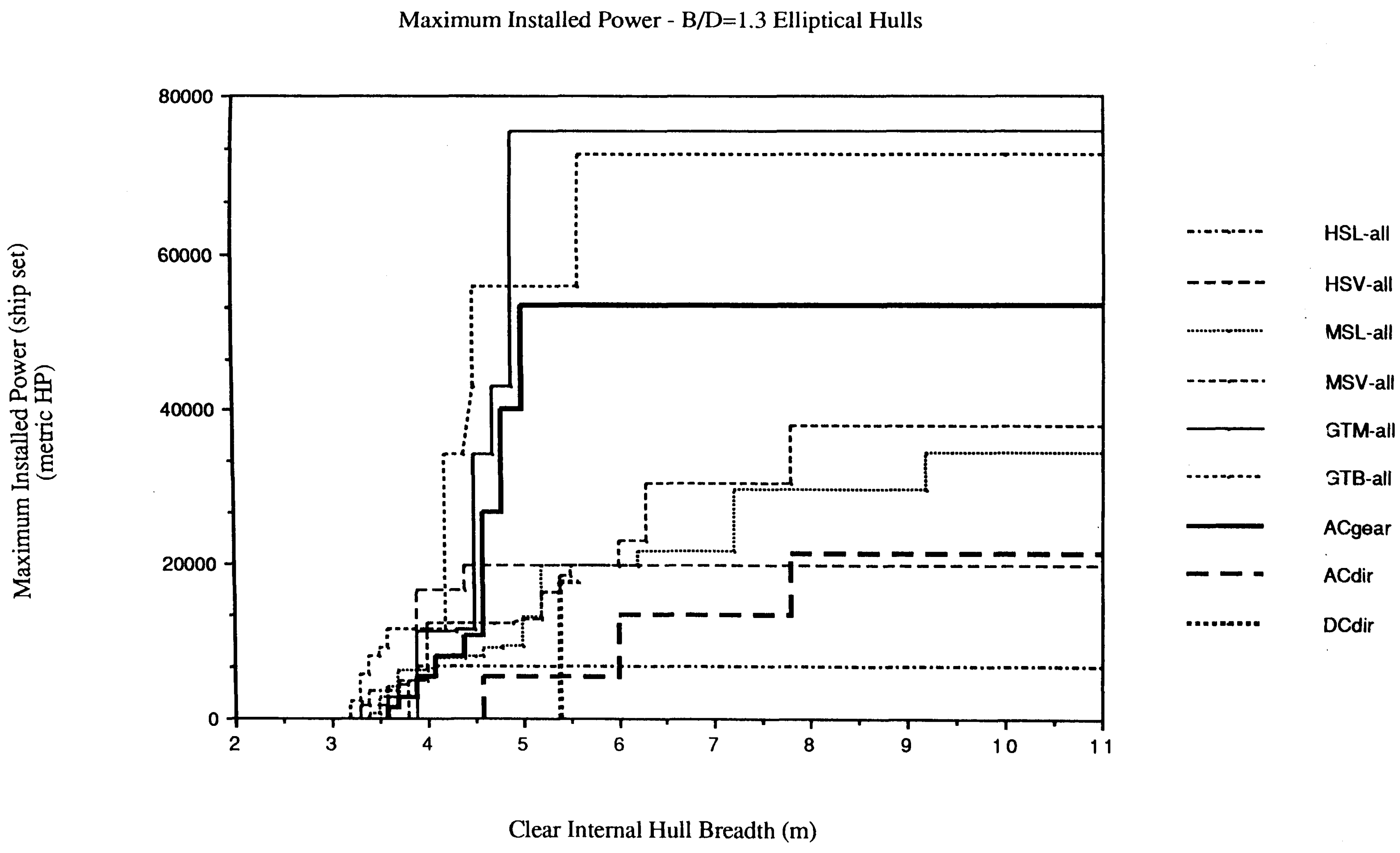


Figure 8.37 Comparison of Installed Powers by Machinery Type - B/D=1.3 Hulls

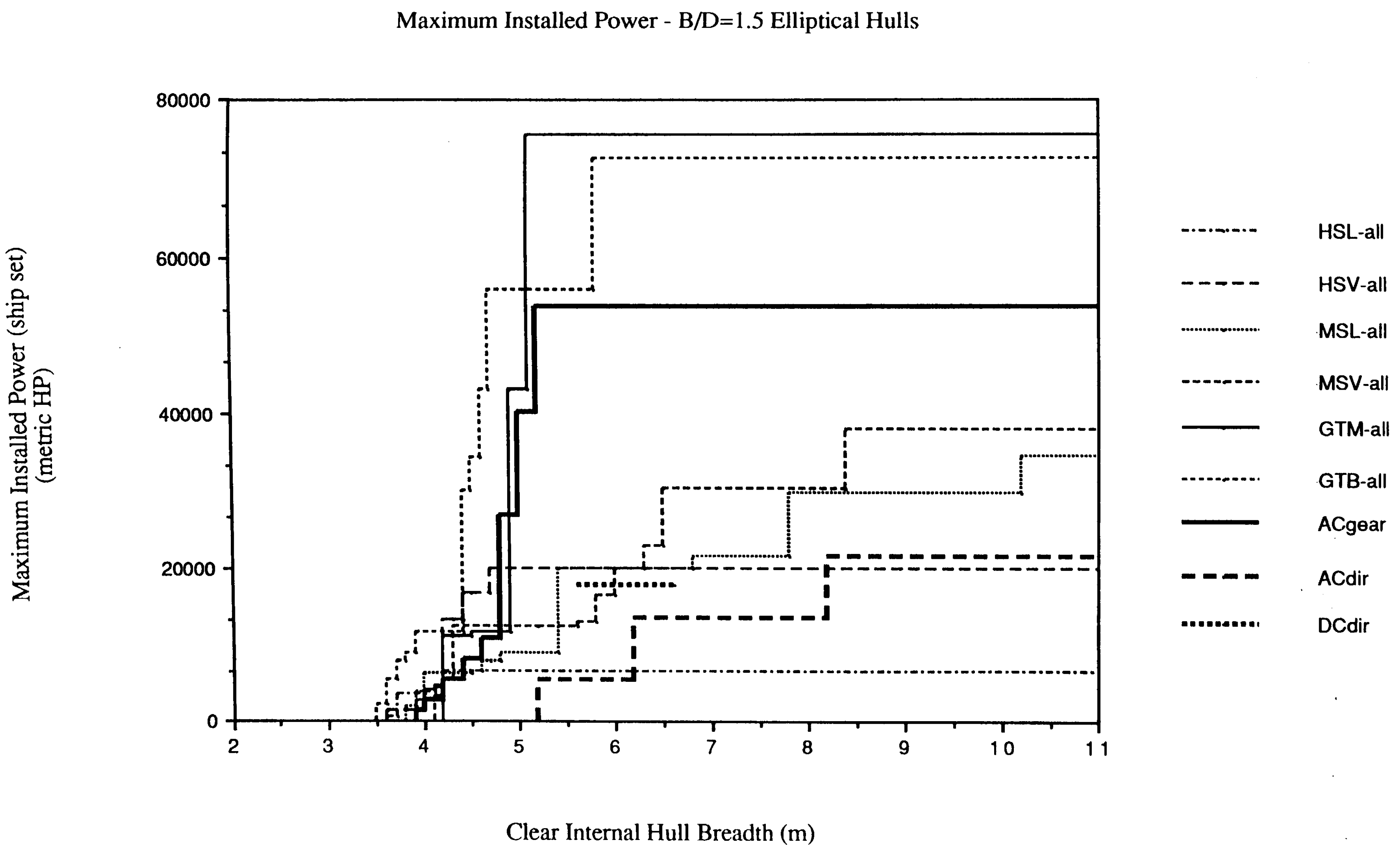


Figure 8.38 Comparison of Installed Powers by Machinery Type - B/D=1.5 Hulls

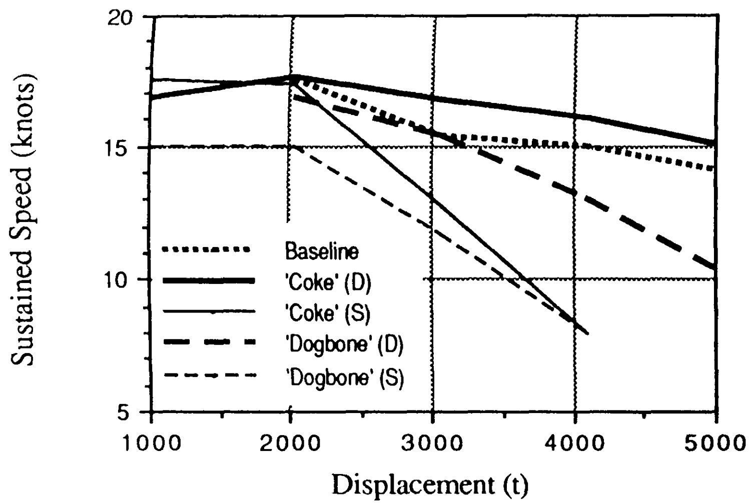


Figure 8.39 Sustained Speed - High Speed Inline Diesels

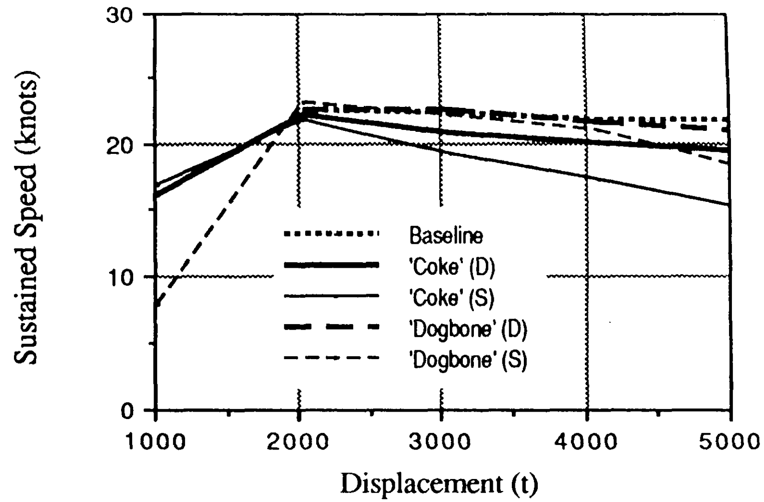


Figure 8.40 Sustained Speed - High Speed Vee Diesels

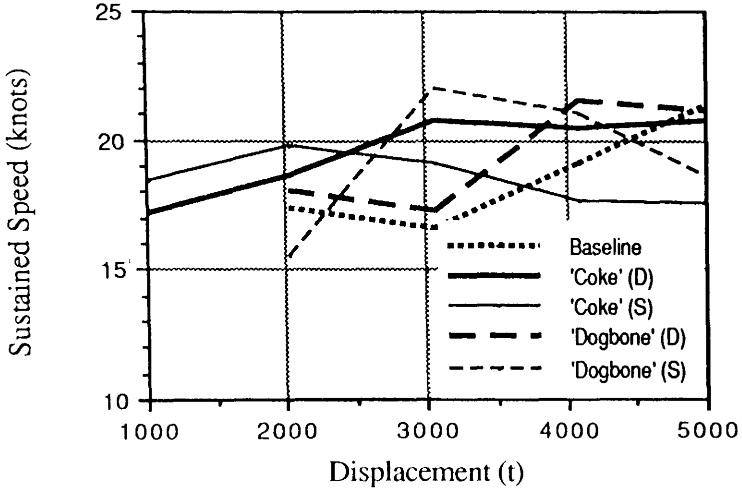


Figure 8.41 Sustained Speed - Medium Speed Inline Diesels

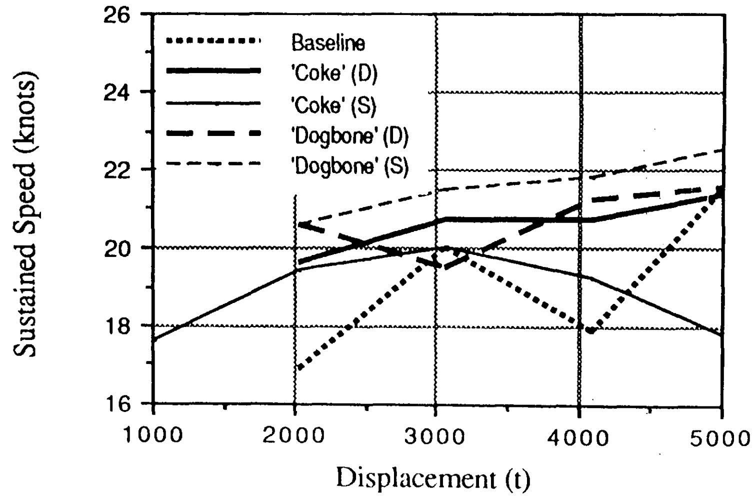


Figure 8.42 Sustained Speed - Medium Speed Vee Diesels

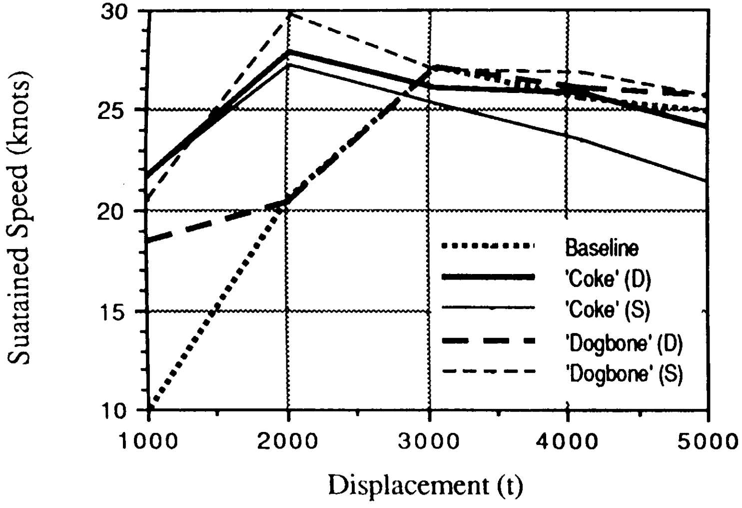


Figure 8.43 Sustained Speed - Bare Gas Turbines

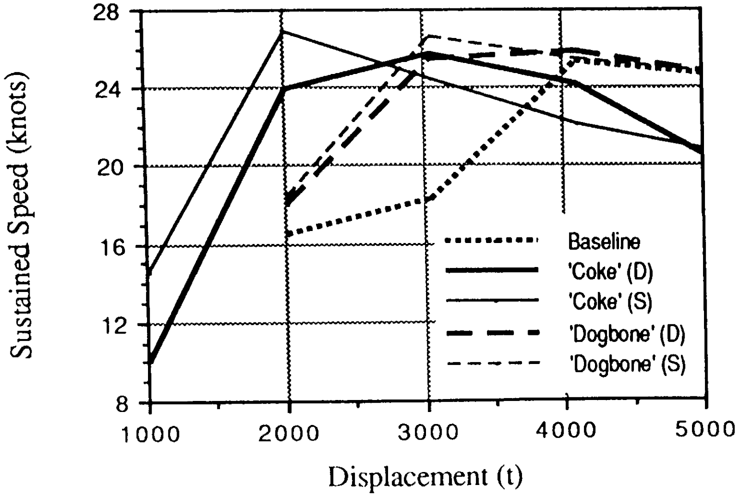


Figure 8.45 Sustained Speed - Geared AC Motors

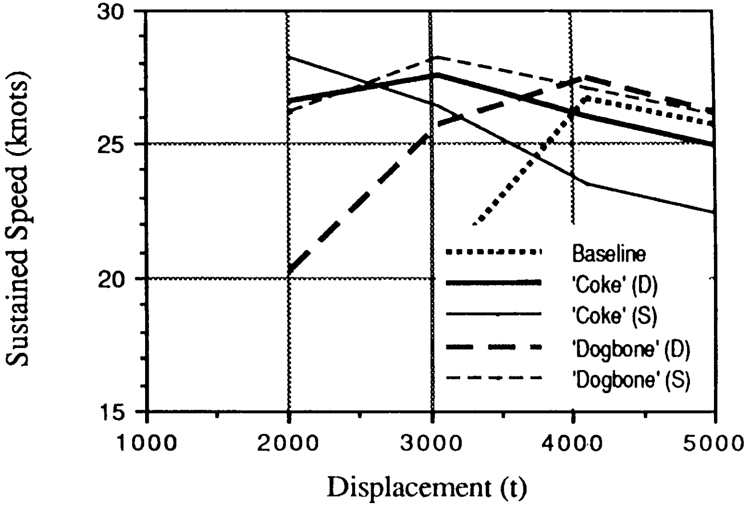


Figure 8.44 Sustained Speed - Gas Turbine Modules

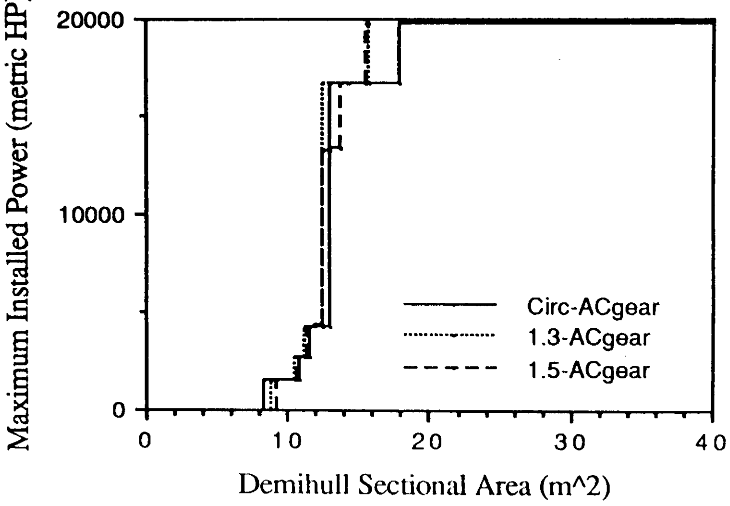


Figure 8.46 Effect of Hull Shape on Maximum SHP - Geared AC Motors

CHAPTER 9

STRUCTURAL WEIGHT ESTIMATION

A method for estimating the structural weight fraction of SWATH ships is developed. Design for primary wave loading and slamming impact is considered. The validation of this tool and its use in parametric studies is described.

9.1 Introduction

The increased weight sensitivity and high structural weight fraction associated with the SWATH form require the viability of the hull structure to be verified early in design. As with any semi-submersible, errors in the structural weight estimate will have a major bearing on performance and payload. A reliable means of estimating structural weight is therefore an essential component of a SWATH synthesis tool.

Early SWATH ship technology as promoted by Dr Lang and others claimed [1] that *'conventional naval ship design methods and the use of standard marine structural steels are not applicable to the semi-submerged ship structural concept'*. This philosophy, and the advanced lightweight designs it led to, were unpopular in the conservative ship design community. Current designs tend to employ conventional plate/stiffener structure and standard marine practices [2]. A comprehensive review of the state-of-the-art may be found in [34].

Despite this, it must be acknowledged [3] that current SWATH structural design criteria are largely empirical and there is little service feedback to inform the designer. Consequently, in any real design, it is ultimately necessary to estimate dynamic sea loads by available theory and employ finite element analysis and wave statistics to assess structural response [55].

Such methods are too computationally demanding for a synthesis model, where semi-empirical methods may be justified. This chapter describes a method for estimating the weights of the major components of structure at a preliminary stage in SWATH design.

9.2 Approximate Methods in Structural Weight Estimation

9.2.1 Gross Estimates of Structural Weight

The first decision facing a SWATH structural designer is the choice of material to employ. Figure 9.1 illustrates the speed-size envelopes in which the principal material types have been employed in previous designs. For example, while a balanced

SWATH design of 1000 tonnes and volumetric Froude Number 0.5 may be achieved using steel, it is unlikely that a Froude Number of 2.0 may be attained without resorting to aluminium or composite materials. An intermediate zone in which no particular material philosophy dominates is also evident.

As described in Chapter 4, a first estimate of structure weight may be made using structural weight fraction (SWF). For the three structural material options considered, SWF was found to decrease with increasing ship displacement.

Mild steel	$SWF = 0.425 - (1.75 \times 10^{-6})\Delta$	Eqn. 9.1
Hybrid/HY/HTS	$SWF = 0.417 - (8.50 \times 10^{-6})\Delta$	Eqn. 9.2
Aluminium	$SWF = 0.388 - (3.11 \times 10^{-5})\Delta$	Eqn. 9.3

where Δ is in tonnes

As will be demonstrated later, these equations are only valid for SWATH ships of normal proportions and vehicle densities (Δ/Volume). The weight fraction method is insensitive to enclosed volume changes at constant ship displacement and is unsuitable for use in a synthesis model of any sophistication.

A higher level of detail is offered by the volumetric density method. Table 9.1 lists structural weights, enclosed volumes and associated gross structural densities for a number of SWATH ships detailed in Appendix 1. Ideally, separate structural densities should be employed for the superstructure, box, struts and hulls as in references [10] and [21]. Information at this level is rare so gross structural densities have been plotted against displacement in Figure 9.2, where some broad trends may be discerned.

Table 9.1 SWATH Ship Structural Weight Data

Design Identification	Appendix 1 Number	Displacement (tonnes)	Enclosed Volume (m^3)	Ship Density (tonne/m^3)	Structure Weight (t)	Structural Fraction	Structural Density (kg/m^3)
Mild Steel Construction							
TAGOS-19	-	3450	16100	0.214	1593	0.4620	98.94
Navsea Frigate	72	7183	23135	0.310	2403	0.3345	103.87
UCL Frigate	90	5470	24500	0.223	1920	0.3510	78.37
Kaysen AGS	92	12786	42758	0.299	4090	0.3199	95.65
YSL SSV	103	2415	9229	0.262	1056	0.4373	114.42
MoD SSV	104	2330	7885	0.295	1056	0.4532	133.93
VSTOL Carrier	88	15067	68717	0.219	6297	0.4179	91.64
Aronne Ship A	49	4064	18673	0.218	1810	0.4450	96.93
Duplus	-	1300		-			126.50
Aluminium Construction							
USCG OPV	5	125	834	0.150	44.6	0.3568	53.48
USCG OPV	6	254	1682	0.151	78.6	0.3094	46.73
USCG OPV	7	765	5991	0.128	257.5	0.3366	42.98
USCG OPV	8	1270	8994	0.141	408.3	0.3215	45.40
Aronne Ship C	51	5334	20256	0.263	739.0	0.1385	36.48
HTS, HY, Hybrid Construction							
Bazan OPV	10	914	2638	0.346	267MS/HTS	0.2921	101.20
Aronne Ship A	49	4064	18673	0.218	1753HY100	0.4313	93.88
Aronne Ship A	49	4064	18673	0.218	1555HTS	0.3826	83.27
Aronne Ship A	49	4064	18673	0.218	1663HY80	0.4092	89.06
Aronne Ship C	51	5334	20256	0.263	1408HTS	0.2639	69.51
Aronne Ship C	51	5334	20256	0.263	1294HTS/Al	0.2426	63.88

Mild steel structural density	90 to 135 kg/m^3
Hybrid/HY/HTS structural density	65 to 100 kg/m^3
Aluminium structural density	35 to 55 kg/m^3

The available data indicates that for a given displacement and structural material, SWATH ships have higher structural densities than monohulls, which, with greater volume, leads to higher structural weight fractions. Use of HY/HT steels or hybrid material arrangements appears to permit structural densities similar to those achieved with contemporary naval monohulls. All material densities appear to decrease with increasing displacement and a regression on the data for mild steel SWATHs yields.

Mild steel SWATH structural density (t/m^3) = $0.116 - (2.03 \times 10^{-6})\Delta$ Eqn. 9.4

The concept of vehicle density (gross weight/enclosed volume ratio) has in the past been useful in the examination of gross vehicle efficiency. For a given mission, efficiently designed ships would be expected to have similar vehicle densities. Combining structural weight fraction, vehicle density and structural density (Figure 9.3) provides [4] a means of assessing relative efficiency of use of structural material. Although structural density is helpful in clarifying the efficiency with which material has been used, it does not differentiate between materials with different densities and strengths or the magnitude of the governing loads.

In general, for a given material type, the lowest structural weight fractions are associated with the highest vehicle densities and vice versa (relatively more material is required to enclose voluminous designs). Thus, although the DTRC VSTOL carrier design has a lower structural density (97kg/m^3) than the NAVSEA frigate design (104kg/m^3), the latter, by virtue of its greater vehicle density, is clearly superior. Interestingly, the UCL ASW frigate design opposes the general trends, comparing poorly with the NAVSEA frigate in terms of gross vehicle density, yet having the same structural weight fraction. A very low structural density is required to reconcile these figures. The diagram also offers an interesting comparison of design philosophies. It can be seen that although the MoD SSV design has the highest structural density in Table 9.1, it is comparable with the (volumetrically inefficient) equivalent YSL SSV in terms of structural weight fraction because its vehicle density is also the highest.

The approximate methods presented in this section provide a SWATH designer with rapid means of estimating and checking structural weights for a new design. It is suggested that new structural weight estimates which depart radically from the trends given in this section should be examined carefully. These methods are, however, inadequate in reflecting the many materials, loadings, and arrangements possible in preliminary SWATH design.

9.2.2 Scaling Scantlings from Previous Designs

In a manual preliminary design situation, it is possible to estimate scantlings for a new vessel by scaling from previous designs. *TAGOS-19* scantlings were scaled to give the first approach to the MoD SSV structural design [6]. Midship sections for several of the designs in Appendix 1 are available for use in this situation. These are *Duplus/Twin Drill* [5], *Halcyon* [7,8], *TAGOS-19* [9], and the designs for the BAZAN OPV [10], PAMESCO crew boat [11], DTRC VSTOL carrier [12], UCL ASW frigate [13], two Korean ferries [14,15], and two SSV concepts from YSL [16] and MoD [17]. Useful guidance on structural arrangements may be obtained from these sources, some of which are more reliable than others. Existing SWATH vessels offer the best 'type' ships, probably followed in order of reliability by the designs from DTRC and MoD, on the grounds that these institutions had access to the greatest degree of expertise and experience. Catamaran design experience [63,64] may also prove useful.

9.3 Structural Weight Estimation in SWATH Synthesis Tools

9.3.1 DREA CEM for SWATH Ships

The DREA CEM for SWATH ships [18] estimates gross structural weight using structural densities for the box, struts and hulls which may be input by the user or computed from programmed algorithms. The latter were developed from studies (using the US Navy Structural Synthesis Design Program [22]) of the weights of plating, bulkheads and decks for a number of SWATH designs.

9.3.2 Boeing/DTRC *ASSET-SWATH* Program

This synthesis program [19] employs a rational approach to determine scantlings and thus derive structural weights at the US Navy SWBS 3 digit level. User inputs are material types, loading conditions, and structural design factors. The only primary loading considered by the program is that of transverse bending which may be input directly, or calculated according to Sikora and Dinsenbacher [56].

Primary stresses in the box and strut grillages due to bending and shear are calculated using simple beam theory. An option to account for stress concentrations near transition points is available. An initial value of smeared thickness is incremented in commercially available steps until stresses due to primary loading are acceptable. With specified stiffener shape and spacing, frame dimensions may be estimated. Secondary loads are then applied and the plate/stiffener combination designed for uniform pressure under fixed-end conditions. If stresses under combined primary and secondary loads prove excessive, the smeared thickness is incremented and stiffener details proportionately increased.

Transverse bulkheads and decks in the lower hull are designed for pressure loads while the shell is designed for combined primary and secondary loading. Superstructure weight is estimated simply on the basis of volumetric density.

A weight minimisation module iterates the complete procedure between specified bounds on stiffener spacing in an attempt to find a minimum weight configuration.

9.4 Other SWATH Structural Design Programs

9.4.1 General Methods

An examination of some computer based methods for SWATH structural design has helped to formulate the design of the current tool.

The US Navy Structural Synthesis Design Program (*SSDP*) [21,22] was adapted for SWATH ships in 1972. This program incorporates all current USN structural design criteria and makes special allowance for stress concentrations in SWATH. Use of the *SSDP* permits rapid estimates of the primary structural weights of many configurations, and is suitable for use in parametric studies.

In the UK, the monohull ultimate strength program *NS94* developed [23] at ARE(D) has been modified [24] to analyse the strength of a transverse SWATH section.

The *MAESTRO* structural optimisation program [26] has been used in the UK [24] and US [25] on SWATH design studies. Based on a coarse finite element analysis and evaluations of yield, buckling, and plastic collapse limit states, it has proved useful in highlighting potential areas of concern at a relatively early stage in design.

In 1983 the US Navy developed [2] a preprocessor for the *NASTRAN* finite element method requiring only a modest amount of SWATH input data to create a model half the transverse bulkhead spacing in length. This tool may be used to examine means of reducing structural weight fraction and to develop new structural concepts. A similar effort is being proposed [24] in the UK.

9.4.2 UCL SWATH Structural Design Program

This computer program [20] is similar in approach to *SWATH-ASSET* (section 9.3.2), but does not consider secondary loads or the effect of different framing arrangements. Smeared thicknesses and weights of major structural elements are outputs of the system. In principle, this approach is suited to use in a SWATH synthesis model.

9.4.3 USCG Small SWATH Structural Design

Allen and Holcomb, in their design of small, lightweight structure, SWATH OPVs, described [27] a structural design approach using a computer program which first estimated scantlings using panel area 'densities' from [28] for plating under predominantly uniformly distributed normal local pressure loads. These initial scantlings were then checked by application of transverse bending loads and, if stresses proved excessive, extra material added at extremities.

9.5 Design of a Structural Weight Module

9.5.1 Requirements

As far as *DESIN* is concerned, a structural weight module need only supply weights of structure at a level of detail sufficient for distribution in the UK NES or US SWBS weight classification systems (described in Chapter 10). An ability to deal with all the vessel geometries permitted by the hull definition method (Chapter 5) was specified. Flexibility in type and disposition of structural material was also required.

9.5.2 Basic Assumptions

For SWATH ships, the critical loading occurs in near beam seas at zero speed. This is in direct contrast to monohull experience. Wave induced bending combined with the effects of the box self weight and local wet deck slamming govern the scantlings of the cross structure. Longitudinal bending and shear are small in comparison, and design to meet transverse loading results in a structure with more than adequate longitudinal strength. Transverse bending is also important in the design of the struts. Hydrostatic pressure and docking loads determine lower hull scantlings.

Use of the *SSDP* in the USA has shown [21,57] that side load variation has relatively small influence on SWATH structural weight. This implies that most scantlings are governed by local loads. In the USCG OPV design study [27], hydrostatic pressure loads in the damaged condition were found to govern the majority of structural areas. These considerations led to a decision to design structure to local loads initially, and then check for adequacy under primary loading.

Transverse framing dominates current SWATH design. This is considered the method most suited to near-circular lower hulls and structure loaded primarily in a transverse direction. Acceptance of this practice is strongly based on the weight advantage (typically 7-10%) of longitudinal over transverse framing in primarily longitudinally loaded monohulls. There are also practical arguments in favour of transverse framing, mainly in terms of vertical access to machinery through the struts and hulls between frames.

Although Gupta [3] has reported a study on alternative framing arrangements[1] suggesting that longitudinal framing may be advantageous for SWATH ships, it was decided to restrict the present study to transversely framed vessels. This decision was taken because of the simplicity of analysing such structure using beam theory. Further study is required to clarify the uncertainties associated with SWATH structures in terms of weight and fabrication cost.

Quasi-static wave balance analysis [3] has shown that longitudinal bending moments for SWATH ships are typically about 10% of the transverse moments (this is a function of ship size). This, coupled with increased ship depth and section modulus, has led to the assumption that adequate longitudinal strength may be provided by the structure required to resist transverse loads.

It has been assumed that the dominant primary loading on SWATH ships occurs at zero speed in pure beam seas. This is in spite of new results [54] showing marginally increased loads for seas approaching from slightly off the beam.

9.5.3 Module Structure

The method developed for the structural design module *(STRUKT)* of *DESIN* is a combination of the techniques adopted in *ASSET* and the USCG design tool. The structure is split into a number of stiffened areas as illustrated in Figure 9.4. A variety of structural materials (listed in Table 9.11) may be selected for these areas. Panels are first designed to uniform local pressure loads, and primary stresses in the box and strut grillages due to bending and shear are then calculated using simple beam theory. Stress concentrations near transition points are dealt with by semi-empirical methods. Lower hull design to hydrostatic pressure is carried out using a rational method. Superstructure weight is estimated simply from structural density algorithms. Figure 9.5 illustrates the structure of the method, the various components of which are described in the following sections.

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[1] Transverse framing has primary frames running athwartships and vertically, acting as plate panel stiffeners. Longitudinal girders/stringers are provided to shorten the span of transverses. Transverse web frames are spaced to support longitudinals and resist lateral hull loads. Longitudinal framing has primary framing in a fore and aft direction, supported by deep web transverse frames, which are generally heavier than their transverse counterparts.

9.6 Initial Panel Sizing

As a first step towards determining adequate scantlings, smeared plate/stiffener thicknesses may be estimated from local loads, including slamming impact.

9.6.1 Standard Local Loads

Although a departure from traditional practice is required in the treatment of wave impacts on SWATH ship wet decks, standard monohull secondary design loads may be applied to most of the remaining stiffened structure. Table 9.2 lists some published secondary loads for SWATH ships.

Table 9.2 Secondary Design Pressures (in kPa) for SWATH Ships

Vessel	*Aronne A*	*Aronne B*	*Aronne C*	*VSTOL*	*ASSET#*
Main deck live load	14.37	14.37	12.20	47.89*	23.94
Second deck live load	7.184	7.184	7.184	-	7.184
Third deck live load	7.184	7.184	7.184	-	7.184
First strut platform live load	9.58	9.58	70.47	-	7.184
Second strut platform live load	11.97	11.97	96.51	-	7.184
Box bulkhead design load	-	-	-	-	10.06BD
Hull/strut transverse bulkhead load	............Hydrostatic head to main deck..........				-
Hull longitudinal bulkhead design load	............Hydrostatic head to main deck..........				-
Lower hull platform design loads	-	-	-	-	7.184

NB: * indicates load for aircraft carrier decks, # indicates *ASSET* algorithms [37], BD is box depth

For *STRUKT*, it was decided to employ the *ASSET* design loads, together with hydrostatic heads (to main deck) for strut and hull bulkheads, and independently derived slamming loads. These are then combined with the methods of section 9.6.3 to yield initial scantlings.

9.6.2. Slamming Loads

Wave impacts on the underside of the cross structure, occurring at low angles of incidence, can generate extreme dynamic pressures and loads. The structure must be designed against possible local damage, while overall hull strength may also be affected by increased moments, shears and vibration. This problem is inextricably linked to the overall structural design since increasing the box clearance to reduce impact pressures will tend to increase bending in the box structure due to the primary dynamic side loads.

It is recommended that full validation of any SWATH design should include a statistical analysis of slamming behaviour. This requires relative motion and velocity RAOs and appropriate random sea spectra to provide probabilities of occurrence of impact pressures. Ochi and Motter [39], Giannotti [40,41], and Kaplan [42] describe general approaches which can be combined with the results of Chuang [43] to give probabilistic estimates of SWATH cross structure slamming loads. However, these methods are unsuited to incorporation in a preliminary design system.

It did not prove possible to establish a simple relationship between slam pressure and principal SWATH design variables from the limited data (Table 9.4). In the absence of any published guidelines the well known semi-empirical technique of Allen and Jones [29] was implemented in the current synthesis model.

9.6.2.1 Background

This method is designer oriented, providing reasonable accuracy, without claiming to be exact. It is simple and straightforward, requiring minimal input and producing uniform equivalent static design pressures which can readily be used in conventional stress analysis. It is claimed to be reliable because it it based upon a solid foundation of experimental data as well as extensive analytical work by the authors [29].

Using a tool capable of calculating instantaneous three dimensional pressure distributions due to water impact, the authors found that maximum impact pressures act over relatively small areas of the hull, thus constituting a small portion of the total impact load. Conversely, smaller pressures were evident over a greater portion of the hull, and represented a higher percentage of the total load.

This yielded the concept of pressure reduction with increasing reference area, and the conclusion that average uniformly distributed pressures should correlate much more closely with measured structural responses in structural elements, than would peak pressures. Semi-empirical methods for estimating such average pressures were developed from analytical and experimental data for a number of vehicles.

9.6.2.2 Implementation of Allen-Jones Design Method

In the following, the method of Allen and Jones as implemented in the present study is described. Reference [29] should be consulted for a detailed explanation of the technique.

A uniform equivalent static pressure P_D is defined as that pressure, which if applied to the structural component, would result in approximately the same deformation and maximum stress as produced by the actual loading on the structure. Table 9.3 defines the design reference areas associated with the principal structural elements.

Table 9.3 Definitions of Design Reference Area A_D

Component	*Design Reference Area*	*Approx. Relative Area*
Plating	product of unsupported plate dimensions	1
Longitudinal Stiffener	product of minimum unsupported stiffener length and the longitudinal stiffener spacing	1
Transverse Stiffener	product of minimum unsupported transverse stiffener length and the transverse stiffener spacing	5
Grillages	product of minimum lengths between longitudinal and transverse bulkheads	10

The above quantities may be determined easily for a known structural arrangement and related to a standard reference area. For more or less flat bottomed bow and cross structures of SWATH vehicles, a standard reference area (A_R) derived from hovercraft data [36] is suggested [29].

$$A_R = \frac{12.6\,(W_L)^{2/3}}{(1 + r_x^2)^{2/3}} \qquad \text{Eqn. 9.5}$$

where the coefficient 12.6 is empirically derived
A_R = desired impact reference area in in^2
W_L = gross vehicle weight (lbs)
r_x = distance from CG to foremost point of impact divided by pitch radius of gyration

The average pressure (Pa) in psi over the impact reference area is equal to the impact induced load divided by the reference area;

$$Pa = N_Z\, W_L / A_R \qquad \text{Eqn. 9.6}$$

where N_Z is an 'impact load factor'

It is proposed [29] that the maximum pressure (in psi) over the reference area may be determined for unprotected structures such as SWATH wet decks from;

$$P_M = Pa/0.09 \qquad \text{Eqn. 9.7}$$

The influence on design pressure of the relative sizes of the design reference area (A_D) and the standard reference area (A_R) may be considered by means of a pressure reduction coefficient K_D. The values illustrated in Figure 9.6 (Figure 19 of [29]) have been curve fitted for use in the current study.

Table 9.4 SWATH Ship Wet Deck Panel Sizes and Slamming Loads

		Ship Particulars				Structural Arrangement			Slam Conditions				Slamming Loads		
Vessel	Ref.	Δ (t)	Length Overall (m)	Depth Main Deck (m)	Clearance of Box (m)	Bulkhead Spacing (m)	Frame Space (mm)	Frame Span (mm)	Speed (knots)	Wave H1/3 (metres)	Slam Location	Required Nz Factor	Published (MPa)	Published (psi)	Program (psi)
USCG OPV	27	125	26.1	*5.5*	-	*3.66*	*386*	*1160*	25.0	-	0.2	3.6	0.414	60.0	34.0
USCG OPV	27	254	35.7	*7.3*	-	*4.71*	*414*	*1240*	25.0	-	0.2	2.7	0.414	60.0	44.6
USCG OPV	27	765	50.3	*10.4*	-	*6.17*	*472*	*1415*	25.0	-	0.2	1.9	0.414	60.0	64.4
USCG OPV	27	1270	59.0	*12.3*	-	*7.07*	*507*	*1520*	25.0	-	0.2	1.6	0.414	60.0	72.1
VSTOL Carrier	12	15067	137.0	26.3	5.58	13.70	762	2500	28.0	7.0	0.2	0.6	0.353	51.2	49.0
VSTOL Carrier	12	15067	137.0	26.3	5.58	13.70	762	2500	28.0	7.0	0.5	0.4	0.100	14.6	19.7
TAGOS19	33	3450	71.7	15.1	3.97	4.29	610	1220	3.0	8.0	0.2	1.0	0.414	60.0	66.0
TAGOS19	33	3450	71.7	15.1	3.97	4.29	610	1220	3.0	8.0	0.5	1.3	0.207	30.0	26.5
Bazan OPV	10	914	43.4	12.2	-	5.13	400	*1600*	25.0	-	0.2	2.7	0.627	91.0	70.0
Halcyon §	7	57.9	18.3	4.3	1.38	2.29	381	914	20.0	-	0.2	1.7	0.138	20.0	24.4
DREA Model	31	5246	110.0	19.0	5.64	*9.73*	*641*	*1640*	25.0	-	0.2	3.8	1.800	261.0	60.0
Sikora 1988	30	3500	*71.0*	*15.0*	3.50	4.30	600	1200	3.0	7.0	0.2	0.9	0.380	55.0	66.4
Sikora 1988	30	3500	*71.0*	*15.0*	3.50	4.30	600	1200	3.0	7.0	0.5	2.5	0.428	62.0	26.6
Aronne Ship A	21	4064	86.0	20.7	5.79	*9.50*	610	*1300*	-	-	0.2	1.6	0.690	100.0	64.4
Aronne Ship A	21	4064	86.0	20.7	5.79	*9.50*	610	*1300*	-	-	0.5	1.8	0.310	45.0	25.8
Aronne Ship B	21	4572	86.0	20.1	4.57	*8.00*	910	*1820*	-	-	0.2	1.7	0.690	100.0	58.0
Aronne Ship B	21	4572	86.0	20.1	4.57	*8.00*	910	*1820*	-	-	0.5	1.9	0.310	45.0	23.2
Aronne Ship C	21	5334	86.0	21.2	4.32	*8.53*	610	*1300*	-	-	0.2	1.4	0.690	100.0	62.8
Aronne Ship C	21	5334	86.0	21.2	4.32	*8.53*	610	*1300*	-	-	0.5	1.7	0.345	50.0	25.1
Kaimalino	34	200	27.0	9.0	1.60	*3.61*	*403*	*1010*	-	-	0.2	0.7	0.097	14.0	41.2
AMCM	32	5869	97.5	*22.2*	*3.55*	*9.50*	*655*	*2000*	-	-	0.2	0.6	0.283	41.0	57.2
AMCM	32	5869	97.5	*22.2*	*3.55*	*9.50*	*655*	*2000*	-	-	0.5	0.8	0.138	20.0	22.9
AMCM	32	5869	97.5	*22.2*	*3.55*	*9.50*	*655*	*2000*	-	-	0.2	0.7	0.09*	13*	15.1
AMCM	32	5869	97.5	*22.2*	*3.55*	*9.50*	*655*	*2000*	-	-	0.5	0.6	0.028*	4*	6.0

Quantities in italics are ESTIMATED
'Required Nz Factor' is that required to reconcile published slam pressure with ship and structural details via Allen-Jones Method
'Slam Location' is location of design area as a fraction of box length from box bow
* indicates load for longitudinal members
∞ indicates a longitudinally framed design

A longitudinal pressure distribution factor (F) related to the longitudinal location of the structural design zone is determined from Figure 9.7 (Figure 20 of [29]). These factors are roughly proportional to the probability of the maximum impact pressure occurring at any longitudinal station along the hull.

The above factors and Equation 9.7 combine to give;

$$P_D = C\ F\ K_D\ P_M \qquad \text{Eqn. 9.8}$$

where P_D is the uniform equivalent static design pressure (in psi), and C = 0.88 for unprotected structures such as SWATH wet decks.

The most difficult and controversial input to the above procedure is the impact load factor N_Z. This may be defined as that portion of the vertical acceleration at the CG due to impact (as opposed to buoyancy) forces. Analytical methods for determining these values exist, particularly for planing hulls, and sea trials data can also prove useful. In Figure 21 of [29] some values are listed for a variety of vehicles. For SWATH ships, however, no published guidance exists at present.

Table 9.4 lists main particulars, structural arrangements (estimated, in many cases), and slamming conditions for a number of SWATH designs. Lack of data prevented correlation of slamming pressures with box clearance, wave height and ship speed. Consequently, it was decided to determine values of N_Z which, in conjunction with the Allen-Jones method, would approximate known SWATH slamming design pressures.

Figure 9.8 plots N_Z values resulting from a reverse analysis of published design pressures. It was necessary in all cases to assume that pitch gyradius could be determined from equation 9.9 due to C.M. Lee [37], and that the VCG was situated amidships at a height of 70% of the moulded ship depth.

$$\text{Pitch Gyradius} = 0.22\ L_H \qquad \text{Eqn. 9.9}$$

It can be seen that the resultant values of N_Z decrease with increasing size, in common with the Allen/Jones curve for displacement ships. Quantitative agreement is poor, with large SWATHs apparently being designed to higher impact pressures than suggested by [29]. It is probable that understandable conservatism in SWATH design is responsible for this. In addition, it should be recalled that some published data for SWATH designs is the result of informed estimation rather than exhaustive study. An approximation to the SWATH data which has been derived for the present study is given in Equation 9.10.

$$N_Z = 2.0 \qquad \text{for } \Delta \text{ (in Long Tons)} < 1000$$
$$N_Z = 85\ \Delta^{-0.538} \qquad \text{for } \Delta \text{ (in Long Tons)} > 1000 \qquad \text{Eqn. 9.10}$$

The above algorithm has been implemented as a subroutine (*ALLEN*) of module *STRUKT*. Although comparison of a technique against the data from which it was derived is an unsatisfactory measure of reliability, Table 9.4 contains values of P_D determined using the program. The high degree of uncertainty in this area of SWATH design is evident in this comparison. However, despite the simplifications involved, it is suggested that the current approach appears to provide plausible values of slamming pressure for a wide range of SWATH ships (60 to 15000 tonnes displacement).

A most serious shortcoming of this technique is that ship speed, wave height and box clearance are not explicitly included in the computation. It is therefore impossible to employ this method in realistic parametric studies of slamming pressure. Nevertheless, it is considered that until a design process has proceeded sufficiently far to justify the techniques discussed in section 9.6.2, either appropriately chosen design pressures from Table 9.4 should be used, or the general method employed directly.

9.6.3 Initial Scantling Sizing

At present, program *STRUKT* computes initial smeared plate/stiffener thicknesses from curves of panel 'area density' versus design pressure. The latter have been obtained from a number of sources. The small USCG SWATH designs [27] used algorithms originally employed in a planing hull synthesis model [28]. These were derived from weights of small, principally longitudinally framed aluminium fast craft. More conservative estimates may be obtained by using the trends for SWATH ship panel weights presented by Sikora [30]. Figure 9.9 compares the various formulations, while equations 9.11 to 9.14 (where P_D is in MPa) approximate the most useful curves.

Elastically designed SWATH panel weight (kg/m^2)	$= 79.8 + 290.8\ P_D$	Eqn. 9.11
Plastically designed SWATH panel weight (kg/m^2)	$= 40.3 + 183.5\ P_D$	Eqn. 9.12
Steel planing craft panel weight (kg/m^2)	$= 34.2 + 141.5\ P_D$	Eqn. 9.13
Aluminium workboat panel weight (kg/m^2)	$= 24.4 + 48.2\ P_D$	Eqn. 9.14

As part of a check on the use of these equations and program *ALLEN*, a quasi-rational design approach was applied to one particular SWATH ship. The design of amidships wet deck panels and transverse framing (spacing 610mm, span 1220mm) of *TAGOS-19* was examined. The published slamming impact [33] for this vessel is 0.207N/mm^2, and examination of the midships section [9] yields a panel/stiffener area density of 145.5 kg/m^2 (program *ALLEN* computes a design pressure of 0.182 N/mm^2). Weight of plating and stiffeners was computed in the following manner.

Panel end support at stringers or longitudinal floors was considered ineffective. Consequently plate thickness was determined by investigating a thin strip of shell of unit width between the transverse frames (spacing b_f) and considering this to be a fixed ended beam. Assuming a factor of safety of 1.5 based on the tensile strength (σ_y) of the material, plate thickness (t_p) was determined from the bending moment and section modulus relationship.

$$t_p = b_f \sqrt{[(1.5\ P_D)/(2\sigma_y)]} \qquad \text{Eqn. 9.15}$$

Frames were designed by assuming the ends to be fixed, with a distributed load equal to the impact pressure acting over the panel area. Frame bending moment (M_F) and required section modulus (Z) for a factor of safety of 1.5 and span S_F were determined as follows:

$$M_F = {}^1/_{12}\ [P_D\ S_F^2] \qquad \text{Eqn. 9.16}$$

$$Z = 1.5\ M_F/\sigma_y \qquad \text{Eqn. 9.17}$$

Plating was assumed to contribute to the transverse strength of the section by means of an effective plate breadth (b_e) of:

$$b_e = b_f\ [0.333\ (S_F/b_f)^{0.6667}] \qquad \text{Eqn. 9.18}$$

A study of *TAGOS-19* [9] yielded the following proportions for wet deck 'angle' web height (h_w) and thickness (t_w), and flange breadth (b_F) and thickness (t_F).

$t_w = h_w/14$
$b_F = h_w/1.75$
$t_F = b_F/8$

A solution for section geometry was found by iteration from a starting value for web height. Table 9.5 compares the results of this study with those of equations 9.11 to 9.14. It can be seen that the agreement between the above 'quasi-rational' procedure and Sikora's elastic design curve is excellent. At the published design pressure, both methods give a 'density' within 4% of the final design value [9], while errors from pressures by program *ALLEN* are less than 10%.

Table 9.5 Area 'Densities' (in kg/m^2) for TAGOS-19 Amidships Wet Deck Panels

Design Pressure (N/mm^2)	0.182 (*ALLEN*)	0.207 (published)
PHFM Steel Planing Craft Density	60.0	63.5
Sikora 'Plastic' Density	73.7	78.3
Sikora 'Elastic' Density	132.8	140.0
'Quasi-Rational' Density	131.5	141.3
Published Midship Section Density		**145.5**

In view of the above agreement, it is suggested that Sikora's elastic design curve may safely be used in initial sizing of panels using normal proportions and practices. However, the fundamental inadequacies of this approach are acknowledged, and it is recommended that a generalised version [38] of the 'quasi-rational' method described above be introduced as an immediate improvement to the current procedure.

9.7 Primary Wave Loading

In program *STRUKT*, initial scantlings developed using the methods described previously are subjected to primary wave loading and increased (if necessary) in an iterative process until the material stresses are acceptable. This program is documented in [62].

References [44-54] describe various techniques for evaluating wave loads. In a true design situation, dynamic loads derived using tools such as [49] or [51] would be combined with statistical analysis [39] and finite element methods to assess the structural design (as described in [55]). These methods are impossible to include in a true synthesis although provision for an interface with such a method [54] has been provided in the current study (Chapter 11). In the current program, a facility to input an arbitrarily chosen wave load is provided. However, the principal method chosen to estimate wave induced loading is the well known Sikora-Dinsenbacher algorithm [56].

$$F/\Delta = 0.73\, D\, T\, L\, Ks \qquad \text{Eqn. 9.19}$$

where

Δ = ship displacement

D = 1.55 - 0.75 tanh (Δ/11000)

T = 0.5319 t

t = (Draught) / $\nabla^{0.333}$

L = -0.725 + 2.989 tanh (Le/24)

Le = Ls + 0.5 (LH - Ls) ($^{HD}/_{t}$) (1 - 0.1G/HD)

LH = 3.271 (Hull length) / $\nabla^{0.333}$

G = 3.271 (Length of gap between tandem struts) / $\nabla^{0.333}$ (0 for single strut)

HD = 3.271 (Lower hull depth) / $\nabla^{0.333}$

Ls = 3.271 (Length of struts at design waterline) / $\nabla^{0.333}$

Ks is a heading function (equal to 1.0 in beam seas)

Dimensions are in metres, ∇ in m^3

This algorithm is based on model tests of 13 SWATHs (9 single strut, 4 tandem) and computer predictions. RAOs from these sources were combined with wave statistics to predict the expected maximum lifetime side forces. Mild steel SWATHs designed to stresses below 130N/mm^2 arising from the side load of equation 9.19 are considered to have strength comparable to the average monohull of the past 30 years. This algorithm is strictly only valid for the dimensions shown in Table 9.6, although it has been used outside these limits by the US Navy [33].

Table 9.6 Range of Validity of Sikora-Dinsenbacher Algorithm

Draught	0.431 <	(Draught/$\nabla^{0.333}$)	< 0.645
Hull depth	0.257 <	(Hull depth/$\nabla^{0.333}$)	< 0.431
Hull length	4.879 <	(Hull length/$\nabla^{0.333}$)	< 6.163
Strut length	3.338 <	(Strut length/$\nabla^{0.333}$)	< 5.099
Hull Separation	1.449 <	(Hull CL Spacing/$\nabla^{0.333}$)	< 2.415

It has been noted [2] that the maximum lifetime side load can vary by a factor of 2 depending on the ship configuration, and that there is a tendency for the sideload/displacement fraction to decrease as displacement increases. Altering draught has the greatest influence on side load (and also box moment) while the algorithm shows little influence of hull separation.

Since studies have shown that varying the longitudinal distribution of this load have relatively little effect on a whole ship finite element model [30] it is assumed that F acts at mid draught with a uniform lengthwise distribution.

In the present study the cross structure is idealised as a simply supported beam and the struts as cantilever beams rigidly fixed to the box. The side loading and the box self weight (assumed to be an UDL of 0.5Δ) give rise to axial and bending stresses in the box and struts. An initial estimate of primary stress is then made for each of the points indicated in Figure 9.10 using simple beam theory.

Box $\sigma_i = \pm (M_i \, y_{B_i})/(I_{Box}) \pm F/A_{Box}$ Eqn. 9.20

Strut $\sigma_j = \pm (M_j \, y_{S_j})/(I_{Strut}) \pm 0.25\Delta/A_{Strut}$ Eqn. 9.21

where M_i and M_j are moments generated by the side load and self weight at points i and j in the box and struts, respectively.

In addition, strut shear is calculated from;

$\sigma_{S_j} = \pm F/A_{Shear_{Strut}}$ Eqn. 9.22

There is still much uncertainty as to how loads are transmitted throughout the structure of a SWATH. Stress concentrations and the occurrence of high shear stresses in the haunch at intersections of longitudinal and transverse plating create problems in design. Although one can calculate shear stresses in strut bulkheads and at the cross-structure midspan accurately using strength of materials idealisations, finite element analysis has shown that haunch stresses can far exceed these values. There is therefore a risk of failure from high cycle fatigue. Intermediate 'half' bulkheads at the haunch [30], insert plates and generous radii can mitigate these effects[2].

It is claimed [58] that because of of their increased structural response to moderate wave heights, SWATH ships will have different fatigue lives from monohulls. Since on the whole SWATH ships are smaller than monohulls, they will be affected by smaller waves which ahave a higher probability of occurrence, especially in coastal waters. On the other hand it is proposed [2] that fatigue is not expected to be problem for SWATHs constructed of using ordinary shipbuilding materials if current design allowable stresses are used. However, Dinsenbacher states [59] that the primary structure of a recent SWATH design was fatigue driven, and it is known that portions of the original *TAGOS-19* design had unacceptably low fatigue lives.

These effects combine to increase the risk involved with SWATH structural design, and require the introduction of a method to account for localised increases in stress. In the present study, algorithms (equations 9.23 to 9.32) developed by Sikora and Swanek [61] for 45° haunch angles have been used to magnify the stresses calculated using simple strength of materials idealisations (Equations 9.20 to 9.22). These account for the effects of shear lag between bulkheads, stress concentrations due to geometry, and shear stresses developed in the bulkheads.

The following equations provide the magnification factors obtained for a number of important points (A to L) in the structure. The nominal stresses obtained for these points using equations 9.20 to 9.22 are multiplied by these factors.

Point A - Centreline longitudinal bulkhead-transverse bulkhead-main deck
Factor = $A(mx^C + b)R$
where x = 0 at centreline, y = 0 at transverse bulkhead (spacing TBS), C = 2
$A = 0.831 + 2.803$ (TBS/BHC) where BHC is hull centreline spacing
$m = 0.41 - 0.625 \sqrt{y}$
$b = 0.579 - 0.194y$
$R = 0.99 - 0.14y^2$
Factor A = 0.573 (0.831 + 2.803 TBS/BHC) Eqn. 9.23

[2]*Kaimalino* used truss members to mitigate stress concentrations in transverse bulkheads. This approach is recommended [2] as worth exploring for larger SWATH ships.

Point B - Transverse bulkhead-main deck (inboard of outboard longitudinal bulkhead)
Factor = $A(mx^C + b)R$
where x = 0.8, y = 0, C = 2, m = 0.41, b = 0.579, R = 0.9004
Factor B = 0.757 (0.831 + 2.803 TBS/BHC) Eqn. 9.24

Point C - Outboard longitudinal bulkhead-transverse bulkhead-main deck
Factor = APR_0
this factor allows for the effect of an insert plate where
t = thickness of insert plate, t_o = thickness of parent plate, and $t/t_o = 1.5$ is assumed
$P = 1.96 - 0.96\sqrt{t/t_o}$
$R_o = 0.85$
A = 1.831 + 2.803 (TBS/BHC)
Factor C = 0.667(0.831 + 2.803TBS/BHC) Eqn. 9.25

Point D - Centreline longitudinal bulkhead-transverse bulkhead-wet deck
Factor = $A(mx^C + b)R$
Where A = 1.829 + 6.114(TBS/BHC)
x = 0, y = 0, C = 2
m = 0.716, b = 0.276, R = 1.15
Factor D = 0.317 (1.829 + 6.114TBS/BHC) Eqn. 9.26

Point E - Transverse bulkhead-wet deck (inboard of outboard longitudinal bulkhead)
Factor = $A(mx^C + b)R$
Where A = 1.829 + 6.114(TBS/BHC)
x = 0.8, y = 0, C = 2
m = 0.716, b = 0.276, R = 0.958
Factor E = 0.703 (1.829 + 6.114TBS/BHC) Eqn. 9.27

Point F - Outboard longitudinal bulkhead-transverse bulkhead-wet deck
Factor = APR_0
Where A = 1.829 + 6.114(TBS/BHC)
t = thickness of insert plate, t_o = thickness of parent plate, $t/t_o = 1.5$ is assumed
P = 0.784, $R_o = 0.91$

Factor F = 0.714(1.829 + 6.114TBS/BHC) Eqn. 9.28

Point G - Outer haunch/strut knuckle - strut platform deck - transverse bulkhead
Factor = APR_0
Where A = 1.198 + 1.784[TBS/(DMD-D_H)]
t = thickness of insert plate, t_o = thickness of parent plate, $t/t_o = 1.5$ is assumed
P = 0.784, $R_o = 1.14 - 0.09(r/TS)$
r/TS = 0.5 where r is the radius of the strut inner shell
Factor G = 0.858[1.198 + 1.784TBS/(DMD-D_H)] Eqn. 9.29

Point H - Outer strut sideshell - transverse bulkhead (below strut platform deck)
Factor = $A(mx^C + b)R$
Where $A = 1.198 + 1.784[TBS/(DMD\text{-}D_H)]$
$x = 0.8$, $y = 0$, $C = 1$, $b = 0$, $m = 0.923$, $R = 1.149$
Factor H = $0.848\ [1.198 + 1.784 TBS/(DMD\text{-}D_H)]$ Eqn. 9.30

Point K - Inner haunch/strut knuckle - strut platform deck - transverse bulkhead
Factor = APR_0
Where $A = 4.212 - 0.182[TBS/(\text{Strut Depth})]$
t = thickness of insert plate, t_0 = thickness of parent plate, $t/t_0 = 1.5$ is assumed
$P = 0.784$, $R_0 = 1.17$
Factor K = $0.917[4.212 - 0.182[TBS/(\text{Strut Depth})]$ Eqn. 9.31

Point L - Inner strut sideshell - transverse bulkhead (below strut platform deck)
Factor = $A(mx^C + b)R$
Where $A = 4.212 - 0.182[TBS/(\text{Strut Depth})]$
$x = 0.8$, $y = 0.0$, $C = 1$, $b = 0$, $m = 0.996$, $R = 1.19$
Factor L = $0.951[4.212 - 0.182[TBS/(\text{Strut Depth})]$ Eqn. 9.32

The stresses obtained after applying these multiplication factors to the values provided by equations 9.20 to 9.22 are compared with the allowable figures of the materials selected for the principal design zones of the vessel. If required, the initial smeared thicknesses are incremented until the stresses are acceptable. It is then possible to estimate structural weight from material densities and thicknesses.

9.7.1 Validation of Design Method

The previous sections describe a generalised method for the structural design of the upper structure and struts of SWATH ships. This facility has the potential to examine a large number of design variables, with a lower degree of risk than the section 9.2 approximations. In order to validate the method, a number of published SWATH structural weights were compared with data produced by *STRUKT*. These are listed in Table 9.7. The performance of *STRUKT* is considered adequate, except in the case of the UC ASW frigate design. Although *STRUKT* appears to have a tendency to overestimate the structural weight, the error of 43% on this design is an indication of serious disagreement.

Despite the fact that the published structural design for the UCL ASW frigate includes the use of HY80 insert plates, achievement of a structural density of $75 kg/m^3$ is considered optimistic, being comparable (Figure 9.2) to that of the lightest frigate designs. Even though the latter are the product of years of evolution, expensive maintenance and repair of their structure is still required. It is considered that to adopt a similar approach in the case of a novel vehicle such as SWATH is potentially dangerous.

Table 9.7 Validation of Structural Design Program

Design	*YSL SSV*			*TAGOS19*			*DTRC Carrier*			*UCL ASW*			*Aronne Ship A*		
Appendix 1 Number	103						88			90			49		
Approx Δ (t)	2500			3500			15000			5500			4000		
No. transverse box bkhds	13			13			9			6			7		
No. longitudinal box bkhds	2			2			4			2			2		
No. box decks	1			1			3			2			2		
No. strut platforms	1			0			1			2			1		
Material	Mild Steel			Mild Steel			Mild Steel			B Quality/HY80			Mild Steel		
	Published		*Program*	*Published*		*Program*	*Published*		*Program*	*Published*		*Program*	*Published*		*Program*
Fwd Slam (MPa)	-		0.432	0.4		0.455	0.353		0.338	-		0.417	0.690		0.440
Amid Slam (MPa)	-		0.173	0.2		0.183	0.100		0.136	-		0.167	0.310		0.178
Side Load (MN)	18.4		18.4	-		24.3	-		85.4	-		43.6	30.7		37.9
Max. BM (MNm)	-		172.0	-		231.4	-		1474.0	-		506.2	466.0		4997.2
Weights (tonnes)															
Superstructure	81.6		99.1	104.5		125.8	116.8		99.1	-		194.7	-		-
Box and upper haunch	459.0		437.9	↑		671.1	↑		2360.0	-		927.8	883.9		834.8
Struts and lower haunch	178.6		185.0	1360.5		284.8	5591.3		1633.2	-		513.2	541.5		596.2
Lower hulls	224.0		242.0	↓		310.1	↓		1312.5	-		606.4	385.0		342.0
Extra weights	112.2		162.4	128.0		209.9	589.1		943.0	-		375.7	325.9		302.3
Total, and % Error	1055.4	*6.70%*	1126.4	1593.0	*0.55%*	1601.7	6297.2	*0.80%*	6347.8	1830.0	*43%*	2617.8	2136.3	*-2.85%*	2075.3
Structural Weight Fraction	**0.437**		**0.466**	**0.462**		**0.464**	**0.418**		**0.421**	**0.335**		**0.479**	**0.526**		**0.511**
Structural Density (kg/m^3)	**114.4**		**122.1**	**98.9**		**99.5**	**91.6**		**92.4**	**74.7**		**106.8**	**114.4**		**111.1**
Structural Weight Margin	116.1			565.1			565.1			91.4					

It is concluded that *STRUKT* can offer a reasonable, if slightly conservative, estimate of SWATH ship structural weights, reflecting variations in structural arrangement and vessel volume. Pursuit of lightweight design solutions would require redesign of the program and is not being considered at present.

9.8 Lower Hull Design

The design of SWATH ship lower hulls is dominated by hydrostatic pressure and docking loads rather than seaway induced forces and moments.

9.8.1 Approximate Methods

A shell area and pressure dominated equation proposed [57] for the total weight of rectangular pontoons on offshore semi-submersibles was generalised to give an expression used in early versions of *STRUKT*.

$$W_H \text{ (tonnes)} = 9.4 \times 10^{-3} (S_H \text{ Design Head})^{1.05} \qquad \text{Eqn. 9.33}$$

where $S_H = 2 L_H$ (Midships hull circumference)

For the rectangular hulled YSL SSV (Appendix 1 design number 103), this equation gives a lower hull weight of 272 tonnes (for 19.2m design head) compared to 278 tonnes from the manual design [16] including margins and fastenings. Aronne's Ship A [21] has a circular hull weight of 454 tonnes (including 18% for margins, welding) when designed in mild steel to 20.73m head, compared to a predicted value of 470 tonnes.

An approximate equation used [20] to estimate the weight of lower hulls for naval SWATH designs of moderate size gives extremely low estimates of hull weight and is not recommended.

$$W_H \text{ (tonnes)} = 0.766 L_H + 0.00981 \Delta + \text{Bulkhead Weights} \qquad \text{Eqn. 9.34}$$

Because it is simple to determine the volume of the lower hulls, a volumetric density approach can provide an extremely quick check on their structural weight. Table 9.8 lists some published lower hull structural densities.

Table 9.8 Typical Lower Hull Structural Densities (kg/m^3)

Vessel	Ref.	Mild Steel	HTS	Aluminium	HY100
BAZAN OPV	[10]	140.7			
Aronne Ship A	[21]	133.4	110.1		105.3
Aronne Ship B	[21]		146.9	69.2	
Aronne Ship C	[21]		100.3	52.5	
YSL SSV	[16]	173.0			

9.8.2 Improved Hull Weight Calculation

In common with other portions of *DESIN*, the modular nature of the program permitted the original calculation to be replaced with an improved solution. In this case, an existing method for marine pressure hull design was introduced to the synthesis model. Appendix 6 contains a fuller description of this rational method, which employs an iterative scheme to determine satisfactory scantlings for circular cylinders under combined pressure, axial, and bending loads. A factor of safety of 1.5 is associated with this technique, which is based on British Standard 5500. The effects of material strength, bulkhead spacing, and arrangeme: ind type of ring frames and stiffeners may be modelled.

9.8.3 Validation of Lower Hull Design Method

Data produced by module *SWATHULL* were checked against 'basic' lower hull weights data for three US designs described by Aronne in [21]. General particulars of these vessels may be found in Appendix 1 (design numbers 49 to 51). In this study, none of the weight estimates includes a margin or allowance for miscellaneous fittings. Two assumptions were necessary in order to compare *SWATHULL* with the US data. It was assumed that 'tee' frames were employed in all cases, and estimates (from sketches in [21]) of transverse bulkhead spacings were required. Table 9.9 presents the results of the comparison study for a variety of frame spacings, material types and design heads. The mean difference in lower hull weights for the various Ship A and B designs is 10%. There is a difference of 8.8% in the estimates for Ship C.

Table 9.9 Validation of Lower Hull Weight - Comparison with US Data

	Ship A								
Hull Diameter (m)	5.33	5.33	5.33	5.33	5.33	5.33	5.33	5.33	5.33
Assumed Bulkhead Spacing (m)	9.50	9.50	9.50	9.50	9.50	9.50	9.50	9.50	9.50
Frame Spacing (mm)	4940	1524	1219	914	610	610	914	914	914
Hydrostatic Design Pressure (N/mm^2)	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208
Structural Material	HY100	HY100	HY100	HY100	HY100	HTS	Mild	HTS	HY80
Assumed Yield Stress (N/mm^2)	740	740	740	740	740	310	275	310	603
Hull (both) Weight by Aronne (tonnes)	*644*	*324*	*308*	*303*	*306*	*304*	*385*	*331*	*313*
Hull (both) Weight by Program (tonnes)	*579*	*382*	*366*	*339*	*313*	*333*	*342*	*336*	*339*

	Ship B								Ship C
Hull Diameter (m)	5.33	5.33	5.33	5.33	5.33	5.33	5.33	5.33	5.64
Assumed Bulkhead Spacing (m)	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.53
Frame Spacing (mm)	610	610	610	610	610	610	610	610	610
Hydrostatic Design Pressure (N/mm^2)	0.098	0.215	0.215	0.215	0.215	0.215	0.215	0.215	0.205
Structural Material	HTS	HTS	HTS	HTS	HTS	HTS	HTS	HTS	HTS
Assumed Yield Stress (N/mm^2)	310	310	310	310	310	310	310	310	310
Hull (both) Weight by Aronne (tonnes)	*301*	*374*	*363*	*387*	*365*	*364*	*363*	*374*	*329*
Hull (both) Weight by Program (tonnes)	*244*	*338*	*338*	*338*	*338*	*338*	*338*	*338*	*358*

In reference [21], differences of 12 to 16% between lower hull weights for Ship C produced by the NAVSEC feasibility model, the DTNSRDC *SSDP* program and the Boeing Company were described as *'close agreement'* and to have *'demonstrated the suitability of the SSDP for SWATH structural design'*. The comparable performance of *SWATHULL* suggests that it may be used (with a 10% assurance margin) as a generalised design tool.

9.8.4 Internal Hull Volume Lost to Structure

Loss of internal space due to structure is important for SWATH ships, particularly in confined spaces such as the lower hulls and struts. Table 9.10 lists some values for lower hull scantlings, providing some indication of the internal space loss typically involved.

Table 9.10 Typical Internal/External Hull Diameter Ratios

Design	Lower hull framing	Hull dimensions	ID/OD
Bazan OPV [10]	300mm 'Tee' longl, 120mm transverses	3.80m dia	0.842
YSL SSV 16]	220mm OBP longitudinals	4.70m/3.60m	0.90/0.88
T-AGOS19 [9]	178mm transverses, with 457mm deep webs	6.70m/5.00m	0.86/0.82
VSTOL Carrier [12]	Ring frame depth 2.5% of hull diameter	Contoured	0.950
UK Combatant [60]	500 (bottom) and 300mm (top) rings, 600mm crs	7.25m/5.18m	0.89/0.84
UK Auxiliary [60]	500 (bottom) and 300mm (top) rings, 600mm crs	7.13m/4.60m	0.88/0.82

Averaging the above data suggests that typical internal hull dimensions approximate to 87% of the external values.

9.9 Superstructure Weight

In common with *ASSET*, *STRUKT* estimates superstructure structure weight via volumetric density. A number of alternative algorithms derived from available data have been provided in *STRUKT*.

US Hydrofoil Aluminium SS Weight (t) $= 0.47 + 0.01239\ SS_{vol}$ Eqn. 9.35

UK Combatant Aluminium SS Weight (t) $= 0.009643\ [SS_{vol}]^{1.106}$ Eqn. 9.36

UK Combatant Mild Steel SS Weight (t) $= 0.046291\ [SS_{vol}]^{1.023}$ Eqn. 9.37

where SS_{vol} is superstructure enclosed volume in m^3

9.10 Program Operation

An outline flowchart for the structural weight estimating module *STRUKT* and its principal subroutines *ALLEN* and *SWATHULL* is given in Figure 9.5. Table 9.11 lists the most important input and output variables for this part of *DESIN*. General ship particulars are input automatically from the current model, but structural input data must be supplied by the user in the first iteration through *DESIN*. Naturally, sensible choices of input are required to ensure that the program produces useful results.

Table 9.11 Input and Output Variables for Module *STRUKT*

Input Variables from Current Model

Ship displacement, estimated KG, current estimate of structural weight fraction
Vessel draught, box depth and clearance, hull centreline spacing
Strut length and thickness, hull length, breadth, depth
Superstructure level 1 length, breadth, depth, superstructure level 2 length, breadth, depth

Interactive Input Variables

General design data

Material for superstructure from; GRP, Aluminium, B Quality steel, mild steel
Material for main deck/box internals from; Aluminium, HY80, B Quality and mild steels
Material for low stress areas of wet deck from; Aluminium, HY80, B Quality, mild steels
Material for high stress areas of wet deck, haunch from; HY80, B Quality and mild steels
Material for lower struts and hulls from; B Quality or mild steel
Design side load or decision to use Sikora algorithm
Number of longitudinal bulkheads (minimum 2)
Transverse bulkhead spacing, transverse frame spacing and span
Number of internal decks in strut (including strut/hull and strut/box platforms)
Number of internal decks in box (maximum 2), vertical locations of box decks

Lower hull design data for sub-module SWATHULL

Material yield stress, modulus of elasticity, initial shell thickness, hull bulkhead spacing,
Frame shape (angles or tees) and spacing, initial frame web and flange dimensions
Number and shape of stringers (angles or tees), initial stringer web and flange dimensions
Design pressure, bending moment, end load

Output Variables

General structural design data

Echo of input data
Design side force and maximum transverse bending moment in box

Smeared plate/stiffener thicknesses	*Weights of structural elements*
Superstructure	Superstructure Level 1
Main deck and box internal structure	Superstructure Level 2
Inner wet deck structure	Main deck structure
Outer wet deck/inner haunch structure	Inner wet deck
Box structure transoms	Outer wet deck/haunch
Box transverse bulkheads	Box sides/upper haunch
Box longitudinal bulkheads	Box transoms
Lower haunch/upper strut sideshell	Box transverse bulkheads
Box/upper haunch sideshell	Box longitudinal bulkheads
Lower strut sideshell	Box internal decks
Strut transverse bulkheads	Upper strut/lower haunch shell
Internal decks	Lower strut shell
	Strut Transverse Bulkheads
	Decks in Strut at Hull and Haunch Levels
	Additional Strut Platforms

Lower hull design data from sub-module SWATHULL

Final shell thickness
Final frame web and flange dimensions
Final stringer web and flange dimensions
Final weight of lower hull structure

9.10.1 Material Selection

A range of material types (listed in Table 9.11) is available for use in various areas of the structure. It is recommended that when beginning a new design, the trends of Figure 9.1 should be consulted before selecting structural material. In most cases it will be desirable to employ mild steel. However, an option is provided in the first iteration through *STRUKT* to reselect structural material should the weight fraction for the first choice prove excessive.

9.10.2 Transverse Bulkhead Spacing

Correct design of the transverse bulkheads is the key to successful SWATH structural design [30]. Table 9.12 lists bulkhead spacings taken from the general arrangements of a number of SWATH designs from Appendix 1. Approximate fits to the data plotted in Figures 9.11 to 9.13 yielded equations 9.38 to 9.43.

Table 9.12 Details of SWATH Ship Bulkhead Arrangements

Design Identification	Appendix 1 Number	Number Compartments Hull	Strut	Box	Continuous Bulkheads	Ave. Compt. Length (m) Hull	Strut	Box	Max. Compt. Length (m) Hull	Strut	Box
Sea Saloon	55	6	6	6	5	2.78	2.98	3.11	3.54	4.60	4.60
Halcyon	-	7/9	17	17	8/6	2.56	1.09	1.09	3.01	1.09	1.09
Fairey OPV	9	7	6	6	5	2.94	3.62	3.69	6.02	6.02	6.02
Kotozaki	-	6	9	5	4	4.07	2.84	5.37	8.27	4.09	8.27
Ohtori	-	7	8	8	4	3.57	3.10	3.15	5.55	4.48	5.44
Seagull	-	6	7	7	3	5.17	4.64	4.67	7.39	6.27	7.97
Bazan OPV	10	8	9	8	4/5	5.13	5.03	5.13	11.59	8.90	8.90
Vospers OPV	2	10	7	5	3	4.18	5.28	6.97	9.03	9.03	9.03
Duplus	-	10	12	8	6	4.30	3.61	5.58	6.45	6.45	17.20
Vospers 1600t	3	10	7	5	4	4.84	7.05	9.63	10.05	18.10	18.10
MoD SSV	104	10	9	9	8/9	6.03	5.55	5.67	7.29	7.29	7.29
Kaiyo	-	9	8	7	4/5	6.20	6.91	7.07	10.94	10.51	10.51
TAGOS-19	-	14	13	14	10/11	5.12	4.52	4.29	8.00	5.53	5.33
UCL Frigate	90	14	12	7	6	7.51	7.65	14.57	15.45	11.24	20.83
Navsea Frigate	72	13	11	9	8/10	9.69	9.18	9.78	13.66	13.66	13.66
Kaysen AGS	92	10	9	8	6/7	11.60	12.62	14.20	16.40	16.40	25.04
VSTOL Carrier	88	14/16	12	10	8	8.79	11.22	13.67	14.40	25.80	25.80
Celena Ferry	96	5	5	5		10.00	10.00	10.00	10.00	10.00	10.00
YSL SSV	103	13	11	14	10	5.10	4.68	3.90	7.10	7.10	7.10

Maximum Strut Compartment Length (m) $= 1.34 + 0.1466\ LS$ Eqn. 9.38

Average Strut Compartment Length (m) $= 1.25 + 0.0814\ LS$ Eqn. 9.39

Maximum Hull Compartment Length (m) $= 3.91 + 0.0908\ L_H$ Eqn. 9.40

Average Hull Compartment Length (m) $= 1.98 + 0.0619\ L_H$ Eqn. 9.41

Maximum Box Compartment Length (m) $= 1.95 + 0.1780\ L_{box}$ Eqn. 9.42

Average Box Compartment Length (m) $= 1.18 + 0.1037\ L_{box}$ Eqn. 9.43

These equations may also be used to estimate the relative proportions of the longest and average compartment lengths in the various areas of a SWATH. It is usual to require at least one long compartment for machinery installation, but for damaged stability reasons this cannot depart too far from the average length. Work is currently in hand [35] to determine the effects on survivability of compartment lengths and other variables. In practice it will often be desirable to employ vertically continuous bulkheads, so that the length of box compartments, for example, will govern the maximum lengths of those in the struts and hulls.

9.10.3 Panel Sizing

Proportions of stiffened panels for SWATH ships tend to follow conventional ship practice. Transverse frame spacings for a number of designs have been plotted in Figure 9.14 to give a first approximation to the frame spacing in a new synthesis. Standard spacings such as 500mm may of course be input to *STRUKT*.

Transverse Frame Spacing (mm) = 372 + 3.37 LBP (in m) Eqn. 9.44

Panel aspect ratios range from 2.0 (*TAGOS-19*, [9], UCL ASW [13]) up to 3.28 (DTRC VSTOL carrier [12]), or 5.3 (YSL SSV [16].

In the design of the lower hulls it is initially necessary to specify the proportions of the stiffeners. This is a free choice of the designer, who may elect to use the dimensions of the *TAGOS-19* stiffeners [9] as guidance.

Further input and output variables for *STRUKT* are listed in Table 9.11.

9.11 Parametric Studies of Structural Weight

The methods described in the preceeding sections were applied in a parametric survey of some important structural design parameters. The family of simple SWATH ships introduced in Chapter 5 was selected as the basis for a study in which the principal variables examined were box clearance and bulkhead spacing.

Mild steel (σ_y = 235 N/mm^2) was selected as the structural material, and transverse frame spacing was determined from equation 9.44, with all panels assumed to have an aspect ratio of 2.0. Each design was examined at a 'high' and 'low' value of box clearance as defined in Table 5.5. It was assumed that all designs had a VCG height of 70% of the depth to the main deck. Three standard hull bulkhead spacings at 6.25%, 12.5% and 8.33% of the hull length were also considered. Figure 9.15 shows that these ratios approximate to lower, upper and mean values for hull compartment lengths as derived from equations 9.40 and 9.41.

Primary wave loads were calculated using the Sikora-Dinsenbacher algorithm, while slamming loads forward and amidships were estimated from section 9.6. The inadequacy of the Allen-Jones method in accounting for increased box clearance can be seen (although maintaining a constant VCG height would result in reduced slamming pressure for the higher box clearances).

Table 9.13 contains the results of this initial survey. Superstructure weight was estimated using equation 9.37 and it can be seen that the large deckhouses defined in Table 5.5 contribute significantly to the total structural weight of the smaller designs. Lower hull weights were estimated using the methods described in section 9.7, and miscellaneous weights (equivalent to NES163 groups 12 to 19) were calculated using the approaches detailed in Chapter 10. The latter algorithms are heavily dependent on total enclosed volume, a feature with which this particular family of designs is over endowed (Table 5.5). Box and strut weight were determined using the algorithms of section 9.7. The results of these calculations are summarised in the values for structural weight fraction and structural density in Table 9.13.

It can be seen that the higher box clearances give rise to transverse bending moments some 15 to 20% greater than the low options, with corresponding increases in structural weight fraction of about 16%. These penalties must be noted when selecting vessel dimensions from a seakeeping and operability standpoint.

The most obvious conclusion is that for the particular geometries considered, provision of any deadweight capacity in the original 1000 tonne design is impossible, with structural weight fractions being close to 100%. Figure 9.1 does suggest that mild steel SWATH designs of 1000 tonnes are rare, but the primary reasons in this particular case are the very low vehicle density of the design (7200m^3, versus 7900m^3 on 2300 tonnes for the MoD SSV), and the slenderness of its components, particularly the struts. Although computed structural densities for this vessel are not unreasonable (see Table 9.1), combination with the extremely low vehicle densities inevitably leads to large weight fractions. This result is in agreement with the general trend described in section 9.2.1, and this illustrates the dangers present in estimating structure by weight fraction alone. Figure 9.16 illustrates the strong relationship between vehicle density and structural weight fraction for this family of SWATH ships.

Even for the designs of normal vehicle density (3000 to 5000 tonnes) 'normal' structural weight fractions of the order of 40% are only achieved with the low box clearance options of the 5000 tonne ship. This is because the structurally inefficient slender struts and wide beam of the parent geometries allow wave loading to dominate the design rather than local loading. This effect is evident in the way that increasing transverse bulkhead spacing increases box weight for all but the 1000 tonne design.

Table 9.13 Results of Structural Weight Study for a Family of SWATH Ships

Ship Particulars				Structural Arrangement			Loading				Weights						Structural	Structural
Δ	Draft	Box	Depth	Compartment	No. bulkheads		Stn. 2 Slam	Stn. 5 Slam	Side F	Sag BM	Basic Structural Weights (tonnes)						Weight	Density
(t)	(m)	Gap (m)	(m)	Length	Hull	Box	Load (MPa)	Load (MPa)	(MN)	(MNm)	SS	Box	Struts	Hulls	Extras	Total	Fraction	(kg/m^3)
				0.0625LH	15	12				95.4	103.8	456.2	224.1	111.5	106.9	1002.5	1.003	137.4
		3.40	11.27	0.0833LH	11	9				95.2	103.8	446.6	224.2	108.2	106.9	989.7	0.990	135.6
				0.1250LH	7	6				94.9	103.8	436.9	217.2	104.8	106.9	969.6	0.970	132.9
1000	4.67						0.503	0.201	11.7									
				0.0625LH	15	12				81.5	103.8	456.0	153.1	98.6	106.1	917.6	0.918	127.5
		2.21	10.08	0.0833LH	11	9				81.2	103.8	446.0	150.1	95.8	106.1	901.8	0.902	125.3
				0.1250LH	7	6				80.9	103.8	436.0	147.0	92.9	106.1	885.8	0.886	123.1
				0.0625LH	15	12				199.4	112.8	565.1	398.2	183.9	153.8	1413.8	0.707	145.3
		4.27	13.70	0.0833LH	11	9				196.4	112.8	585.5	392.3	177.1	153.8	1421.5	0.711	146.0
				0.1250LH	7	6				192.1	112.8	621.0	387.3	178.8	153.8	1453.7	0.727	149.4
2000	6.23						0.486	0.195	20.5									
				0.0625LH	15	12				171.3	112.8	555.7	270.0	183.9	152.0	1274.4	0.637	134.0
		2.77	12.20	0.0833LH	11	9				167.4	112.8	577.9	264.9	177.1	152.0	1284.7	0.642	135.1
				0.1250LH	7	6				163.5	112.8	609.9	260.4	170.4	152.0	1305.5	0.653	137.3
				0.0625LH	15	12				297.1	118.2	665.1	550.2	271.0	197.8	1802.3	0.601	150.0
		4.91	15.46	0.0833LH	11	9				291.8	118.2	717.1	542.4	260.4	197.8	1835.9	0.612	152.8
				0.1250LH	7	6				284.6	118.2	807.4	535.9	249.8	197.8	1909.1	0.636	158.9
3000	7.35						0.465	0.186	27.6									
				0.0625LH	15	12				252.2	118.2	651.9	252.2	269.8	194.9	1487.0	0.496	127.7
		3.17	13.72	0.0833LH	11	9				246.1	118.2	705.2	246.1	259.2	194.9	1523.6	0.508	130.3
				0.1250LH	7	6				239.5	118.2	786.4	239.5	248.6	194.9	1587.6	0.529	136.3
				0.0625LH	15	12				388.6	117.3	768.2	675.4	365.4	238.6	2164.9	0.541	154.6
		5.38	16.83	0.0833LH	11	9				381.5	117.3	872.5	665.7	350.6	238.6	2244.7	0.561	160.3
				0.1250LH	7	6				374.3	117.3	1076.2	657.9	335.8	238.6	2425.8	0.606	173.3
4000	8.25						0.451	0.181	33.3									
				0.0625LH	15	12				326.8	117.3	726.9	456.3	363.9	234.5	1898.9	0.475	140.8
		3.48	14.93	0.0833LH	11	9				318.9	117.3	809.1	447.6	349.1	234.5	1957.6	0.489	145.1
				0.1250LH	7	6				310.3	117.3	974.4	432.5	334.3	234.5	2093.0	0.523	155.2
				0.0625LH	15	12				484.8	120.4	911.9	804.3	469.4	281.3	2587.3	0.517	159.2
		5.94	18.16	0.0833LH	11	9				475.0	120.4	1070.9	792.8	449.9	281.3	2715.3	0.543	167.1
				0.1250LH	7	6				464.6	120.4	1361.5	780.5	430.4	281.3	2974.1	0.595	182.9
5000	9.02						0.440	0.176	38.1									
				0.0625LH	15	12				386.3	120.4	802.5	480.4	416.7	275.8	2095.8	0.419	134.5
		3.38	15.60	0.0833LH	11	9				376.4	120.4	943.0	470.4	398.9	275.8	2208.5	0.442	141.7
				0.1250LH	7	6				366.1	120.4	1203.8	459.9	398.6	275.8	2458.5	0.492	157.7

Notes Lower hull weights obtained using program SWATHULL
'Extra' weights (i.e. NES163 groups 12 to 19) obtained from methods described in Chapter 10
All structure transversely framed at 100% of reference spacing; 372mm + 3.37 LBP

Table 9.14 Variations in Structural Weight Fraction with Strut Thickness and Hull Spacing

Hull Separation/Baseline Separation = 1.0

Δ (t)	Number of Box TBs	*Strut thickness/hull breadth ratios* 0.200	0.300	0.400	0.500	0.600	0.700
	12	0.957	0.913	0.882	0.857	0.835	0.815
1000	9	0.954	0.899	0.864	0.834	0.807	0.785
	6	0.951	0.886	0.842	0.808	0.782	0.760
	12	0.699	0.652	0.622	0.597	0.574	0.551
2000	9	0.731	0.668	0.626	0.588	0.560	0.537
	6	0.784	0.692	0.630	0.583	0.549	0.524
	12	0.611	0.564	0.530	0.507	0.483	0.461
3000	9	0.660	0.594	0.548	0.508	0.475	0.448
	6	0.764	0.651	0.572	0.515	0.471	0.441
	12	0.506	0.469	0.442	0.420	0.398	0.379
4000	9	0.571	0.513	0.467	0.429	0.397	0.369
	6	0.719	0.598	0.509	0.444	0.395	0.368
	12	0.512	0.467	0.436	0.412	0.392	0.370
5000	9	0.592	0.528	0.475	0.437	0.399	0.374
	6	0.804	0.659	0.547	0.475	0.417	0.378

Hull Separation/Baseline Separation = 0.9

Δ (t)	Number of Box TBs	*Strut thickness/hull breadth ratios* 0.200	0.300	0.400	0.500	0.600	0.700
	12	0.921	0.877	0.846	0.822	0.800	0.780
1000	9	0.920	0.865	0.830	0.799	0.773	0.751
	6	0.919	0.853	0.809	0.775	0.749	0.727
	12	0.679	0.633	0.601	0.576	0.554	0.531
2000	9	0.711	0.649	0.606	0.569	0.540	0.517
	6	0.764	0.674	0.610	0.564	0.529	0.505
	12	0.595	0.548	0.516	0.492	0.468	0.446
3000	9	0.646	0.581	0.533	0.493	0.460	0.432
	6	0.749	0.637	0.558	0.500	0.455	0.426
	12	0.493	0.457	0.430	0.408	0.385	0.367
4000	9	0.560	0.501	0.454	0.417	0.385	0.357
	6	0.707	0.586	0.497	0.432	0.387	0.359
	12	0.500	0.456	0.425	0.405	0.381	0.359
5000	9	0.581	0.518	0.464	0.425	0.391	0.362
	6	0.793	0.674	0.543	0.463	0.409	0.368

Hull Separation/Baseline Separation = 0.8

Δ (t)	Number Box TBs	*Strut thickness/hull breadth ratios* 0.200	0.300	0.400	0.500	0.600	0.700
	12	0.886	0.842	0.811	0.787	0.764	0.744
1000	9	0.886	0.831	0.796	0.766	0.739	0.717
	6	0.886	0.820	0.776	0.742	0.716	0.694
	12	0.659	0.612	0.581	0.557	0.534	0.511
2000	9	0.692	0.629	0.587	0.550	0.521	0.497
	6	0.746	0.656	0.592	0.545	0.510	0.484
	12	0.581	0.533	0.500	0.476	0.452	0.430
3000	9	0.630	0.566	0.518	0.478	0.445	0.418
	6	0.736	0.622	0.543	0.485	0.441	0.415
	12	0.481	0.445	0.417	0.396	0.373	0.354
4000	9	0.547	0.490	0.442	0.405	0.373	0.345
	6	0.695	0.573	0.485	0.421	0.374	0.347
	12	0.490	0.445	0.418	0.393	0.369	0.348
5000	9	0.571	0.506	0.454	0.414	0.379	0.353
	6	0.782	0.638	0.532	0.452	0.397	0.359

Hull Separation/Baseline Separation = 0.7

Δ (t)	Number Box TBs	*Strut thickness/hull breadth ratios* 0.200	0.300	0.400	0.500	0.600	0.700
	12	0.851	0.806	0.775	0.751	0.729	0.709
1000	9	0.852	0.797	0.761	0.731	0.705	0.683
	6	0.853	0.787	0.743	0.709	0.683	0.661
	12	0.639	0.592	0.560	0.537	0.514	0.490
2000	9	0.672	0.610	0.567	0.530	0.500	0.477
	6	0.726	0.636	0.573	0.526	0.490	0.465
	12	0.565	0.518	0.484	0.461	0.436	0.414
3000	9	0.616	0.551	0.503	0.463	0.430	0.402
	6	0.721	0.609	0.528	0.470	0.430	0.399
	12	0.469	0.433	0.405	0.383	0.360	0.341
4000	9	0.536	0.477	0.431	0.393	0.361	0.332
	6	0.683	0.562	0.474	0.409	0.366	0.337
	12	0.479	0.438	0.407	0.381	0.361	0.339
5000	9	0.561	0.496	0.446	0.406	0.368	0.341
	6	0.771	0.626	0.520	0.446	0.388	0.345

Table 9.14 illustrates results of a study to determine the results of varying box beam and strut thickness on structural weight fraction for the low box clearance options of Table 9.13. These results show that structural weight fractions between 30 and 40% are indeed achievable, even with such non-optimised parent hullforms. Figure 9.18 illustrates reduction in weight fraction with reducing ship beam, due primarily to reduced box bending moments. Figure 9.17 illustrates a similar effect for increasing strut thickness, due to increasing structural efficiency. It can also be seen from Table 9.14 that increasing bulkhead spacing results in reduced structural weight fraction for ships up to 4000 tonnes with strut thickness/hull diameter ratios of 0.7. This result is in agreement with [30] where it is stated that since local loads dominate the shell sizing, the lowest weight SWATH design is the one with the largest compartment length.

The particular family of parent ships studied in this survey are of low vehicle density, and improved designs would be more compact, employing shorter, less slender struts, smaller upperworks, and reduced ship depth and beam. Although the simple parent forms described in Chapter 5 are hydrodynamically attractive their arrangement is inefficient in terms of structure and requires redesign if viable deadweight ratios are to be realised.

A need to incorporate an accurate space balance in the synthesis loop is implicit in these results, since volumetrically efficient designs are required if low structural weight fractions are to be attained.

9.12 Studies of Lower Hull Weight

9.12.1 General Parametric Study of Lower Hull Design

Lower hull designs from the US Navy are generally longitudinally stiffened, with a deep web frame between transverse bulkheads. However, it is admitted [30] that recent parametric studies have shown ring frame stiffeners to be more efficient than longitudinally stiffened structures. In the case of a *TAGOS-19* size hull, a ring stiffened solution proved 100 tonnes lighter than the conventional baseline design [30]. This encouraged the use of *SWATHULL* in a parametric study of lower hulls designed without longitudinal stiffening.

The construction material for this study was mild steel with σ_y=235 N/mm^2 and 'tee' ring frames were specified. Simple circular hulls with lengths between 20 and 130 metres and length/diameter ratios of 10, 12.5, 15, 17.5 and 20 were considered. Three standard bulkhead spacings were examined for each hull, giving compartment lengths of 6.25%, 8.33% and 12.5% of the hull length. A further option in structural arrangement was introduced by defining three frame spacings. These were a reference value determined by Equation 9.44, and alternative spacings at 85% and 115% of this value. Three hydrostatic heads (*low*, *medium* and *high*) were applied to each hull. These pressures are intended to approximate heads to the height of the wet deck, main deck, and main deck plus dynamic wave pressure, respectively. Reference to Equations 2.14, 2.15 and 2.24 of Chapter 2 yields approximate definitions of these design pressures.

P_{Dlow}	=	2.42 ρ g (Hull Diameter in m) x 10^{-6}	Eqn. 9.45
$P_{Dmedium}$	=	3.28 ρ g (Hull Diameter in m) x 10^{-6}	Eqn. 9.46
P_{Dhigh}	=	4.14 ρ g (Hull Diameter in m) x 10^{-6}	Eqn. 9.47

where P_D is in N/mm^2 and $\rho = 1025$ kg/m^3

If required, the actual design pressures associated with each value of hull weight may be obtained from Equations 9.45 to 9.47.

Table 9.15 contains the results of a survey of the above variables. This collection of data is primarily intended as an easily used reference aid for designers. A generalised analysis would be complicated by the presence of assumptions such as those for design pressures. Nevertheless, some general observations may be made.

It can be seen that for a given ship length, compartment length and frame spacing, the lowest weight is associated with the most slender hulls. It must be remembered that this is due in part to the reduced pressure loading on these hulls as well as increased structural efficiency.

For the smallest hulls (all 20m designs and some 30m options), hull weight is insensitive to the design pressure. For larger hulls the effect of pressure on weight becomes evident, although less so for the more slender hulls, and dependent on frame and bulkhead spacing. The 'optimum' choice of frame spacing does not follow a clear pattern, and is strongly dependent on the design pressure/hull slenderness effect.

An analysis of the weights of the 'optimum' framing designs for 8.33% bulkhead spacing at the 'medium' design pressure is presented in Figure 9.19. This shows that the structural density of the various L/D ratios is similar, and decreases with increasing ship size for typical slenderness ratios. This general trend is opposed by hulls with L/D values of 10 and 12.5 which begin to perform poorly above lengths of 50 metres. On balance, a L/D value of 15 seems to offer the best solution structurally, and is at the same time hydrodynamically attractive (Chapter 2).

Table 9.15 Weights of Transversely Framed Circular Lower Hulls

Weights (in tonnes) of two lower hulls

L (m)	Bulkheads	L/D	Frame Spacing	Design Pressure Low	Medium	High
			85% Reference	16.30	16.30	16.30
		10.0	Reference	15.56	15.56	15.56
			115% Reference	15.01	15.01	15.01
			85% Reference	10.15	10.29	12.46
		12.5	Reference	9.63	11.94	11.94
			115% Reference	9.24	11.56	11.56
			85% Reference	7.78	7.78	7.78
	6.25% L	15.0	Reference	7.37	7.37	7.37
			115% Reference	7.07	7.07	7.07
			85% Reference	6.71	6.71	6.71
		17.5	Reference	6.35	6.35	6.35
			115% Reference	6.09	6.09	6.09
			85% Reference	5.55	5.55	5.55
		20.0	Reference	5.25	5.25	5.25
			115% Reference	5.03	5.03	5.03
			85% Reference	15.52	15.52	15.52
		10.0	Reference	14.78	14.78	14.78
			115% Reference	14.23	14.23	14.23
			85% Reference	9.74	9.88	11.92
		12.5	Reference	9.22	11.40	11.40
			115% Reference	8.83	11.01	11.01
			85% Reference	7.52	7.52	7.52
20	8.33% L	15.0	Reference	7.11	7.11	7.11
			115% Reference	6.81	6.81	6.81
			85% Reference	6.51	6.51	6.51
		17.5	Reference	6.15	6.15	6.15
			115% Reference	5.89	5.89	5.89
			85% Reference	5.40	5.40	5.40
		20.0	Reference	5.10	5.10	5.10
			115% Reference	4.89	4.89	4.89
			85% Reference	14.73	14.73	14.73
		10.0	Reference	13.99	13.99	13.99
			115% Reference	13.45	13.45	13.45
			85% Reference	9.33	9.47	11.37
		12.5	Reference	8.81	10.85	10.85
			115% Reference	8.43	10.47	10.47
			85% Reference	7.26	7.26	7.26
	12.5% L	15.0	Reference	6.85	6.85	6.85
			115% Reference	6.54	6.54	6.54
			85% Reference	6.30	6.30	6.30
		17.5	Reference	5.95	5.95	5.95
			115% Reference	5.68	5.68	5.68
			85% Reference	5.25	5.25	5.25
		20.0	Reference	4.96	4.96	4.96
			115% Reference	4.74	4.74	4.74
			85% Reference	42.77	42.77	49.39
		10.0	Reference	41.19	41.19	47.80
			115% Reference	40.01	46.19	46.63
			85% Reference	28.94	34.14	34.14
		12.5	Reference	27.63	32.84	32.84
			115% Reference	31.56	31.87	31.87
			85% Reference	22.16	22.16	22.16
	6.25% L	15.0	Reference	21.13	21.13	21.13
			115% Reference	20.37	20.37	24.09
			85% Reference	15.08	18.28	18.28
		17.5	Reference	17.51	17.51	17.51
			115% Reference	16.94	16.94	16.94
			85% Reference	12.37	12.37	15.13
		20.0	Reference	11.72	11.72	14.48
			115% Reference	11.24	13.89	14.00
			85% Reference	40.57	40.57	46.74
		10.0	Reference	38.98	38.98	45.16
			115% Reference	37.81	43.54	43.98
			85% Reference	27.72	32.61	32.61
		12.5	Reference	26.41	31.31	31.31
			115% Reference	30.03	30.34	30.34
			85% Reference	21.38	21.38	21.38
30	8.33% L	15.0	Reference	20.35	20.35	20.35
			115% Reference	19.59	19.59	23.11
			85% Reference	14.62	17.67	17.67
		17.5	Reference	16.90	16.90	16.90
			115% Reference	16.33	16.33	16.33
			85% Reference	12.04	12.04	14.69
		20.0	Reference	11.39	11.39	14.04
			115% Reference	10.91	13.45	13.56
			85% Reference	38.36	38.36	44.09
		10.0	Reference	36.78	36.78	42.51
			115% Reference	35.60	40.89	41.33
			85% Reference	26.49	31.08	31.08
		12.5	Reference	25.18	29.77	29.77
			115% Reference	28.50	28.81	28.81
			85% Reference	20.59	20.59	20.59
	12.5% L	15.0	Reference	19.56	19.56	19.56
			115% Reference	18.80	18.80	22.13
			85% Reference	14.16	17.06	17.06
		17.5	Reference	16.29	16.29	16.29
			115% Reference	15.72	15.72	15.72
			85% Reference	11.71	11.71	14.24
		20.0	Reference	11.06	11.06	13.60
			115% Reference	10.58	13.01	13.12
			85% Reference	89.19	100.94	98.17
		10.0	Reference	86.16	97.92	95.56
			115% Reference	83.92	93.63	104.61
			85% Reference	61.88	71.14	71.14
		12.5	Reference	59.38	68.63	68.63
			115% Reference	66.24	66.79	75.49
			85% Reference	38.81	45.77	45.77
	6.25% L	15.0	Reference	43.68	44.03	44.03
			115% Reference	42.39	42.74	49.36
			85% Reference	33.51	33.51	39.48
		17.5	Reference	31.99	37.68	37.95
			115% Reference	30.86	36.55	36.83
			85% Reference	27.76	27.76	27.76
		20.0	Reference	26.48	26.48	26.48
			115% Reference	25.53	25.53	30.23
			85% Reference	84.49	95.46	92.69
		10.0	Reference	81.46	90.08	90.08
			115% Reference	79.22	88.15	98.34
			85% Reference	59.16	67.87	67.87
		12.5	Reference	56.66	65.37	65.37
			115% Reference	62.98	63.52	71.69
			85% Reference	37.42	44.03	44.03
40	8.33% L	15.0	Reference	41.94	42.29	42.29
			115% Reference	40.65	41.00	47.27
			85% Reference	32.43	32.43	38.12
		17.5	Reference	30.90	36.33	36.60
			115% Reference	29.78	35.20	35.47
			85% Reference	26.98	26.98	26.98
		20.0	Reference	25.70	25.70	25.70
			115% Reference	24.75	24.75	29.25
			85% Reference	79.78	89.96	87.20
		10.0	Reference	76.75	84.58	84.58
			115% Reference	74.51	82.66	92.06
			85% Reference	56.44	64.60	64.60
		12.5	Reference	53.94	62.10	62.10
			115% Reference	59.71	60.25	67.87
			85% Reference	36.02	42.29	42.29
	12.5% L	15.0	Reference	40.20	40.55	40.55
			115% Reference	38.91	39.26	45.18
			85% Reference	31.34	31.34	36.77
		17.5	Reference	29.82	34.97	35.24
			115% Reference	28.69	33.84	34.11
			85% Reference	26.19	26.19	26.19
		20.0	Reference	24.91	24.91	24.91
			115% Reference	23.96	23.96	28.27
			85% Reference	153.11	170.25	197.68
		10.0	Reference	166.40	174.10	192.47
			115% Reference	163.55	187.40	205.77
			85% Reference	109.76	120.83	121.68
		12.5	Reference	119.67	117.64	132.10
			115% Reference	116.93	128.89	129.74
			85% Reference	72.93	83.81	83.81
	6.25% L	15.0	Reference	80.33	80.88	91.22
			115% Reference	78.16	78.71	89.05
			85% Reference	60.90	60.90	69.79
		17.5	Reference	58.63	67.53	67.53
			115% Reference	56.95	65.85	65.85
			85% Reference	42.74	50.40	50.40
		20.0	Reference	48.18	48.49	48.49
			115% Reference	46.77	47.08	54.42
			85% Reference	144.54	169.52	186.67
		10.0	Reference	156.61	164.31	181.46
			115% Reference	153.76	176.38	201.21
			85% Reference	104.67	114.88	115.73
		12.5	Reference	113.72	111.69	125.30
			115% Reference	108.48	122.09	128.46
			85% Reference	70.21	80.55	80.55
50	8.33% L	15.0	Reference	77.07	77.61	87.41
			115% Reference	74.90	75.44	85.24
			85% Reference	58.78	58.78	67.25
		17.5	Reference	56.51	64.99	64.99
			115% Reference	54.84	63.31	63.31
			85% Reference	41.52	48.87	48.87
		20.0	Reference	46.65	46.96	46.96
			115% Reference	45.24	45.55	52.59
			85% Reference	135.95	159.71	175.63
		10.0	Reference	146.80	154.50	170.42
			115% Reference	150.65	165.34	188.94
			85% Reference	99.55	108.92	109.77
		12.5	Reference	104.87	105.73	118.48
			115% Reference	102.51	115.27	121.65
			85% Reference	67.48	77.28	77.28
	12.5% L	15.0	Reference	73.80	74.34	83.59
			115% Reference	71.63	72.17	77.85
			85% Reference	56.66	56.66	64.71
		17.5	Reference	54.39	62.44	62.44
			115% Reference	52.71	60.76	60.76
			85% Reference	40.29	47.33	47.33
		20.0	Reference	45.12	45.43	45.43
			115% Reference	43.71	44.01	50.75

Table 9.15 Weights of Transversely Framed Circular Lower Hulls

Weights (in tonnes) of two lower hulls

L (m)	Bulkheads	L/D	Frame Spacing	Design Pressure Low	Design Pressure Medium	Design Pressure High
			85% Reference	263.2	322.7	349.1
		10.0	Reference	279.9	313.4	353.5
			115% Reference	274.0	331.3	369.6
			85% Reference	173.6	203.4	224.2
		12.5	Reference	188.8	217.1	218.4
			115% Reference	185.6	212.8	242.3
			85% Reference	119.3	131.3	131.3
	6.25% L	15.0	Reference	115.2	127.8	142.7
			115% Reference	127.2	125.3	140.1
			85% Reference	102.2	102.8	115.6
		17.5	Reference	98.7	99.3	107.2
			115% Reference	96.1	109.5	105.2
			85% Reference	71.7	71.7	82.7
		20.0	Reference	69.1	79.6	80.1
			115% Reference	67.1	77.7	78.2
			85% Reference	249.1	305.0	329.7
		10.0	Reference	264.0	295.8	334.1
			115% Reference	264.3	311.9	348.5
			85% Reference	165.0	193.6	213.2
		12.5	Reference	179.0	206.1	207.3
			115% Reference	183.4	201.8	230.0
			85% Reference	114.6	125.8	125.8
60	8.33% L	15.0	Reference	110.5	122.3	136.4
			115% Reference	119.0	119.8	133.9
			85% Reference	98.5	99.2	111.4
		17.5	Reference	95.0	95.6	102.9
			115% Reference	92.4	105.2	100.9
			85% Reference	69.5	69.5	80.1
		20.0	Reference	66.9	77.0	77.4
			115% Reference	64.9	75.1	75.5
			85% Reference	234.9	287.4	326.3
		10.0	Reference	248.1	278.2	314.7
			115% Reference	248.4	292.5	327.3
			85% Reference	156.4	183.8	202.2
		12.5	Reference	169.2	195.1	206.3
			115% Reference	173.6	190.7	217.8
			85% Reference	109.8	120.3	120.3
	12.5% L	15.0	Reference	102.7	116.8	130.2
			115% Reference	113.5	114.3	131.1
			85% Reference	94.9	95.5	101.3
		17.5	Reference	91.4	87.0	98.6
			115% Reference	88.8	96.7	96.7
			85% Reference	67.3	67.3	77.4
		20.0	Reference	64.7	74.4	74.8
			115% Reference	62.7	72.4	72.9
			85% Reference	445.7	503.3	599.2
		10.0	Reference	432.5	520.5	579.2
			115% Reference	472.3	526.0	598.0
			85% Reference	275.8	319.4	347.7
		12.5	Reference	294.9	336.2	379.1
			115% Reference	289.3	355.5	396.6
			85% Reference	177.1	198.4	230.2
	6.25% L	15.0	Reference	172.6	202.9	224.2
			115% Reference	189.6	218.7	219.7
			85% Reference	138.4	152.5	170.8
		17.5	Reference	147.7	148.6	166.8
			115% Reference	144.8	163.1	170.7
			85% Reference	113.9	114.5	128.9
		20.0	Reference	110.0	125.0	119.6
			115% Reference	107.2	122.2	117.5
			85% Reference	421.7	476.9	568.0
		10.0	Reference	426.9	491.7	548.0
			115% Reference	445.9	497.2	575.9
			85% Reference	262.5	304.4	331.1
		12.5	Reference	279.9	319.5	360.8
			115% Reference	285.5	337.2	376.6
			85% Reference	169.6	189.9	220.6
70	8.33% L	15.0	Reference	165.1	194.3	214.6
			115% Reference	181.0	209.1	210.1
			85% Reference	133.4	146.7	164.1
		17.5	Reference	141.9	142.7	160.2
			115% Reference	139.0	156.5	164.1
			85% Reference	110.3	110.9	118.3
		20.0	Reference	106.4	120.8	115.4
			115% Reference	103.6	113.3	113.3
			85% Reference	397.7	408.7	471.1
		10.0	Reference	402.8	483.2	461.0
			115% Reference	419.5	419.8	482.3
			85% Reference	249.1	289.4	331.5
		12.5	Reference	264.9	302.8	342.4
			115% Reference	270.5	318.9	356.5
			85% Reference	162.1	191.8	211.0
	12.5% L	15.0	Reference	157.7	185.8	205.0
			115% Reference	172.5	199.5	209.4
			85% Reference	124.2	140.8	157.5
		17.5	Reference	136.1	136.9	161.3
			115% Reference	133.2	149.8	157.4
			85% Reference	106.7	107.3	114.1
		20.0	Reference	102.8	116.6	111.2
			115% Reference	100.0	109.1	109.1
			85% Reference	653.5	777.3	900.9
		10.0	Reference	702.3	824.2	901.4
			115% Reference	727.9	802.2	919.4
			85% Reference	456.4	517.8	569.1
		12.5	Reference	442.9	535.8	584.9
			115% Reference	467.7	523.3	570.9
			85% Reference	270.3	298.2	341.0
	6.25% L	15.0	Reference	262.8	303.4	331.3
			115% Reference	283.7	322.7	350.6
			85% Reference	197.5	232.8	256.7
		17.5	Reference	215.4	226.2	250.1
			115% Reference	211.8	244.1	268.0
			85% Reference	147.9	163.2	182.0
		20.0	Reference	158.3	159.0	177.9
			115% Reference	155.2	174.8	178.9
			85% Reference	648.8	769.3	889.5
		10.0	Reference	664.7	780.3	854.4
			115% Reference	687.1	758.3	869.2
			85% Reference	434.7	493.9	543.0
		12.5	Reference	421.1	509.6	556.6
			115% Reference	460.1	497.2	542.6
			85% Reference	259.2	285.6	327.1
80	8.33% L	15.0	Reference	251.7	290.9	317.4
			115% Reference	271.2	308.8	335.2
			85% Reference	189.9	224.1	246.9
		17.5	Reference	206.7	217.6	240.3
			115% Reference	203.1	234.4	266.9
			85% Reference	143.2	157.7	175.7
		20.0	Reference	152.8	153.6	171.6
			115% Reference	149.7	168.5	172.7
			85% Reference	532.6	614.1	842.4
		10.0	Reference	557.6	639.1	807.3
			115% Reference	646.3	629.8	708.2
			85% Reference	412.9	469.9	516.9
		12.5	Reference	399.3	483.5	528.3
			115% Reference	404.4	481.6	514.2
			85% Reference	248.0	273.1	313.2
	12.5% L	15.0	Reference	240.5	278.3	303.4
			115% Reference	258.6	294.8	332.4
			85% Reference	182.3	215.4	237.1
		17.5	Reference	198.0	208.9	230.6
			115% Reference	202.9	224.6	256.0
			85% Reference	134.2	152.2	169.4
		20.0	Reference	147.3	148.1	170.1
			115% Reference	144.2	162.3	166.4
			85% Reference	1013.6	1175.6	1396.7
		10.0	Reference	1033.2	1188.8	1389.7
			115% Reference	1006.7	1247.4	1403.3
			85% Reference	648.8	772.2	851.7
		12.5	Reference	672.5	747.3	866.0
			115% Reference	679.4	797.2	859.6
			85% Reference	381.9	427.8	483.6
	6.25% L	15.0	Reference	414.3	449.6	502.2
			115% Reference	405.6	456.0	491.3
			85% Reference	292.1	322.3	368.4
		17.5	Reference	313.0	356.7	358.1
			115% Reference	307.1	349.1	379.3
			85% Reference	204.9	229.7	265.2
		20.0	Reference	199.9	234.6	258.5
			115% Reference	220.0	253.5	253.5
			85% Reference	962.1	1116.2	1325.3
		10.0	Reference	977.7	1125.4	1318.4
			115% Reference	951.2	1180.0	1328.0
			85% Reference	618.5	736.4	813.1
		12.5	Reference	639.4	711.5	824.7
			115% Reference	646.3	758.6	818.3
			85% Reference	366.1	410.2	464.2
90	8.33% L	15.0	Reference	396.7	430.2	481.1
			115% Reference	388.0	436.6	470.1
			85% Reference	281.1	310.0	354.7
		17.5	Reference	300.6	343.0	344.4
			115% Reference	294.7	335.3	364.2
			85% Reference	198.0	221.8	256.3
		20.0	Reference	193.0	226.7	249.5
			115% Reference	212.1	244.6	244.6
			85% Reference	785.7	888.8	1253.7
		10.0	Reference	816.1	919.3	1246.8
			115% Reference	803.3	954.2	1252.4
			85% Reference	536.2	700.5	774.5
		12.5	Reference	562.2	703.4	783.3
			115% Reference	552.8	720.0	776.9
			85% Reference	360.8	392.5	444.7
	12.5% L	15.0	Reference	379.0	428.1	459.9
			115% Reference	370.3	417.2	465.7
			85% Reference	270.1	313.5	340.9
		17.5	Reference	288.3	329.2	330.6
			115% Reference	282.4	321.6	362.3
			85% Reference	191.0	225.5	247.3
		20.0	Reference	186.0	218.8	240.6
			115% Reference	212.8	235.6	245.5

Table 9.15 Weights of Transversely Framed Circular Lower Hulls

Weights (in tonnes) of two lower hulls

L (m)	Bulkheads	L/D	Frame Spacing	Design Pressure Low	Design Pressure Medium	Design Pressure High
100	6.25% L	10.0	85% Reference	1458.0	1734.8	2048.8
			Reference	1473.3	1703.3	1972.4
			115% Reference	1475.6	1722.3	2034.0
		12.5	85% Reference	889.8	1044.1	1198.3
			Reference	915.0	1099.1	1249.9
			115% Reference	976.2	1122.9	1214.3
		15.0	85% Reference	533.6	604.5	664.2
			Reference	559.7	626.7	684.0
			115% Reference	566.9	665.9	709.5
		17.5	85% Reference	395.0	451.1	509.6
			Reference	437.2	474.5	529.8
			115% Reference	428.2	481.1	518.4
		20.0	85% Reference	281.7	324.9	371.4
			Reference	287.6	317.0	361.1
			115% Reference	311.1	352.2	382.9
	8.33% L	10.0	85% Reference	1384.6	1646.6	1946.0
			Reference	1395.0	1615.2	1869.6
			115% Reference	1397.3	1629.3	1926.3
		12.5	85% Reference	849.0	996.5	1143.9
			Reference	870.8	1048.1	1192.1
			115% Reference	928.6	1068.5	1156.5
		15.0	85% Reference	511.9	580.5	573.3
			Reference	557.1	600.6	600.7
			115% Reference	542.9	637.7	631.2
		17.5	85% Reference	379.7	434.1	490.9
			Reference	420.2	455.8	474.2
			115% Reference	411.2	462.5	467.4
		20.0	85% Reference	285.8	313.9	359.2
			Reference	277.8	306.0	348.9
			115% Reference	300.1	340.0	369.4
	12.5% L	10.0	85% Reference	1090.9	1593.9	1843.0
			Reference	1129.4	1261.7	1823.5
			115% Reference	1114.4	1305.5	1818.3
		12.5	85% Reference	808.2	948.8	1089.4
			Reference	859.3	997.0	1134.1
			115% Reference	781.2	1014.0	1098.5
		15.0	85% Reference	490.1	556.5	547.1
			Reference	533.1	588.2	572.3
			115% Reference	519.0	609.3	670.4
		17.5	85% Reference	383.3	417.2	472.3
			Reference	403.3	455.2	453.8
			115% Reference	394.2	443.8	447.0
		20.0	85% Reference	276.0	302.9	346.9
			Reference	268.0	308.4	336.6
			115% Reference	289.1	327.7	355.9
110	6.25% L	10.0	85% Reference	1989.1	2489.6	2912.7
			Reference	2060.1	2463.9	2850.6
			115% Reference	1999.5	2469.1	2831.7
		12.5	85% Reference	1267.0	1440.0	1689.1
			Reference	1313.8	1502.6	1690.6
			115% Reference	1278.3	1461.3	1753.5
		15.0	85% Reference	724.9	859.9	950.6
			Reference	752.8	832.9	968.4
			115% Reference	760.3	889.2	961.5
		17.5	85% Reference	551.6	611.4	685.9
			Reference	579.0	636.6	707.0
			115% Reference	578.3	643.6	733.9
		20.0	85% Reference	390.5	445.9	483.0
			Reference	381.3	434.0	488.6
			115% Reference	423.6	460.7	513.1
	8.33% L	10.0	85% Reference	1888.4	2365.2	2764.7
			Reference	1953.5	2339.5	2702.5
			115% Reference	1892.9	2338.8	2683.6
		12.5	85% Reference	1209.5	1426.8	1615.0
			Reference	1252.1	1432.7	1612.4
			115% Reference	1216.6	1391.4	1671.2
		15.0	85% Reference	695.9	737.1	789.8
			Reference	721.2	723.4	823.5
			115% Reference	728.7	760.7	813.4
		17.5	85% Reference	531.1	540.6	661.3
			Reference	556.5	571.1	616.2
			115% Reference	555.7	563.2	649.4
		20.0	85% Reference	377.1	431.1	466.7
			Reference	367.9	419.1	472.3
			115% Reference	408.8	444.4	495.3
	12.5% L	10.0	85% Reference	1467.0	2240.5	2666.8
			Reference	1443.5	2214.8	2554.1
			115% Reference	1497.3	2208.2	2535.2
		12.5	85% Reference	1151.7	1360.8	1540.8
			Reference	1190.2	1362.6	1534.1
			115% Reference	1154.8	1363.1	1588.8
		15.0	85% Reference	666.9	791.4	752.8
			Reference	717.0	689.1	783.9
			115% Reference	697.0	815.4	773.8
		17.5	85% Reference	510.5	518.0	561.1
			Reference	546.3	546.4	589.5
			115% Reference	533.1	538.6	620.6
		20.0	85% Reference	363.8	416.3	471.1
			Reference	370.2	404.3	456.0
			115% Reference	394.0	443.4	477.5
120	6.25% L	10.0	85% Reference	2728.3	3430.3	4053.7
			Reference	2720.6	3295.8	3959.1
			115% Reference	2807.8	3271.4	3922.7
		12.5	85% Reference	1639.2	1989.6	2303.6
			Reference	1711.6	1994.5	2282.2
			115% Reference	1739.9	1991.2	2290.4
		15.0	85% Reference	955.1	1121.0	1287.3
			Reference	983.9	1143.7	1243.8
			115% Reference	1050.6	1149.0	1292.4
		17.5	85% Reference	734.3	822.8	948.6
			Reference	763.3	846.9	918.4
			115% Reference	746.9	878.2	947.3
		20.0	85% Reference	484.5	570.9	638.7
			Reference	513.2	577.4	621.5
			115% Reference	503.1	607.0	670.6
	8.33% L	10.0	85% Reference	2594.4	3261.2	3849.3
			Reference	2579.6	3126.6	3754.6
			115% Reference	2659.8	3102.2	3718.3
		12.5	85% Reference	1565.7	1901.5	2200.8
			Reference	1633.2	1901.5	2179.4
			115% Reference	1656.7	1898.2	2182.8
		15.0	85% Reference	816.2	935.4	1237.2
			Reference	943.1	976.2	1035.8
			115% Reference	1006.7	964.7	1080.7
		17.5	85% Reference	650.9	704.6	914.5
			Reference	686.0	739.7	884.3
			115% Reference	675.8	778.4	910.8
		20.0	85% Reference	468.6	575.3	617.6
			Reference	495.5	558.0	622.8
			115% Reference	485.5	585.9	647.7
	12.5% L	10.0	85% Reference	2460.2	3091.6	3644.4
			Reference	1921.4	2957.0	3549.7
			115% Reference	1983.7	2932.6	3513.3
		12.5	85% Reference	1553.9	1813.2	2097.8
			Reference	1554.7	1867.0	2076.4
			115% Reference	1573.3	1805.0	2074.8
		15.0	85% Reference	879.8	891.4	947.9
			Reference	936.7	929.1	985.6
			115% Reference	962.7	917.6	1027.3
		17.5	85% Reference	624.0	675.3	770.5
			Reference	656.6	707.9	756.7
			115% Reference	646.5	744.1	793.0
		20.0	85% Reference	452.7	555.8	549.9
			Reference	477.9	499.1	539.7
			115% Reference	485.3	530.4	570.9
130	6.25% L	10.0	85% Reference	3679.8	4472.1	5447.7
			Reference	3593.2	4405.8	5354.4
			115% Reference	3596.9	4477.1	5250.3
		12.5	85% Reference	2170.9	2618.6	3142.3
			Reference	2250.1	2654.2	3022.1
			115% Reference	2277.5	2667.0	3093.9
		15.0	85% Reference	1230.8	1427.7	1628.6
			Reference	1259.1	1448.6	1690.5
			115% Reference	1335.0	1521.9	1711.8
		17.5	85% Reference	954.5	1060.4	1209.6
			Reference	984.1	1084.1	1229.3
			115% Reference	961.5	1117.2	1259.6
		20.0	85% Reference	627.0	744.4	828.0
			Reference	673.2	750.3	734.2
			115% Reference	658.9	782.3	860.3
	8.33% L	10.0	85% Reference	3497.8	4248.8	5174.7
			Reference	3411.2	4182.5	5081.4
			115% Reference	3406.7	4245.5	4977.3
		12.5	85% Reference	2148.0	2503.7	3004.4
			Reference	2146.7	2533.5	2884.2
			115% Reference	2168.3	2540.6	2950.3
		15.0	85% Reference	1022.9	1162.8	1566.1
			Reference	1071.6	1211.5	1351.3
			115% Reference	1124.8	1264.7	1404.6
		17.5	85% Reference	819.8	1023.2	1166.6
			Reference	861.6	924.6	1183.5
			115% Reference	850.2	970.5	1210.9
		20.0	85% Reference	606.3	719.6	801.1
			Reference	605.9	725.5	777.2
			115% Reference	636.1	755.4	831.4
	12.5% L	10.0	85% Reference	3380.5	4024.9	4901.0
			Reference	2462.1	3958.6	4807.7
			115% Reference	2536.4	4013.3	4703.7
		12.5	85% Reference	2050.1	2388.5	2866.2
			Reference	2043.1	2412.6	2825.0
			115% Reference	2117.9	2414.0	2806.3
		15.0	85% Reference	975.0	1107.5	1240.0
			Reference	1020.0	1152.5	1285.0
			115% Reference	1224.6	1202.1	1334.6
		17.5	85% Reference	785.3	845.5	957.3
			Reference	824.3	884.5	996.2
			115% Reference	812.9	927.5	1039.2
		20.0	85% Reference	601.5	642.2	691.9
			Reference	583.1	630.7	680.4
			115% Reference	574.6	667.7	717.4

Regression on this data gives

Lower hulls weight (tonnes) = $A\ L_H^{b}$ Eqn. 9.48

where $A = 3.604 \times 10^{-4} + 7.299 \times 10^{-5}\ (L/D)$
and $b = 5.414\ (L/D)^{-0.244}$

This equation performs very well for L/D ratios up to 17.5, and lengths up to 100 metres, above which it tends to underestimate structural weight.

9.12.2 Lower Hull Weights for a Family of SWATH Ships

In a similar, but more restricted study to the above, *SWATHULL* was applied to the five simple circular SWATH hulls introduced in Chapter 5. Again, three standard hull bulkhead spacings were examined for each of the five hulls, giving compartment lengths of 6.25%, 12.5% and 8.33% of the hull length. Damaged stability characteristics of these designs are currently being examined [35] so that trade-offs between structural design and survivability may be made. Figure 9.15 shows that the chosen compartment lengths approximate to the lower, upper and mean values derived from equations 9.40 and 9.41. Three frame spacings were determined using a reference figure of 100% from Equation 9.22, and alternative spacings at 85% and 115% of this value. Hydrostatic heads equivalent to the vessel floating at its wet deck with a superimposed wave height of $0.6\sqrt{L_H}$ were applied to each hull. The 'high' and 'low' values of box clearance detailed in Table 5.5 were used to derive two design heads for each hull. The results for this study are listed in Table 9.16.

Table 9.16 Lower Hull Weights for a Family of SWATH Ships

Design Displacement t)		1000		2000		3000		4000		5000	
Box Clearance (m)		3.40	2.21	4.27	2.77	4.91	3.17	5.38	3.48	5.94	3.88
Design Pressure (N/mm^2)		0.132	0.120	0.159	0.143	0.178	0.161	0.193	0.174	0.208	0.187
Bulkhead Spacing	*Frame Spacing*										
6.25% Hull Length	85% Reference	102.1	102.1	188.1	168.7	278.0	252.0	376.0	328.9	430.2	428.5
	Reference	111.5	98.6	183.9	183.9	271.0	269.8	365.4	363.9	469.4	416.7
	115% Reference	108.9	108.9	188.1	180.7	290.5	264.6	387.0	356.1	458.4	456.6
8.33% Hull Length	85% Reference	99.2	99.2	181.4	162.8	267.4	242.7	361.2	331.8	412.5	410.7
	Reference	108.2	95.8	177.1	177.1	260.4	259.2	350.6	349.1	449.9	398.9
	115% Reference	105.6	105.6	181.3	174.0	278.8	254.0	370.7	341.3	438.9	437.2
12.5% Hull Length	85% Reference	96.4	96.4	174.6	156.9	256.8	233.3	346.3	318.5	415.2	393.0
	Reference	104.8	92.9	178.8	170.4	249.8	248.6	335.8	334.3	430.4	398.6
	115% Reference	98.1	102.3	174.6	174.6	277.4	243.4	354.4	326.5	419.4	417.6

9.13 Conclusions

A review of current practice in SWATH design can be useful in suggesting initial structural weights for new designs.

A general approach due to Allen and Jones has been applied to estimate wet deck slamming pressures for SWATH ships. An impact load factor necessary to this method has been proposed. Application of simple beam theory in conjunction with magnification factors for shear lag and stress concentration has been found to give adequate estimates of primary structural weight of struts and cross structure. A rational method for estimating the weight of circular pressure hulls has been adapted for SWATH ships synthesis. These components form part of an integrated overall design methodololgy which has been validated and applied to the family of SWATH ships studied throughout this thesis.

The design methods proposed are considered to offer an accuracy of 10% in preliminary structural weight estimates.

Parametric studies of a family of SWATH ships have illustrated the importance of vehicle density and vessel slenderness in driving structural weight fractions. The related need to minimise enclosed volume, and employ 'stocky' struts can conflict with certain low density payloads and basic hydrodynamic considerations.

References to Chapter 9

1. Lang, T.G. et al, "Preliminary Design Study of a 3000 Ton S^3", Report NUC TN 574, Naval Undersea Center, San Diego, 1971

2. Gore, J. (editor), "SWATH Ships", *Naval Engineers Journal*, February 1985

3. Gupta, S.K. and Schmidt, T.W., "Developments in SWATH Technology", ASNE *Naval Engineers Journal*, May 1986

4. Heller, S.R. and Clark, D.J., "The Outlook for Lighter Structures in High Performance Marine Vehicles", AIAA Paper 74-330, AIAA Advanced Marine Vehicles Conference, San Diego, February1974

5. *Fact Book for MV Twin Drill*, International Underwater Contractors Inc., Houston, Texas, June 1985

6. Pattison, D.R. and Rose, P.H.A., "SWATH - The UK MoD Design and Assessment Programme", Proceedings, International Symposium on SWATH Ships and Advanced Multihulled Vessels II, RINA, London, November 1988

7. Luedeke, G., Montague, J., Posnansky, H. and Lewis, Q., "The RMI SD-60 SWATH Demonstration Project", *Proceedings*, International Symposium on SWATH Ships and Advanced Multihulled Vessels, RINA, London, April 1985

8. Luedeke, G. and Montague, J., "RMI's Small Waterplane Area Twin Hull (SWATH) Boat Project", San Diego Local Section Paper, SNAME, Nov. 1984

9. Covich, P., "T-AGOS 19: An Innovative Program for an Innovative Design", ASNE *Naval Engineers Journal*, May 1987

10. Fernandez-Gonzalez, F., "Mission Related Preliminary Design Solutions for Small SWATH Ocean Patrol Vessels", Proceedings, International Symposium on SWATH Ships and Advanced Multihulled Vessels, RINA, London, April 1985

11. Wilkie, L.J., "A SWATH Crew Boat Design", Hawaii Local Section Paper, SNAME, April 1983

12. Pieroth, C.G. and Lamb, G.R., "The SWATH Option as a V/STOL Aircraft Carrier", Proceedings, 7th AIAA/SNAME/ASNE Marine Systems Conference, New Orleans, February 1983

13. Betts, C.V., Ferreiro, L.D., Grzeskowiak, S.R., McDonald, N.A. and Parlett, P.J., "Design Study for an Anti Submarine Warfare SWATH Frigate", *Proceedings*, International Symposium on Anti Submarine Warfare, RINA, London, May 1987

14. Lee, K.Y., Lee, D.K., Kim, E.S., Kim, J.G. and Kim J.H., "On the Design Technology of SWATH Ship for High Speed Coastal Passenger Vessel", *Proceedings*, High Speed Surface Craft Conference, January 1988

15. Lee, K.Y., Lee, D.K., Kim, E.S., Kim, J.G. and Kim, J.H, "On the Design Technology of SWATH High Speed Passenger Ship", *Proceedings*, International Symposium on SWATH Ships and Advanced Multihulled Vessels II, RINA, London, November 1988

16. Smith, D.L., Cuthbertson, W., MacGregor, J.R. and McGregor, R.C., "SWATH Sonar Support Vessel (SSV)", Contract NSS 41A/1800, Concept Study Report, Yarrow Shipbuilders Limited, July 1987

17. "SWATH Concept Structural Design", MAESTRO Modelling of SWATH Structure Calculation Files, YARD Naval Architecture Group, January 1989

18. Nethercote, W.C.E., and Schmitke, R.T., "A Concept Exploration Model for SWATH Ships", *Transactions*, RINA, Vol. 124, 1982

19. Mulligan, R.D. and Edkins, J.N., "ASSET/SWATH - A Computer Based Model for SWATH Ships", RINA Conference on SWATH Ships and Advanced Multi-Hulled Vessels, London, April 1985

20. Walker, M.A., "SWATH versus Monohull Initial Design", *MSc Dissertation* in Naval Architecture, University College London, 1984

21. Aronne, E.L, Lev, F.M. and Nappi, N.S., "Structural Weight Determination for SWATH Ships", AIAA Paper 74-326, AIAA/SNAME/USN Advanced Marine Vehicles Conference, San Diego, Ca., February 25-27 1974

22. Devine, E., "Modifications to the Ship Structural Design Program (SSDP) for Enhanced Application to US Navy SWATH Ships", DTNSRDC Report, January 1987

23. Creswell, D.J. and Dow, R.S., "The Application of Non-linear Analysis to Ship and Submarine Structures", *Advances in Marine Structures*, Elsevier Applied Science Publishers, 1986

24. Stirling, A.G., Jones, G.L. and Clarke, J.D., "Development of a SWATH Structural Design Procedure for Royal Navy Vessels", *Proceedings*, International Conference on SWATH Ships and Advanced Multi-hulled Vessels II, RINA, London, November 1988

25. Stone, K.F., "Advanced Marine Vehicles and Structural Design: An Opportunity for Optimisation", Intersociety Advanced Marine Vehicles Conference, Washington D.C., June 1989

26. MacGregor, J.R., "Notes of Meeting with Professor Owen Hughes at YARD Ltd 23/11/87", Department of Naval Architecture and Ocean Engineering, Glasgow University, November 1987

27. Holcomb, R.S. and Allen, R.G., "Investigation of the Characteristics of Small SWATH Ships Configured for United States Coast Guard Missions", DTNSRDC Report No. SDD-83-3, June 1983

28. Hadler, J.B., Hubble, E.N., Allen, R.G. and Blount, D.L., "Planing Hull Feasibility Model - Its Role in Improving Patrol Craft Design", *Proceedings*, Symposium on Small Fast Warships, RINA, 1978

29. Allen, R.G. and Jones, R.R., "A Simplified Method for Determining Structural Design Limit Pressures on High Performance Marine Vehicles", Paper 78-754 AIAA/SNAME Advanced Marine Vehicles Conference, San Diego, April 1978

30. Sikora, J.P., "Some Design Approaches for Reducing the Structural Weight of SWATH Ships", *Proceedings*, International Conference on SWATH Ships and Advanced Multi-hulled Vessels II, RINA, London, November 1988

31. Graham, R., "Slamming Experiments with a Radio-Controlled SWATH Model", *Proceedings*, International Conference on SWATH Ships and Advanced Multi-hulled Vessels II, RINA, London, November 1988

32. Kerr, G.D., Anderson, A. and Kennell, C., "SWATH Ship Design - State of the Art", AIAA Paper 78-737, AIAA/SNAME Advanced Marine Vehicles Conference, San Diego, Ca., 1978

33. Kennell, C.G., "Lecture on SWATH Design", Department of Naval Architecture & Ocean Engineering, University of Glasgow, May 1987

34. Report of Committee V-4, "Novel Design Concepts - SWATH", 19th International Ship & Offshore Structures Congress, Denmark 1988

35. Miller, A.F., "SWATH Design Evaluation Project - First Progress Report", Vickers Shipbuilding and Engineering Limited, February 1989

36. British Hovercraft Safety Requirements", Issue 2, Civil Aviation Authority, January 1974

37. Mulligan, R.D. and Edkins, J.N., *Small Waterplane Area Twin Hull Advanced Surface Ship Evaluation Tool - Preliminary Theory Manual*, DTNSRDC Advanced Concepts Office, April 1983

38. Drummond, T.G., MacKay, M. and Schmitke, R.T., "Wave Impacts on Hydrofoil Ships and Structural Implications", *Proceedings*, 11th Symposium on Naval Hydrodynamics, University College London, 1976

39. Ochi, M.K. and Motter, L.E., "Prediction of Extreme Values of Impact Pressure Associated with Ship Slamming", SNAME *Journal of Ship Research*, Vol. 13, No. 2, June 1969

40. Giannotti, J.G., "Estimate of Wave Impact Loads and Pressures for Cross-Structure of a SWATH Ship", Report No. 6136-74-22, Hull Form and Fluid Dynamics Branch, NAVSEC, November 1974

41. Giannotti, J.G., "Prediction of Slamming Loads for Catamarans", OTC Paper 2281, *Proceedings*, 7th Offshore Technology Conference, Houston, May 1975

42. Kaplan, P., "Analysis and Prediction of Flat Bottom Slamming Impact of Advanced Marine Vehicles in Waves", *International Shipbuilding Progress*, Vol. 34, No. 391, March 1987

43. Chuang, S.L., "Experiments on Flat Bottom Slamming", SNAME *Journal of Ship Research*, March 1966

44. Dinsenbacher, A.L., "A Method for Estimating Loads on Catamaran Cross Structure", SNAME *Marine Technology*, October 1970

45. Jones, H.D., and Gerzina, D.M., "Motions and Hull Induced Bridging Structure Loads for a Small Waterplane Area Twin Hulled Attack Aircraft Carrier in Waves", DTNSRDC REport 3819, August 1973

46. Lee, C.M., Jones, H.D. and Curphey, R.M., "Prediction of Motion and Hydrodynamic Loads of Catamarans", SNAME *Marine Technology*, Oct. 1973

47. Curphey, R.M. and Lee, C.M., "Analytical Determination of Structural Loading on ASR Catamaran in Beam Seas", DTNSRDC Report 4267, April 1974

48. Curphey, R.M., "Computation of Loads Acting on the Cross Structure and Struts of Twin Hull Ships in Beam Waves", DTNSRDC Report No. SPD-651-01, November 1975

49. Lee, C.M. and Curphey, R.M., "Prediction of Motion, Stability and Wave-Load of Small-Waterplane-Area-Twin-Hull Ships", *Transactions*, SNAME, Vol. 85, 1977

50. Santos, R. and Sartori, G., "An Example of Dynamic Wave Loads Assessment for a Non-Conventional Vehicle (SWATH) in the Mediterranean Sea", CETENA Report No. 1290, Genoa, July 1981

51. Bishop, R.E.D., Price, W.G. and Temarel, P., "On the Hydroelastic Response of a SWATH to Regular Oblique Waves" in *Advances in Marine Structures* (ed. C.S. Smith and J.D. Clarke), pp. 89-110, Elsevier, London, 1986

52. Price, W.G., Temarel, P. and Wu, Y., "Responses of a SWATH Travelling in Unidirectional Irregular Seas", *Underwater Technology*, Vol. 13, Number 4, Winter 1987

53. Eatock-Taylor, R., and Hung, S.M., "Some Wave Load Effects on the Design of SWATH Ships", *Proceedings*, PRADS'87, Trondheim, June 1987

54. Zheng, X., "Prediction of Motions and Wave Load of Mono and Twin Hull Ships in Waves", *Ph.D Thesis*, University of Glasgow, March 1988

55. Reilly, E.T., Shin, Y.S. and Kotte, E.H., "A Prediction of Structural Load and Response of a SWATH Ship in Waves", *Naval Engineers Journal*, May 1988

56. Sikora, J.P., Dinsenbacher, A. and Beach, J.E., "A Method for Estimating Lifetime Loads and Fatigue Lives for SWATH and Conventional Monohull Ships", ASNE *Naval Engineers Journal*, May 1983

57. Penney, P.W. and Riiser, R.M., "Preliminary Design of Semi Submersibles", *Transactions*, NECIES, Vol. 101, 1984-1985

58. Sielski, R.A., Discussion to White, G.J. and Ayyub, B.M., "Reliability Based Fatigue Design for Ship Structures" (ASNE *Naval Engineers Journal*, May 1987), ASNE *Naval Engineers Journal*, July 1987

59. Dinsenbacher, A.L. Malakhoff, A. and Richardson, W.M., Discussion to Richardson, W.M., "A Probability Based Load Estimation Technique for Ship Structure Design and Technology Evaluation", (ASNE *Naval Engineers Journal*, May 1987), ASNE *Naval Engineers Journal*, July 1987

60. "SWATH Ship Electric Propulsion", Contract MP17/58, YARD Ltd Surface Ship Machinery Group, November 1988

61. Sikora, J.P. and Swanek, A.D., "SWATH Preliminary Structure; Design Considerations and Stress Calculation Method", Enclosure to DTNSRDC letter 173 ADS, 5605, 82-173-55, 27 April 1982

62. MacGregor, J.R., "Program *STRUKT* - SWATH Structural Design and Weight Estimation", SWATH User Guides Vol. 1, YM5670/005/00A, YARD Ltd, 1988

63. Lankford, B.W., "The Structural Design of the ASR Catamaran Cross Structure", ASNE *Naval Engineers Journal*, August 1967

64. Unozawa, M. and Shimitzu, K., "The Design of Catamarans", *Proceedings*, PRADS, Tokyo, October 1977

65. Loscombe, R., "An Exploratory Study of Alternative Structural Materials for Small SWATH Ships", *International Shipbuilding Progress*, No. 404, December 1988

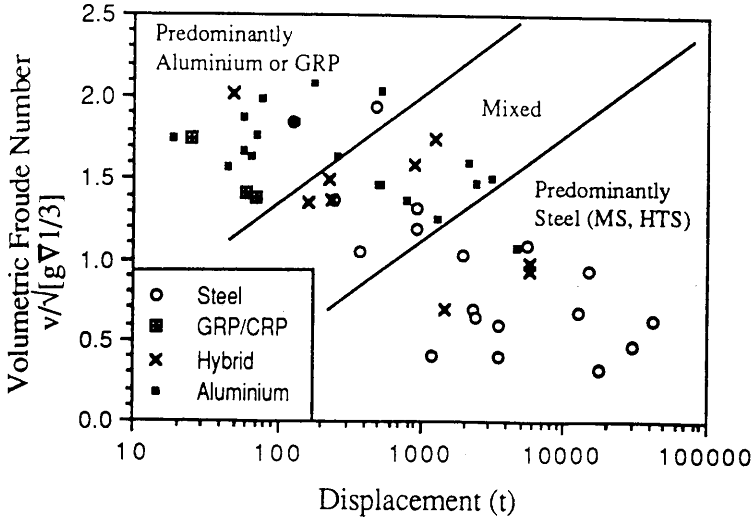


Figure 9.1 Use of Structural Materials in SWATH Design

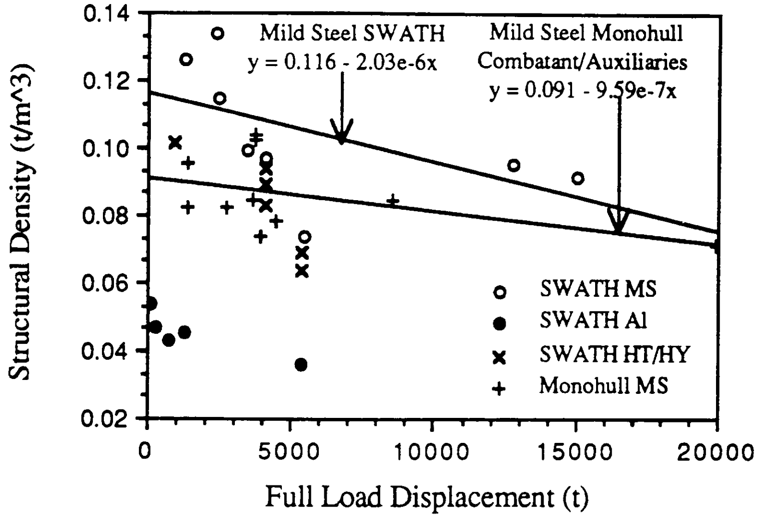


Figure 9.2 SWATH Ship Structural Densities

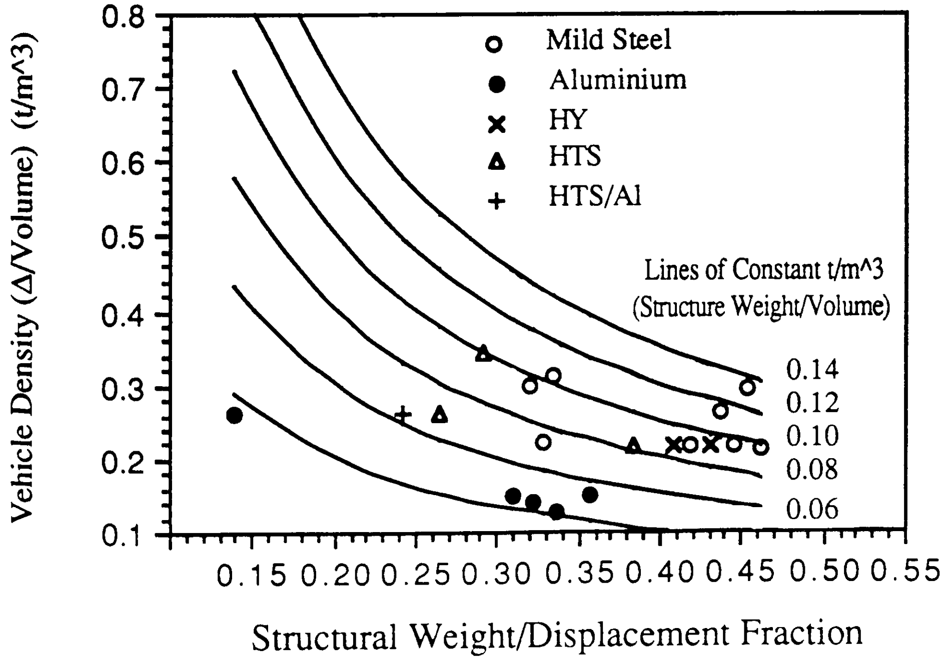


Figure 9.3 Vehicle Density - Structural Weight Fraction Relationship

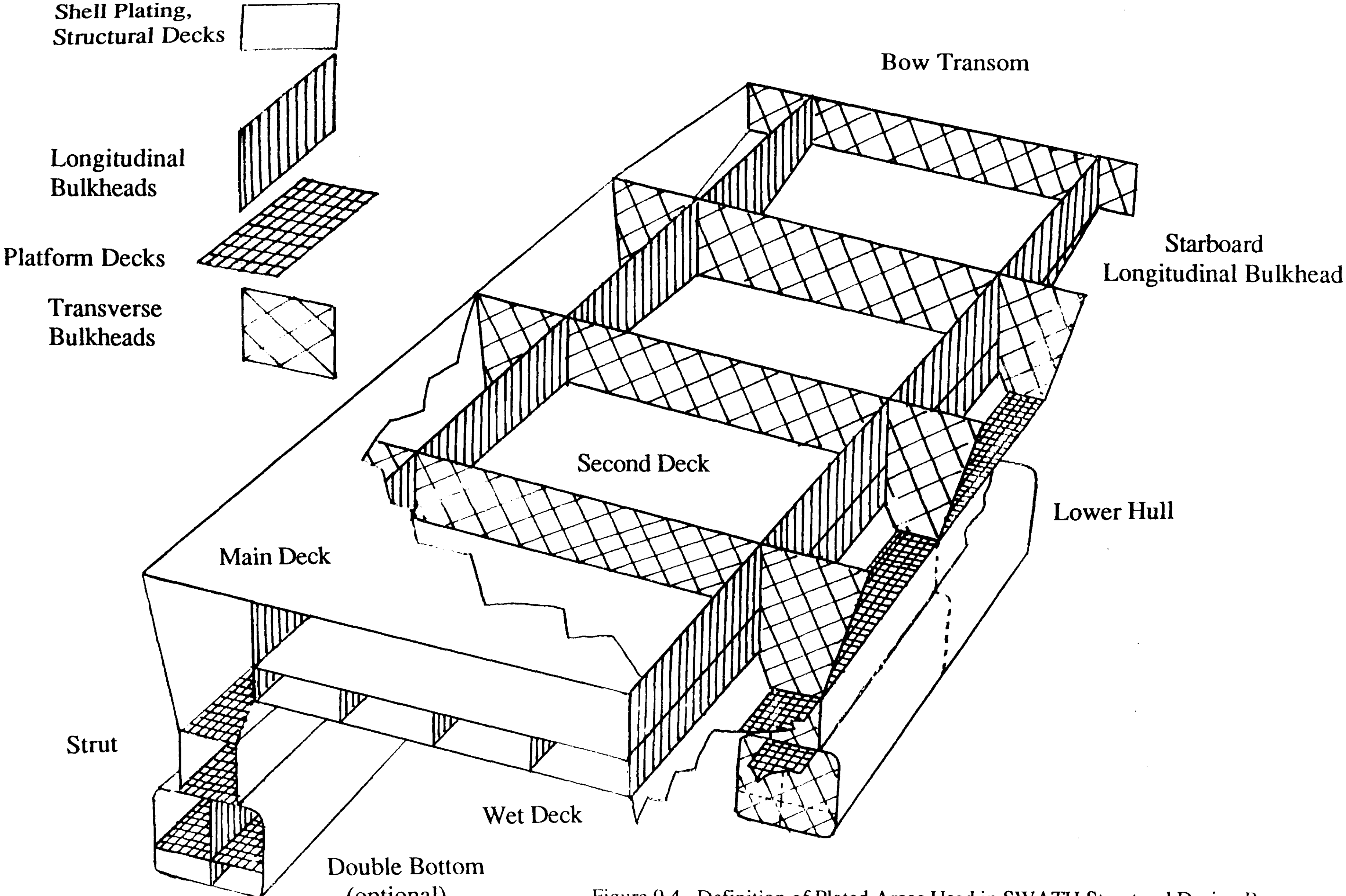


Figure 9.4 Definition of Plated Areas Used in SWATH Structural Design Program

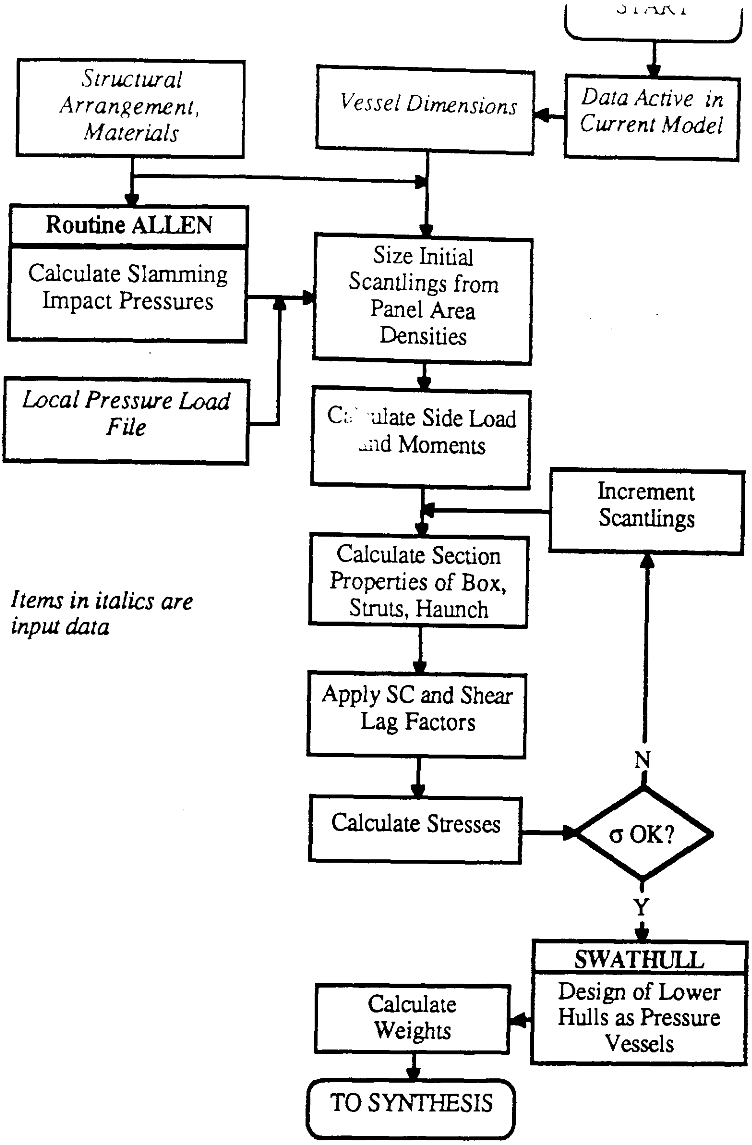


Figure 9.5 Flow Chart for Structural Design Program

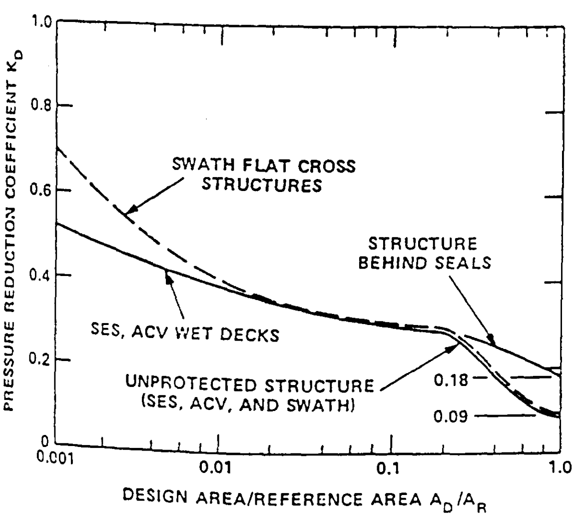


Figure 9.6 Pressure Reduction Coefficient for SES, ACV and SWATH (from ref. [29])

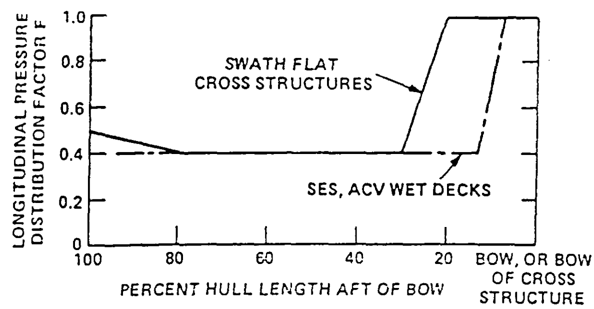


Figure 9.7 Longitudinal Pressure Distribution Factors for SES, ACV, SWATH (from ref. [29])

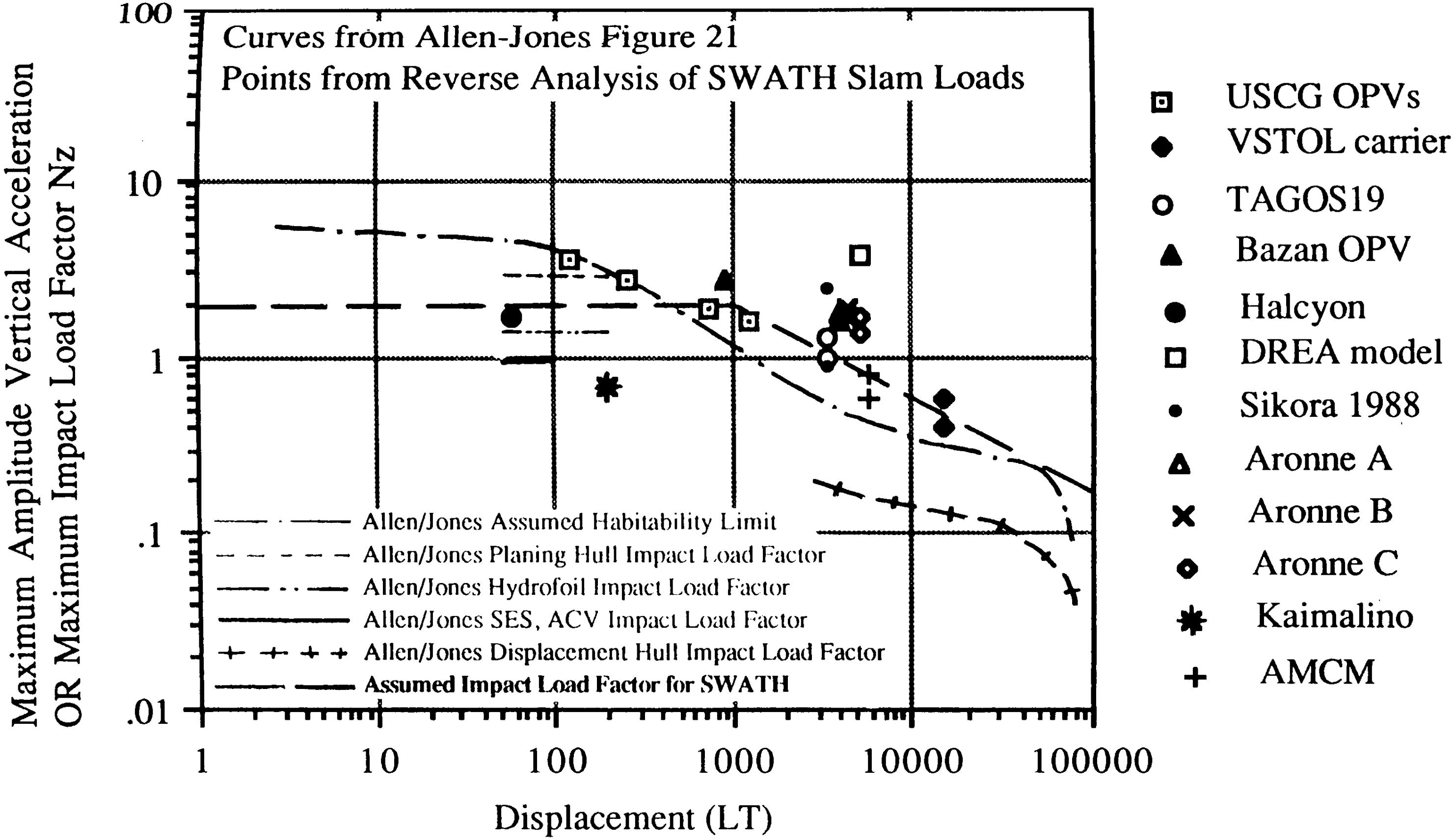


Figure 9.8 Impact Load Factors for Use in Determining SWATH Wet Deck Slamming

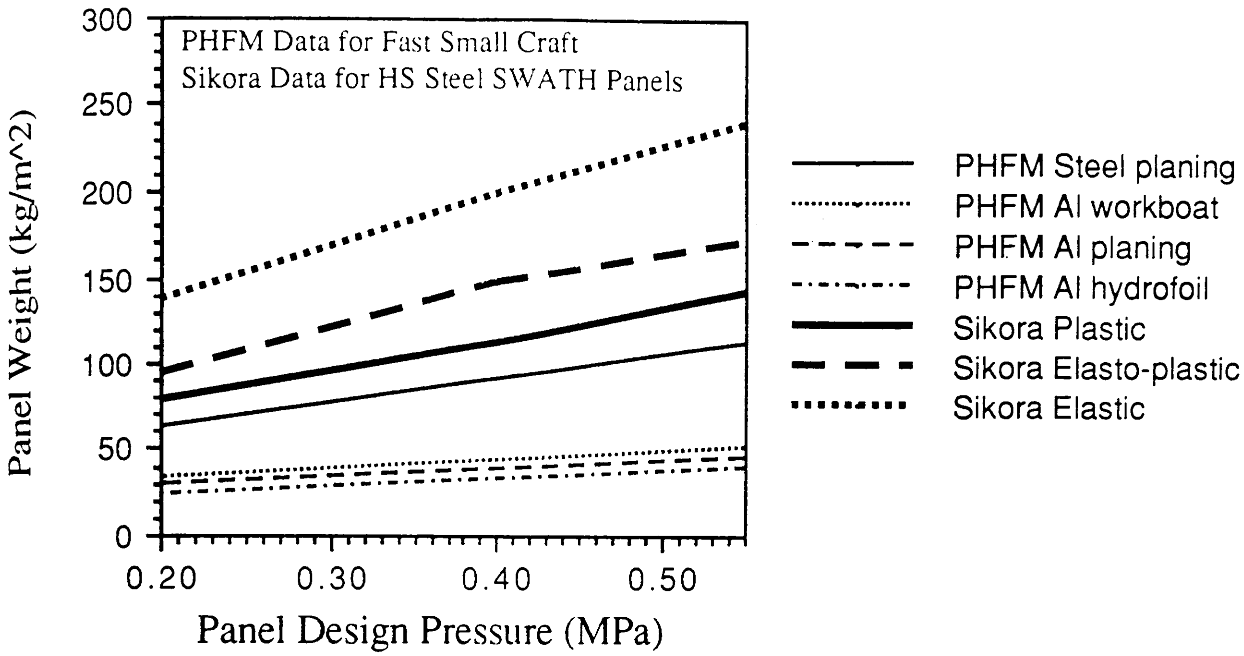


Figure 9.9 Stiffened Panel Area Densities versus Design Pressure

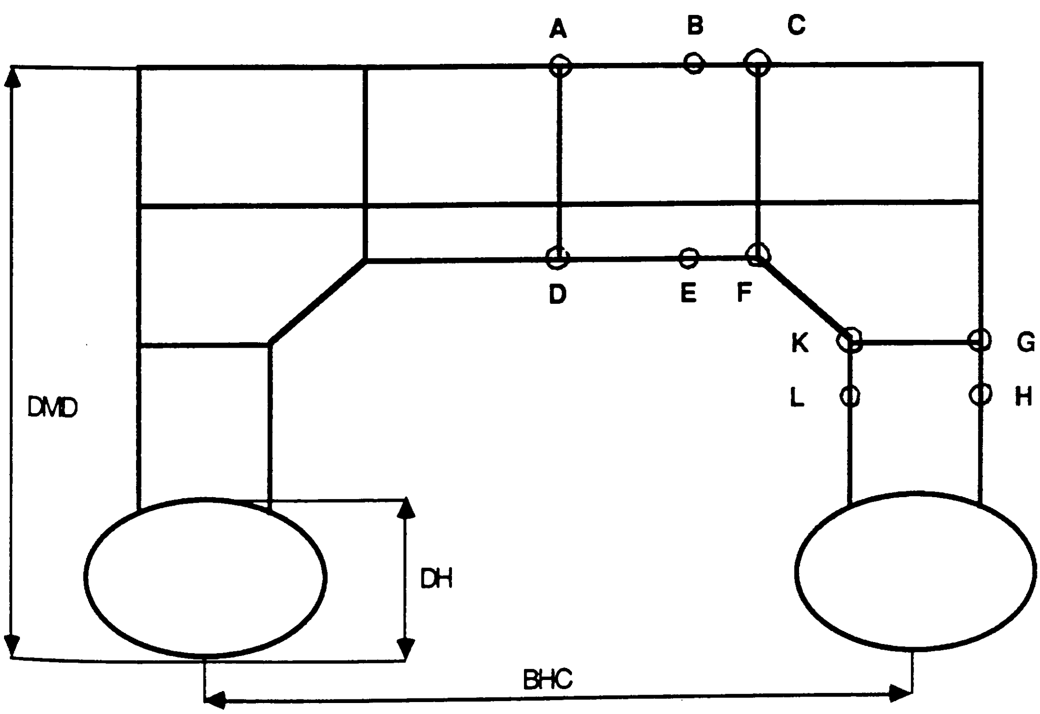


Figure 9.10 Location in Cross Structure of Points of Stress Calculation (from ref. [37])

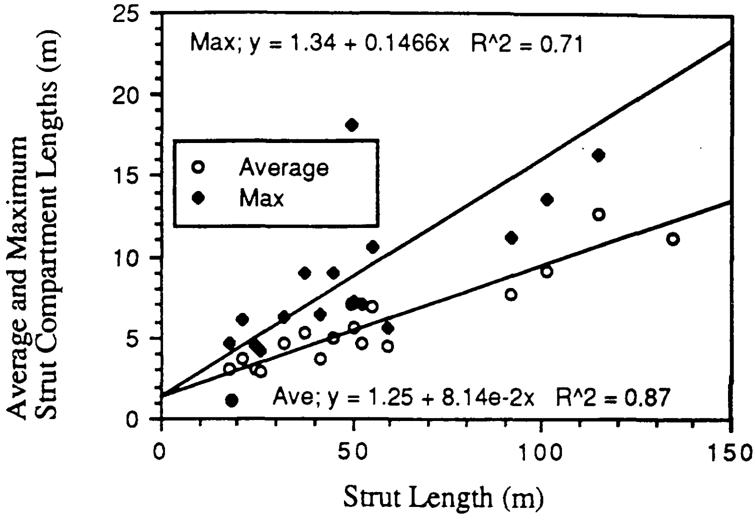


Figure 9.11 Lengths of Compartments in Struts

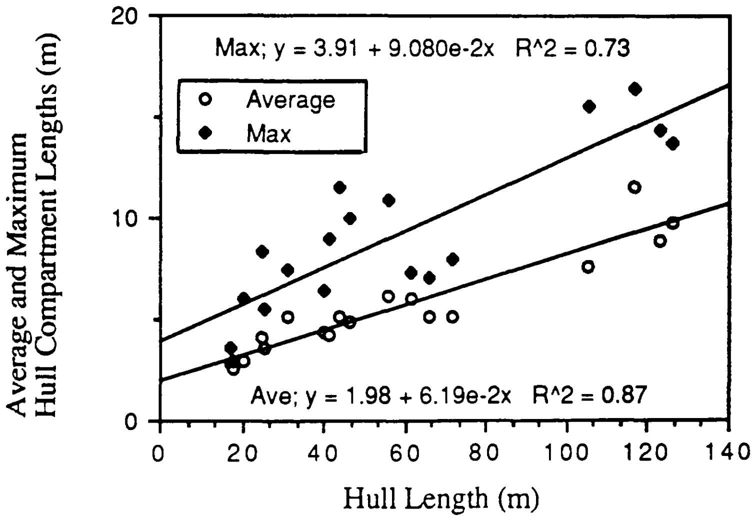


Figure 9.12 Lengths of Compartments in Lower Hulls

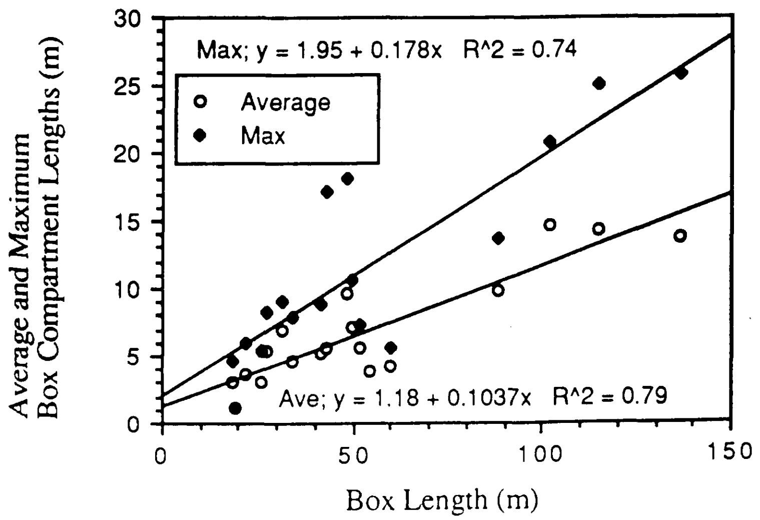


Figure 9.13 Lengths of Compartments in Box Structure

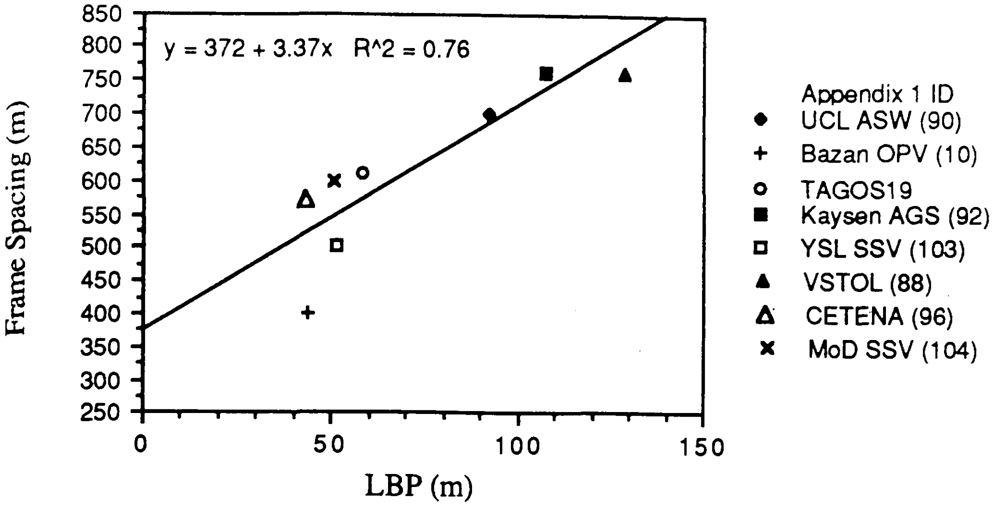


Figure 9.14 Transverse Frame Spacing as Function of SWATH Length

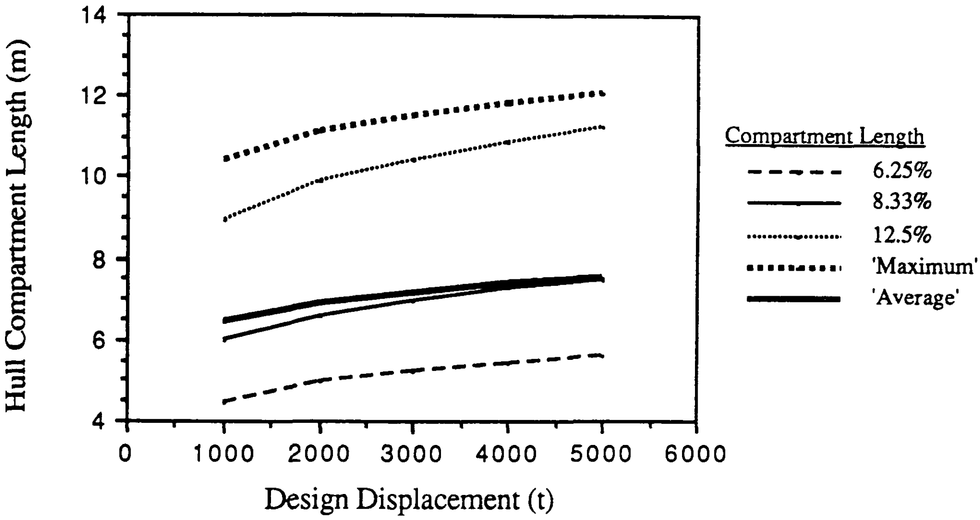


Figure 9.15 Comparison of Compartment Lengths Used in Parametric Study

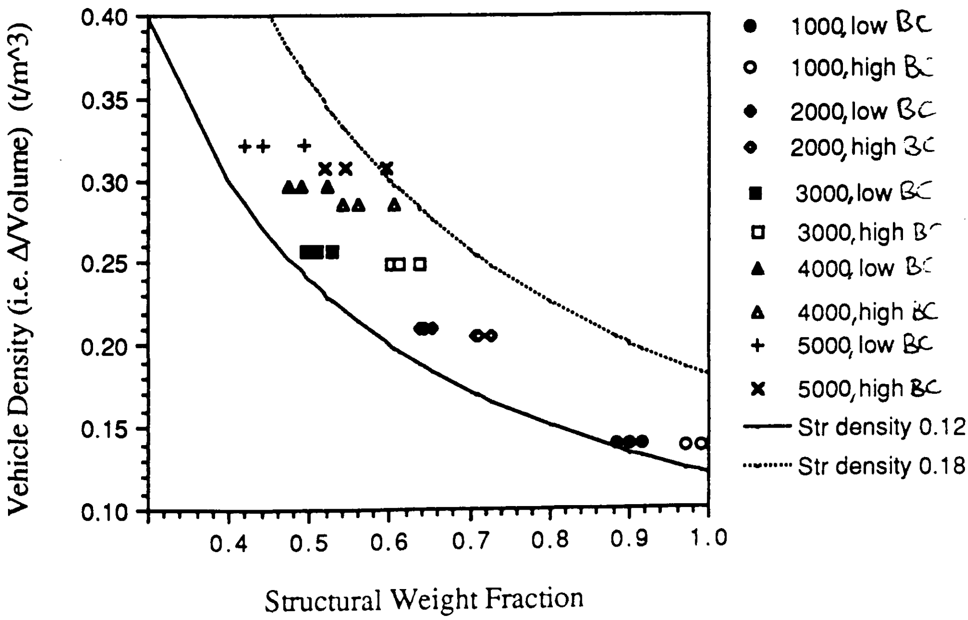


Figure 9.16 Structural Weight Fractions - Vehicle Densities for Family of SWATH Ships

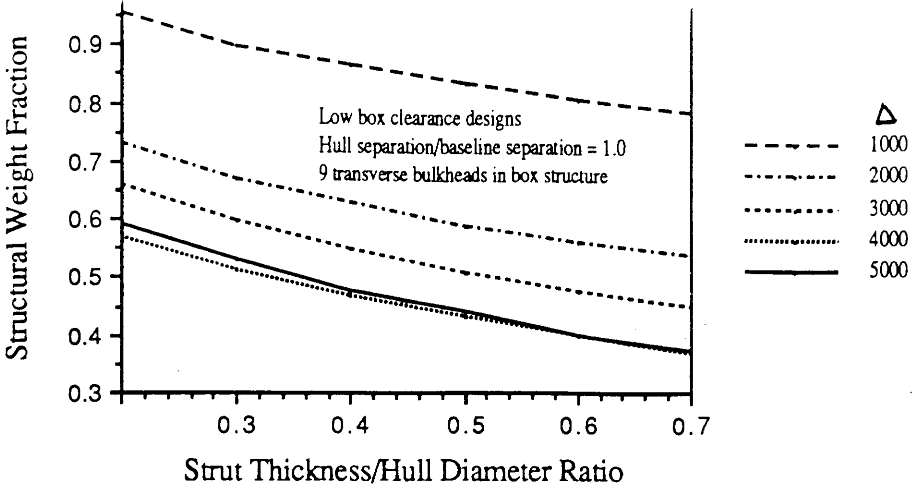


Figure 9.17 Variation of Structural Weight Fraction with Strut Thickness

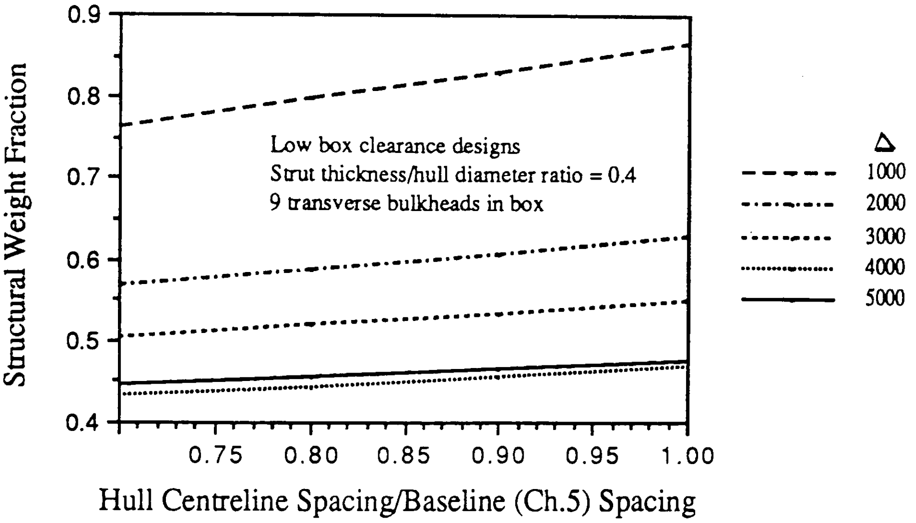


Figure 9.18 Variation of Structural Weight Fraction with Hull Spacing

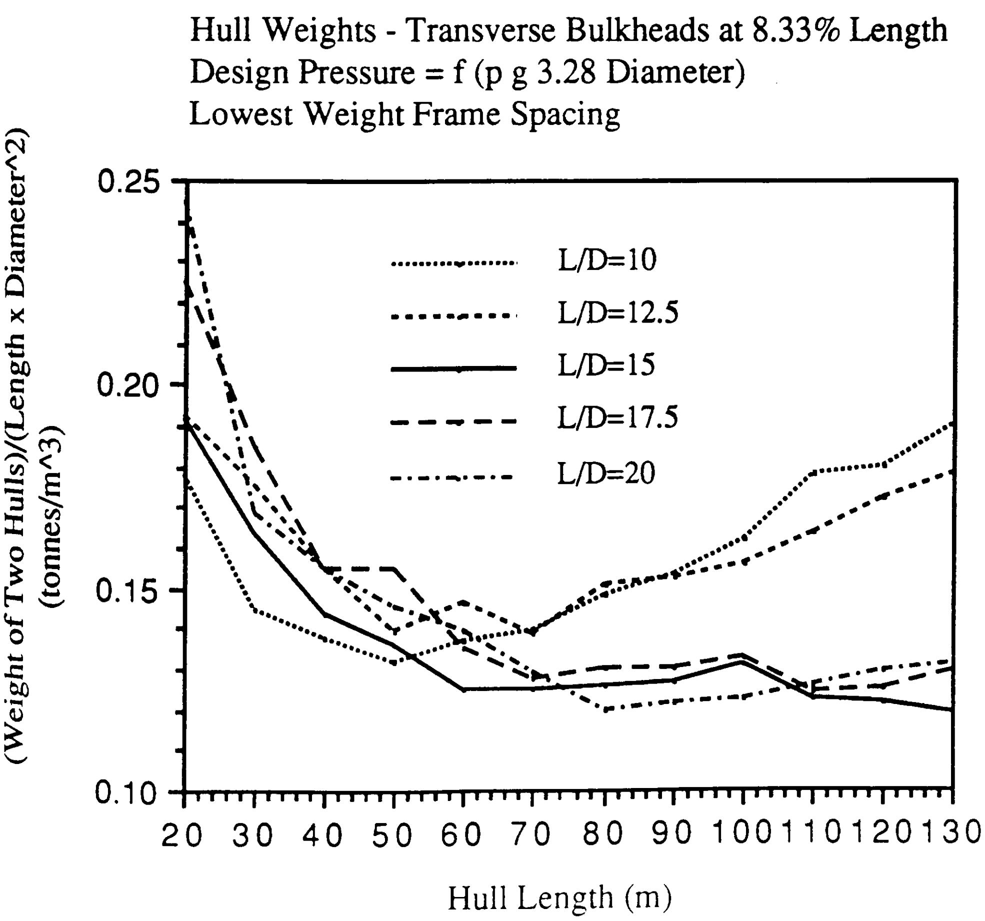


Figure 9.19 Structural Densities of Transversely Framed Circular Lower Hulls

CHAPTER 10

WEIGHT AND SPACE BALANCE

A regression analysis performed on a collection of data is used to develop a parametric method for weight estimating. The development of a generalised computer program for estimating the space requirements of escort warships is also described. These weight and space routines have been applied to the design of SWATH escort vessels. For the geometries considered, a strong conflict between space and weight demand is identified, and the importance of vehicle density in balancing SWATH designs is illustrated.

10.1 Introduction to Weight Estimating

10.1.1 Ship Weight Estimating

Calculations involving weight are fundamental in naval architecture. This is especially true of those vessels which may be considered to be *weight limited,* as opposed to *volume limited.*

In the early stages of design, estimates of lightship weight and deadweight largely determine the basic characteristics of such vessels. As the design proceeds, it is important to determine weights and moments more accurately in order to ensure satisfactory freeboard, trim and stability. Later, light ship weights are often used as inputs to cost estimates.

Space limited ships, such as most modern warships, must also consider weight calculations carefully. Weight estimation retains its importance for reasons of stability and because of its close links with cost estimating.

Designers of advanced marine vehicles must give equal consideration to both weight and volume as it may not be immediately clear which is to be the governing parameter. In the case of many such vehicles, weight is the critical factor, and this is often true of SWATH ships. These vessels have greater structural weight fractions than equivalent monohulls, and usually require heavier machinery systems. This leads to a reduction in payload capacity. Additionally, the characteristically low waterplane area is unforgiving of underestimated lightship weights.

Accurate weight estimation is therefore especially important in SWATH design. The validity of any study of the SWATH concept is heavily dependent on the accuracy of the weight estimation methods employed.

10.1.2 Weight Classification Terminology

In the first iterations of the ship design spiral, weight calculations are usually performed on large groupings of weights. Typically, as in Chapter 4, the weight of the hull is considered as one weight group, propulsion machinery, outfit items etc as others. These may be referred to as main weight *groups*. The groups used by the UK MoD are reproduced below.

Group 1	Hull Structure
Group 2	Propulsion
Group 3	Electrical
Group 4	Control and Communication
Group 5	Auxiliary Systems
Group 6	Outfit and Furnishings
Group 7	Armament
Group 8	Variable Load

Later, it becomes necessary to refine the calculations by breaking the main weight *groups* into *subgroups*, and these into *sub-subgroups*. For instance, the propulsion group may contain 9 subgroups, and one of these (e.g. Steam Systems) may contain 5 sub-subgroups.

In the early stages of design, weights must be estimated using *top down* methods, where weights are calculated using information derived from previous designs. As the design proceeds, more refined methods should be used to improve the accuracy of the predictions.

Finally, as drawings and equipment lists become available, sub-subgroup weights should be calculated *bottom up* from known individual items, and then summed to give subgroup, main group weights and, finally, the displacement.

A systematic approach to the classification of ship items is fundamental to practical weight estimation. In ship design and shipbuilding it is usual to classify ship weight items according to some criterion such as function or shipboard location. In this report, the UK MoD(N) weight classification system (NES163, [1]) has been used. This largely employs functional criteria to classify the different items and is reproduced in Appendix 7. The Ship Work Breakdown Structure (SWBS, [2]) used by the US Navy is another example of this approach. Other functional classification systems are MARAD (used by the US Maritime Administration, [3]) and SFI (developed by the Shipping Research Institute, Norway, [4])

In this hierarchical type of classification structure, *one digit* numbers are assigned to main groups, *two digit* numbers to subgroups and *three digit* numbers to sub-subgroups. This chapter is concerned with *top down* estimation of weights at a *three digit level of detail.*

10.2 Parent Ship Data for Manual Weight Estimates

10.2.1 Scaling Ship Weights Manually

The primary purpose of this chapter is to describe a parametric method for SWATH ship weight estimation (section 10.3). This method is founded upon a regression analysis of a collection of ship weights currently held on a microcomputer spreadsheet (*EXCEL* on Apple Macintosh). Estimation by scaling from previous designs is likely to continue as the most common means of generating data for new ship designs. This collection offers a useful starting point for a manual approach. For these reasons, inclusion of the original data in this thesis would be desirable but has not proved possible for reasons of military and commercial security. Reference must be made instead to a commercial-in-confidence addendum [6] to the thesis.

A portion of this database is illustrated in Table 10.1, with identifying features of the parent vessels removed. The data sets are not necessarily complete for each vessel, but each individual entry is potentially useful as a source for estimating a sub-subgroup weight for a future design.

Scaling factors for use with this data have not been suggested. These choices remain with the individual user, although the bases used in section 10.3 may prove useful. Additional suggestions for scaling factors may be found in ref. [13]. This work refers to the US Navy SWBS classification system, but there are many similarities between this and the MoD(N) system.

Scaling will produce a reasonable basic estimate for most items and is conveniently carried out with spreadsheet utilities. However, it should be noted that only some of the Group 4 (Control and Communications) and none of the Group 7 (Armament) may be calculated in this way. For combatant ships, these are essentially the payload of the ship, and may be taken as given requirements.

10.2.2 Use of Basis Vessels

The exercise of judgement in the use of existing data is an important aspect of the manual method and it is necessary for the naval architect to be familiar with the basis designs employed. It is important to be aware of the presence of any unusual design features, and the degree of accuracy associated with the particular basis estimates.

Since the accuracy of weights estimated by scaling is dependent upon the suitability of the basis ship weights it is important to use weights from a basis ship system that closely approximates the new ship system in size and configuration. It is also advisable to use data from several basis ships to cross check the new estimates.

Table 10.1 Sample of Database of Three Digit Weights

Illustration of database of group 'A' sub-subgroup weights (tonnes) for 15 ships (unidentified)

Weight Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A00	182.0	269.8	235.9	202.8	248.3	101.8	94.4	270.0	1409.6	512.4	1171.0	342.0			
A01	129.3	194.3	173.9	130.4	177.9	53.7	61.5	196.0	1176.7	330.5	781.4	264.4			
A02	13.1	17.4	64.4		2.9	15.6		37.0	192.1		114.2	62.7		760.4	
A03											12.3			507.6	
A04														74.2	
A05				25.4			1.5						23.4	8.0	
A06						1.2									
A10	27.0	41.3	54.8	41.2	60.2	21.6	9.8		198.3		125.2	33.5			
A11					20.9	4.8	2.2		30.6		3.3	7.6			
A12	34.5	62.1	82.4	50.8	119.0	33.7	15.8		905.0		306.5	181.3		99.4	
A13	26.8	36.7	43.3	31.6	44.3	12.5	7.2		350.1			30.1		2.6	
A14				38.6	30.4				25.5					243.2	
A15					1.8	0.3			8.9						
A16					1.2				59.7						
A17						0.5	0.3								
A18															
A20	39.2	48.1	84.9	66.9	85.5	29.9	27.9		721.6	256.4	470.0	94.7	490.9		
A21									264.5	53.8	699.0	153.7	294.8		
A22	67.8	66.3	78.4	50.3	99.4	6.7	7.9		341.3			25.8		305.2	
A23	2.7	3.2	5.4	8.9	17.9	7.7	5.8	4.0	61.9	20.7	173.0	61.4	23.9	453.3	
A24			3.7						2.0						
A25						0.5	0.5							112.4	
A30	214.4	227.0	268.5	278.8	311.7	59.1	47.3	300.0	2056.7	230.8	1918.8	711.8	2252.8	1246.0	
A31	6.6	9.2	13.7	8.2	5.2	31.2	34.7	27.0	248.0	29.5	17.0	13.9	191.3	11.0	34.0
A32															
A33	8.4	2.4	0.7			1.0	1.0								149.0
A34	1.7	6.5	3.4												31.0
A40	1.5	1.2	2.1	1.0	1.2	1.7	0.8		15.0	2.8	4.0	6.4			
A41	9.7	14.5	22.3	21.8	33.4	2.5	3.1		65.8	19.2	90.4	133.6	86.5	58.7	
A42	4.5	7.3	11.2			4.4	1.5		5.0	5.7			31.5		
A43	3.2	2.5	3.8	3.6	4.5		0.4		5.0		16.2			10.5	
A44				0.2	0.3										
A45															
A46		8.3	9.8							9.8					
A50									150.0						
A51				2.5	3.1	1.4	1.4		8.5		5.3	12.8		3.4	
A52	41.7	76.4	40.9	37.0	41.2	12.0	15.0	34.0	44.3	17.3	119.0	31.5	143.3	77.3	
A53	6.7	10.5	19.8	6.1	5.1	5.0	8.0			16.9	34.0	10.0	67.0		
A54	3.4	9.3	5.7	23.0	26.0	4.1	5.8		35.7	5.9	5.9	7.2	21.0	3.9	
A55	19.0	13.7	23.3	10.3	11.2	10.0	13.5			22.3	145.0	6.1	151.4		
A56		8.9	4.0	2.8	22.5	2.0	4.5		70.7	2.6	31.0	25.6	8.6		
A57	15.7	11.4	8.9	6.5	9.5	4.0	4.0				9.2		20.0	5.9	
A58					0.1						0.9			0.6	
A60	24.2	24.9	14.1	18.0	18.0	10.9	10.4	22.0	62.3		51.6	10.1		23.5	
A61															
A62															
A63															
A64	3.1	2.8	2.5	4.6	5.4	2.6	2.6		9.7		25.9	2.3		23.3	
A65															
A70	29.3	25.7	30.5	17.2	23.0	10.0	13.7		33.5		32.9	7.3		21.4	
A71	3.1	5.0	7.1		5.0	0.5	1.0		3.0	9.0	0.9	2.7		0.6	
A72						0.5	1.0	6.0	10.0	2.0		5.7			
A73	1.2	3.8	2.3	2.3	2.9	1.0	1.0		15.0	3.8		3.0		9.6	
A74						1.0	1.6		7.3		14.8	1.8		1.2	
A75	2.9	4.8	6.0	1.8	2.2	0.5	1.0		10.0		1.9				
A76															
A77	1.6	4.4	3.3												
A80										2.8					
A81			23.1		205.2										
A90						5.0	4.0		130.0		94.9			61.6	
A91															
A92					2.9	1.0	2.0		5.0		64.9				

Reference [6] contains comprehensive data describing the ships forming the database for this study. This information is sufficient for the user to identify the ships involved and gives some guidance as to the characteristics of the vessels involved. It is not possible to correlate basis ship details with individual weights, but the ship types forming the database are described broadly in Table 10.2. It can be seen that this database is heavily influenced by UK escort design philosophy, and the regression equations should only be used with caution (if at all) for ships of different character.

Table 10.2 Description of Vessels in Database

Escort 1	UK designed and built 3600 tonne, 30 knot ASW frigate, CODOG propulsion. Weights are shipbuilders data.
Escort 2	UK designed and built 2800 tonne, 35 knot ASW frigate, COGOG propulsion. The weights are shipbuilders data .
Escort 3	UK designed and built 3700 tonne, 30 knot, guided missile destroyer, COGOG propulsion. The weights are shipbuilders data.
Escort 4	UK designed 3900 tonne, 28 knot ASW frigate (study), CODLAG drive. Weights are shipbuilders data.
Escort 5	UK designed and built 3700 tonne, 30 knot ASW frigate, COGOG propulsion. Weights are shipbuilders data.
Escort 6	UK designed 1300 tonne, 29 knot corvette, CODOG drive. Weights from designer.
Escort 7	UK designed 1300 tonne, 25 knot corvette (study), CODAD drive. Weights from designer.
Escort 8	UK designed 4500 tonne, 29 knot frigate (study). Weights from designer.
Auxiliary 1	UK designed and built 31000 tonne, 21 knot auxiliary. Weights from designer.
Auxiliary 2	UK designed 20000 tonne, 21 knot auxiliary (study). Weights from designer.
Auxiliary 3	UK designed and built 8600 tonne, 18 knot auxiliary. Weights from designer.
Auxiliary 4	UK designed and built 12000 tonne, 21 knot auxiliary. Weights from builder.
Warship 1	UK designed and built 20000 tonne, 28 knot major combatant. Weights from builders.
TAGOS	US Navy auxiliary SWATH vessel (see Appendix 1). Diesel electric propulsion, designed to deploy the SURveillance Towed Array Sonar System (SURTASS). Weights are shipbuilders estimates [22].
SWATH83	US design study for SWATH V/STOL carrier by DTNSRDC/Grumman (Appendix 1 number 88).
MoDSSV	UK design study for SWATH Sonar Support Vessel (Appendix 1 number 104). Weights from marine systems consultant.

10.2.3 SWATH Ship Weight Database for Synthesis Model *DESIN*

A number of SWATH ship weights (listed in Table 10.3) have been collected and computerised to form a database which may be used by the synthesis program DESIN. These weights may either be used without modification, or scaled using simple equations to provide alternatives to the parametric method described in the following section.

Table 10.3 SWATH Ship Weights Linked to *DESIN*

US SWBS	3 digit weights	for 3500 tonne auxiliary	(Groups 1 - 8)
UK NES163	2 digit weights	for 2400 tonne auxiliary	(Groups 1 - 8)
UK NES163	3 digit weights	for 2300 tonne auxiliary	(Groups 2,3,5)
US SWBS	3 weights	for 15000 tonne aircraft carrier	(Group 1)

In addition, DESIN is designed to allow weights developed manually by specialist engineers to be used in the synthesis. Thus, Group 4 weights defined for a given role may be placed on file and used throughout the design process to give a higher degree of accuracy than generalised methods.

10.3 Parametric Methods

10.3.1 Automated Weight Estimation

It is anticipated that manual scaling methods employing the data presented in reference [6] are most likely to be used in design office practice. However, it is possible to develop automated weight estimation using scaling techniques. It is now technically feasible to store all the information presented in [6] on computer files, and to develop scaling programs which can apply user-defined factors to produce new weights. A system of this type is potentially very powerful, but would require a significant development effort in order to ensure flexibility of use and integration with other design technologies.

Other alternatives include use of microcomputer based spreadsheet utilities to store and manipulate large amounts of weight data according to the designers wishes. This is a most efficient means of exploiting the data collected in reference [6]. While this approach provides a most useful standalone package, it is not (as yet) suited to integration with an iterative design synthesis tool.

A simpler but less precise approach is to employ continuous functions to express the relationship of each weight to some convenient base. This method tends to obscure effects of particular outfit or systems fits and should really be restricted to use for vessels of a certain class. It is, however, suited for use in an automated ship design system.

10.3.2 Parametric Equations

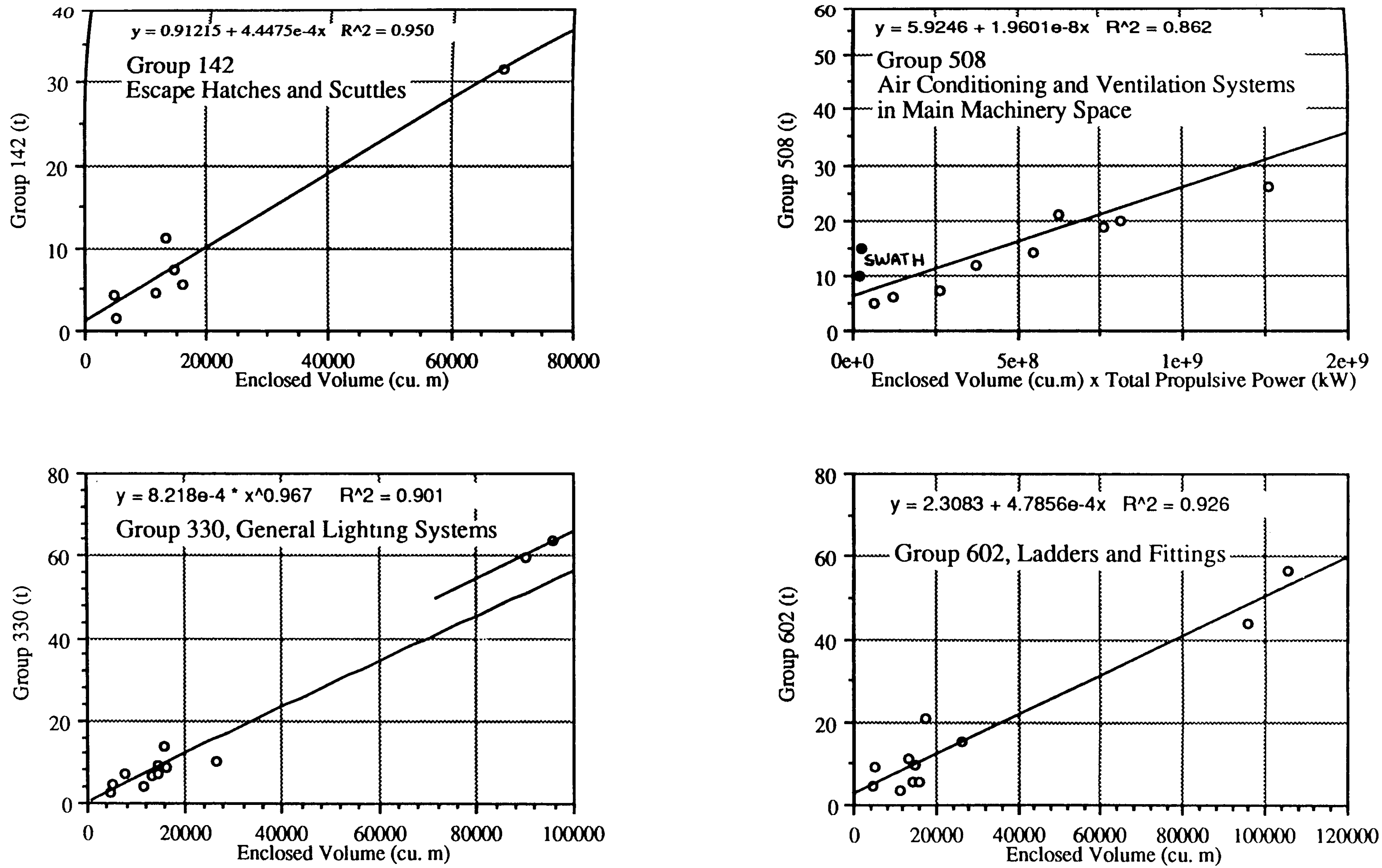
A set of parametric equations was developed by regression analysis of the data presented in reference [6]. The full range of ship types listed in Table 10.2 was employed in this analysis. It is recognised that this database is composed of differing types of vessel, and that it is not stricly correct to compare all on the same basis. It is likely that better correlation would be achieved by restricting the database to the first 8 vessels listed in Table 10.2. This would be useful in any small warship design system. However, in order to develop a generalised method with an application beyond that of UK frigate/destroyer types, it was decided to include all available information. It is also appreciated that future work may show two digit weights to be more useful as bases.

The equations thus derived have been incorporated in a computer program *(EMPIREWT)*. The functions are listed in Appendix 7, against the appropriate NES163 three digit classifications.

No equations have been developed for the major (subgroups 20 to 23) propulsion items or major (subgroups 10 to 13) structural items. These weights are obtained from the methods described in Chapters 8 and 9. For combatant ships, the Group 4, Group 7 and Group 8 weights form part of the payload of the vessel, and may be taken as *given* weights in the context of this report. It is not reasonable to expect scaling or parametric equations to produce accurate estimates of these weights. Consequently no equations have been produced for Group 7 or 8 weights, although an attempt has been made at providing equations for Group 4 items.

A variety of parameters were employed as bases against which to plot the various sub-subgroups. The choice of base was influenced by the closeness of fit which could be obtained, and the logic behind the factors. In many cases, the enclosed volume of the vessels was used. This is intended to represent the relationship between systems and their weights and the spaces which they occupy and service. This relationship is felt to be particularly important [7] for SWATH ship synthesis.

The original data used to derive the equations is contained in graphical form in reference [6]. It is possible to identify individual datapoints on the various plots by referring to the associated listing of ship characteristics. The values of the functions used as bases for the sub-subgroup weights may be related to particular vessels in this way. This allows the user to identify trends of particular interest, and to modify the tabulated equations if necessary. Figures 10.1a to 10.1d illustrate the curve fits used to derive four of the equations in Appendix 7.



Figures 10.1a to 10.1d Example Derivations of Weight Estimating Equations

10.3.3 Method Validation

In order to test the performance of the equations, the characteristics of 14 of the ships identified in section 10.2 were used as input to *EMPIREWT*. Individual sub-subgroup weights were assumed to provide main group weights for each of the ships. *Known* weights were used for major (groups 10 to 13) structural and major (groups 20 to 23) propulsion items.

Tables 10.4 and 10.5 contain the results of this analysis. In Table 10.4, for each vessel, the known (DB) and calculated group weights (C) are listed, together with the errors/differences (E) as percentages of the known displacement. Additionally, the differences between known and calculated 'lightship' weights (Groups 1 to 6) are given as percentages of the known displacements. Table 10.5 contains the same information, but with the errors expressed as percentages of the known group weights.

Individual group weights have different errors associated with them. It can be seen from Table 10.5 that, as expected, the generalised method is most inaccurate when estimating Group 4 weights. On average, results for other groups are subject to errors varying from 7% to 18% of the known weights. These individually rather large errors tend to cancel one another when Groups 1 to 6 are summed to produce the 'lightship' weight. Estimated 'lightship' weights are in error by an average of some 4.5%.

Table 10.4 shows that, the error in estimating Groups 1 to 6 will typically result in a ship displacement in error by 3%. It can also be seen that on average the individual group errors are equivalent to 1.1% of ship displacement.

On the sample tested, the parametric methods may thus be taken to provide a prediction of the sum of the weights of Groups 1 to 6 with an error less than ±5%. This is considered an acceptable degree of accuracy for the first stages of design.

It has not proved possible to test the parametric method against a vessel not included in the original database. Full validation is dependent on this being done. It should however be noted that the contribution of several of the vessels to the database was incomplete. In particular, the data for *SWATH83* only contains Group 1 information at the three digit level. The data for *MoDSSV* does not include Group 1,4 or 6 weights. Additionally, SWBS derived data (such as *TAGOS* and *CPF78*) translates incompletely into NES163 format. These ships, which were not fully represented in the database, are the best available independent measure of the performance of the method. It can be seen that these ships are estimated with accuracy comparable to the others.

Table 10.4 - Group weights from database (DB), from calculation (C), with error (E) as percentage of database displacement

SHIP	GROUP 1			GROUP 2			GROUP 3			GROUP 4			GROUP 5			GROUP 6			Σ [1 - 6]
	DB(t)	C(t)	E(%)	DB(t)	C(t)	E(%)	DB(t)	C(t)	E(%)	DB(t)	C(t)	E(%)	DB(t)	C(t)	E(%)	DB(t)	C(t)	E(%)	E(%)
Escort 1	1247	1274	+0.75	449	455	+0.17	294	243	-1.41	113	150	+1.02	267	263	-0.11	384	347	-1.02	-0.61
Escort 2	952	991	+1.41	377	360	-0.62	219	176	-1.56	88	126	+1.38	236	221	-0.54	297	284	-0.47	-0.40
Escort 3	1390	1424	+0.91	361	353	-0.21	232	239	+0.19	202	239	+0.99	422	280	-3.80	386	385	-0.03	-0.35
Escort 4	1089	1209	+2.03	255	233	-0.57	225	250	+0.65	213	135	-2.03	249	247	-0.05	310	336	+0.67	+1.79
Escort 5	1649	1571	-2.09	333	374	+1.10	194	245	+1.37	252	152	-2.68	362	282	-2.15	416	418	+0.05	-4.40
Escort 6	414	444	+2.27	184	204	+1.52	104	84	-1.52	68	87	+1.44	75	93	+1.36	147	140	-0.53	+4.55
Escort 7	458	508	+3.85	216	217	+0.08	86	69	-1.31	31	53	+1.69	51	79	+2.15	124	130	+0.46	+6.92
Escort 8	1368	1504	+3.04	496	412	-1.88	318	251	-1.50	191	169	-0.49	448	360	-1.97	478	435	-0.96	-3.76
Auxiliary 1	8738	9760	+3.19	618	512	-0.33	538	554	+0.05	406	335	-0.22	1008	928	-0.25	2485	2307	-0.56	+1.88
Auxiliary 2	6809	7167	+1.80	601	531	-0.35	637	596	-0.21	171	191	+0.10	844	1048	+1.02	2758	2115	-3.23	-0.86
Auxiliary 3	2249	2419	+1.98	229	248	+0.22	166	176	+0.12	35	74	+0.45	277	353	+0.89	703	626	-0.90	+2.76
TAGOS	1593	1501	-2.67	66	69	+0.09	130	150	+0.58	42	54	+0.35	586	507	-2.29	*In Group 5*			-3.94
SWATH83	6297	6812	+3.42	649	687	+0.25	512	692	+1.19	254	309	+0.37	2448	2643	+1.29	*In Group 5*			+6.52
MoDSSV	1056	1124	+2.92	132	126	-0.26	134	154	+0.86	39	48	+0.39	92	102	+0.43	196	178	-0.77	+3.56
Mean			2.31%			0.41%			0.89%			0.97%			1.31%			0.69%	3.02%

Table 10.5 - Group weights from database (DB), from calculation (C), with error (E) as percentage of database weight group(s)

SHIP	GROUP 1			GROUP 2			GROUP 3			GROUP 4			GROUP 5			GROUP 6			Σ [1 - 6]
	DB(t)	C(t)	E(%)	DB(t)	C(t)	E(%)	DB(t)	C(t)	E(%)	DB(t)	C(t)	E(%)	DB(t)	C(t)	E(%)	DB(t)	C(t)	E(%)	E(%)
Escort 1	1247	1274	+2.1	449	455	+1.3	294	243	-17.3	113	150	+32.7	267	263	-1.5	384	347	-9.6	-0.80
Escort 2	952	991	+4.1	377	360	-4.5	219	176	-19.6	88	126	+43.2	236	221	-6.4	297	284	-4.4	-0.51
Escort 3	1390	1424	+2.4	361	353	-2.2	232	239	+3.0	202	239	+18.3	422	280	-33.6	386	385	-0.3	-0.44
Escort 4	1089	1209	+11.0	255	233	-8.6	225	250	+11.1	213	135	-36.6	249	247	-0.8	310	336	+8.4	+2.95
Escort 5	1649	1571	-4.7	333	374	+12.3	194	245	+26.3	252	152	-39.7	362	282	-22.1	416	418	+0.5	-5.12
Escort 6	414	444	+7.4	184	204	+10.9	104	84	-19.2	68	87	+27.9	75	93	+24.0	147	140	-4.8	+6.05
Escort 7	458	508	+10.8	216	217	+0.5	86	69	-19.8	31	53	+71.0	51	79	+54.9	124	130	+4.8	+9.32
Escort 8	1368	1504	+10.0	496	412	-16.9	318	251	-21.1	191	169	-11.5	448	360	-19.6	478	435	-9.0	-5.09
Auxiliary 1	8738	9760	+11.7	618	512	-17.2	538	554	+3.0	406	335	-17.5	1008	928	-7.9	2485	2307	-7.2	+4.23
Auxiliary 1	6809	7167	+5.3	601	531	-11.6	637	596	-6.4	171	191	+11.7	844	1048	+24.2	2758	2115	-23.3	-1.46
Auxiliary 1	2249	2419	+7.6	229	248	+8.3	166	176	+6.0	35	74	+111.4	277	353	+27.4	703	626	-10.9	+6.48
TAGOS	1593	1501	-5.8	66	69	+4.5	130	150	+15.4	42	54	+28.6	586	507	-13.5	*In Group 5*			-5.63
SWATH83	6297	6812	+8.2	649	687	+5.9	512	692	+35.1	254	309	+21.7	2448	2643	+8.0	*In Group 5*			+9.68
MoDSSV	1056	1124	+6.4	132	126	-4.5	134	154	+14.9	39	48	+23.1	92	102	+10.9	196	178	-9.2	+5.03
Mean			6.9%			7.8%			15.6%			35.4%			18.2%			7.7%	4.5%

10.4 Probabilistic Analysis of Weight Estimates

10.4.1 Probabilistic Methods

All activities involving uncertainty are subject to risk. In ship weight estimation the risks include failure to provide the intended payload capacity or, less seriously, expensive provision of excess capacity. Also, since cost estimates are often linked to weight estimates, direct financial risks can be involved. The use of probabilistic methods in naval architecture has been discussed by Hutchison [8] and Sen [9].

Probabilistic methods offer the means of quantifying risk so that the user can select the level of risk to be accepted. Additionally, individual items which contribute most to the overall risk can be identified. This section is intended to provide an assessment of the confidence which can be placed in the method described in section 10.3. Basic probability and statistics theory as presented in standard references [10] is employed. A brief description of the terms employed in this section is included in Appendix 8 for completeness.

This study assumes *normal* (*Gaussian*) probability distributions which are dependent on only two parameters, the mean and variance. In practice this is by far the most commonly encountered distribution. This is due to a number of reasons, foremost being the *central limit* set of mathematical theorems. Informally, and in general terms, these state that any process which can be conceived of as the sum of many small independent random variables will tend towards a normal distribution. The estimation of ship weights from the sum of many sub-subgroups (which may be viewed as random variables) is a problem adhering to the conditions of this theorem.

The theory of functions of random variables provides the following results;

if $y = \sum x_i$, where x_i are independent random variables, then

$$E[y] = \sum E[x_i]$$

$$V[y] = \sum V[x_i]$$

which state that the mean ($E[y]$) and variance ($V[y]$) of y may be obtained from the sum of the individual means and variances of x_i. This is fundamental to the methods used to provide variances in ship weight estimates. The mean and variance of the constituent weights (sub-subgroups) are used to obtain the mean and variance of the composite parts (groups). This allows the standard deviation for the total weight to be derived, and thus permit the *confidence limits* to be defined.

10.4.2 Estimation of Variance in Weight Estimates

To calculate the confidence limits on predicted weights, it is necessary to estimate the variance associated with each item weight. This measures the uncertainty in the expected or mean value assigned to each item. It is convenient to treat these uncertainties through the use of coefficients of variation. Particular classes of weights may have one COV associated with them, while other classes have different COVs. These coefficients may also be varied as the design progresses; with smaller values being used as the design becomes more refined.

According to Hutchison [8], typical choices of COV in ship design may be

Steel	7.5%
Machinery	15.0%
Outfit	15.0%

These relate to fairly well defined contract design estimates but for the regression derived methods for early design described in section 10.3, larger COVs are appropriate.

Rather than derive individual COVs for each of the many sub-subgroups involved in the weight estimation problem, it was decided to divide all the items into eight categories (Table 10.6). The weights of classes 1 and 3 are 'known' values so that the low COVs suggested by Hutchison [8] may be used for these categories. An analysis of the data used to derive the regression equations was made to determine suitable COVs for the remaining six classes of weights. A number of sub-subgroups were examined within each category in Table 10.6, and the individual COVs averaged to give the COV associated with that category. Although different sub-subgroups within the same group possessed different COVs, in general the various groups exhibited distinctly separate trends.

For example, Group 4 items which are not expected to closely follow parametric trends show the highest COV. Group 5 items are seen to be considerably more difficult to estimate accurately than Groups 2, 3 and 6. This reflects the influence which different degrees of systems fit can have on Group 5 weights for ships of apparently similar general characteristics.

Table 10.6 COVs Associated with Sub-subgroups

	Category	COV
1	Major structural elements of Group 1, (subgroups 10-13)	7.5%
2	Minor elements of Group 1 (subgroups 14-19)	31.4%
3	Main propulsion items of Group 2 (subgroups 20-23)	15.0%
4	Minor items of Group 2 (subgroups 24-29)	21.7%
5	All Group 3 items	25.5%
6	All Group 4 items	43.6%
7	All Group 5 items	30.5%
8	All Group 6 items	27.0%

The validity of the above assumptions was studied by examining the variances in the total weight of Groups 1-6 for the sample vessels in Table 10.2.

By deriving appropriate variances for the relevant sub-subgroups and summing, the overall variance is calculated by *EMPIREWT* for each weight estimate. These are tabulated in the form of COVs in Table 10.7. The mean COV is 3.16%, which means that, typically, 95.5% of 'lightship' estimates will be within ±6.32% of the expected value.

The validity of the calculations of the mean, and the associated confidence limits, was gauged by comparing the accuracy of the estimates with the known weights.

It can be seen from Table 10.8 that;

70% of the known weights fall inside the 68.0% confidence limits on the calculated value
85% of the known weights fall within the 95.5% confidence limits on the calculated value
100% of the known weights fall within the 99.7% confidence limits on the calculated value

On the small number (14) of vessels studied, this level of correlation is considered reasonable, and the assumed COVs are considered suitable for use in the program *EMPIREWT*.

Table 10.8 also shows the extreme values of the weights of Groups 1-6 which correspond to the different confidence limits.

Table 10.7 - Group weights from calculation (C), with associated Coefficients of Variation (COV)

SHIP	GROUP 1		GROUP 2		GROUP 3		GROUP 4		GROUP 5		GROUP 6		Σ [1 - 6]		
	C(t)	COV(%)	C(t)	COV(%)	C(t)	COV(%)	C(t)	COV(%)	C(t)	COV(%)	C(t)	COV(%)	C(t)	COV(%)	DB(t)[1]
Escort 1	1274	*4.12*	455	*6.81*	243	*14.00*	150	*14.07*	263	*7.98*	347	*6.25*	2732	*2.89*	2754
Escort 2	991	*4.54*	360	*7.64*	176	*14.20*	126	*13.49*	221	*7.69*	284	*6.20*	2158	*3.04*	2169
Escort 3	1424	*4.28*	353	*7.80*	239	*13.81*	239	*9.21*	280	*7.14*	385	*5.90*	2920	*2.86*	2933
Escort 4	1209	*5.05*	233	*7.25*	250	*15.20*	135	*13.33*	247	*8.10*	336	*6.46*	2410	*3.38*	2341
Escort 5	1[illegible]71	*4.46*	374	*7.49*	245	*13.88*	152	*13.82*	282	*7.91*	418	*7.53*	3042	*3.08*	3206
Escort 6	444	*4.73*	204	*8.09*	84	*14.88*	87	*13.37*	93	*8.28*	140	*6.71*	1052	*3.23*	992
Escort 7	508	*4.33*	217	*8.76*	69	*14.49*	53	*20.75*	79	*7.96*	130	*6.92*	1056	*3.26*	966
Escort 8	1504	*4.65*	412	*7.04*	251	*13.55*	169	*14.2*	360	*6.67*	435	*6.21*	3131	*2.99*	3299
Auxiliary 1	9760	*3.89*	512	*7.23*	554	*10.65*	335	*22.38*	928	*11.10*	2307	*5.81*	14396	*2.97*	13793
Auxiliary 2	7167	*4.41*	531	*7.34*	596	*12.58*	191	*23.56*	1048	*9.99*	2115	*6.05*	11648	*3.17*	11820
Auxiliary 3	2419	*4.34*	248	*8.67*	176	*13.64*	74	*14.60*	353	*8.78*	626	*5.59*	3896	*3.08*	3659
TAGOS	1501	*5.20*	69	*7.25*	150	*15.33*	54	*14.07*	507	*5.92*	*In Group 5*		2281	*3.82*	2417
SWATH83	6812	*4.17*	687	*8.92*	692	*10.66*	309	*19.74*	2643	*5.52*	*In Group 5*		11143	*3.04*	10160
MoDSSV	1124	*4.45*	126	*8.71*	154	*16.88*	48	*15.0*	102	*9.80*	178	*5.62*	1732	*3.44*	1649
Mean		***4.47%***		***7.79%***		***13.84%***		***15.83%***		***8.06%***		***6.27%***		***3.16%***	

Note 1 - Column DB contains the sum of the database values for weight groups 1 to 6

Table 10.8 - Analysis of Weight Estimates for Groups 1 to 6

	C(t)	COV(%)	DB(t)	68% Limits (t)		95% Limits (t)		99% Limits (t)	
Escort 1	2732	2.89	2754	2653	2810	2574	2890	2495	2969
Escort 2	2158	3.04	2169	2092	2224	2027	2289	1961	2355
Escort 3	2920	2.86	2933	2837	3003	2753	3086	2669	3170
Escort 4	2410	3.38	2341	2328	2491	2246	2573	2165	2654
Escort 5	3042	3.08	3206	2948	3135	2854	3229	2760	3323
Escort 6	1052	3.23	992	1018	1085	984	1119	950	1153
Escort 7	1056	3.26	966	1021	1090	987	1124	952	1159
Escort 8	3131	2.99	3299	3037	3224	2943	3318	2850	3411
Auxiliary 1	14396	2.97	13793	13968	14824	13539	15252	13111	15680
Auxiliary 2	11648	3.17	11820	11278	12017	10909	12386	10540	12756
Auxiliary 3	3896	3.08	3659	3776	4016	3656	435	3436	4255
TAGOS	2281	3.82	2417	2193	2368	2106	2455	2019	2542
SWATH83	11143	3.04	10160	10804	11481	10465	11820	10126	12159
MoDSSV	1732	3.44	1649	1672	1791	1612	1851	1553	1910

Note 70% of the database values (DB) for Σ[1-6] fall within the 68% confidence limits on the calculated estimates (C)
85% of the database values (DB) for Σ[1-6] fall within the 95% confidence limits on the calculated estimates (C)
100% of the database values (DB) for Σ[1-6] fall within the 99% confidence limits on the calculated estimates (C)

10.4.3 Selection of Weight Margins

The issues involved in ship design margins have been studied in references [11, 12]. Differences in margin policy can influence ship characteristics as much as differences in payload requirements. It is important to include sufficient margins to ensure adequate performance without unduly penalising the ship design.

Margins are introduced to the weight estimate during the earliest stages of development. These margins are determined on the basis of the inherent uncertainties in the initial weight estimates, and on the estimated weight growth during design, construction and life.

The latter type of margin is often derived from studies of previous weight growth trends, and are often presented to the designer in the form of requirements. The other margins must be related to the degree of precision employed in the weight estimate. Selection of these margins is thus closely related to the main weight estimation process.

Based on the observations of sections 3.3 and 4.2, it is suggested that an assurance margin of 5% should be applied to the sum of Groups 1 to 6 as estimated by the parametric method and computer program *EMPIREWT*.

10.5 Weight Program Operation

The data described above has been incorporated in *DESIN* to provide a weight balance in the SWATH synthesis. Principal input requirements for these weight estimation programs are listed in Table 10.9.

In the first design iteration, program *DESIN* presents the user with the calculated sum of ship weights, and indicates the imbalance existing with respect to the current displacement. The user may choose to accept the status quo, or seek a $\Delta \geq \Sigma$Weights situation by increasing/decreasing ship displacement by the methods described in Chapters 3 and 4.

Table 10.9 Input and Output Variables for Weight Estimation Modules

Input Variables
Margins (%) applied to estimates of each major weight group, growth margin, other margin
For each of Groups 1 to 6....
Select estimation method from; A - Direct use of existing data
B - Scaling from existing data
C - Use of generalised parametric equations

In the case of A or B, select appropriate basis data from -

Group 1 - US SWBS 3 digit weights for 15000 tonne aircraft carrier and 3500 tonne auxiliary, UK NES163 2 digit weights for 2400 tonne auxiliary
Group 2 - UK NES163 3 digit weights for 2300 tonne auxiliary and 2 digit weights for 2400 tonne auxiliary, US SWBS 3 digit weights for 3500 tonne auxiliary,
Group 3 - UK NES163 3 digit weights for 2300 tonne auxiliary and 2 digit weights for 2400 tonne auxiliary, US SWBS 3 digit weights for 3500 tonne auxiliary
Group 4 - US SWBS 3 digit weights for 3500 tonne auxiliary, UK NES163 2 digit weights for 2400 tonne auxiliary
Group 5 - UK NES163 3 digit weights for 2300 tonne auxiliary and 2 digit weights for 2400 tonne auxiliary, US SWBS 3 digit weights for 3500 tonne auxiliary
Groups 6 to 8 - US SWBS 3 digit weights for 3500 tonne auxiliary, UK NES163 2 digit weights for 2400 tonne auxiliary

In the case of C, provide following information -
LOA, LBP, moulded beam, depth, draught, enclosed volume, full load displacement, estimated Group 1 weight, estimated Group 2 weight, estimated Group 3 weight, estimated Group 4 weight, estimated Group 5 weight, estimated Group 6 weight, estimated Group 7 weight, estimated fuel weight, *total* installed propulsive power, *maximum* shaft power, electrical power, total complement, number of officers, number of crew, number of aircraft carried

Output Variables
Listing of three digit, two digit, and one digit weights for Groups 1 to 6, with associated coefficients of variation. Listing of margin weights.

10.6 Volume Estimating

10.6.1 Volume Considerations in SWATH Synthesis

Provision of space is costly in any ship. It is estimated [14] that it costs £5000 (1987) to add 1m^2 of empty deck area to a frigate. In the current study, it was demonstrated in Chapter 9 that SWATH structural weight is strongly dependent on total enclosed volume. In addition, the parametric weight estimating methods described in this chapter involve many functions of vessel volume. These factors reinforce the usual desire to avoid excessively voluminous designs. On the other hand, experience with practical SWATH designs has indicated that SWATH sizing may be governed in some circumstances by minimum allowable values of deck area and volume. These considerations indicate the need to provide a space balance within a SWATH synthesis model.

10.6.2 Automated Space Estimation

At present, *DESIN* employs a general method (module *VOLUME*) for estimating the space requirements for warships of the corvette/frigate/destroyer classes. Addition of similar routines for commercial vessels would be a relatively simple matter using available basis data.

Program *VOLUME* is derived from an analysis [5] of the general arrangements of 6 UK designed warships. Deck areas were listed in a 'group' structure (listed in Appendix 9) according to function. Trends and parameters dictating deck areas were identified in the data and used to develop equations for general use. It was found useful to include some measure of the sophistication of the vessel being designed by means of a 'category number'. This allows vessels as diverse as large NATO standard destroyers or small commercial standard corvettes to be designed using the system. These expressions are listed in Appendix 9.

10.6.3 Validation of Program *VOLUME*

In the absence of independent data, the computerised volume estimating procedure was checked satisfactorily against the six vessels used in its development. Table 10.10 lists deck areas and volumes for these vessels obtained manually from the GA analysis and from program *VOLUME*. For these vessels, the average error in deck area is 5.5% and the mean volume error 5.9%. Further testing is required to confirm the validity of the program beyond these limits.

10.6.4 Volume Distribution

Considerations in the spatial architecture of vessels as complex as warships are numerous [14]. As yet, it not possible to deal with this aspect of synthesis in an automatic manner, although research continues [15,16]. This section describes the simplistic approach to volume distribution used in the current SWATH synthesis model.

An analysis of the six monohull warships used to develop program *VOLUME* shows that the average difference between total required volume and total enclosed ship volume (void volume) is 4.47%, with upper and lower limts of 6.68% and 2.35%. A recent US monohull frigate design has 2.84% void volume, approximately half the

Table 10.10 Comparison of Program Deck Areas and Volumes with Measured Data

		SHIP 1			SHIP 2			SHIP 3		
		From GA	From	Program	From GA	From	Program	From GA	From	Program
Group	Classification	Area (m^2)	Area (m^2)	Vol. (m^3)	Area (m^2)	Area (m^2)	Vol. (m^3)	Area (m^2)	Area (m^2)	Vol. (m^3)
1	Aviation	265	*265*	*663*	202	*175*	*438*	174	*175*	*446*
2	Main Armament	202	*202*	*504*	246	*246*	*615*	296	*296*	*755*
3	Secondary Armament	9	*9*	*21*	15	*15*	*38*	33	*33*	*84*
4	Sonars	87	*87*	*217*	57	*57*	*143*	85	*85*	*217*
5	Radars	147	*147*	*368*	145	*145*	*363*	52	*52*	*133*
6	Operations Spaces	168	*221*	*552*	132	*192*	*479*	155	*192*	*489*
7	Communications	102	*109*	*273*	126	*94*	*235*	92	*94*	*239*
8	Navigational Spaces	57	*52*	*130*	36	*52*	*130*	94	*52*	*133*
9	Machinery	1651	*1720*	*4299*	1485	*1479*	*3698*	1694	*1699*	*4333*
10	Electrical Spaces	149	*185*	*463*	136	*158*	*396*	133	*158*	*404*
11	Offices	78	*91*	*227*	53	*79*	*198*	73	*79*	*202*
12	Workshops	81	*92*	*229*	90	*79*	*197*	93	*79*	*201*
13	Stores	435	*418*	*1046*	406	*480*	*1200*	433	*336*	*857*
14	Accommodation	1155	*985*	*2463*	1182	*1188*	*2970*	1079	*838*	*2136*
15	Ventilation and AC	231	*222*	*554*	134	*138*	*346*	161	*115*	*292*
16	Lobbies & Passageways	717	*693*	*1732*	508	*519*	*1296*	675	*597*	*1522*
17	Miscellaneous	226	*103*	*257*	32	*109*	*273*	46	*86*	*221*
18	Fuel, AVCAT			*714*			*655*			*667*
19	Fresh Water			*68*			*82*			*55*
	Total Area of Groups 1-17 (m^2)	5758	*5508*		4985	*5125*		5370	*4887*	
	Total Volume Groups 1-19 (m^3)	15174		*14780*	12969		*13748*	14089		*13385*
	Ship Enclosed Volume (m^3)	16055			13413			14680		
	Error in Area Estimate (%)		*-4.34*			*2.81*			*-9.00*	
	Error in Volume Estimate (%)		*-2.60*			*6.00*			*-5.00*	

		SHIP 4			SHIP 5			SHIP 6		
		From GA	From	Program	From GA	From	Program	From GA	From	Program
Group	Classification	Area (m^2)	Area (m^2)	Vol. (m^3)	Area (m^2)	Area (m^2)	Vol. (m^3)	Area (m^2)	Area (m^2)	Vol. (m^3)
1	Aviation	115	*175*	*446*	-	-	-	9	-	-
2	Main Armament	90	*90*	*230*	204	*204*	*519*	96	*96*	*245*
3	Secondary Armament	-	-	-	3	*3*	*9*	11	*11*	*28*
4	Sonars	57	*57*	*146*	46	*46*	*118*	12	*12*	*31*
5	Radars	58	*58*	*147*	24	*24*	*61*	56	*56*	*143*
6	Operations Spaces	130	*163*	*415*	58	*105*	*267*	83	*76*	*193*
7	Communications	67	*78*	*200*	34	*47*	*121*	39	*32*	*81*
8	Navigational Spaces	122	*52*	*133*	37	*52*	*133*	21	*52*	*133*
9	Machinery	1422	*1417*	*3613*	636	*633*	*1616*	655	*734*	*1871*
10	Electrical Spaces	114	*131*	*335*	77	*77*	*197*	15	*50*	*128*
11	Offices	62	*68*	*173*	41	*37*	*94*	13	*25*	*65*
12	Workshops	75	*66*	*168*	44	*40*	*101*	21	*27*	*68*
13	Stores	422	*297*	*758*	214	*234*	*596*	104	*130*	*330*
14	Accommodation	916	*731*	*1864*	575	*606*	*1546*	484	*453*	*1154*
15	Ventilation and AC	142	*91*	*232*	46	*69*	*176*	40	*48*	*122*
16	Lobbies & Passageways	320	*475*	*1210*	223	*259*	*660*	173	*179*	*456*
17	Miscellaneous	60	*73*	*185*	9	*55*	*129*	10	*36*	*93*
18	Fuel, AVCAT			*655*			*476*			*155*
19	Fresh Water			*48*			*40*			*20*
	Total Area of Groups 1-17 (m^2)	4173	*3954*		2271	*2454*		1844	*1912*	
	Total Volume Groups 1-19 (m^3)	11056		*10958*	6008		*6868*	4752		*5117*
	Ship Enclosed Volume (m^3)	11518			6438			5024		
	Error in Area Estimate (%)		*-5.25*			*8.06*			*3.69*	
	Error in Volume Estimate (%)		*-0.89*			*13.32*			*7.68*	

proportion (6.94%) wasted in the payload equivalent SWATH design (Appendix 1 no. 72). It is reported that the *TAGOS-19* design has 850m^3 (5.28%) of unused volume in the haunch area alone.

It is probably safe in initial monohull synthesis to assume some fairly constant ratio of void volume due to hull flare, awkwardly shaped spaces etc. This approach is considered inappropriate for SWATH ships because of the large amount of space in the struts and haunches which, depending on dimensions, is difficult to use effectively. Table 10.11 illustrates volume distributions resulting from differing design requirements and approaches.

Table 10.11 Volume Distributions for Three SWATH Designs

Ship	YSL SSV		NAVSEA Frigate		SWATH83	
Appendix 1 number	*103*		*72*		*88*	
Space Group	m^3	%	m^3	%	m^3	%
Propulsion	1545	16.74	9190	39.73	12300	17.9
Tankage	1051	11.39	-	-	-	-
Personnel	1715	18.58	3097	13.38	11680	17.0
Auxilaries and Electrics	435	4.71	-	-	-	-
Ship Support	-	-	6858	29.64	18897	27.5
Access	-	-			8590	12.5
Payload	365	3.95	2384	10.31	23914[2]	34.8
Others	1479	16.02	-	-	-	-
Voids	2619[1]	28.38	1605	6.94	-	-
Unassigned	-	-	-	-	1924[3]	2.8
Total	9229	100.0	23134	100.0	68717	100.0

Notes; 1 Very deep strut design, 2 Includes aircraft hangar, 3 Equivalent to 'Voids'

In the present method, void volume is calculated directly from the imbalances existing between available and required volumes in the struts and haunches.

Lobbies and passageway volume is assigned to the various areas of a SWATH in proportion to their enclosed volumes. SWATH ships generally require more access volume than monohulls owing to the vertical access required in the struts and this has been recognised in the current method. Other functional spaces are allocated on the following basis.

Superstructure is assumed to house, aviation, operations and navigational spaces. The box structure is the first choice location for weapons, accommodation, machinery (if so specified), electrical spaces and the ventilation and AC allowance. Interchange of these functions between the superstructure and box may be required.

Lower hulls are reserved for fuel, main machinery spaces (if so specified), workshops and ballast tankage. Usually there is excess volume available in the hulls, but if this does not occur, the tankage is located in the struts.

Table 10.12 Input and Output Variables for Program *VOLUME*

Input Data

Select level of capability and sophistication from list described below.

Category 1 - NATO standard destroyer/large frigate, complex weapons fit (e.g. Type 22)
Category 2 - NATO standard destroyer/large frigate, simpler weapons fit than above
Category 3 - Large frigate, standards slightly reduced from NATO
Category 4 - NATO standard small frigate (e.g. Type 21)
Category 5 - Light frigate, commercial standards (e.g. VT Mark 5)
Category 6 - Corvette, commercial standards

Select Ocean Going Ship OR Coastal Vessel, Ship Displacement, Days at sea
No. officers, no. senior rates, no. junior rates
NBCD philosophy (pre OR post 1980), Maximum OR minimum width passageways
Select number and type (*Lynx* OR *Sea King)* of helicopters
Deck areas required by - Main and Secondary Armament, Radars and Sonars
Machinery space length, beam, sectional area, no. deck heights
No. deck heights in uptakes, downtakes
Select machinery type - COGOG, CODOG, Diesel
Ship fuel weight, AVCAT weight, ballast weight
Nominal Deck height

Output Data (Deck areas and volumes)

Group 1 - Aviation
Hangaring and Maintenance areas
Group 2 - Main Armament
Group 3 - Secondary Armament
Group 4 - Sonar & Group 5 - Radar
Group 6 - Operations Spaces (part of PAYLOAD)
Operations Room, Electronic Warfare Spaces, Ship Control Centre, Gyro Room
Group 7 - Communications (part of PAYLOAD)
Main Communications Spaces, SRE/Telephones
Group 8 - Navigation Spaces
Bridge and Chartroom
Group 9 - Machinery Spaces
Machinery Rooms, Uptakes, downtakes, Steering Gear, Miscellaneous
Group 10 - Electrical
Switchboard Room, Electrical Distribution Spaces, Conversion/Generator Rooms, Battery Rooms
Group 11 - Offices
General Offices, Air Office
Group 12 - Workshops
Group 13 - Stores
Stores, Naval and Spare Gear Stores
Group 14 - Accommodation
Officers Spaces, Senior Rates Spaces, Senior Rates WC/Showers, Junior Rates Mess, Junior Rates Showers, Junior Rates WC, Galley, Scullery, Laundry, Canteen, Sickbay
Group 15 - Ventilation and Air Conditioning
Group 16 - Lobbies and Passageways
Group 17 - Miscellaneous
NBCD Cleansing Station, Sewage Treatment, Others
Group 18 - Fuel
Dieso, Avcat
Group 19 - Fresh Water
Group 20 - Trimming/Ballast

Total required deck area, enclosed volume

Struts are required to contain their proportion of the machinery uptakes and general access passages, while the haunches are assumed to house the fresh water tanks and stores (only for struts with width greater than 2.5m)

10.7 Operation of Program *VOLUME*

The volume estimating program described above has been incoporated in *DESIN*, and provides the user with a check on the total enclosed and total required volume of the current model. Input and output variables associated with the method are listed in Table 10.12.

10.8 Studies of Weight and Space for a Family of SWATH Escorts

Programs *EMPIREWT* and *VOLUME* described in this chapter were applied to the family of SWATH vessels introduced in Chapter 5. The performance of an escort frigate role is a common factor in the designs reported in this section.

The four largest (2000 to 5000 tonnes) standard designs of Chapter 5 were assessed in terms of their ability to provide cheap/commercial, small NATO ASW, large NATO area air defence, and large NATO ASW patrol frigate designs respectively. Nominal (in some cases obsolescent) weapons and electronics fits associated with these roles are listed in Table 10.13.

It was assumed that the complement of each vessel could be estimated according to the expression $N_{CREW} = 1.1\Delta^{2/3}$ (Chapter 4, page 96) in the ratios 1:3:8 for officers, senior rates, junior rates. By modern standards, this gives rather large manning requirements, with heavy demands on space and weight. Storing for sixty days was included in the variable loads of each ship. Main propulsion machinery was assumed to be located in the lower hulls, driving through epicyclic gearboxes. Structural weights were estimated using equation 9.4.

Table 10.13 indicates that for all the vessels, the total required volume is less than the total available volume. However, a more detailed analysis of the volume distribution (Table 10.14) reveals that the upperworks of the 4000 and 5000 tonne designs are too small as originally designed. This condition may be rectified by additional superstructure or using two decks in the box structure (decreasing ship density). However, these measures would tend to increase structural and system weights. Reduced manning would provide the simplest solution.

Table 10.13 SWATH Escort Vessel Characteristics and Functional Volume Requirements

Vessel / Role / Category	2000 tonne Design	3000 tonne Design	4000 tonne Design	5000 tonne Design
Role	'Commercial' frigate	NATO ASW	NATO area air defence	NATO ASW patrol
Category	5	4	2	1
Aircraft	1 x Lynx	1 x Lynx	1 x Lynx	1 x Lynx
Main gun	Mk 8 4.5"	Mk 8 4.5"	Mk 8 4.5"	Mk 8 4.5"
Secondary guns	2 x 35mm	2 x 20mm	2 x 20mm	2 x 40mm
SSM launchers	5 x Seakiller	4 x Exocet		4 x Exocet
SAM launchers	Seacat (triple)	Seacat (quad)	Sea Dart (twin)	2 x Seawolf (sextuple)
Other		Corvus Chaff	Corvus Chaff	Corvus Chaff
ASW weapons	3 barrel AS mortar	6 Mk 46 torpedo tubes	6 Mk 46 torpedo tubes	6 Mk 46 torpedo tubes
Radars	Plessey AWS1 Contraves Seahunter for 35mm and missiles	Type 992Q surveillance 2 GWS24 (Seacat) Type 978 navigation	Type 965 search Type 992Q surveillance 2 Type 909 (Sea Dart) Type 1006 navigation	Type 967 Type 968 surveillance 2 Type 910 (Seawolf) Type 1006 navigation
Sonars		Type 184 hull mounted	Type 184 hull mounted	Type 2016 Type 2008
Information/Communication Systems		SCOT Skynet aerials CAAIS C&C	SCOT Skynet aerials ADAWS4 C&C ECM, DF	SCOT Skynet aerials CAAIS C&C ECM, DF
Officers	15	19	23	27
Senior Rates	44	57	69	81
Junior Rates	116	153	185	215
Total Complement (RN standards)	175	229	277	323
Days at Sea	60	60	60	60
Sustained Speed (knots)	22.4	27.0	26.6	25.6
Propulsion Machinery (in hulls)	2 MTU 6.2MW diesel	2 Olympus modules	2 P&W FT9 modules	2 P&W FT9 modules
Propulsive Power (MW)	12.4	41.8	56.2	56.2
Length of Machinery Spaces (m)	19	20	21	22
Electrical Power (kW)	2000	3000	4000	5000
Fuel Carried (t)	400	500	600	650

Group	Classification	Volume (m^3)	Volume (m^3)	Volume (m^3)	Volume (m^3)
1	Aviation	739	739	739	739
2	Main Armament	520	230	627	588
3	Secondary Armament	8	38	38	22
4	Sonars	118	146	145	221
5	Radars	61	147	370	375
6	Operations Spaces	267	341	489	563
7	Communications	121	160	239	279
8	Navigational Spaces	133	133	133	133
9	Machinery (total)	700	1017	1290	1543
	(main machinery blocks)	*532*	*760*	*1008*	*1250*
10	Electrical Spaces	197	266	404	472
11	Offices	113	143	202	232
12	Workshops	101	134	201	233
13	Stores	749	981	1186	1379
14	Accommodation	1837	2321	2803	3243
15	Ventilation and AC	233	269	590	713
16	Lobbies & Passageways	1213	1400	1843	2228
17	Miscellaneous	168	208	269	318
18	Fuel, AVCAT	476	595	714	773
19	Fresh Water	48	63	76	88
20	Ballast Tankage	390	490	585	635
Total Area of Groups 1-17 (m^2)		2811	3331	4458	5379
Total Volume Groups 1-20 (m^3)		8194	9823	12945	14632
Ch. 5 Enclosed Volume (m^3)		9507	11646	13489	15586

Group	Classification	Weight (t)	Weight (t)	Weight (t)	Weight (t)
1	Structure	1064	1280	1455	1650
2	Propulsion	119	229	298	316
3	Electrical	110	161	216	268
4	C & C	69	88	202	252
5	Auxiliary	169	214	252	280
6	Outfit	290	376	447	514
7	Armament	24	52	73	80
1-7	Lightship	1845	2400	2943	3360
Available Variable Load		155	600	1047	1640
Required Variable Load		512	850	1020	1220

Table 10.14 Distribution of Volumes for SWATH Escort Vessels

Distribution of Volumes in Superstructure				
1 Aviation	739	739	739	739
4 Sonars		146		
5 Radars	61	147	370	375
6 Operations Spaces	267	341	489	563
7 Communications	121	160	239	279
8 Navigational Spaces	133	133	133	133
11 Offices	113	143	202	232
16 Lobbies & Passageways	318	327	383	421
Total Required Volume	1752	2136	2555	2742
Available Volume	2053	2148	2133	2187
Void Volume	301	12	-422	-555

Distribution of Volumes in Box				
2 Main Armament	520	230	627	588
3 Secondary Armament	8	38	38	22
4 Sonars	118		145	221
9 Machinery	84	129	141	147
10 Electrical Spaces	197	266	404	472
17 Miscellaneous	168	208	269	318
13 Stores	749	981		
14 Accommodation	1837	2321	2803	3243
15 Ventilation and AC	233	269	590	713
16 Lobbies & Passageways	756	844	1072	1250
17 Miscellaneous	168	208	269	318
Total Required Volume	4838	5494	6358	7292
Available Volume	4884	5537	5967	6500
Void Volume	46	43	-391	-792

Distribution of Volumes in Struts				
9 Machinery	84	129	141	147
16 Lobbies & Passageways	81	122	192	264
Total Required Volume	165	251	333	411
Available Volume	520	797	1056	1375
Void Volume	355	546	733	964

Distribution of Volumes in Hulls				
9 *(main machinery blocks)*	*532*	*760*	*1008*	*1250*
12 Workshops	101	134	201	233
13 Stores			593	690
18 Fuel, AVCAT	476	595	714	773
20 Ballast Tankage	390	490	585	635
Total Required Volume	1499	1979	3101	3581
Available Volume	1674	2466	3237	3998
Void Volume	175	487	136	417

Distribution of Volumes in Haunch				
13 Stores			593	690
16 Lobbies & Passageways	58	107	195	293
19 Fresh Water	48	63	76	88
Total Required Volume	106	170	864	1071
Available Volume	376	699	1085	1524
Void Volume	270	529	221	453

Modifications to Ch. 5 Particulars				
Topsides Volume Change (m^3)	-300		813	1347
Superstructure Depth (m)	2.7		5.1	5.1
Superstructure Beam (m)	18.2		26.8	28.3
Superstructure Length Change (m)	-6.1		5.9	9.3
New Superstructure Length (m)	25.5		40.7	45.2

Total Volume (m^3)	9207	11647	14301	16931
Void Volume (m^3)	846	1605	1090	1834
Void Volume (%)	9.19	13.78	7.62	10.83

NB Voids in Hulls, Struts and Haunches may find use as ballast tankage

A contrasting situation exists for the smaller designs. These vessels are unable to provide useful variable load capacity on their designed displacements of 2000 and 3000 tonnes, but have excess space as originally sized. Reducing the volume (increasing ship density) and manning levels of these ships would tend to reduce structural and other group weights, and increase the variable load capacity.

It is interesting to consider the imbalances in weights and volume for the four designs as functions of vehicle density. Figure 10.2 shows that a low vehicle density results in excess volume and poor deadweight capacity for the escort missions considered. Using too high a vehicle density results in lack of space. For the escort missions and vessel configurations discussed in the present study, it appears that a vehicle density of 300 kg/m^3 is the best choice. This is in agreement with the figure of 310kg/m^3 for the NAVSEA ASW frigate (Appendix 1 no. 72).

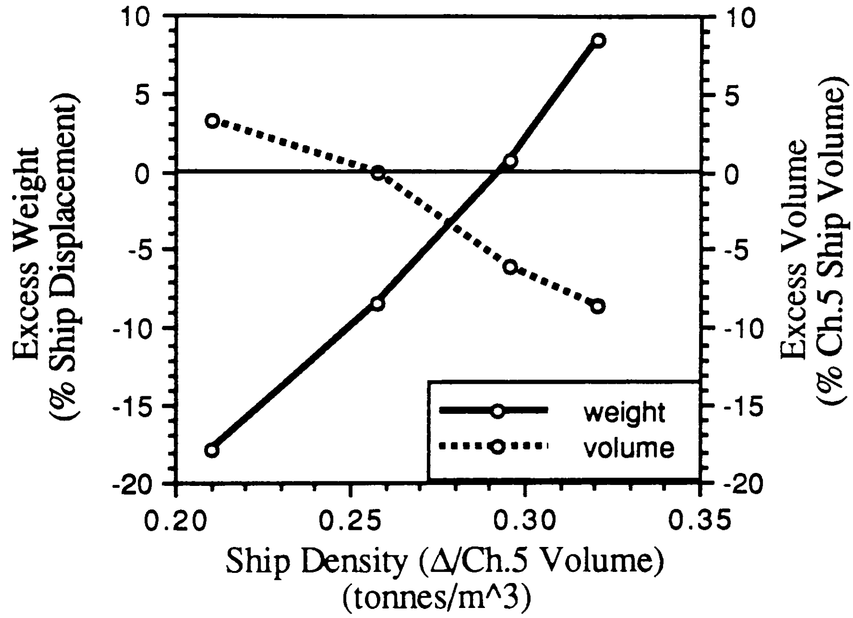


Figure 10.2 SWATH Escort Design Balance as Function of Ship Density

The hullforms and abovewater geometries used in this study were arbitrarily chosen and do not reflect good, modern SWATH design practice. Nevertheless, it is considered that care in selecting vehicle density is important in ensuring efficient design of all SWATH vessels, particularly combatants.

Table 10.14 indicates that the lower hulls of all these vessels are of greater dimensions than required to house their allocated systems. This excess volume may be usefully employed as trimming/ballasting tankage. Measures such as these would reduce the void volumes quoted in Table 10.14. Without modification, the mean void volume is close to 10%, largely due to the slender struts employed in these geometries.

10.9 Conclusions

A regression analysis has been performed on a collection of weights at the three digit level of the classification method used by the UK M0D(N). A parametric method for weight estimating has been derived from this study. On average, this method can predict warship 'lightship' weights to within 4.5% of known values. On the designs analysed, the estimation of Groups 1 to 6 produced an average error in ship displacement of 3%. A statistical analysis of this method indicates that there is typically 95% confidence of predicting 'lightship' weights to within ±6.3%. It is suggested that this method be used with an assurance margin of 5%.

A generalised computer program for estimating the space requirements of escort warships has been developed. This shows an average error of less than 6% when compared against the basis data.

These weight and space routines have been applied to the design of NATO escort frigate SWATHs. For the vessel geometries considered, a strong conflict between space and weight demand is identified. Below 4000 tonnes displacement, excess space and difficulty in providing adequate payload weight occurred, while above this size, inadequacy in terms of volume was observed. The importance of care in selecting vehicle density to ensure balanced SWATH designs is stressed.

References to Chapter 10

1. Ministry of Defence, Controllerate of the Navy, *Naval Engineering Standard 163, Issue 1, Classification of Weight Groups for Surface Ships*, June 1982, (Restricted)

2. NAVSEA 0900-LP-039-9010, *Ship Work Breakdown Structure*, Naval Ship Engineering Center, August 1977

3. Hogg, W.A.G. and Cimino, D., "Methodology to Qualify and Quantify Preliminary Ship Design Estimates", *Proceedings*, 6th Annual Conference of the Society of Allied Weight Engineers, San Diego, May 9-12, 1977

4. Urke, T., "SFI Group System - A Coding System for Ship Information", Symposium on Computer Applications in the Automation of Shipyard Operation and Ship Design, June 8-11, 1976, Gothenburg, North-Holland Publishing Company, Amsterdam, 1976

5. *Warship Volumetric Analysis*, YARD Internal Memorandum No. YIM412/81, 1981, (Confidential)

6. MacGregor, J.R., "Data for Estimation of Ship Weights at the Three Digit Level of the UK MoD(N) Classification", YARD Internal Memorandum (Commercial-in-Confidence), 1989

7. Kennell, C., Discussion to "A Concept Exploration Method for SWATH Ships", by Nethercote, W.C.E. and Schmitke, R.T., *Transactions*, RINA, 1982

8. Hutchison, B.L., "Application of Probabilistic Methods to Engineering Estimates of Speed, Power, Weight, and Cost", SNAME *Marine Technology,* Vol. 22, No. 4, October 1985

9. Sen, P., "Methods for Incorporating Uncertainty in Preliminary Ship Design", *Transactions* NECIES, Vol. 102, 1985-86

10. Mood, A. and Graybill, F., *Introduction to the Theory of Statistics*, McGraw-Hill, New York, 1963

11. Gale, P.A., "Margins in Naval Surface Ship Design", ASNE *Naval Engineers Journal*, April 1975

12. Hockberger, W.A., "Ship Design Margins - Issues and Impacts", ASNE *Naval Engineers Journal*, April 1976

13. Straubinger, E.K., Curran, W.C. and Fighera, V.L, "Fundamentals of Naval Surface Ship Weight Estimating", ASNE *Naval Engineers Journal*, May 1983

14. Brown, D.K., "The Architecture of Frigates", *Proceedings*, International Symposium on Anti-Submarine Warfare, RINA, London, May 1987

15. Carlson, C.M., "General Arrangement Design Computer System and Methodology", ASNE *Naval Engineers Journal*, May 1987

16. Cort, A. and Hills, W., "Space Layout Using Computer Assisted Methods", ASNE *Naval Engineers Journal*, May 1987

CHAPTER 11

SUPPLEMENTARY ANALYSIS

Some additional systems which provide greater definition of the designs provided by the synthesis model are briefly described. In particular, a graphics interface and link with a 3D motions and loading program are introduced.

11.1 Graphics Interface

Visualisation of a proposed geometry is an important part of any modern computer aided engineering tool [5,6,7]. Rapid sketches of external and internal layout can sometimes expose fundamental weaknesses in a design which would not be revealed by a purely mathematical design model. Such a facility has been provided in the current study by transforming the mathematical descriptions employed by *DESIN* into those required by a commercially available 3D CAD package.

The technique employed [1] enables the automatic generation on the *INTERGRAPH* CAD system of graphical displays of the SWATH geometries produced by *DESIN*. FORTRAN code has been written to translate the Chapter 5 mathematical definition into the IGDS language specification [2] of the *INTERGRAPH* Corporation. Body plans, general arrangement drawings, framing plans, and 3-D representations are among the options generated automatically by this system (see Figure 11.1). The SWATH surface geometry is represented by third order polynomials, line strings and geometrical elements.

The basic philosophy and standards employed are intended to allow professional CAD draughtsmen to begin work on refinement of these drawings immediately if necessary. For instance, it is a simple matter to apply standard CAD facilities, such as coloured surface shading (e.g. Frontispiece). Existing libraries of ship fittings (generators, pumps, office equipment, etc) may be used to examine compartment dimensions for access and other practical considerations.

This work has been implemented on one of the most capable and respected CAD systems available, and provides a direct route into the arrangement design of SWATHs, where there is at present some inefficiency in volume utilisation. It also represents a link between the expertise and experience of the human designer and the ability of the computer to deal rapidly with many numbers.

11.2 Motion Assessment

Because seakeeping performance is the primary reason for selecting a SWATH solution, this aspect should be given due consideration in the design process. However, it is difficult as yet to deal with this problem adequately within a synthesis model. Until suitable alternatives are developed, links to detailed motions analysis packages therefore form an important part of the process of verifying the designs synthesised by *DESIN*. Efficiency in using these tools is aided by following past practice and performing a number of simple checks during the initial synthesis phase. Chapters 2 and 5 make some reference to good design practice with regard to seakeeping, while references [8[to [16] contain details of SWATH model seakeeping tests.

11.2.1 Seakeeping Design in the Synthesis Phase

In the synthesis stages of *DESIN,* some recognition of the seakeeping objective is provided by allowing the user to specify the intended operational sea states in terms of significant wave height and peak period. The natural heave, pitch and roll periods of the current model are checked during design loops for coincidence with simple multiples of one another, and with the peaks of the input energy spectra. These conditions result in warnings being issued to the designer, in which event the designer may choose to alter certain design parameters.

In this simplified model, the resonant periods are calculated from

Heave period (s)	$T_h = 2\pi \sqrt{[\Delta(1+C_h)/(\rho\ g\ A_w)]}$	Eqn. 11.1
Pitch period (s)	$T_p = 2\pi \sqrt{[k_p^2(1+C_p)/(g\ GM_L)]}$	Eqn. 11.2
Roll period (s)	$T_r = 2\pi \sqrt{[k_r^2(1+C_r)/(g\ GM_T)]}$	Eqn. 11.3

where k_p, k_r are the longitudinal and transverse radii of gyration, and C_h, C_p and C_r are the coefficients of added mass in heave, pitch and roll. GM_T and GM_L are determined from KG and the KM_T and KM_L values provided by the methods of Chapter 5

These variables are clearly dependent on the particular vessel configuration being designed, and their exact determination is not usually possible until an advanced stage of design. It was therefore necessary to develop a number of approximations for use in the iterative synthesis loops. These have been derived from the collection of data listed in Table 11.1.

Table 11.1 SWATH Ship Dimensions, Weight Distributions and Natural Periods

Ship Identification	App. 1 no. Ref no. []	Δ (t)	Lengths (m) Overall	Box	BOA (m)	Draft (m)	Depths (m) Main Deck	Wet Deck	Lower Hull B/D	Waterplane Area (m^2)	Gyradii (m) Pitch	Roll	Vertical CG (m)	Metacentric Heights GMt (m)	GMl (m)	Natural Periods (seconds) Heave	Pitch	Roll
Vosper OPV	2	935.0	44.25	37.00	20.30	7.10	14.80		1.000							8.5	14.5	16.0
USCG	5	125.0	26.10	23.90	10.90	2.61			1.000	22.4				3.50	5.90			
USCG	6	254.0	35.70	34.00	15.00	3.50			1.000	32.0				3.80	5.60			
USCG	7	765.0	50.30	48.10	20.70	5.00			1.000	67.9				2.50	8.80			
USCG	8	1270.0	59.00	56.80	25.60	5.90			1.000	94.8				2.90	10.40			
VSTOL 83 Carrier	88	15067.0	140.80	126.20	44.80	11.58	26.30	17.16	1.000				17.51					
UCL ASW Frigate	90	5470.0	107.00	92.00	28.00	7.90	18.60	12.80	1.435	461.5			11.37	3.50		10.0	15.0	13.5
Korean Ferry	98	71.0	19.20	19.20	9.20	2.30	4.50	3.80	1.000	16.7						5.3		
YSL SSV	103	2415.0	66.00	51.00	26.00	7.40	14.30	10.40	1.300	194.4	14.54	10.46	9.64	2.15	4.34	8.8	19.0	15.0
Jones Cruise Liner (deep)	122	41609.0	144.00	143.00	62.50	16.00	31.50	21.50	2.000	1292.0			25.16	4.31				
Jones Cruise Liner (light)	122	33137.0	144.00	143.00	62.50	9.60	31.50	21.50	2.000	1292.0			25.16	3.22				
TAGOS baseline (design)	[9]	3062.0	74.40	60.70	30.70	6.70		11.30	1.800	199.7	17.40	12.40	8.80	2.50	8.00	12.0	17.5	20.7
TAGOS baseline (heavy)	[9]	3463.0	74.40	60.70	30.70	8.90		11.30	1.800	199.7	17.90	12.70	7.70	4.30	11.60	11.7	16.0	16.9
Baitis Ship D	70, [10]	798.0	47.24	34.10	17.99	5.03	12.04	8.69	1.000	108.0				1.22	6.10	6.6	12.5	19.5
Baitis Ship E	71, [10]	1307.0	60.96	39.90	19.68	5.91	12.92	9.57	1.000	125.0				1.22	6.10	8.5	17.4	20.7
MoD SSV (UoG data)	104, [11]	2330.0	61.75	50.40	25.09	6.50	13.11	10.16	1.510	196.9			8.23	2.02	7.93			
MoD SSV (YARD)	104, [11]	2221.0	61.75	50.40	25.09	6.50	13.11	10.16	1.510	196.9	14.14		8.32	2.06	7.97	9.7	14.0	
MoD SSV (YARD)	104, [11]	2221.0	61.75	50.40	25.09	6.50	13.11	10.16	1.510	196.9	16.46	11.14	7.44	2.94	8.85	9.7		18.0
Stretched SSP (twin strut)	[12]	628.0	48.00	39.00	15.60	5.00			1.000	68.4	12.40	5.60	4.90	1.50	18.70			
CETENA Ferry	96, [13]	1200.0	50.00	43.00	25.50	5.00	12.50	8.50	1.500				8.20	6.80		7.3		11.0
SWATH 6A	[14]	2847.0	73.20	52.50	27.50	8.10		14.20	1.000	193.9	16.90	10.21	10.40	2.90	6.80	9.2		18.7
SWATH 6D	[14]	2860.0	73.20	68.00	27.50	8.10			1.000	211.2	19.00		9.10		26.40			
SWATH 1	[14]	29000.0	158.50	134.00	51.50	17.30			1.000	1272.7	32.80		15.30			10.0		13.1
SWATH 2 (tandem strut)	[14]	102616.0	259.10	228.90	85.00	21.20			1.000	2198.1	67.40		23.80	28.00		19.8		25.5
SWATH 4	[14]	4181.0	87.70	69.10	28.40	9.10		14.30	1.000	251.3	20.80		9.60	2.40	11.10	10.3		18.0
NSMB long strut	[15]	4967.0	97.00	93.42	29.04	7.34	21.40	14.69	1.000		26.01		10.94	3.00		8.5	12.7	20.4
NSMB long strut	[15]	5211.0	97.00	93.42	29.04	8.60	21.40	14.69	1.000		26.01		10.94	3.00		8.5	12.9	19.0
NSMB long strut	[15]	5453.0	97.00	93.42	29.04	9.85	21.40	14.69	1.000		26.01		10.94	3.00		8.5	13.0	18.8
NSMB short strut	[15]	4692.0	95.82	72.83	31.31	7.49	21.61	14.90	1.000		22.70		10.51	3.00		10.4	18.7	21.4
NSMB short strut	[15]	5104.0	95.82	72.83	31.31	8.82	21.61	14.90	1.000		22.70		10.51	3.00		10.6	18.7	21.0
NSMB short strut	[15]	5516.0	95.82	72.83	31.31	10.15	21.61	14.90	1.000		22.70		10.51	3.00		10.9	18.7	20.7
3000t ABS SWATH	[16]	3144.0	70.41	43.41	24.64	8.29			1.000		17.00	10.00	9.03	3.21	6.49	9.0	18.0	16.5
TAGOS19 by ABS	[16]	3553.0	70.87	57.91	24.38	8.01					15.33	10.82	10.49	1.47	7.33			
Halcyon		57.9	18.29	17.00	9.14	2.13	4.27	3.51	1.000				3.91					
Duplus (as built)		1200.0	47.00	42.00	17.06	5.50	10.89	8.17	0.900							10.8	14.5	24.8
Duplus (sponsons)		1490.0	47.00	42.00	17.06	5.50	10.89	8.17	0.900							9.7	11.5	9.5
TRISEC 1		1.2	6.10	4.88	2.44	0.61		1.22	1.000							2.8		
Kaimalino (twin strut)		220.0	27.10	23.50	14.17	4.66	9.00	6.55	1.000	23.0	7.59				3.84	8.6	9.7	15.8
Kotozaki		236.0	27.00	25.00	12.50	3.20	6.70	4.60	1.179	49.8						5.8	8.9	10.7
Marine Ace (twin strut)		18.4	12.35	12.35	6.50	1.55	2.97	2.30	1.363							5.5	4.8	11.2
Marine Ace (single strut)		22.2	12.35	12.35	6.50	1.55	2.97	2.30	1.363							3.9	4.5	4.7
Seagull		343.0	35.90	35.90	17.10	3.15	7.70	5.85	1.340							6.2	9.5	11.8
Kaiyo		3500.0	61.55	61.55	28.00	6.30	13.25	10.60	1.400							10.5	14.0	18.0
Marine Wave		25.4	15.10	15.10	6.20	1.60			1.380								6.5	8.5

Vertical Centre of Gravity

Roll and pitch restoring coefficients are heavily dependent on the value of KG. Two approximations (equations 11.4 and 11.5) for KG have been presented in reference [24]. These are intended for use in synthesis of escort vessels, and in the current study have been found unsuitable for smaller SWATH ships. The present synthesis tool allows the user to fix KG as a constant percentage of the ship depth, or to use equation 11.6, derived from Figures 11.2 and 11.3.

$KG = 8.84 + 0.000305\ \Delta$ Eqn. 11.4

$KG = 2.75 + 2.691 \ln [10^{-6}(L_S/L_{OA})\Delta^2]$ Eqn. 11.5

$KG = 0.325\ DMD + 0.524\ \Delta^{0.273}$ Eqn. 11.6

This is clearly a rather arbitrary method of deriving the value of KG which will control the critical variables of GM_T and GM_L in a new design, and may result in unsuitable stiffness if coupled with unusual hydrostatics. It is therefore worth noting metacentric heights chosen by previous designers. In reference [23], the following ratios are recommended for vessels of frigate size;

$GM_T = 0.36\Delta^{0.333}$ Eqn. 11.7

$GM_L = 0.89\Delta^{0.333}$ Eqn. 11.8

Figure 11.4 shows that these ratios give much stiffer designs than the majority of vessels in Table 11.1, from which other guidance may be obtained. Figures 11.5 and 11.6 show that the proportions of GM to vessel beam and strut length decrease with increasing ship size. This is to be expected since stiffness ($\rho g \nabla GM$) increases nearly in proportion to the fourth power of the linear dimensions while wind loads etc obey a square law or less. Thus, GM need not be increased proportionately with size. Following the approach of Lamb [22] in plotting the ratios of beam and strut length to $\sqrt{GM}$ against displacement (Figures 11.7 and 11.8) yields equations 11.9 and 11.10.

$GM_T = BOA^2/[5.81\Delta^{0.478}]$ Eqn. 11.9

$GM_L = L_S^2/[20.16\Delta^{0.368}]$ Eqn. 11.10

These equations apply to single strut vessels

Radii of Gyration

At present, the best sources for estimating SWATH ship gyradii are those describing various model tests. In some cases [16] these figures attempt to model 'real' design conditions, while others [8] are determined mainly by experimental conditions.

Numata suggested [21] the following expressions for roll, pitch and yaw gyradii.

$k_r = 0.39 \sqrt{[DMD^2 + BHC^2]}$ for single strut vessels
$k_r = 0.38 \sqrt{[DMD^2 + BHC^2]}$ for tandem strut vessels   Eqn. 11.11
$k_p = k_y = 0.22\ L_{OA}$ Eqn. 11.12

Examination of Table 11.1 (and Figures 11.9 and 11.10) provides equations 11.13 and 11.14.

$k_r = 0.243\ BOA^{1.158}$ Eqn. 11.13
$k_p = 0.459\ L_{Box}^{0.897}$ Eqn. 11.14

Added Mass Coefficients

The added masses associated with different hullforms have been discussed in general terms in Chapters 2 and 5, and are ultimately best determined by application of potential flow theory. In the preliminary design phase it is necessary to make some estimates of these quantities using simple approximations. There is some disagreement as to appropriate values for these coefficients.

Numata [21] - single strut SWATHs	$C_h = C_r = 0.5\ B_H/D_H$	Eqn. 11.15
Numata [21] - single strut SWATHs	$C_p = 0.7\ B_H/D_H$	Eqn. 11.16
Numata [21] - tandem strut SWATHs	$C_h = C_r = C_p = 0.9\ B_H/D_H$	Eqn. 11.17

Analysis of Lamb's suggestions [22] yields

Single strut SWATH ships $C_h = 0.058 + 0.625\ B_H/D_H$ Eqn. 11.18

A reverse analysis of published natural periods, gyradii and restoring coefficients (Table 11.1) provided expressions for single strut SWATHs. Both the heave and pitch coefficients displayed distinct trends with respect to hull B/D ratio, but no clear relationship could be identified for the roll coefficient, and the mean value (1.0) was selected for all hullforms.

$C_h = 0.836\ B_H/D_H - 0.238$ Eqn. 11.19
$C_p = 0.268\ B_H/D_H + 0.525$ Eqn. 11.20
$C_r = 1.0$ Eqn. 11.21

These values will be affected by the degree of 'masking' of the hulls due to the strut, and the size of fins fitted.

As a check on the approximations for mass inertias and added masses, published natural periods were compared with those derived using equations 11.1 to 11.3. Figures 11.11 to 11.13 illustrate the comparisons achieved. It can be seen that heave period may typically be estimated within ±5%, while potential errors of ±10% may be expected in the pitch and roll periods. It should be noted that estimation of roll period at the design stage is prone to error, even when using modern hydrodynamics tools.

Natural Periods of Family of SWATH Ships

Equations 11.1 to 11.3, 11.6, 11.13 11.14, and 11.19 to 11.21 have been used to estimate the natural periods of the five simple hulled SWATH ships of Chapter 5. These periods are listed in Table 11.2, where it can be seen that the roll and pitch periods of some designs are uncomfortably close. Closer spacing of the hulls would provide much longer roll periods, as well as mitigating some the structural and weight problems discussed in Chapters 9 and 10. A comparison of the estimated GM values with those recommended by equations 11.9 and 11.10 is also included. This indicates that, as designed, these vessels are stiffer than normal in roll.

Table 11.2 Natural Periods of Family of SWATH Ships (Chapter 5)

		Estimated Natural periods (seconds)			Recommended		Estimated	
Δ (t)	Box Clearance	T_{heave}	T_{pitch}	T_{roll}	GMt(m)	GMl(m)	GMt(m)	GMl(m)
1000	High	8.6	13.6	11.9	3.76	12.86	4.42	11.74
	Low	8.6	13.4	11.4	3.76	12.86	4.81	12.13
2000	High	9.1	14.6	14.3	3.27	12.07	3.70	12.13
	Low	9.1	14.3	13.5	3.27	12.07	4.19	12.62
3000	High	9.4	15.2	15.8	3.11	11.64	3.57	12.40
	Low	9.4	14.9	14.7	3.11	11.64	4.14	12.97
4000	High	9.7	15.6	17.6	2.92	11.35	3.12	12.63
	Low	9.7	15.2	16.1	2.92	11.35	3.74	13.25
5000	High	9.8	16.2	18.2	2.91	11.14	3.31	12.40
	Low	9.8	15.5	16.3	2.91	11.14	4.14	13.57

The above methods, whilst useful in early design, only provide a means for ensuring that a design will have broadly acceptable motion characteristics. Further analysis is essential in any SWATH design study.

11.2.2 Seakeeping at the Analysis Stage

A method for converting output from *DESIN* into input data for a modern three dimensional diffraction theory program for estimating ship motions and loads has been created during the current study. Some examples of motions predictions for SWATH ships obtained using this method are presented in Chapter 12. Both background theory and experimental validation of the hydrodynamics software have been described elsewhere [17], and will not be discussed further in this thesis.

Finite element methods of this type are powerful and versatile tools for the analysis of complex engineering problems. However, the usefulness of these techniques is offset by the need to create a mesh representing the geometry in question [19, 20]. The seakeeping program used in the current project requires the underwater geometry to be defined in terms of quadrilateral surface panels, identified by the Cartesian co-ordinates of their corner nodes. This is a task which is time consuming and prone to error if done manually.

There are two basic approaches to mesh generation: *Top Down* and *Bottom Up*. In full top-down mesh generation, a mesh is constructed making reference to the overall geometrical representation of the object. Once an object geometry is defined, the form of the mesh is determined. No mesh generator however, is totally top-down, and the bottom-up approach in which the model is built up in small components is common. This involves sequential definition of individual components at the CAD workstation, in a process analogous to that of constructing a wall from many bricks. The disadvantages of this method are its labour intensivity, and related lack of flexibility once the mesh has been built. Given a facility for definition of a complete SWATH geometry, an approach based on the top-down method is the obvious choice.

A fully general automatic mesh generation technique has not been the aim of the present study. Although basically top-down in principle, the current approach is specific to SWATH ships. Within a top-down type of mesh generator, the process is broadly described by the expression *'Geometry+Mesh Control = Mesh'*
i.e. the user supplies the object geometry, selects mesh control parameters, and the mesh is then automatically generated.

The desirability of using such automatic mesh generation methods has resulted in a large number of approaches to the problem. The various techniques have been surveyed by Ho-Le [18]. While there are many techniques for 2D mesh generation, the added complexity of the 3D problem has limited the amount of publications on the subject. There are in fact no published algorithms for automatic 3D node generation. Therefore 3D mesh generation usually requires nodes to be created manually. However, in this case, they are present as the nodes of wire frame CAD models (section 11.1) of SWATH geometries.

Given the large number of nodes available from the CAD representation, the panel generation must next consider the degree of fineness desired by the user (i.e. mesh control). This is aided by the availability on *INTERGRAPH* workstations of 3D views of the SWATH geometry. From this information, the engineer may decide the general disposition of elements required. This information may then be input to the mesh generation program and used as mesh control.

A program (*PANJEN*) has been written to allow the user to control the panel mesh in the following ways;
a) longitudinally, by number and distribution of panels
b) vertically, by number and distribution of panels, especially on struts
c) by identifying transitions from triangular to quadrilateral elements.

It is possible, by controlling the above parameters, to ensure satisfactory definition in regions of rapidly changing shape, while maximising computational efficiency (CPU time is roughly proportional to the square of the number of panels). Graphical checks (Figure 11.14) of the panel mesh thus defined are important in confirming the chosen panel distribution.

This automated mesh generator allows a SWATH designer to proceed rapidly from an initial statement of vessel geometry to a fully comprehensive analysis of motions in regular seas. The usual irregular seaway analysis may then be applied and conclusions as to ship operability may be drawn. Traditionally, the time consuming nature of motions analysis has discouraged naval architects from truly including seakeeping assessment in the design spiral. It was contended in Chapter 1 that this <u>must</u> form an integral part of the SWATH design process if the full benefits of the concept are to be realised, and such an ability has been provided in the current study.

Integration of the panel definition required for hydrodynamic analysis with the generation of a finite element mesh for a structural analysis tool such as *MAESTRO* is a desirable long term target. Provison of such a facility would offer considerable increases in productivity in the analysis phases of a SWATH design project. Prospects for this development will rest heavily on a study to determine whether features of one mesh may be used as the structure for the other.

11.3 SWATH Ship Economics

One of the major failings of the present synthesis model is its inability to quantify its designs by some measure of economic merit. This is partly due to the difficulty in applying traditional ship economics techniques to SWATH ships which will tend to have 'service' or combatant roles which do not have easily determined 'freight rates'. It has

Table 11.3 Published Costs of Construction of SWATH Designs

Vessel Identification		Role	Structure	Disp (t)	LOA(m)	Machinery	Speed	SHP	Cost
T-AGOS 19		US sonar surveillance	Steel	3450	70.7	Diesel Electric	9.6	1600	$25.4m-1988
FDC 400		Fast ferry	Al. alloy	172	37.0	MTU Diesel	30	5470	£4-4.5m-1988
Hawaiian ferry		Interisland ferry	Steel	365	43.0	Diesel	17	2700	$2m-1987
Ocean Systems 2000		US survey		75	20.2	Diesel	26.5	2160	$1.8m-1988

NB Designs listed above are building, while those below (identified by numbering used in Appendix 1) are proposals only

Vessel Identification		Role	Structure	Disp (t)	LOA(m)	Machinery	Speed	SHP	Cost
UCL corvette	12	RN corvette	Steel/HTS	1950	66.0	GT Electric	22	10730	£50m-1983
UCL frigate	13	RN ASW frigate		5500	92.0	GT Electric	28	64400	£130m-1983
UCL frigate	14	RN heavy frigate		6500	107.0	GT Electric	28	64400	£145m-1983
UCL frigate	90	RN ASW role	Steel	5470	107.0	CODLAG	28	46667	£138.3m-1987
YSL SSV	103	Sonar support	Steel	2415	66.0	Diesel Electric	14.2	3758	£25.5m-1987
HHI/KIMM	114	Korean ferry	Al. alloy	132	27.1	Diesel	25	2560	$2-3m-1986
San Fransisco	121	Pilot tender	Steel	245	30.5	Diesel			$5.5m-1988
SSSCO ferry	115	US ferry		225	30.5		28.5	5195	$5m-1988
SSSCO OPT	116	US crewboat		225	22.5		28.5	5195	$4.5m-1988
SSSCO OPV	117	US patrol boat		500	46.9		22	5400	$10m-1988
SSSCO research	118	Research vessel		2500	75.3		17.3	6200	$36.5m-1988
SSSCO cruise	119	Cruise vessel		2500	75.3		17.2	6200	$40.4m-1988
SSSCO carrier	120	V/STOL carrier		4500	91.4		35	60000	$60m-1988

however been argued [3] that the financial value of seakeeping performance may be measured by placing a value on the cost of keeping a ship at sea for one day. Each day gained because of improved vessel 'operability' may be assumed to have this value, which for a frigate may be of the order of £100,000 [4]. Coupling this simple approach with modern seakeeping tools may allow comparison of operating economics.

First cost estimates for SWATH ships are also difficult to make at the present time simply because of a lack of reliable data. No attempt has been made in this thesis to provide such an algorithm, although a simple method would be desirable for comparison purposes. Methods to accurately reflect the increased/decreased costs associated with the SWATH geometry are a required addition to this work. There is a need to analyse potential building methods, since the regular shapes of SWATH ships may lend themselves to automation rather than traditional shipbuilding techniques.

Table 11.3 lists the main particulars and quoted building costs of a number of SWATH designs (some built). Some of these figures may be used to give approximate costs/tonne for new designs having similar features.

Conclusions

An interface between computer aided engineering of a SWATH ship and computer aided draughting of the design has been created. The provision of this facility completes an automated route from an initial statement of vessel requiremnts through to production of drawings. A related method for linking practical design of SWATH ships with a means of assessing seakeeping performance has been developed. This is considered to be an essential feature of any SWATH design procedure.

References to Chapter 11

1. MacGregor, J.R., "Users Guide - Program *SWATHDRAW*", YARD Document Reference Number YM5670/007/00A, 1988

2. "Interactive Graphics Design Software (IGDS) Users Guide (8.8)", Intergraph Corporation, Huntsville, Alabama, January 1985

3. Brown, D.K., "The Value of Reducing Ship Motions", *Naval Review*, 1984

4. Brown, D.K., Defining a Warship", ASNE *Naval Engineers Journal*, March 1986

5. LaBozzetta, W.F. and Cole, P.E., "Interactive Graphics for Geometry Generation- A Program with a Contemporary Design", AIAA, *Journal of Aircraft*, December 1985

6. Smyth, S.J., "CADAM Data Handling from Conceptual Design through Product Support", AIAA, *Journal of Aircraft*, October 1980

7. Stack, S., "Computer Aided Design System Geared Toward Conceptual Design in a Research Environment", AIAA, *Journal of Aircraft*, February 1982

8. Djatmiko., E.B., "Experimental Investigation of SWATH Ship Motion and Wave Loading", *M.Sc Thesis*, University of Glasgow, Decemner 1987

9. Gersten, A., "Seakeeping Characteristics of the Baseline Design for a SWATH T-AGOS Ship", DTNSRDC Report SPD-1007-01, February 1982

10. Baitis., A.E. et al, "A Seakeeping Comparison Between three Monohulls, two SWATHs, and a Column Stabilised Catamaran Designed for the Same Mission", DTNSRDC Report SPD-622-01, July 1975

11. MacGregor, J.R., "Prediction of the Seakeeping of a SWATH vessel (as Tested at ARE (Haslar)", YARD Report YR3690. December 1988

12. Ming-Chung Fang, "Lateral Drift Force and Moment on a SWATH Ship in Waves", *International Shipbuilding Progress*, vol. 35, no. 402, 1988

13. Santos, R. and Sartori, G., "An Example of Dynamic Wave Load Assessment for a Non-conventional vehicle (SWATH) in Mediterranean Sea", CETENA Report No. 1290, July 1981

14. Lee, C.M. and Curphey, R.M., "Prediction of Motion, Stability and Wave Load of SWATH Ships", SNAME, *Transactions*, 1977

15. Dallinga, R.P., "Seakeeping Tests for a Small Waterplane Area Twin Hull Ship", NSMB Report No. 043755-2-ZT, November 1981

16. Reilly, E.T., Shin, Y.S. and Kotte, E.H., "A Prediction of Structural Load and Response of a SWATH Ship in Waves", *Naval Engineers Journal*, May 1988

17. Zheng, X., "Prediction of Motion and Wave Load of Mono and Twin Hull Ships in Waves", *PhD Thesis*, University of Glasgow, March 1988

18. Ho-Le, K., "Finite Element Mesh Generation Methods: A Review and Classification", *Computer Aided Design*, Jan/Feb 1988

19. Rudd, B.W., "Impacting the Design Process Using Solid Modelling and Automated Finite Element Mesh Generation", *Computer Aided Design*, May 1988

20. Revelli, V.D., "Getting CAD and FE to Co-operate", *Computers in Mechanical Engineering*, September 1985

21. Numata, E., "Predicting Hydrodynamic Behaviour of SWATH Ships", SNAME, *Marine Technology*, January 1981

22. Lamb, G.R., "Influence of Seakeeping Requirements on SWATH Ship Geometry", SNAME Local Section (Chesapeake) Paper, June 1987

23. Bebar, M.A. et al, "Advanced Marine Vehicles", *Proceedings*, Workshop on Hull Form Design, Wageningen, October 1985

24. Nethercote, W.C.E. and Schmitke, R.T., " A CEM for SWATH Ships", *Transactions*, RINA, 1982

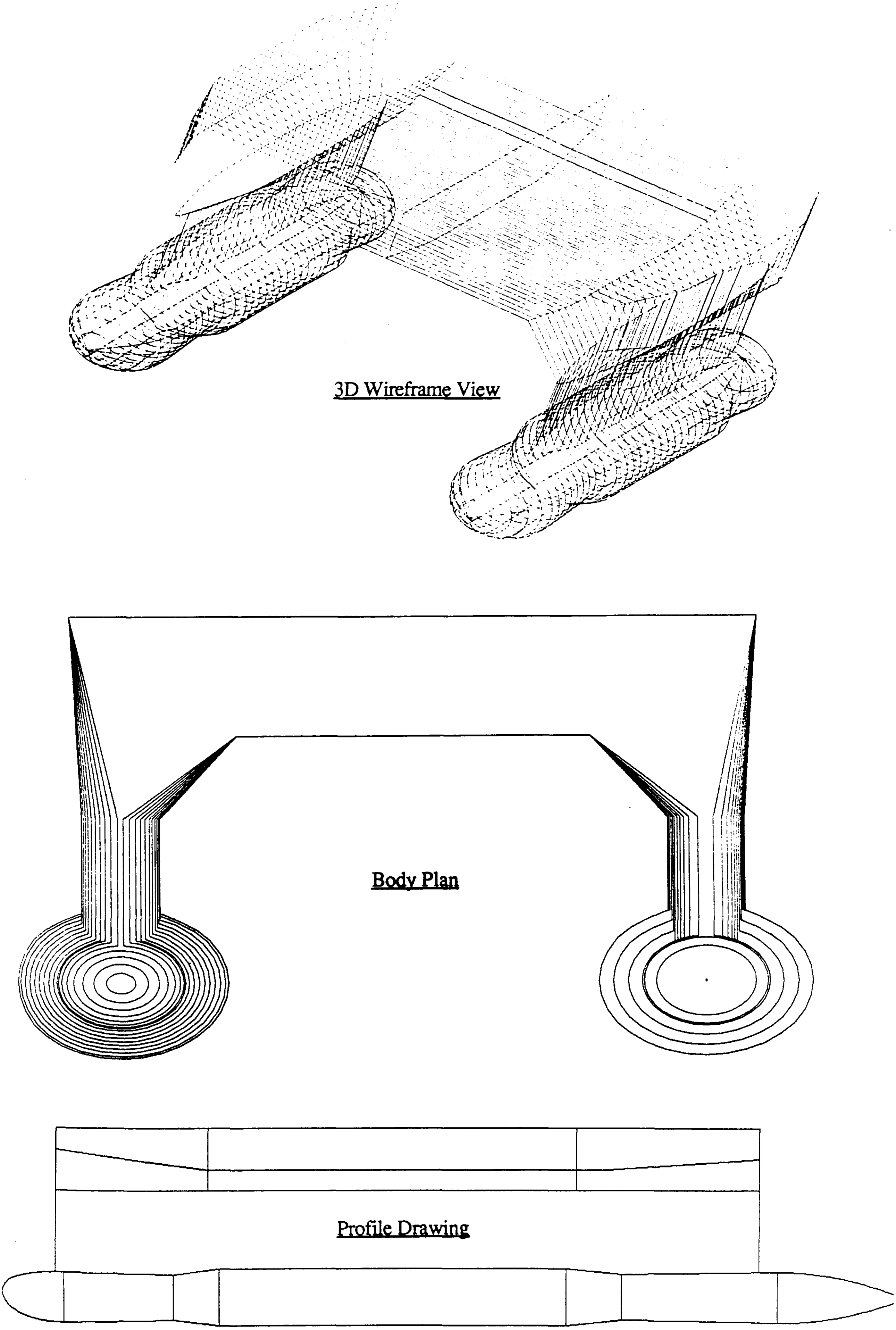


Figure 11.1 Typical Drawings Produced by SWATH CAD System

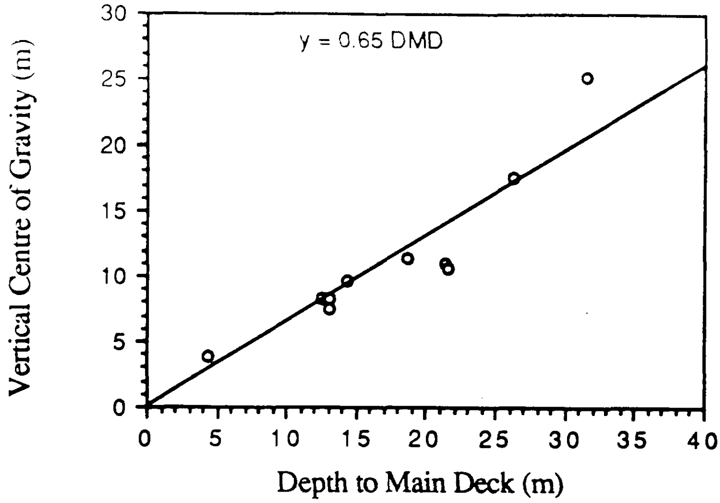


Figure 11.2 Vertical Centre of Gravity as Function of SWATH Ship Depth

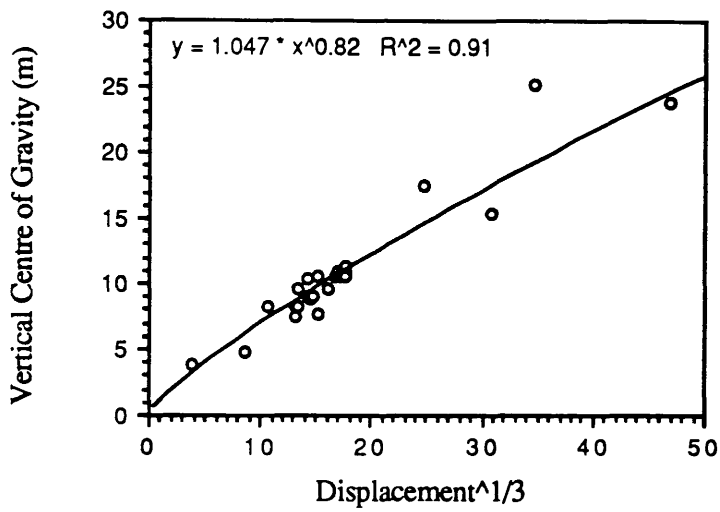


Figure 11.3 Vertical Centre of Gravity as Function of SWATH Ship Displacement

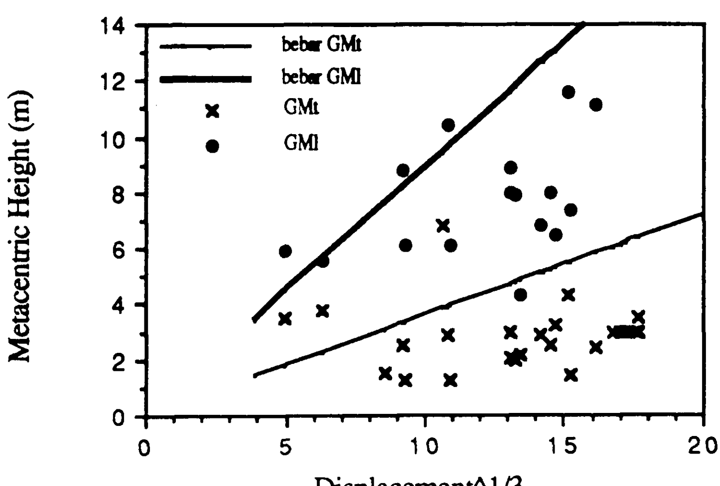


Figure 11.4 Comparison of Published Metacentric Heights and Trends from Bebar

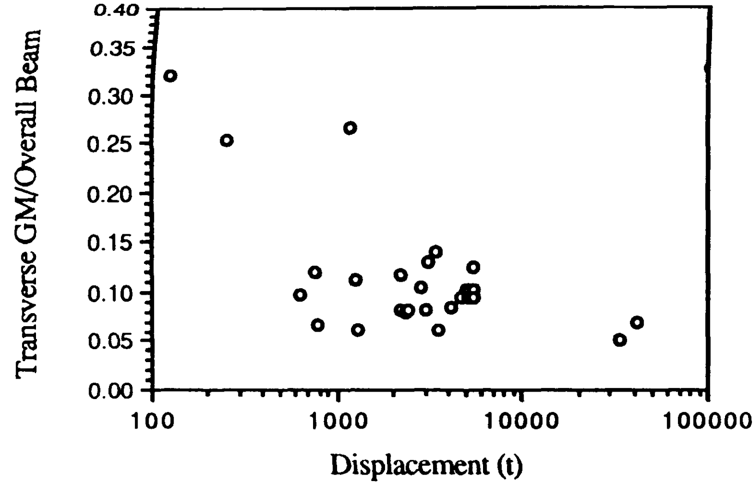


Figure 11.5 Transverse GM/Beam Ratio versus Displacement

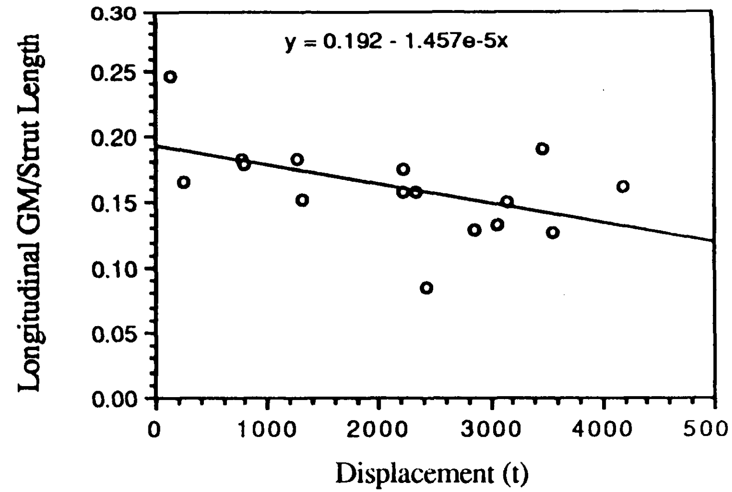


Figure 11.6 Longitudinal GM/(Strut Length) Ratio versus Displacement

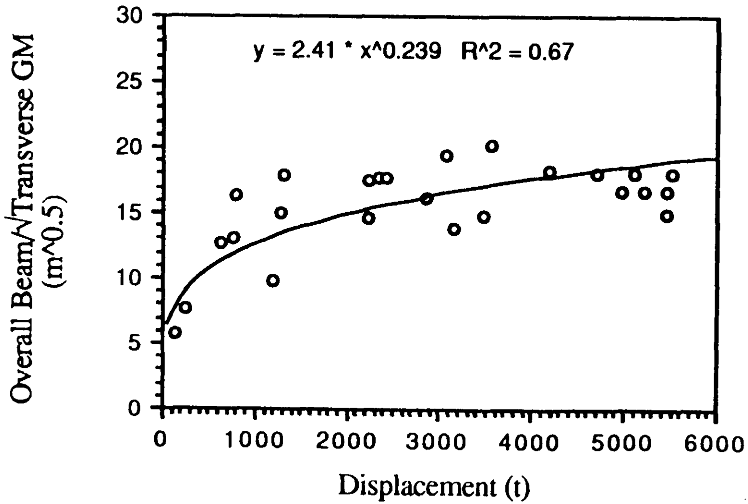


Figure 11.7 Beam/√Transverse GM Function versus Displacement

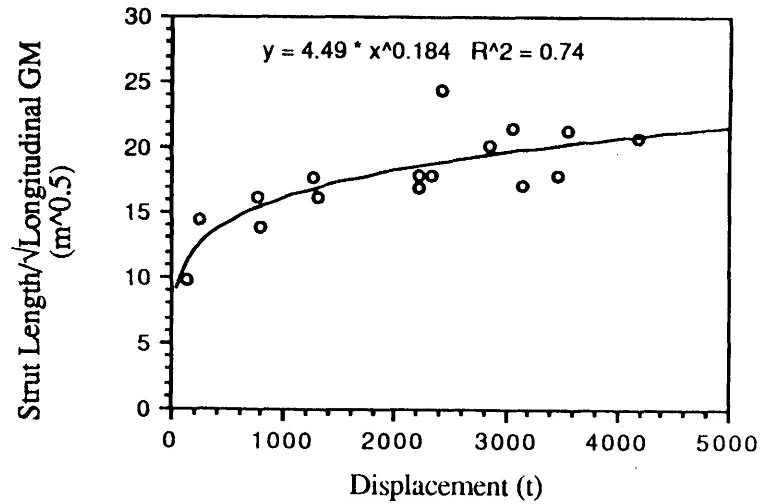


Figure 11.8 Strut Length/√Longitudinal GM Function versus Displacement

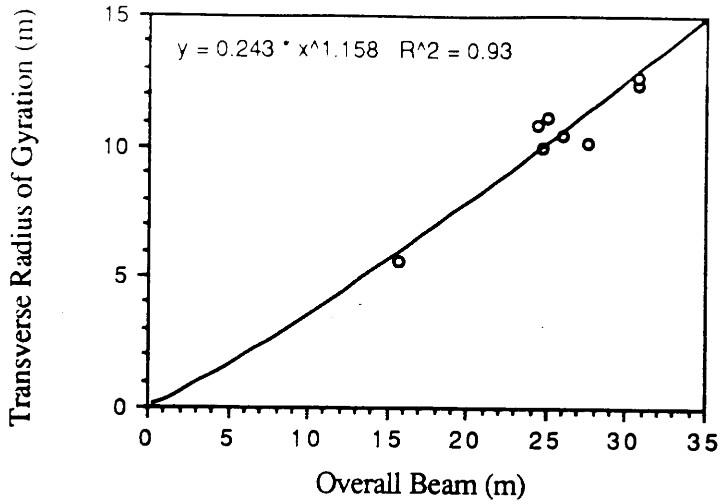


Figure 11.9 Transverse Radius of Gyration versus Breadth Overall

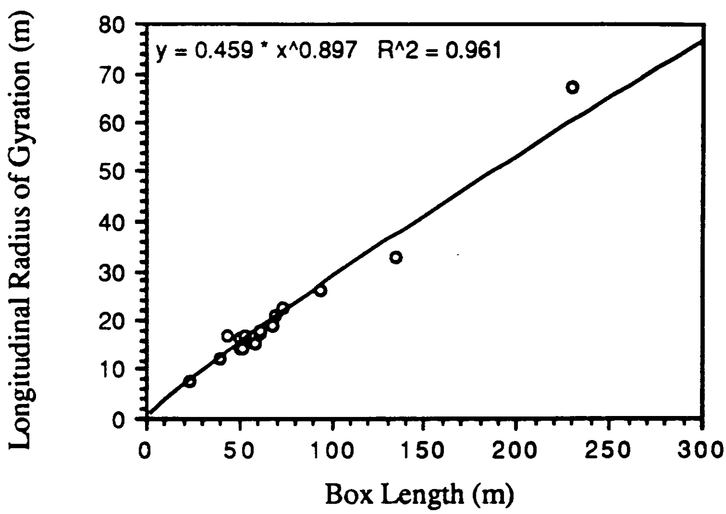


Figure 11.10 Longitudinal Radius of Gyration versus Box Length

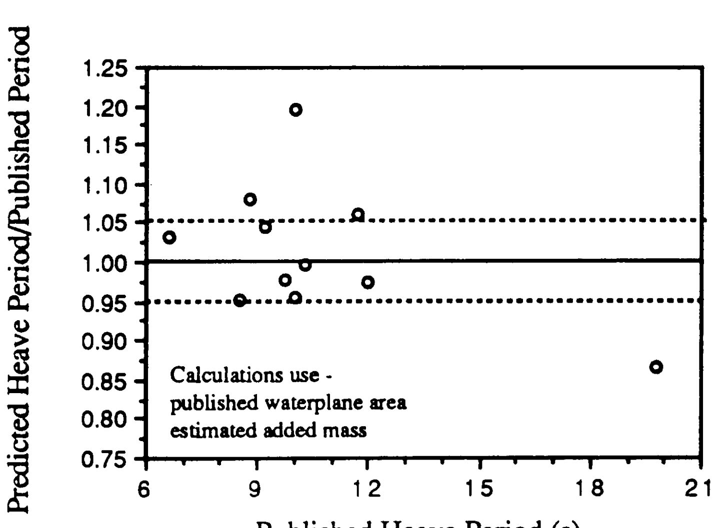


Figure 11.11 Comparison of Published and Estimated Heave Periods

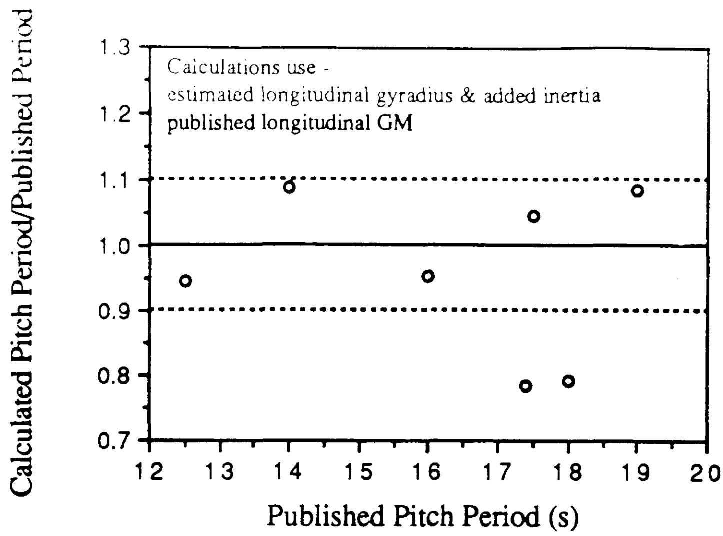


Figure 11.12 Comparison of Published and Estimated Pitch Periods

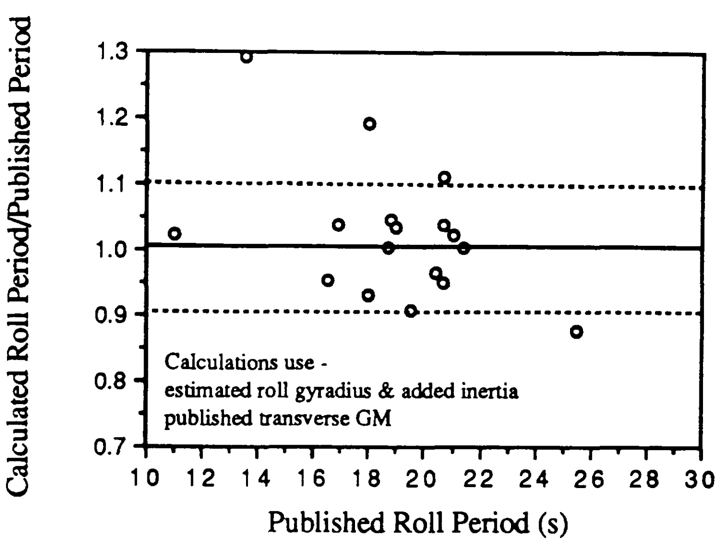


Figure 11.13 Comparison of Published and Estimated Roll Periods

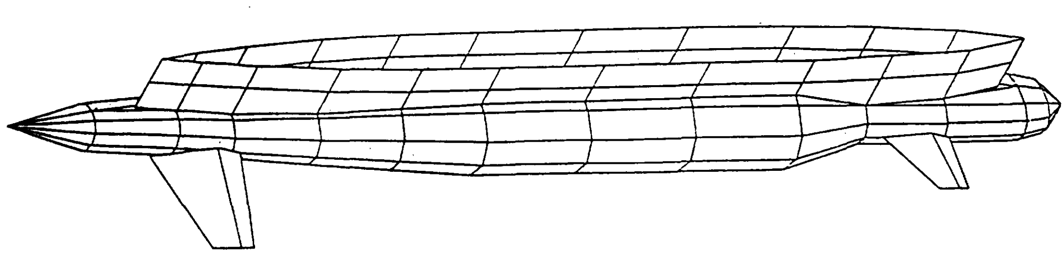


Figure 11.14 CAD Representation of Hydrodynamic Panel Mesh for SWATH Demihull

CHAPTER 12

PRACTICAL APPLICATIONS

This chapter illustrates the use of the SWATH design method described in the thesis by means of examples. The method has been applied to two conceptual SWATH designs for the UK MoD and the design of the first SWATH ship to be constructed in the UK. Some conclusions are drawn with regard to seakeeping assessment.

12.1 Introduction

Chapters 4 to 11 of this thesis have concentrated upon specific aspects of the design method proposed in Chapter 3. In this chapter, use of the system in a number of practical design scenarios is illustrated.

12.2 Use in Conceptual Design

The idealised usage of the method presented in this thesis involves the use of experience and/or Chapters 2 and 4 to develop first estimates of size and produce a baseline definition of the design. The synthesis loop is operated in iterative mode to provide a more accurate estimate of the required dimensions. Command files are then set up to operate the main synthesis modules in a series of parametric studies of the effects of different design variables.

The design of a non-combatant vessel with requirements as listed in Table 12.1 may be considered.

Table 12.1 SWATH Design Requirements

Payload	60 tonnes, 885m^3, 500 kW
Operating profile	maximum sustained speed 14 knots with range of 3000 nm at 8 knots plus 30 days at 3 knots with a tow drag of 20 kN
Design sea state	5.0 m significant wave height, modal period 12.4 seconds
Manning	4 officers, 10 senior rates, 10 junior rates (civilians)
Endurance	46 days
Structure	Mild steel
Propulsion	Integrated diesel electric

Figure 12.1a illustrates the use of several optional routes to a first estimate of ship size. In this case, the consensus suggests that a displacement around 2100 tonnes is likely. It is then necessary to transfer this initial estimate into a hull definition for use in the full synthesis. This may be achieved using program *INITIAL* or the manual method illustrated in Figure 12.1b. These dimensions combine with a selected parent

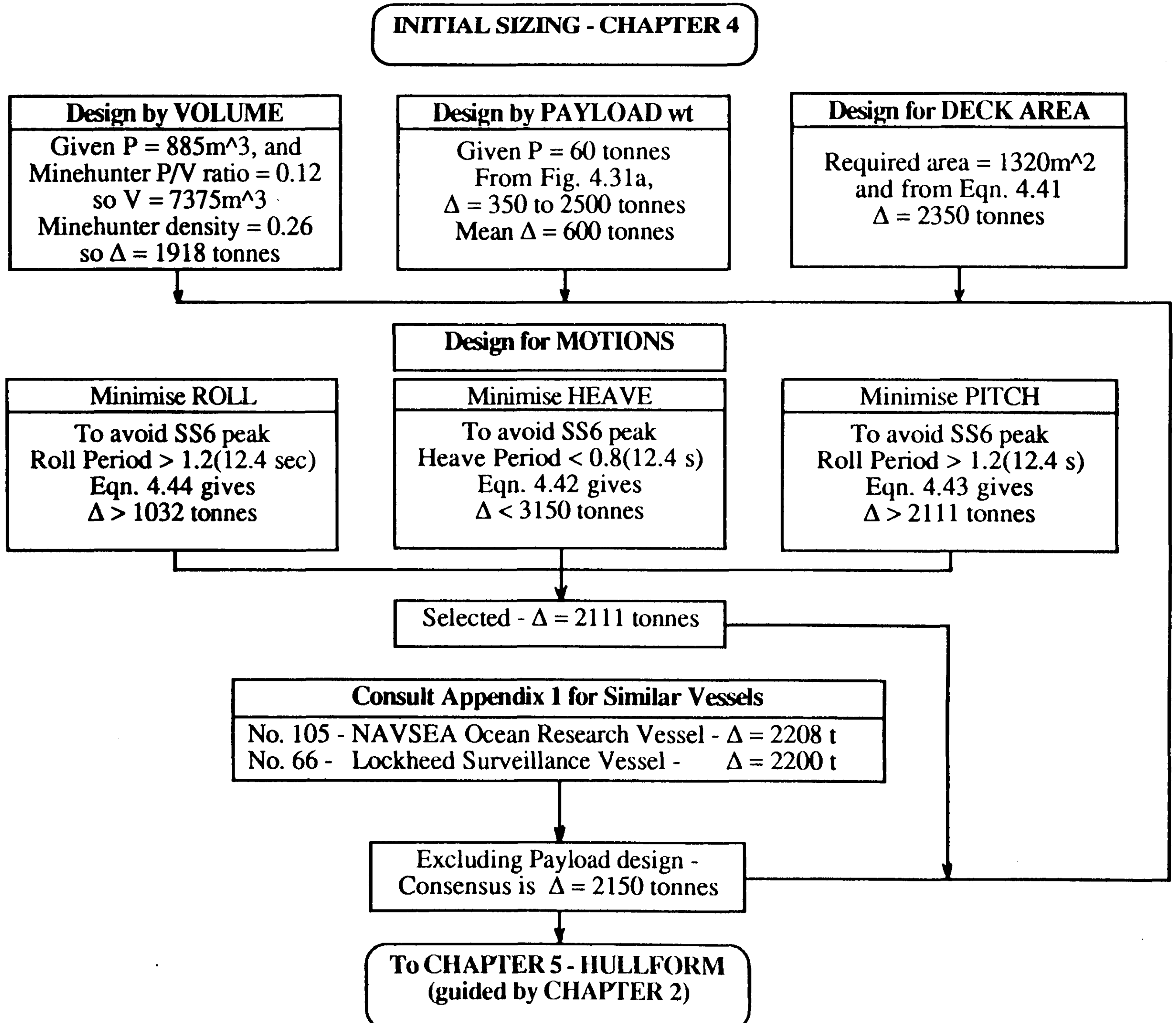


Figure 12.1a Initial Sizing Methodology

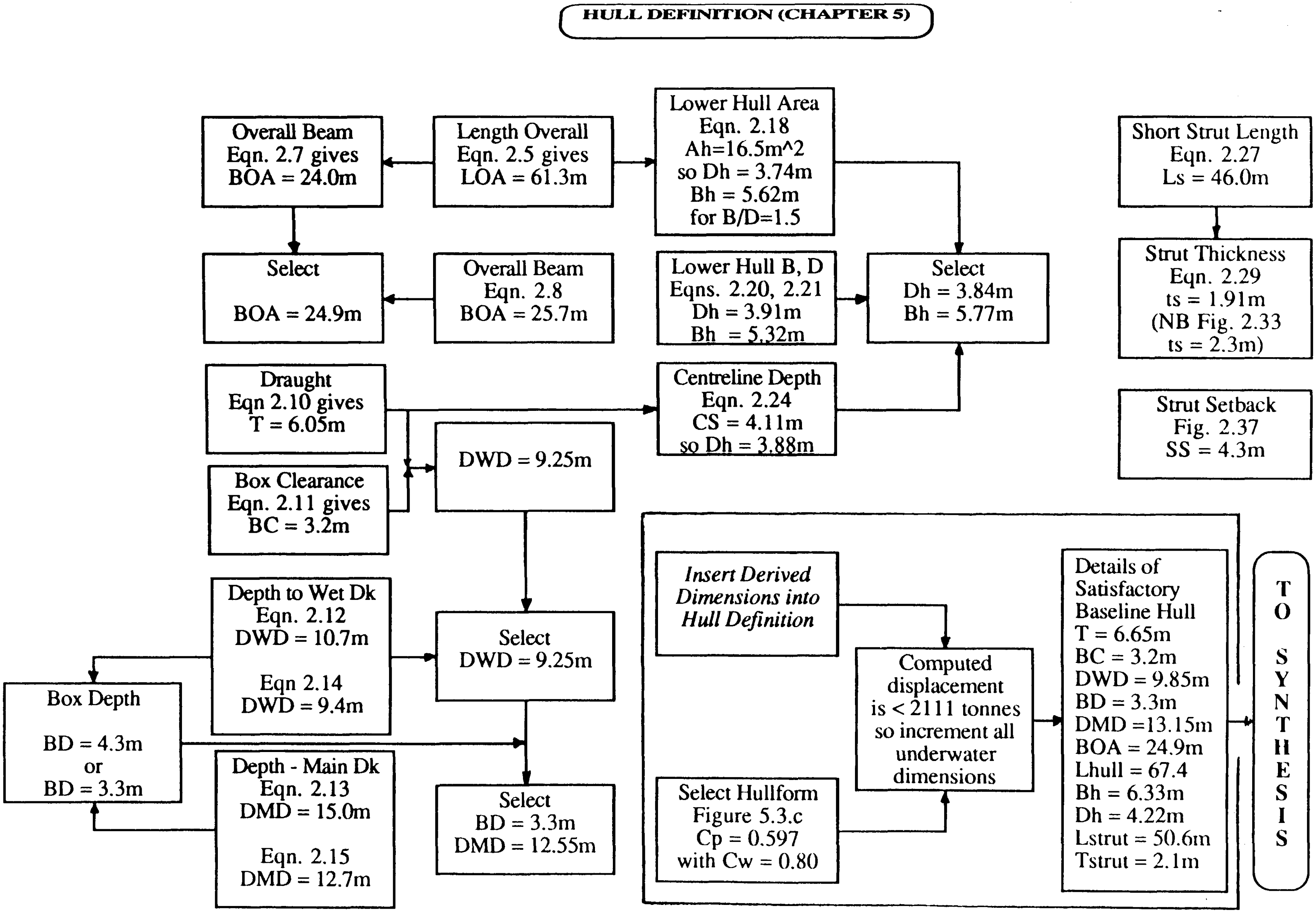


Figure 12.1b Baseline Hull Definition Methodology

hullform to provide accurate estimates of hydrostatics using the methods described in Chapter 5. In this example the initial dimensions suggested by Chapter 2 prove smaller than required to provide the desired displacement of 2100 tonnes. Geosims of the specified underwater form are examined until one with adequate buoyancy is found.

At this point the remaining modules of *DESIN* are applied to seek a design with

$\Delta \geq \sum$weights,

available volume ≥ required volume,

available power ≥ required power.

This is an iterative process, and the design variables take different values (e.g. Figure 12.2) during the synthesis as the program converges to a balanced design. In this example increases in ship size are again required, and the dimensions yielded by the final iteration are listed in Table 12.2.

Table 12.2 Main Dimensions of Synthesised Design

Displacement	2250 tonnes
Draught	6.80m
Box Clearance	3.20m
Depth to Wet Deck	10.00m
Box Depth	3.30m
Depth to Main Deck	13.30m
Overall Beam	25.48m
Hull Length	68.97m
Hull Maximum Beam	6.48m
Hull Maximum Depth	4.32m
Strut Length	51.80m
Strut Thickness	2.15m
Enclosed Volume	7715m^3

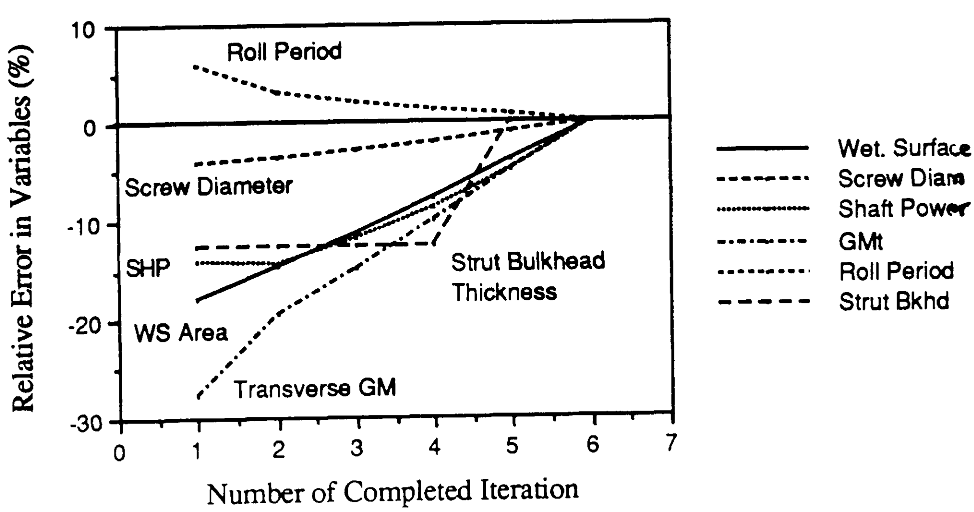


Figure 12.2 Convergence of Design Variables During Synthesis Iteration Sequence

A parametric survey around these baseline figures is required to determine 'optimum' geometries. All the input parameters listed in Chapters 5 to 10 may be controlled either explicity or implicitly, while the corresponding output variables may be monitored. Thus, for example, values of ship displacement or installed power may be obtained for a range of length/displacement ratios and waterplane area/displacement ratios, while other variables are held constant. Alternatively, a matrix of solutions may be provided for a range of weight margins, beam/draught ratios and hull length/breadth ratios.

In effect the parametric studies reported in Chapters 5 to 10 represent a multi-dimensional parametric survey of many variables. The results of this study have been condensed in reference [18]. Even so, it is difficult for most designers to deal with all the implications of a matrix of such complexity, so that simpler studies (Figure 12.3) with many fixed variables are common.

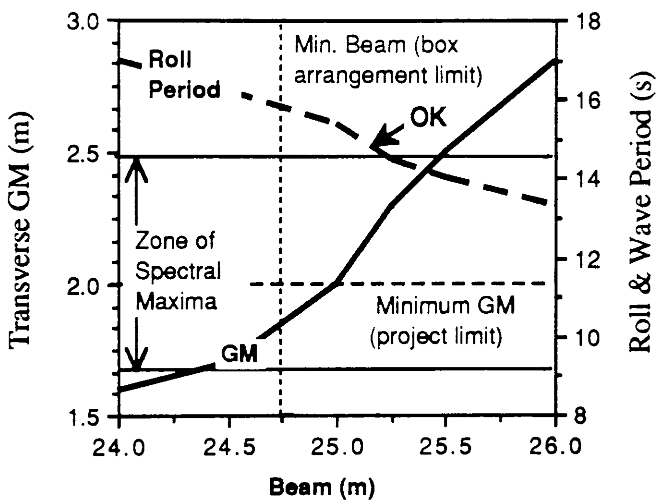


Figure 12.3 Variation of Vessel Beam to Determine 'Optimum' Value

12.3 Conceptual Design of a SWATH to MoD Requirements

The preliminary design method described in this thesis was used (at an intermediate stage of its development) in the design of a SWATH ship to UK MoD requirements. Both the vessel and design process are described in [1,2,3]. Principal ship particulars are listed in Appendix 1 (design number 103). A brief discussion of this experience is useful in illustrating several features of the design method.

In this joint project between Yarrow Shipbuilders Ltd (YSL) and Glasgow University, the yard took responsibility for general arrangement, weights and centres, detailed scantlings, propulsion machinery and systems. The University dealt with initial sizing, hull design and hydrostatics, resistance and maneouvering, seakeeping and structural loading.

With such an arrangement, the design process was necessarily highly interactive and this experience strongly influenced subsequent development of the design method. A requirement for a tool which could be freely driven by external constraints rather than a rigid (and necessarily limited) internal logic was identified. This was particularly evident in the area of weight estimation, a discipline which had not been developed at the time of the study. The need for the design program to respond to continuously updated weights specified by an external party led to the estimating philosophy described in Chapter 10, where predetermined weights may be introduced readily into the synthesis as an alternative to generalised methods.

It is accepted that the final design is far from optimum because of an early decision to avoid the use of contoured hulls and time constraints during the project. In particular, a box arrangement and propulsion scheme developed for an early version of the design were retained throughout the final design iterations despite displacement increasing by 60%. With vessel dimensions influenced by the box sizing, and in the absence of the hull-contouring option, a short, deep, fine strut and slender lower hull were needed to attain the design speed with the available machinery. These proportions lead to large enclosed volume (with associated weight), deep draught, low longitudinal stiffness, a significant separation between LCF and LCB, and low values for added mass and damping.

Despite these qualifications, the completed study was judged to have met the specified requirements, and the design is considered convincing [9]. As far as the current study is concerned, both awareness of the need to respond to external constraints and confidence in the design algorithms were increased.

During the early phases of the design, the program was effectively used in a synthesis mode, producing matrices of feasible designs for different initial conditions. These studies centred around providing minimum power for a vessel subject to the previously described constraints. Full automatic synthesis was not possible because of the dependency upon the shipbuilder for weight data.

When the design had virtually converged, use of the program in an 'analysis' mode (where a fixed geometry is assessed) was extensive. In particular, many checks on the influence of discrete changes in form on resistance and motions were required. Figure 12.3 illustrates a particular situation in which the final value of beam was deduced from computer modelling of several variables. A lower limit of 2.0m had been set for GM_T, while arrangement considerations dictated that the box beam be greater than 24.7m. In addition it was desired to ensure that roll resonance would not occur within ±20% of the energy peak of the specified seastate (modal period 12.4s). These considerations combined to suggest the selected value of 25.2m.

Table 12.3 lists some of the principal design variables for this vessel, and the reasoning behind their choice.

Table 12.3 Choice of Primary Variables in Design of SWATH SSV

Design Variable		*Selected Value*	*Comments*
Displacement (t)		2415	Balance with estimate of weights and margins
Box	Length (m)	48.00	Internal arrangement considerations
	Beam (m)	25.50	Internal arrangement considerations, berth limitations
	Depth (m)	3.90	Internal arrangement, structural efficiency
	Clearance (m)	3.00	Compromise between structural efficiency and slamming incidence
Hull	Section	'Obround'	To maximise use of flat plate for ease of construction
	Shape	'Simple'	Non-contoured for ease of design and construction
	Length (m)	66.0	Large, to increase slenderness and reduce drag
	Breadth (m)	4.68	Small, to reduce sectional area (increase slenderness) and reduce drag at expense of low AVM, damping
	Depth (m)	3.60	Driven by machinery installation considerations
	Corner Radius (m)	1.50	Large, to maximise breadth for given depth and area
	CL Depth (m)	5.60	Large, to minimise wavemaking drag of body, but limited by draught and strength considerations
	CL Spacing (m)	20.52	To give suitable GM for hydrostatics and roll motion
	C_p	0.815	Large, to maximise PMB length for construction
Strut	Length (m)	48.00	Small, because driven by choice of box length
	Thickness (m)	2.70	Large, to compensate hydrostatics for small length and C_w, also for access and strength considerations
	Setback (m)	4.35	Optimised to reduce hull/strut interference drag
	C_w	0.75	Small, to reduce strut wavemaking drag
Heave Period (s)		8.8	Driven by waterplane area and low AVM of hulls. At least 20% below energy peak of SS6 spectra. Not a sub-multiple of pitch or roll periods
Pitch Period (s)		19.0	At least 20% greater than energy peak of SS6 spectra. Strongly influenced by choice of strut C_w
Roll Period (s)		15.0	At least 20% greater than energy peak of SS6 spectra. Strongly influenced by choice of strut C_w

12.4 SWATH Seakeeping Assessments

As part of the study reported in section 12.3 above, a comprehensive seakeeping assessment [1] was carried out. In addition, towards the end of the current study, modules of *DESIN* were used in a commercial contract to predict the seakeeping of a given SWATH design [4]. In view of the scarcity of motion data available for 'real' SWATH designs, some of these results may be of general interest.

12.4.1 Regular Sea Responses

Response amplitude operators for the 2415 tonne YSL design at speeds of 0, 4, 8 and 14 knots and several headings are presented in reference [1]. These were computed using a 5 degree of freedom strip theory approach [11] and the 6 degree of freedom three dimensional panel method (program *SHIPM*) introduced in Chapter 11 which can provide a semi-empirical estimate of the effects of viscous damping.

Figures 12.4 to 12.6 present comparisons of the heave, pitch and roll responses for the YSL design at zero speed in head and beam seas. It can be seen that viscosity is significant in reducing the resonant peaks, particularly for pitch. As discussed later, this effect is significant for SWATH ship comparative seakeeping assessments. Some coupling of heave and pitch motion (not evident in the other computations) can be seen in the 3D potential theory results. This is to be expected for a design possessing significant LCB-LCF separation. There is some disagreement between the 2D and 3D theories regarding the peaks of the roll and pitch responses primarily due to the the use of different radii of gyration in the computations.

The 3D seakeeping program *SHIPM* was used [4] to predict the seakeeping responses of the MoD hullform detailed in Figure 1 of [10]. *DESIN* was used to scale the model dimension to full size (2300 tonnes), and thence generate a panel mesh of the geometry. Some of the results obtained for this design (Appendix 1 number 104) are illustrated in Figures 12.7 to 12.9. Varying the drag coefficient ('original' = 0.6, 'modified' = 1.2) used to estimate viscous damping effects can be seen to have a significant effect on predicted peak responses. This can be important in seakeeping comparisons involving SWATH ships which tend to show very high resonant responses, and this is an area requiring further research. Currently, most SWATH motions programs model viscosity by using coefficients derived many years ago from tests on airship hulls.

12.4.2 Irregular Seaway Analysis

The principle of superposition, introduced by Pierson and St Denis, allows ship motions in irregular seas to be predicted from responses calculated in regular waves. Irregular seas are represented by semi-empirical energy spectra from which various statistical quantities may be computed. During this study, routines to evaluate irregular sea responses were developed, and use was also made of existing tools [12]. However, these methods are now well known and are not discussed in this thesis.

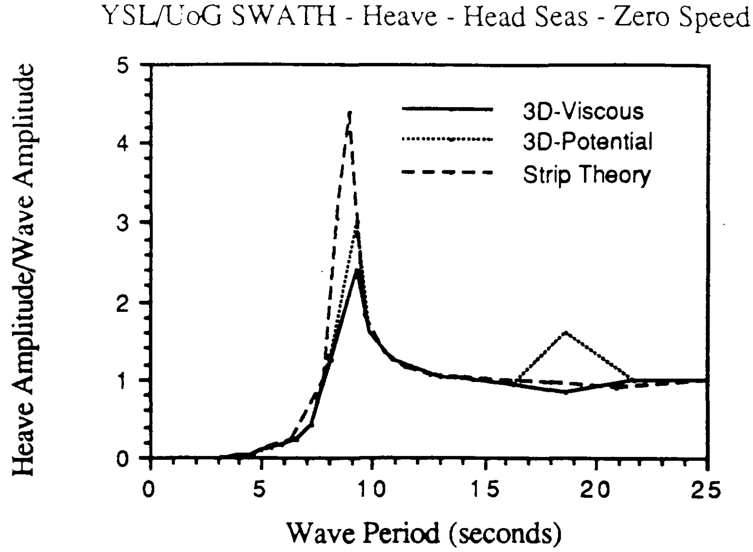


Figure 12.4 Comparison of Heave Response Amplitude Operator Predictions

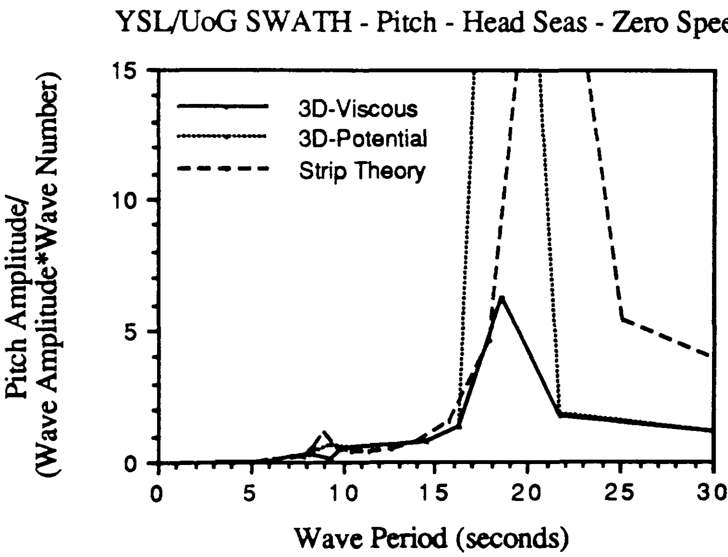


Figure 12.5 Comparison of Pitch Response Amplitude Operator Predictions

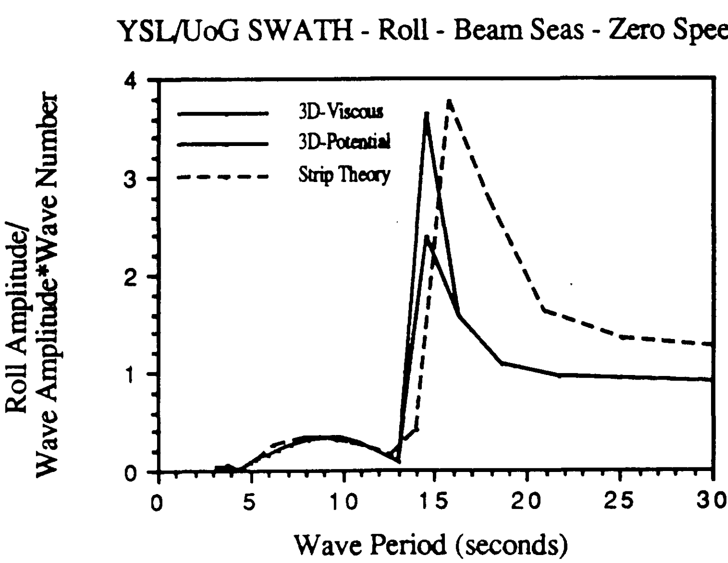


Figure 12.6 Comparison of Roll Response Amplitude Operator Predictions

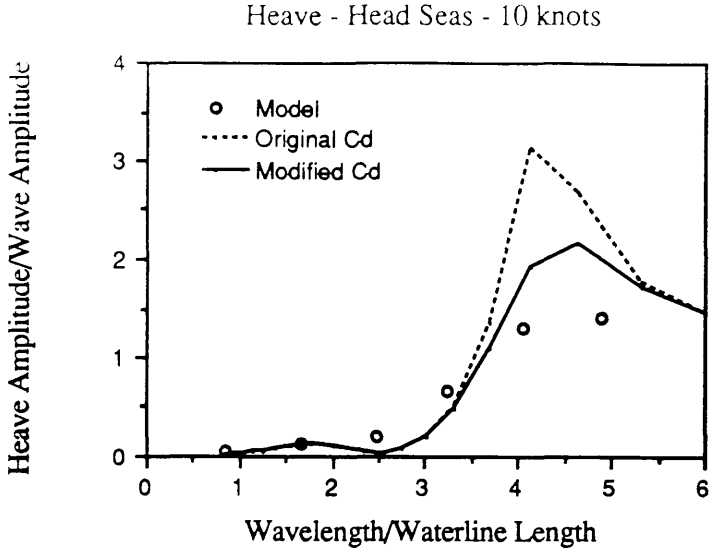


Figure 12.7 Comparison of Predicted and Experimental Heave RAOs

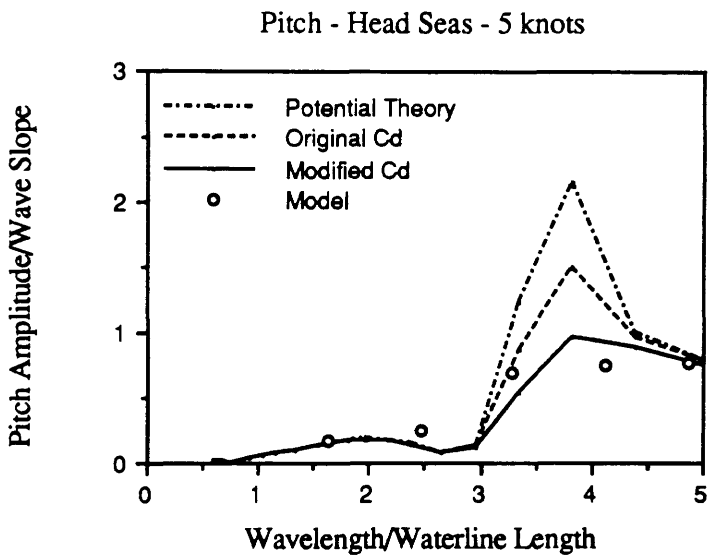


Figure 12.8 Comparison of Predicted and Experimental Pitch RAOs

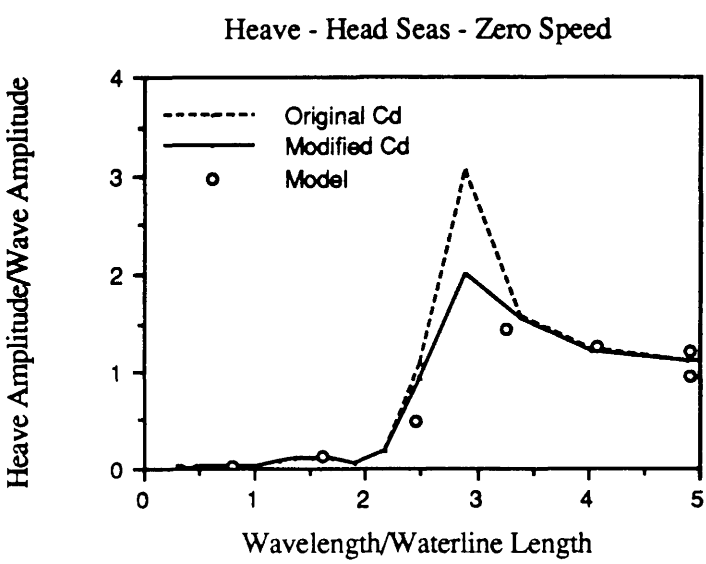


Figure 12.9 Comparison of Predicted and Experimental Roll RAOs

Use of statistical analysis, and specified limiting motion criteria can allow comparisons of seakeeping effectiveness. Approaches to this problem have been described by Olsen [16] and Comstock [17]. There is some controversy as to what constitutes realistic criteria, especially since most existing limits are based on monohull experience. Some published limits for naval ships are listed in Table 12.4.

Table 12.4 Alternative Limiting Ship Motions (Significant, Single Amplitude)

Source	Roll (deg)	Pitch (deg)	Vert Vel. (m/s)	Vert Acc. (m/s^2)	Lateral Acc. (m/s^2)	Wetness	Slams	Comments
[14]	6.0	3.0	2.0	-	-	-	-	Helicopters, general
[14]	8.0	3.0	2.0	3.92	1.96	30/hr	20/hr	Helicopters, general
[15]	2.5	2.0	2.0	1.47	2.45	30/hr	60/hr	Patrol boats
[15]	5.0	2.0	3.0	-	-	-	-	Lynx helicopter
[17]	5.0	3.0	2.0	-	-	-	-	-

From experience associated with the current study it appears that the pitch criterion is the most difficult for SWATH ships to meet, certainly when neglecting the effect of control fins.

Regular sea responses for the YSL and MoD SWATH designs were combined with ISSC 2 parameter spectra to produce significant (single amplitude) motions in irregular seas. Tables 12.5 to 12.8 list the (unstabilised) heave and pitch responses for these vessels at a range of speeds and headings. Motions which exceed the criteria of Table 12.4 are indicated by **bold** type. Figures 12.10 to 12.11 compare the significant motions computed for these vessels (which were designed for the same role). The plots identify responses by ship (2330 or 2415), calculation method (2D or 3D) and seastate (SS4 to SS6).

The dangers present in specifying a discrete number of sea states for operability analysis are revealed by comparing Tables 12.7 and 12.8 where alterations in the specified modal periods radically alter the computed vessel responses. Because SWATH ship RAOs have finely tuned resonant peaks, the choice of spectral modal periods specified for motions calculations can have a dramatic effect on computed operability. It can therefore be misleading to draw conclusions on vessel seakeeping based on a few sea states which may occur infrequently in practice. Full scatter diagram type analyses which model the frequency of occurrence of a number of sea states provide more realistic comparisons.

Table 12.5

Significant Single Amplitude Responses - 2415 tonne SWATH design (no fins) - 3D Theory (inc viscous damping)

Sea state	*4 - H1/3 1.88m, Tp 11.0s*				*5 - H1/3 3.25m, Tp 12.3s*				*6 - H1/3 5.0m, Tp 12.3s*			
Speed (kts)	0	4	8	14	0	4	8	14	0	4	8	14
Head Seas ß=180												
Heave (m)	1.17	1.26	1.34	1.50	1.97	2.12	2.23	2.45	3.02	3.27	3.43	3.76
Pitch (deg)	0.72	0.96	1.51	2.81	1.33	1.65	2.48	**4.39**	2.04	2.54	**3.82**	**6.76**
Bow Quartering Seas ß=135												
Heave (m)	1.11	1.21	1.29	1.48	1.88	2.03	2.15	2.41	2.89	3.13	3.31	3.70
Pitch (deg)	0.69	1.04	1.35	2.51	1.22	1.65	2.20	**3.89**	1.88	2.54	**3.39**	**5.99**
Beam Seas ß=90												
Heave (m)	1.09	1.07	1.07	1.16	1.85	1.82	1.81	1.92	2.84	2.79	2.78	2.95
Pitch (deg)	0.64	0.71	0.88	1.23	1.13	1.17	1.42	1.90	1.74	1.80	2.18	2.93
Stern Quartering Seas ß=45												
Heave (m)	1.07	0.90	0.66	0.14	1.83	1.55	1.19	0.41	2.81	2.39	1.84	0.64
Pitch (deg)	0.99	0.86	0.57	0.40	1.68	1.45	1.06	0.63	2.59	2.23	1.63	0.98

Table 12.6

Significant Single Amplitude Responses - 2415 tonne SWATH design (no fins) - 2D Theory

Sea state	*4 - H1/3 1.88m, Tp 11.0s*				*5 - H1/3 3.25m, Tp 12.3s*				*6 - H1/3 5.0m, Tp 12.3s*			
Speed (kts)	0	3	8	14	0	3	8	14	0	3	8	14
Head Seas ß=180												
Heave (m)	1.64	2.09	-	-	2.61	3.41	-	-	4.01	5.24	-	-
Pitch (deg)	1.17	1.73	-	-	1.93	2.79	-	-	2.98	**4.30**	-	-
Bow Quartering Seas ß=135												
Heave (m)	1.48	1.81	1.92	2.00	2.38	2.95	3.27	3.63	3.66	4.54	5.03	5.59
Pitch (deg)	1.02	1.36	1.76	2.20	1.64	2.20	**3.00**	**4.00**	2.52	**3.38**	**4.62**	**6.17**
Roll (deg)	0.42	0.33	-	-	1.01	0.62	-	-	1.56	0.96	-	-
Beam Seas ß=90												
Heave (m)	1.31	1.29	1.25	1.55	2.13	2.10	2.03	2.42	3.28	3.23	3.12	3.72
Pitch (deg)	0.88	0.93	1.15	1.71	1.36	1.49	1.92	2.72	2.09	2.30	2.96	**4.19**
Roll (deg)	0.76	0.77	-	-	1.32	1.34	-	-	2.04	1.94	-	-
Stern Quartering Seas ß=45												
Heave (m)	1.49	1.65	0.78	0.43	2.36	2.52	1.23	0.83	3.64	3.88	1.90	1.28
Pitch (deg)	1.13	1.52	0.88	0.79	1.79	2.40	1.73	1.32	2.76	**3.69**	2.66	2.03
Roll (deg)	0.76	0.43	-	-	1.8	1.13	-	-	2.77	1.74	-	-
Following Seas ß=0												
Heave (m)	1.64	1.31	0.52	0.58	2.61	2.03	0.93	0.74	4.01	3.13	1.43	1.14
Pitch (deg)	1.17	1.21	0.93	2.44	1.93	2.17	2.13	**3.61**	2.98	**3.34**	**3.28**	**5.55**

Table 12.7

Significant Single Amplitude Responses - 2330 tonne SWATH Design (with fins) - 3D Theory (inc viscous effects)

Sea state	*4 - H1/3 1.88m, Tp 11.0s*				*5 - H1/3 3.25m, Tp 12.3s*				*6 - H1/3 5.0m, Tp 12.3s*			
Speed (kts)	0	5	10	14	0	5	10	14	0	5	10	14
Head Seas ß=180												
Heave (m)	1.24	1.29	1.21	1.12	2.10	2.36	2.36	2.30	3.23	3.63	3.63	3.55
Pitch (deg)	1.46	0.65	1.02	1.18	**3.70**	1.43	2.02	2.44	**5.69**	2.20	**3.11**	**3.75**
Following Seas ß=0												
Heave (m)	1.25	0.71	0.60	0.77	2.12	1.26	1.08	1.36	3.26	1.95	1.66	2.09
Pitch (deg)	1.23	0.85	0.94	2.08	**3.12**	1.99	1.81	**3.49**	**4.80**	**3.06**	2.79	**5.37**

Table 12.8

Significant Single Amplitude Responses - 2330 tonne SWATH Design (with fins) - 3D Theory (inc viscous effects)

Sea state	*4 - H1/3 1.88m, Tp 8.8s*				*5 - H1/3 3.25m, Tp 9.7s*				*6 - H1/3 5.0m, Tp 12.4s*			
Speed (kts)	0	5	10	14	0	5	10	14	0	5	10	14
Head Seas ß=180												
Heave (m)	1.02	0.78	0.56	0.42	2.02	1.82	1.52	1.28	3.22	3.62	3.64	3.58
Pitch (deg)	0.26	0.34	0.46	0.48	1.08	0.84	1.26	1.34	**5.80**	2.24	**3.14**	**3.78**
Following Seas ß=0												
Heave (m)	1.02	0.64	0.54	0.70	2.04	1.22	0.98	1.26	3.24	1.96	1.66	2.10
Pitch (deg)	0.30	0.34	0.82	2.18	0.98	0.86	1.46	**3.40**	**4.90**	**3.10**	2.82	**5.36**

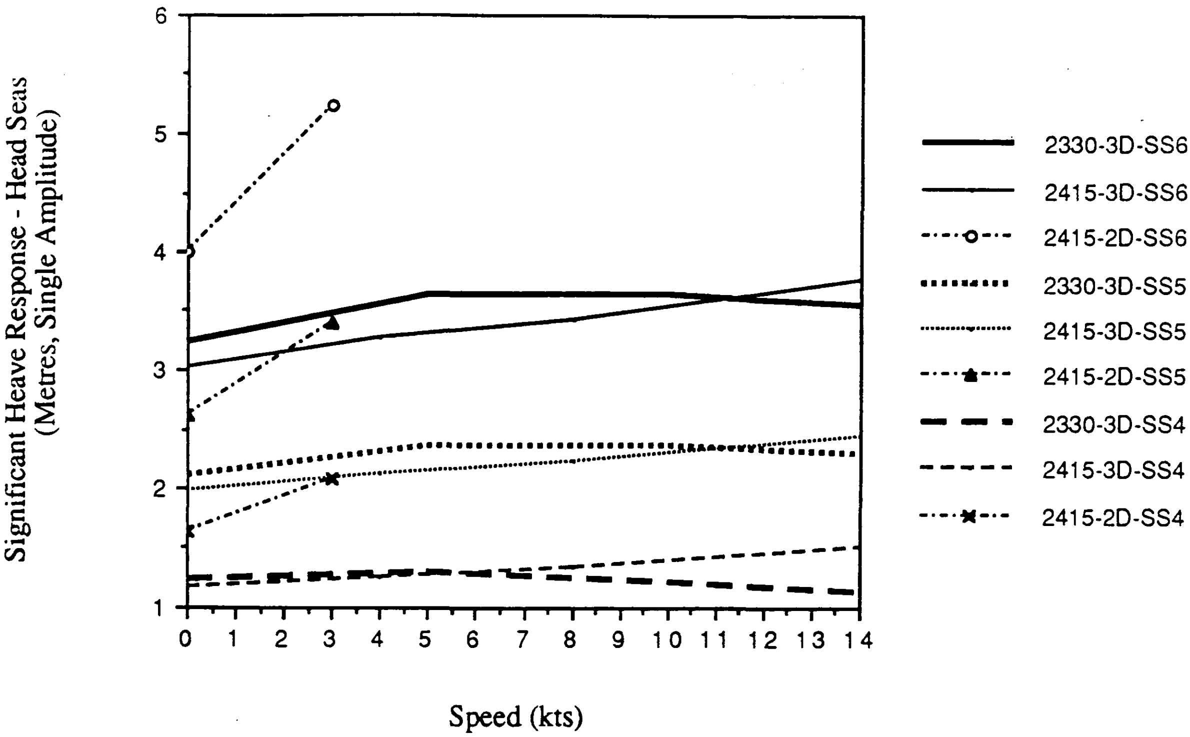


Figure 12.10 Comparison of Significant Heave Reponses of Two SWATH Ships

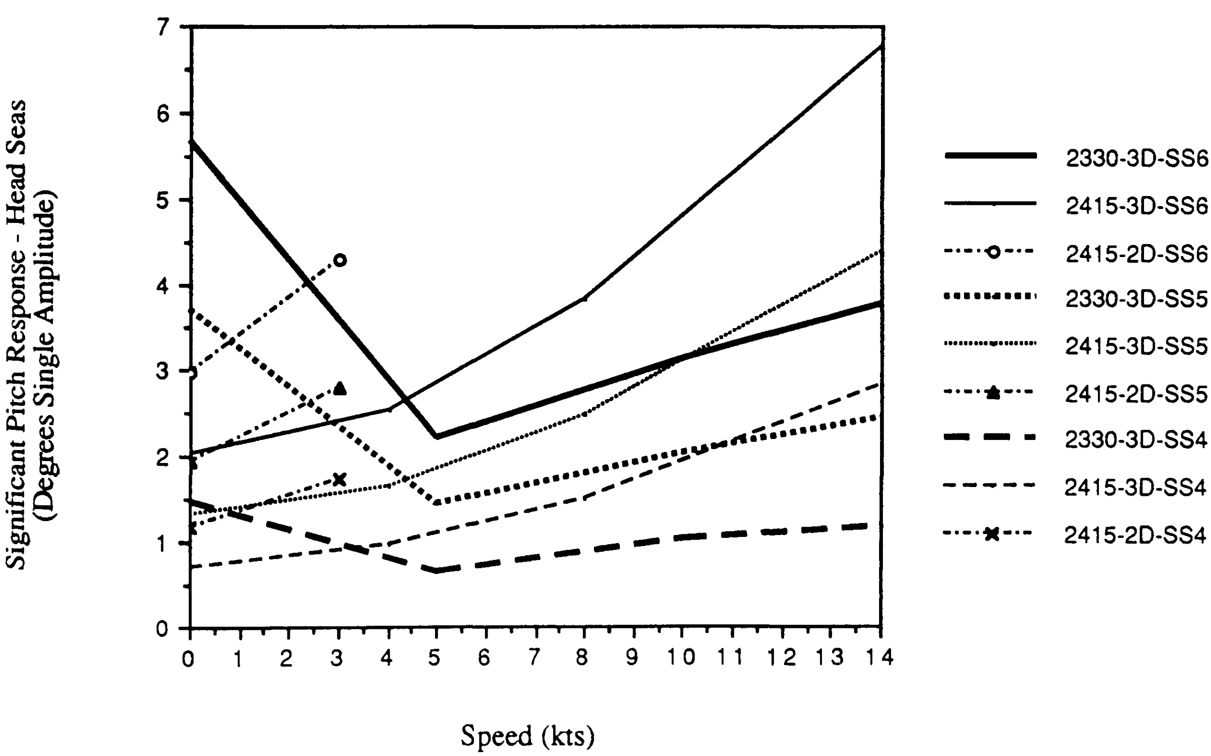


Figure 12.11 Comparison of Significant Pitch Reponses of Two SWATH Ships

12.4.2.2 SWATH-Monohull Comparison

A basic comparison was made of the motions of the 2330 tonne SWATH and those of some contemporary naval monohulls. Table 12.9 compares results from the MoD seakeeping program *AEW4* [8] for an aircraft carrier (18060 tonnes, 2.06m GM) and a frigate (2750 tonnes, 0.54m GM), with those from the YARD strip theory program *MOTION* for the same frigate (2830 tonnes, 0.69m GM) [7] and results for the 2330 tonne SWATH using the 3D program *SHIPM*. The frigate used in this study is widely regarded as one of the best seaboats of its generation.

RMS single amplitude responses were computed for Sea State 5 ($H_{1/3}$ 3.25m, T_z 9.3s, T_p 13.1s, T_s 10.1s), Sea State 6 ($H_{1/3}$ 5.0m, T_z 9.4s, T_p 13.24s, T_s 10.21s), and Sea States 7-8 ($H_{1/3}$ 9.0m, T_z 11.61s, T_p 16.35s, T_s 12.61s) using ISSC 2 parameter spectra.

Table 12.9 Motion Comparison of 18000 tonne carrier, 2700 t frigate, 2300 t SWATH

Program/Ship	*AEW4* carrier			*AEW4* frigate			*MOTION* frigate			*SHIPM* SWATH		
Sea State	5	6	7-8	5	6	7-8	5	6	7-8	5	6	7-8
Pitch (degrees)	0.70	1.10	2.00	1.25	2.00	3.25	1.06	1.61	2.37	1.71	2.62	4.97
FP Accln (m/s^2)	0.84	1.30	2.00	1.50	2.30	3.50	1.43	2.17	2.88	0.60	0.93	1.49
AP Accln (m/s^2)	0.60	0.85	1.25	1.00	1.50	2.00	0.82	1.25	1.69	0.66	1.02	1.65

Responses are RMS single amplitudes at worst heading at 15 knots (14 knots for SWATH)

Although predicted motions can vary significantly depending on computer method (*AEW4* or *MOTION*) some points may be observed. Because the modal periods of these sea states are closer to the natural pitch period (14 seconds) of the SWATH than the monohulls, the SWATH has greater pitch motions. However, SWATH ship vertical accelerations are closer to those of the much larger carrier than those of the frigate. Much of this is due to the much smaller levers from the CG to the AP for the short SWATH ship.

In view of the inconclusive nature of this study, it was decided to extend the analysis to compare head sea responses for a distribution of wave heights and periods to be expected in an area of interest to UK naval operations (Table 12.10).

Table 12.10 Percentage Occurrence Scatter Diagram for Iceland-Faeroes-Norway Area

T_z (s) / $H_{1/3}$ (m)	2.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5
0.5	0.1	1.4	3.5	3.0	1.1	0.3	0.0	0.0	0.0
1.5	0.0	0.6	5.2	10.2	7.8	3.1	0.8	0.2	0.0
2.5	0.0	0.2	2.4	7.7	9.2	5.5	2.0	0.5	0.1
3.5	0.0	0.0	0.8	3.6	5.8	4.5	2.1	0.7	0.2
4.5	0.0	0.0	0.2	1.4	2.8	2.6	1.5	0.6	0.2
5.5	0.0	0.0	0.1	0.5	1.2	1.3	0.9	0.4	0.1
6.5	0.0	0.0	0.0	0.2	0.5	0.6	0.5	0.2	0.1
7.5	0.0	0.0	0.0	0.1	0.2	0.3	0.2	0.1	0.1
8.5	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.0
9.5	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0

Regular sea responses were obtained from programs *SHIPM* (for unstabilised SWATH) and *MOTION* (for frigate). For each waveheight and period combination, significant single amplitude responses were computed using head seas RAOs and the ISSC 2 parameter spectra. By multiplying the calculated responses by the relevant percentage occurrence data, the yearly responses were obtained. These results are presented in Table 12.11 where it can be seen all calculated SWATH motion responses are considerably less than the corresponding frigate values. This is in contrast to the conclusion which would be drawn from Table 12.9.

Table 12.11 Comparison of SWATH and Frigate Seakeeping Using Scatter Diagram

Significant Single Amplitude Responses - Head Seas - ISSC 2 Parameter Spectra

	2330 tonne SWATH			2700 tonne Frigate		
Speed (knots)	5	10	14	4	10	15
Heave (metres)	1.63	1.50	1.39	0.62	0.66	0.75
Pitch (degrees)	0.94	1.29	1.47	1.64	1.73	1.79
Vertical Acceleration at AP (m/s^2)	0.75	0.79	0.82	0.96	1.29	1.55
[1]Subjective Motion Magnitude at AP	2.91	3.12	3.25	3.60	4.99	6.05

Despite the more advantageous situation detailed in Table 12.11, these results do not support the claims to superior SWATH seakeeping as convincingly as might be expected. A number of possible reasons for this may be mentioned. This particular SWATH is designed for low speed operation, and consequently is not optimised for performance the speeds used in this comparison. Headings likely to cause rolling have been ignored, to the advantage of the monohull. In addition, the considerable influence of control fins in reducing SWATH motions has been neglected. The presence of large resonant heave responses in the SWATH data compared to the frigate RAOs (which never exceed 1.0) explains the heave results in Tables 12.9 and 12.11.

[1]N.B. $SMM = [30 + 13.53 (\log_e f)^2] (s/g)^{1.43}$

where $f = \frac{1}{2\pi}$ [2nd moment vertical response spectrum/zeroth moment of vertical response spectrum]$^{1/2}$
and s = vertical acceleration at the point of interest

12.5 Design of a SWATH for Construction in the UK

The ultimate test of any design is successful construction and operation. However, the great majority of conceptual designs are never built, and this is especially true of those produced in large numbers with relative ease by computer.

In the case of the present design method, the process of testing by construction has begun. As described in [5], the SWATH synthesis method has been used in the preliminary design of a SWATH vessel under construction (Endplate) in the UK. The vessel is of mild steel construction, with box/haunch mounted diesels and high torque belt drives. This vessel is of greater size than the Japanese prototype *Marine Ace* and, in addition to its role as an inshore fishing vessel, is intended to offer a realistic base for validation of SWATH technolgy in the UK.

A full description of the operational requirements, practical constraints, and selected solution may be found in [5] and is not included in this thesis. Elements of this thesis and program *DESIN* were used for initial sizing, hullform development, resistance and propulsion estimates and motion stiffness predictions. The latter were confirmed by strip theory calculations, extended to an irregular sea analysis. This indicated that in the seas off North West Scotland, the vessel will have a heave response half that of an equivalent monohull, with pitch response as low as 5% of the monohull value. Static gear fishing for high value species is identified [13] as the most suitable role for this craft.

Model tests of this design are being carried out at Glasgow University to determine the relationships which exist between theoretical, experimental and full scale behaviour of SWATH ships.

12.6 Conclusions

The object of the present study is the development of a tool able to bridge the gap between the conceptual design and more advanced theoretical aspects of SWATH technology. While previous chapters of this thesis have described the development of such a system, this chapter has outlined three separate projects in which it has been commercially employed. The present method has directly aided the development of a concept design of a SWATH ship, and a seakeeping analysis using three dimensional potential flow methods. Future model testing and full scale trials of a seagoing SWATH ships are projected as further validation of this design tool.

References to Chapter 12

1. Arthur, E.K., MacGregor, J.R. and Zheng, X., "Seakeeping Assessments of SWATH SSV Design Using 2D Strip Theory and 3D Panel Method", Appendix to reference [2], 1987

2. "Concept Study Report - SWATH Sonar Support Vessel (SSV)", Contract Number NSS 41A/1800, Yarrow Shipbuilders Ltd, July 1987

3. Smith, D.L., Cuthbertson, W., MacGregor, J.R. and McGregor, R.C., "SWATH Design - A Shipbuilders View and a Practical Example", *Proceedings,* 2nd International Conference on SWATH Ships and Advanced Multi-Hulled Vessels", RINA, London, November 1988

4. MacGregor, J.R., "Prediction of the Seakeeping of a Given SWATH Vessel - As Tested at ARE (Haslar)", YARD Report YR3690, December 1988

5. MacGregor, J.R., Bose, N. and Small, G.H., "Design and Construction of a SWATH Fishing Vessel", Proceedings, International Symposium on Fishing Gear and Fishing Vessel Design", St. Johns, Newfoundland, November 1988

6. *Global Wave Statistics*, British Maritime Technology Limited (ed.), Published by Unwin, Surrey, England, 1986

7. "Seakeeping Analysis of Batch 2A Leander Class Frigates", YARD Memorandum Number 5197-01-B, Contract RP51/5, June 1987

8. Naval Engineering Standard 108, MoD(PE) CNA Seakeeping Manual, 1984

9. "SWATH SSV Design Comparison - MoD Comments", MoD memorandum D/SSC/DGFMP(N)/1/1/150, 20th October 1987

10. Pattison, D.R. and Rose, P.H.A., "SWATH - The UK MoD Design and Assessment Programme", *Proceedings,* 2nd International Conference on SWATH Ships and Advanced Multi-Hulled Vessels", RINA, London, November 1988

11. Seren, D.B., Miller, N.S., Ferguson, A.M. and McGregor, R.C., "Some Motion and Resistance Aspects of SWATH Ship Design", *Proceedings*, International Conference on SWATH Ships and Advanced Multi-Hulled Vessels", RINA, London, April 1985

12. "*SEAWAY* User Guide", *ATHENA* User Guides Volume 1, YARD Ltd, Naval Architecture Group, 1988

13. "Fishing Catamarans", *Small Craft,* Supplement to *The Naval Architect,* April 1989, page 31

14. Kennell, C.G., White, B., Comstock, E.N., "Innovative Naval Designs for North Atlantic Operations", SNAME Annual Meeting, New York, November 13-16, 1985

15. Brown, D.K., "Seaworthy by Design - Patrol Boat Requirements", *Ship & Boat International,* December 1986

16. Olson, S.R., "An Evaluation of the Seakeeping Properties of Naval Combatants", ASNE *Naval Engineers Journal,* February, 1978

17. Comstock, E.N., Bales, S.L. and Gentile, D.M., "Seakeeping Performance Comparison", ASNE *Naval Engineers Journal,* April 1982

18. MacGregor, J.R., Simpson, R.R. and Norton, P., "Parametric Studies in the Design of a Series of SWATH Ships", to be published in *Proceedings,* Intersociety Advanced Marine Vehicles Conference, Washington, DC, June 1989

CHAPTER 13

CONCLUSIONS

13.1 General

The principal aim of the research reported in this thesis has been the development of a capability which integrates the initial sizing and hydrodynamic assessment of SWATH designs. This objective has been achieved through the development of a computer aided preliminary design and analysis method. The task of defining a mathematical model of a vehicle concept and predicting its performance can be accomplished in hours instead of days or weeks as this tool aids the designer in performing all the tedious operations that tend to obscure the problem at hand. This program has been used successfully in the preliminary design phase of commercial SWATH design exercises.

As part of the creation of this design tool, several aspects of SWATH design have been investigated and, as a result, a collection of data is presented which may be of use in the manual design of such vessels. Some findings of these studies are discussed below, although several individual chapter summaries are contained in the main body of the thesis.

13.2 Collection and Analysis of SWATH Design Data

Although the number of SWATH ships at sea is still small, the research projects of recent decades and the growing design effort have already produced a useful database for these vessels. The thesis includes a reference section listing the performance characteristics and dimensions of over 100 published conceptual and existing designs. This data has been presented in a form suitable for ready reference. An analysis of this information was conducted to identify trends and equations for guiding the manual selection of SWATH dimensions and for use in simple design tools.

Several distinct trends relating the main dimensions of SWATH ships have been identified. This information has been presented graphically and in the form of equations. The existence of some consensus of opinion in SWATH design is revealed by the well defined relationships between certain main dimensions. This implies that recent efforts in the fields of SWATH resistance and motions have already influenced many designers to select vessel proportions which reflect the desire to optimise hydrodynamic performance, whilst meeting practical needs. As an example, the relationship between available length and displacement data exhibits a correlation coefficient of 0.97.

The analysis also allows comparisons to be made of the performance of published SWATH designs and other ships. This has shown that the SWATH concept is one of the more inefficient of marine vehicles and must be clearly demonstrated to offer radical seakeeping advantages if it is to coexist with conventional vessels of greater 'transport effectiveness'. At a basic level these comparisons also provide a facility for rapidly assessing the likely effects of increased speed or size on the performance of a design.

13.3 Design of a SWATH Synthesis Method

A methodology for a SWATH synthesis model has been developed, drawing on research in the fields of computer aided aircraft and ship design. In the adopted method, the relationship between designer, design data and design program is intended to place all design decisions with the engineer; in other words, the system does not optimise, minimise, or perform other mysterious operations. A continuously updated ship description or *'current model'* necessary to this form of program is defined, and the flow of data through the complete design system is indicated.

The selected method employs the concept of three levels of complexity in which one simple or *'baseline'* ship description is first created, then synthesised until convergence by iteration is achieved, when the final synthesised design may be further analysed.

13.4 Initial Sizing Aids

A number of alternative *'baseline'* methods for initial sizing of SWATH ships have been developed. Use of these aids increases the probability of satisfactory convergence of the more complex synthesis programs.

In particular, a distinct need for a simple early stage design program for SWATH ships was identified. The database contained within this thesis provided an opportunity for deriving parametric methods for such a program. Approximations for estimating the required power and weight budget for SWATH ships of conventional form have been proposed. A design algorithm based on these parametric approaches has been programmed and tested. Designs produced by the program compare well with equivalent in-depth concept studies. This mini-synthesis tool produces initial estimates of power, weights and dimensions from inputs of desired speed, range, payload and selected machinery and structural options.

A weight equation technique for the initial sizing of SWATH ships using existing data has been developed and programmed. Given the performance characteristics and weight breakdown of a known SWATH design, the weights of a design with a different payload, speed or range may be estimated. Studies using this tool give results which are in agreement with the conclusions of manual design projects. It is shown that between 3 and 4 tonnes of SWATH displacement are required to support 1 tonne of extra payload. A number of published design studies have been assessed using this procedure to provide further data for ready use by designers.

Further aids for initial sizing have been provided in the form of graphs which link SWATH ship weight, volume, density, payload, deck area and seakeeping characteristics. These simple plots of data provide a rapid check on the size and balance of SWATH designs. For example, the range of practical vehicle densities for steel SWATH ships is seen to lie between 0.22 and 0.30 tonnes/m^3. It is recommended that these methods be used to confirm sizes developed by other means.

13.5 Geometry Definition

A generalised procedure for SWATH ship hull definition has been developed. This forms an important component of the synthesis tool as it provides a mathematical model of the geometry for use in hydrodynamics and graphics packages. The method adopted allows the rapid definition and analysis of a wider range of SWATH configurations than competing design packages, including contoured hulls of circular, elliptical and rectangular section. Hydrostatic calculations using this tool are in good agreement with results obtained by other methods.

13.6 Resistance Estimation

Three alternative methods for prediction of SWATH ship resistance have been linked to the geometry generation package in order to provide an integrated design and assessment facility.

13.7 Propeller Design

A study of the theoretical and experimental data on the propulsive performance of SWATH ships indicates the potential for hull efficiencies considerably in excess of 100%, and the existence of Froude Number dependent oscillations in the wake fraction and thrust deduction factor.

In the absence of other approximations, empirical expressions have been derived to predict the self propulsion factors of SWATH ships. These incorporate the effects of propeller diameter/hull diameter ratio and ship speed but are not sophisticated enough to fully represent the experimental data. There are some contradictions in the available data which indicate the need for more study of the fluid flow at the aft end of these vessels.

A method for use in estimating propeller dimensions and performance in the SWATH synthesis program has been developed using these relations. This algorithm also uses the Wageningen B Series data to determine the required shaft power for any SWATH design, given the effective power and geometrical details of the vessel. An estimate of QPC and its components is provided, making reference to physical constraints, with the secondary aim of defining a suitable propeller geometry. For a selected range of designs, this algorithm was found to estimate QPC to within 2% of published values, and propeller diameter to within 10%.

Parametric studies of the effects on propulsive performance of variations in major design parameters indicate that for a typical family of SWATH vessels, a QPC in excess of 0.7 may be readily achieved. It is also demonstrated that at Froude Numbers near to 0.36 (which correspond to hollows in the residuary resistance curves) the QPC possesses a local maximum. These significant oscillations in the value of propulsive coefficient reinforce the desirability of operating in this speed regime.

13.8 Machinery Design

There is an extremely complex interaction which requires careful attention between the design of a SWATH hullform and that of the machinery installation. A collection of machinery data at a level of detail sufficient for use by the SWATH designer has been incorporated in a machinery system design program.

This program has allowed the maximum powers which can be installed in the lower hulls of SWATH ships to be identified for a wide range of hull sections and machinery types. This indicates that high speed diesels and bare gas turbines may be installed in the hulls of typical SWATHs with displacements below 1000 tonnes. Lower hull mounted medium speed diesels are possible in vessels between 1000 and 2000 tonnes displacement. Geared AC motors become feasible about 1500 tonnes while modularised gas turbines may be fitted in SWATHs of 2000 tonnes.

Circular hulls allow greater powers for a given cross-sectional area than elliptical hulls for SWATH demihulls with sectional areas below 10m^2. For larger hulls, the situation is reversed, and non-circular hulls are the most efficient in terms of attainable power density.

It has also been shown that UK manufactured diesel engines offer considerably less power for a given hull size than the best European competitors. For high speed 'vee' engines the difference is of the order of 100% with associated speed penalties of the order of 5 knots. Restrictions on country of origin thus impose a significant constraint on designers of SWATH vessels for the Royal Navy .

Where they may be fitted, gas turbines provide the most power for a given hull size. It is not possible to fit modularised gas turbines in some smaller SWATHs where compact diesels may be fitted.

In a parametric study of 25 nominal SWATH hullforms it was found impossible to provide a sustained speed of 30 knots with a single lower hull mounted prime mover per shaft. This particular study indicates that different hullforms can influence sustained speed as much by their effect on the size of propulsion unit as by their resistance characteristics. In the 1000 to 5000 tonne size range considered, maximum speed effectively becomes limited by lower hull volume rather than machinery weight.

Within the assumptions and limits of size of the above study it is concluded that three routes are necessary if SWATH ships are to attain speeds in excess of 30 knots; more than one engine may be fitted in each of the lower hulls, prime movers may be fitted in the box and more slender hulls employed, and/or radically contoured hull designs may be used.

13.9 Structural Weight Estimation

The association between high structural weight fractions and SWATHs of low vehicle density is illustrated using published data, and the potential for error in the simple weight fraction method for estimating SWATH structural weight indicated. Most mild steel SWATH designs exhibit structural densities in the region of 100 kg/m^3.

An existing empirical approach has been extended to estimate underdeck slamming pressures for SWATH ships. This algorithm indicates wet deck slamming pressures between 0.1 and 0.5 MPa for a range of designs.

Application of simple beam theory in conjunction with magnification factors for shear lag and stress concentration has been found to give adequate estimates of the primary structural weight of struts and cross structure. The importance of transverse bulkhead spacing in structural weight determination is illustrated by example, and a collection of data is provided to assist preliminary structural arrangement.

A rational method for calculating the weight of circular pressure hulls has been adapted for SWATH ships and used to provide data to assist in estimating the weight of circular lower hulls of varying proportions.

A computer program employing these methods has been developed, and is considered to offer an accuracy of 10% in preliminary structural weight estimates.

Parametric studies of a family of SWATH ships have illustrated the importance of vehicle density and vessel slenderness in driving structural weight fractions. The related need to minimise enclosed volume, and employ 'stocky' struts can conflict with certain low density payloads and basic hydrodynamic considerations.

13.10 Weight and Space Balance

Accurate estimation of weights is fundamental to reliable SWATH ship design. A regression analysis has been performed on a collection of combatant and auxiliary ship data to derive a parametric weight estimating method. On average, this method predicts combatant 'lightship' (Groups 1 to 6) weights to within 4.5% of known values. A statistical analysis indicates that there is typically 95% confidence of predicting 'lightship' weights to within ±6.3%. It is suggested that this estimating tool be used with an assurance margin of 5%.

Despite the generally held view that SWATH is a weight limited concept, deck area and enclosed volume can be drivers of ship size in certain projected roles. Based on combatant data, a procedure for estimating the area and volume requirements of SWATH ships has been developed. This shows an average error of less than 6% when compared against the basis data.

A strong conflict between weight and spatial aspects has been identified in considering some nominal SWATH frigate designs. Below 4000 tonnes displacement, excess space and difficulty in providing adequate payload weight occurred, while above this size, inadequacy in terms of volume was observed. This illustrates the importance of care in selecting vehicle density to ensure balanced and efficient SWATH designs.

13.11 Interface with Graphics and Hydrodynamics Packages

Visualisation of the product is an important part of any design tool, and prediction of seakeeping performance is essential in SWATH design. To perform these functions, interfaces have been created between the synthesis model, the *INTERGRAPH* computer aided draughting system, and a three dimensional panel method for SWATH ship motions and load prediction. The provision of these facilities completes an automated route from an initial statement of vessel requirements through to production of drawings and seakeeping assessment.

13.12 Use of Design System

The design method described in this thesis has directly aided the development of the concept design of a SWATH ship, and a seakeeping analysis using three dimensional potential flow methods. In addition, the procedure has been employed in the design of a seagoing SWATH ship. Future model testing and full scale trials are projected as further validation of the design tool.

13.13 Future Work

The synthesis model described in this thesis is constructed in modular form so that alterations to individual areas of technology may readily be carried out. Improvements in flexibility and accuracy are possible in all areas of the program. Some of the more important areas for projected work may be described briefly.

The usefulness of the initial sizing program would be greatly increased if a simple space balance was introduced and distinctions made between ship type in the weight estimating routines. Modifications of the hull definition and resistance procedures to allow canted and flared struts to be considered are desirable, as is the extension of the propeller design package to consider contra-rotating propellers. In addition, a more satisfactory means of deriving self propulsion factors is required to improve the accuracy of the latter.

In the area of machinery design, aspects of mechanical and electrical drive from box mounted prime movers should also be studied to determine the parameters of major importance to the overall synthesis. Further work is necessary to quantify the strut dimensions associated with different machinery schemes. Periodic updates to the existing database of prime movers will be necessary in order to avoid obsolescence.

While advances in available hydrodynamic design tools are expected to be of a minor nature, structural design methods will benefit most noticeably from ongoing research. Replacement of the more empirical aspects of the current structural design method will improve the reliability of the structural weight estimates.

At present, the design system does not perform any optimisation functions, and all judgements as to design effectiveness require manual analysis of the computer output. It is considered that an automated scheme for grading designs according to some user defined measure of merit would add considerably to the value of the design tool.

The generality of the design method may also be enhanced by simply extending the scope of the empirical methods for weight and space estimation. In particular, this is required for the design of commercial vessels. Information to aid this task is readily available.

In common with other software tools, continuous maintenance and documentation is necessary. Support in these areas is essential if the program is to remain useful and intelligible to users.

13.14 Closure

This thesis has described research aimed at providing a practical SWATH design capability. By its use in design contracts and in a SWATH construction project, this work has contributed to the transfer of SWATH technology to industry.

It is hoped that this thesis will help to close a loop linking the design oriented work which initiated UK SWATH research in the late 1970s with the more theoretical hydrodynamics research programmes of the 1980s.

SWATH Fishing Vessel Under Construction, Glasgow, August 1988

APPENDIX 1

SWATH DESIGN DATABASE

The basic data used to derive many of the approximations presented in Chapters 2 and 4 of the thesis is presented in this Appendix. Details of the completed SWATH vessels *Duplus, Trisec1, Kaimalino, Marine Ace, Seagull, Kotozaki, Kaiyo, Ohtori, Suave Lino, Halcyon, Charwin, Chubasco, Marine Wave* and *Sun Marina* are listed together with those of *USS Victorious* (*T-AGOS19*), FBM's *FDC400*, Pacific Marine's *Navatek* ferry, and the Ocean Systems *2000 Class* SWATHs now building. This 'real' data is supplemented by a collection of proposed designs from various sources.

Each ship or design is identified by name or number (in the case of proposed designs). Intended role, name of the builder/designer and date of completion/ publication are also provided. If further information on a given design is required, original source material is indicated. The references for Appendix 1 are those listed in Chapter 2 of the thesis.

For each design, the leading dimensions (employing the definitions of Chapter 2) are tabulated. This includes the design displacement, and (where known), the total internal/enclosed volume of the vessel (referred to as EV) in m^3. This is followed by the performance of the vessel (in knots) and range (in nautical miles).

Type and performance of the propulsion plant are indicated next, followed by a description of the auxiliary systems, including fin control.

The geometry of the lower hulls and prismatic struts is listed. Hull longitudinal section (or 'shape') is described either as 'simple' or contoured. Strut arrangement is indicated by the the number of struts per hull and the presence (or otherwise) of an overhang aft.

Structural materials employed to fabricate the hulls, struts, box, and superstructure are indicated separately. This is followed by a listing of the natural periods of heave, pitch and roll if these are known.

Accommodation provided for crew and passengers is listed, followed by a description of the useful load. This may simply be payload in tonnes, or a description of fitted deck equipment, weapons, or other items. Finally, the weights of structure, machinery, outfit, auxiliaries, fuel, FW/stores, margins are given where known. The definitions of these weight groups are given in Chapter 4.

DESIGN IDENTIFICATION	Twin Drill #	TRISEC 1	Kaimalino	Marine Ace 1	Marine Ace 2	Seagull #
Vessel Role	Seabed Ops	Experimental	Workboat	Experimental	Experimental	Fast Ferry
Designer	J J Stenger	Litton Industry	Dr Tom Lang	Mitsui	Mitsui	Mitsui
Builder	Boele, Holland	Litton Industry	USCG	Mitsui	Mitsui	Mitsui
Date of Completion	1969 (1971)	1971	1973	Oct-77 #	1978 #	Sep-79
Sources (References)	10 11,12	13	14 to 23	26, 29, 39	26, 29, 39	24 to 26, 29, 39
DIMENSIONS						
Length Overall (m)	47	6.096	27.1	12.35	12.35	35.9
Length BP (m)			23.5	11	11	31.5
Breadth Overall (m)	17.06	2.44	14.17	6.5	6.5	17.1
Hull Centreline Spacing (m)	12.81		12.19	5.3	5.3	13.5
Depth to Main Deck (m)	10.89		9	2.7, 2.97 fwd	2.7, 2.97 fwd	7.7
Depth to Wet Deck (m)	8.17	1.219	6.55	2.3	2.3	5.845 min
Box Depth (m)	2.72		2.45	0.4	0.4	1.855 max
Design Draught (m)	5.5	0.6096	4.66	1.55	1.55	3.15
Max Scantling Draught (m)			4.95			3.8
Box Clearance (m)	2.67	0.6096	1.6	0.75	0.75	2.7, 2.05
Gross Registred Tonnage	690 (836)			29.9	31.56	670
Displacement (t)	**1200 (1490)**	**1.18**	**193, 224 #**	**18.4**	**22.2**	**343**
PERFORMANCE						
Maximum Speed (kts)	8	8	25 then 18	17.3	15.4	27.1
Cruise Speed (kts)	6-7		25 , 18 #			23
Range at Max (nm)	5000 @ 8kt		400 @ max			
Range at Cruise (nm)	7600 @ 6kt					
MACHINERY						
Prime Movers	2x694kW DGs	2 outboards	2xGT, 2 slospd	2 x gasoline	2 x gasoline	2 x HSD
Location	In box	Outboard aft	In box	On box	On box	In box
Transmission	Electrical to	Direct	Chain drive	Bevel drive	Bevel drive	Bevel drive
Gearing	2x630kW motor		Reduct on GT	3700:1380rpm	3700:1380rpm	1475:485rpm
Installed Power (hp)	1860	12	4200	400	400	8100
Slow Speed Power	1.03m CP Kort		330			
Propeller Type	350 rpm P/D.89	Outboard	1.98 CP 4blade	3 bladed FP	3 bladed FP	3 bladed FP
ELECTRICAL/SYSTEMS	16 kW					
Auxiliary Machinery	140 kW DG		2 x 200kVa	6.9kVa	6.9kVa	2 x 206kVa
Fin Control	2 large bracings	2 diag finruddr	Automatic	Automatic	Automatic	Automatic
STRUT ARRANGEMENT						
Strut Type	Long + sponson	Single, short	Twin, long	Twin, long	Single, long	Single, long
Strut Length (m)	40	4.88	7.01, 7.01	3.42, 3.89	@ 11.5	32.14
Strut Thickness (m)	3.05		1.35	0.57, 0.57	0.57	1.25
	(sponsons 1971)	2 x diagonal	Aw=22.95m^2			
Rudder Arrangement	On overhang	fin/rudders aft	On overhang	On overhang	On overhang	On overhang
LOWER HULL FORM						
Lower Hull Section	Shaped to struts	Octagonal	Circular	Elliptical	Elliptical	Elliptical
Lower Hull Shape	Simple	Simple	Simple	Simple	Simple	Simple
Hull Length (m)	40.36	6.096	22	10.47	10.47	30.85
Hull Breadth (m)	4.24	0.3048	1.98	1.24	1.24	2.95
Hull Depth (m)		0.3048	1.98	0.91	0.91	2.2
STRUCTURE						
Hull Material	Steel	Plywood	HTS	Aluminium	Aluminium	Aluminium
Strut Material	Steel	Plywood	HTS	Aluminium	Aluminium	Aluminium
Box Material	Steel	Plywood	Aluminium	Aluminium	Aluminium	Aluminium
SS Material	Steel	Plywood	Aluminium	Aluminium	Aluminium	Aluminium
NATURAL PERIODS						
T roll (s)	24.8 (9.5)		15.8	11.2	4.7	11.8
T pitch (s)	14.5 (11.5)		9.7	4.8	4.5	9.5
T heave (s)	10.8 (9.7)	2.8	8.6	5.5	3.9	6.2
ACCOMODATION						
Crew Size	37	2	45	20 inc pax.	20 inc pax.	7
Passengers				20 inc crew	20 inc crew	446
USEFUL LOAD						
Payload (t) / No. helos etc	75t derrick		25 or 34 t	20 persons	20 persons	446 pax.
Equipment Fit	18t crane moonpool sat dive system		inc. fuel	inc. crew	inc. crew	
WEIGHTS						
Structure (t)	lightship 951					
Propulsion (t)	deadweight 519					
Outfit (t)						
Auxiliary (t)						
Fuel (t)	250		19	320 gall.	320 gall.	14.8
FW/Stores etc (t)	120					
Margins (t)						
COST						
COMMENTS	# ex Jaramac 57 ex Duplus		# GRP blisters added	# Original ship twin strut	# Conversion single strut	# ex Mesa'80

DESIGN IDENTIFICATION	Ohtori	Kotozaki	Betsy #	Charwin	Kaiyo	Halcyon
Vessel Role	Hydrographic	Hydrographic	Sport Fishing	Scallop Fishing	Diving Support	Demonstration
Designer	Mitsubishi	Mitsui			Mitsui	RMI Inc.
Builder	Mitsubishi	Mitsui	Ocean Systems		Mitsui	RMI Inc.
Date of Completion	Dec-80	Dec-80	Jan-81	1983	Oct-84	Mar-85
Sources (References)	29	26, 29, 39, 44	37, 38, 64	41	26 to 28, 39	30 to 33
DIMENSIONS						
Length Overall (m)	27	27	19.2		61.55	18.29
Length BP (m)	24	25	16.8		53	
Breadth Overall (m)	12.5	12.5	9.1		28	9.14
Hull Centreline Spacing (m)		9.15				7.47
Depth to Main Deck (m)	5.1	6.7mx,5.51mn			13.25	4.27
Depth to Wet Deck (m)		4.6			10.6	3.51
Box Depth (m)		2.1, 0.91 #			2.65	0.76
Design Draught (m)	3.4	3.2	2.13 or 1.9		6.3	2.13
Max Scantling Draught (m)		3.5				
Box Clearance (m)		1.4, 1.1 min	0.7		4.3 or 3.35	1.38
Gross Registred Tonnage		250			2849	
Displacement (t)	239	236	39 light 49 FLD	@ 100	3500	43light, 57 deep
PERFORMANCE						
Maximum Speed (kts)		20.5			14.1	22.4
Cruise Speed (kts)	20.6	19	18		13.25	18
Range at Max (nm)						
Range at Cruise (nm)						600 @ 18kt
MACHINERY						
Prime Movers	2 x HSD	2 x HSD	2 x HSD		4x1380kW DG	2 x HSD
Location	In box	In box	On box		In box	On box
Transmission	Bevel drive	Bevel drive	Bevel drive		Electrical to 4	Belt drive
Gearing	1475:474rpm	1475:472rpm	2300:1121rpm		860kW motors	2100:700rpm
Installed Power (hp)	3800	3800	850		4613 propulsive	1020
Slow Speed Power						
Propeller Type	CP	1.75m CPP	1121rpm FPP		3.9m CP 150rpm	1.1m CPP
ELECTRICAL/SYSTEMS						
Auxiliary Machinery	130kVa,5kVa	120kVa,5kVa	50kW, 15kW		Integrated	2 x 25kW
Fin Control	Manual	Manual	Automatic		Manual	Automatic
STRUT ARRANGEMENT						
Strut Type	Single, long	Single, long	Single, long		Single, long	Long, flared
Strut Length (m)	34	25.6			55	16.78
Strut Thickness (m)	0.6	1.16 Aw=49.8m^2	0.33			Variable
Rudder Arrangement	On overhang	On overhang	On overhang		On overhang	On overhang
LOWER HULL FORM						
Lower Hull Section		Elliptical	Circular		Elliptical	Circular
Lower Hull Shape		Simple	Simple		Simple	Simple
Hull Length (m)		24.4			55.19	16.13
Hull Breadth (m)		2.44	1.168			1.524
Hull Depth (m)		2.07	1.168		5.81	1.524
STRUCTURE						
Hull Material	Steel	HTS	Aluminium		HTS	Aluminium
Strut Material	Steel	HTS	Aluminium		HTS	Aluminium
Box Material	Steel	Aluminium	Aluminium		HTS	Aluminium
SS Material	Aluminium	Aluminium	Aluminium		Steel	Aluminium
NATURAL PERIODS						
T roll (s)		10.7			18	
T pitch (s)		8.9			14	
T heave (s)		5.8			10.5	
ACCOMODATION						
Crew Size	20	4	4 bunks		29	3
Passengers		9 survey staff			40 extra	20
USEFUL LOAD						
Payload (t) / No. helos etc	20 personnel	41t cargo	14 t		260 t	5.3t plus
Equipment Fit	plus equipment				Sat dive system Moonpool 2 bells, cranes	20 passengers
WEIGHTS					1159t DWT	
Structure (t)						20.9
Propulsion (t)						7.4
Outfit (t)						5.1
Auxiliary (t)						7.6
Fuel (t)			3500 US gall.		446m^3	2.2
FW/Stores etc (t)			1.8t FW		36.8m^3 FW	0.2
Margins (t)					959m^3 WB	3.5
COST						
COMMENTS		# Quarter deck style of box	#ex SuaveLino		4x6.8t thrusters fwd, 4x4t aft	

DESIGN IDENTIFICATION	Marine Wave	Chubasco	Sun Marina	T-AGOS 19	FDC 400	
Vessel Role	Leisure/Demo	Yacht	Leisure/Demo	Surveillance	Fast Ferry	Interisland Ferry
Designer	Mitsui	Ocean Systems	Mitsui	NAVSEA	FBM Cowes	Pacific Marine
Builder	Mitsui	Ocean Systems	Mitsui	McDermotts	FBM Cowes	Vancouver, Wa.
Date of Completion	Jul-85	Mar-87	Feb-87	early 1990 #	Autumn 1989	1988/1989
Sources (References)	39, 45	38, 43	39	34, 35	40	36
DIMENSIONS				EV 16100 m^3		
Length Overall (m)	15.1	21.95	15.05	70.7	37	43
Length BP (m)	11.95		11.925	57.9		39.9
Breadth Overall (m)	6.2	9.45	6.4	28.65	13	16
Hull Centreline Spacing (m)	2.74		2.75	21.793		
Depth to Main Deck (m)				15.09		
Depth to Wet Deck (m)				11.506	4.9	
Box Depth (m)				3.584		
Design Draught (m)	1.6	2.13	1.6	7.54 or 8.01	2.7	2.4 - 3.7
Max Scantling Draught (m)						
Box Clearance (m)	0.81			3.966 or 3.5	2.2	
Gross Registred Tonnage	19					
Displacement (t)	**25.4**	**56 light 79 deep**		**3450**	**117 lite 172 deep**	365
PERFORMANCE						
Maximum Speed (kts)	18.2	20			30	
Cruise Speed (kts)	16	17		9.6		17
Range at Max (nm)					10 hours	
Range at Cruise (nm)	20 hours					1700 @ 17kt
MACHINERY						
Prime Movers	2 x HSD	2 x HSD	2 x HSD	4x835kW DG	2x16v MTU 396	2 x HSD
Location	In box		In box	In box	In box	
Transmission	Angled shafts		Angled shafts	Electrical to DC	Angled drive	
Gearing	2500:1231rpm		Universal joints	2x800hp motor	1940:600 rpm	
Installed Power (hp)	500	1500	600	1600 propulsive	5470	2700
Slow Speed Power					outward turning	
Propeller Type	FPP		FPP		3 bladed FPP	
ELECTRICAL/SYSTEMS						
Auxiliary Machinery	15kW DG			Integrated		2 x 99kW DGs
Fin Control	Automatic		Automatic	Stabiludders	No fins fitted	
STRUT ARRANGEMENT						
Strut Type	Long, raked	Single, long	Single, long	Single, short	Single, long	Twin
Strut Length (m)				57.78		
Strut Thickness (m)	0.458	0.813		2.75		
				Cw=0.782		
Rudder Arrangement	On overhang	On overhang	On overhang	Stabiludders	On overhang	On stinger
LOWER HULL FORM						
Lower Hull Section	Elliptical			Elliptical	Circular	Circular
Lower Hull Shape	Simple	Bulge fwd and		Contoured	Simple	Simple
Hull Length (m)	11.7	bulge aft		70.7		
Hull Breadth (m)	1.23			6.858		
Hull Depth (m)	0.89			5		
STRUCTURE						
Hull Material	GFRP/CFRP	Aluminium	GFRP/CFRP	Steel	All Aluminium	Steel
Strut Material	GFRP/CFRP	Aluminium	GFRP/CFRP	Steel	built in "planks"	Steel
Box Material	GFRP/CFRP	Aluminium	GFRP/CFRP	Steel	of plate + stiffnrs	Steel
SS Material	GFRP/CFRP	Aluminium	GFRP/CFRP	Steel	longl framed	Steel
NATURAL PERIODS						
T roll (s)	8.5					
T pitch (s)	6.5					
T heave (s)						
ACCOMODATION						
Crew Size	2	3		33		
Passengers	15	9			400	500
USEFUL LOAD						
Payload (t) / No. helos etc	15 pax.	9 passengers		130 t	400 pax + bagg	500 pax
Equipment Fit				SURTASS	(@ 90kg each)	
				sonar array		
				and winch		
WEIGHTS						
Structure (t)				1593	52	
Propulsion (t)				66.1		
Outfit (t)				236		
Auxiliary (t)				522		
Fuel (t)	2000 litres	5000 US gall.		638		
FW/Stores etc (t)	300 litres	500 US gall.				
Margins (t)				149		
COST				$ 25.4m (1988)	£ 4-4.5m 1988	$ 2m 1987
COMMENTS	Toray Industries		Japan Golf Promotions	# Now building	Designed for H1/3 3.5m	

DESIGN IDENTIFICATION	2000 Class					
Vessel Role	Survey					
Designer	Ocean Systems					
Builder	Ocean Systems					
Date of Completion	began Sept-1988					
Sources (References)	38					
DIMENSIONS						
Length Overall (m)	20.17					
Length BP (m)						
Breadth Overall (m)	9.91					
Hull Centreline Spacing (m)						
Depth to Main Deck (m)						
Depth to Wet Deck (m)						
Box Depth (m)						
Design Draught (m)	2.438					
Max Scantling Draught (m)						
Box Clearance (m)						
Gross Registred Tonnage						
Displacement (t)	**75 FLD**					
PERFORMANCE						
Maximum Speed (kts)	26.5					
Cruise Speed (kts)						
Range at Max (nm)						
Range at Cruise (nm)	1750					
MACHINERY						
Prime Movers	2 x HSD					
Location	In hulls					
Transmission	Direct					
Gearing						
Installed Power (hp)	2160					
Slow Speed Power						
Propeller Type						
ELECTRICAL/SYSTEMS						
Auxiliary Machinery						
Fin Control						
STRUT ARRANGEMENT						
Strut Type	Single, long					
Strut Length (m)						
Strut Thickness (m)						
Rudder Arrangement	On overhang					
LOWER HULL FORM						
Lower Hull Section	Circular					
Lower Hull Shape	Bulged aft					
Hull Length (m)						
Hull Breadth (m)						
Hull Depth (m)						
STRUCTURE						
Hull Material						
Strut Material						
Box Material						
SS Material						
NATURAL PERIODS						
T roll (s)						
T pitch (s)						
T heave (s)						
ACCOMODATION						
Crew Size	7					
Passengers						
USEFUL LOAD						
Payload (t) / No. helos etc	18t inc. consumables					
Equipment Fit						
WEIGHTS						
Structure (t)						
Propulsion (t)						
Outfit (t)						
Auxiliary (t)						
Fuel (t)						
FW/Stores etc (t)						
Margins (t)						
COST	$1.8m 1988					
COMMENTS	186m^2 deck area					

DESIGN IDENTIFICATION	1	2	3	4	5	6
Vessel Role/Name	*Patrol Boat*	*OPV*	*OPV*	*OPV*	*OPV*	*OPV*
Designer/Builder	RMI Inc	Vospers	Vospers	Fairey	US Coastguard	US Coastguard
Date of Publication	1985	1982	1985	1983	1982	1982
Sources (References)	32	47	48, 49	46	50, 51	50, 51
DIMENSIONS					EV=834m^3	EV=1682m^3
Length Overall (m)	22.86	44.25	56.2	16.8	26.1	35.7
Length BP (m)			49			
Breadth Overall (m)	9.14	20.3	23	7.8	10.9	15
Depth to Main Deck (m)	4.27		14.8			
Depth to Wet Deck (m)	3.51			3.7		
Box Depth (m)	0.76					
Design Draught (m)	2.13	7.1/5.1 harb	7.4	2.35	2.61	3.5
Box Clearance (m)	1.38	4.2		1.35		
Displacement (t)	**77.5**	**935**	**1600**	**48**	**125**	**254**
PERFORMANCE						
Maximum Speed (kts)	25	22.5	22	23.5-21	25	25
Cruise Speed (kts)	20	14		14	10	12
Range at Max (nm)				830 @ 20		
Range at Cruise (nm)	1000 @ 20 kts	3000 @ 14kt		1050 @ 14	1490 @ 10 kt	3260 @ 12 kt
MACHINERY						
Prime Movers	2 x HSD	2 x HSD	4 x HSD	2 x HSD	HSD	HSD
Location	On box	In hulls	In box	On box	Box	Box
Transmission	Belt drive	Direct drive	Bevel drive	Belt drive	Bevel drive	Bevel drive
Gearing	On motors	In hulls	In hulls	In hulls		
Installed Power (hp)		16650		1300	3350	5364
Slow Speed Power						
Propeller Type	CPP		FPP		CPP	CPP
ELECTRICAL/SYSTEMS						
Auxiliary Machinery	2 x DGs	3 x 260kW		2 x 15kW		
Fin Control	Automatic	Automatic		Automatic		
STRUT ARRANGEMENT						
Strut Type	Long, flared	Short, haunch	Long, haunch	Long, haunch	Long, haunch	Long, haunch
Strut Length (m)	21.35	37	49		23.9	34
Strut Thickness (m)		1.35		0.535	0.5	0.6
Rudder Arrangement	On overhang	On pod aft	On overhang	On overhang	On overhang	On overhang
LOWER HULL FORM						
Lower Hull Section	Circular	Circular	Circular	Circular	Circular	Circular
Lower Hull Shape	Simple	Simple+bulge	Simple	Simple	Simple	Simple
Hull Length (m)	20.7				23.6	31.4
Hull Breadth (m)	1.5				1.9	2.4
Hull Depth (m)	1.5				1.9	2.4
STRUCTURE						
Hull Material	Aluminium	Steel		Steel	Aluminium	Aluminium
Strut Material	Aluminium	Steel		Steel	Aluminium	Aluminium
Box Material	Aluminium	Steel		Aluminium	Aluminium	Aluminium
SS Material	Aluminium	Aluminium		Aluminium	Aluminium	Aluminium
NATURAL PERIODS						
T roll (s)		16		9.2		
T pitch (s)		14.5		7		
T heave (s)		8.5		4.7		
ACCOMODATION						
Complement	12	45		9	14	29
Passengers						
USEFUL LOAD						
Payload (t) / No. helos etc	Light helo	Lynx, 2xRBI	2 x Seaking	Inflatable	4.7 inc 2 RBI	8.4 inc 2 RBI
Weapons Fit/Special Items	20mm gun 7.62mm MG 0.7t ammo.	76mm gun 2 x 20mm	76mm, CIWS 2x20mm 8 Harpoon	MGs		2 x 20mm
WEIGHTS						
Structure (t)	33.7				44.6	78.6
Propulsion (t)	9.7				19.7	31.3
Outfit (t)	7.9				10.1	27.9
Auxiliary (t)	8.7				22.4	42.6
Weapons (t)	0.7+1.1 helo					
Fuel (t)	11.8+1.4 helo	140+13 helo		8	10.7	33.8
FW/Stores etc (t)	0.3	20			5.58	12.09
Margins (t)					10.6	20.6
COST						

DESIGN IDENTIFICATION	7	8	9	10	11	12
Vessel Role/Name	OPV	OPV	Patrol Craft	OPV	Fast Attack	Corvette
Designer/Builder	US Coastguard	US Coastguard	Fairey Marine	BAZAN	BAZAN	UCL
Date of Publication	1982	1982	1985	1985	1985	1985
Sources (References)	50, 51	50, 51	52	53	53	55
DIMENSIONS	EV=5991m^3	Ev=8994m^3				
Length Overall (m)	50.3	59	23.2	43.45	33.2	66
Length BP (m)			21			
Breadth Overall (m)	20.7	25.6	11.15	22.68	17.87	20
Depth to Main Deck (m)			5.4	12.17		
Depth to Wet Deck (m)			4.45			
Box Depth (m)			0.95			
Design Draught (m)	5	5.9	2.7	5.67	3.67	6.3
Box Clearance (m)			1.75		3.5	4
Displacement (t)	**765**	**1270**	**125**	**914**	**393**	**1950**
PERFORMANCE						
Maximum Speed (kts)	25	25	23.5 - 20	25	33	22
Cruise Speed (kts)	13	15	14	15		15
Range at Max (nm)			830 @ 20 kts		700 @ 33 kt	
Range at Cruise (nm)	3800 @ 13 kt	5700 @ 15 kt	1050 @ 14 kts	6400 @ 15 kt		4000 @ 15kt
MACHINERY						
Prime Movers	HSD	HSD	2 x HSD	2 x HSD	2 x HSD	2 x Tyne GTE
Location	Box	Box	Hull bulge	In hulls		In box
Transmission	Bevel drive	Bevel drive	Direct drive	Direct drive		Electrical
Gearing			In hulls	On motors		
Installed Power (hp)	13400	21450	2400	16650	12000	10730
Slow Speed Power						3x200hp DG
Propeller Type	CPP	CPP		CPP		
ELECTRICAL/SYSTEMS						
Auxiliary Machinery				4 x DGs		
Fin Control				Automatic		
STRUT ARRANGEMENT						
Strut Type	Long, haunch	Long, haunch	Long, haunch	Long, bulged	Long	Long, haunch
Strut Length (m)	48.1	56.8	21			
Strut Thickness (m)	0.9	1		2.05		
Rudder Arrangement	On overhang	On overhang	On overhang	On overhang	On overhang	On overhang
LOWER HULL FORM						
Lower Hull Section	Circular	Circular	Circular	Circular	Circular	Circular
Lower Hull Shape	Simple	Simple	Simple+bulge	Simple+bulge	Simple	Simple
Hull Length (m)	44.4	52.5	20.58		33.2	
Hull Breadth (m)	3.4	4	1.61	3.8	2.62	
Hull Depth (m)	3.4	4	1.61/2.17	3.8	2.62	
STRUCTURE						
Hull Material	Aluminium	Aluminium	Steel	Steel	HTS+MS stiffs	Steel
Strut Material	Aluminium	Aluminium	Steel	HTS	HTS plate+MS	MS/HTS
Box Material	Aluminium	Aluminium	Steel	HTS	MS/HTS	MS/HTS
SS Material	Aluminium	Aluminium	Aluminium	Aluminium	Aluminium	GRP
NATURAL PERIODS						
T roll (s)			9.2			
T pitch (s)			7			
T heave (s)			4.7			
ACCOMODATION						
Complement	65	90	12			75
Passengers						
USEFUL LOAD						
Payload (t)	20.5 inc 2 hel	26.7 inc 2 hel	Searider RBI	Lynx helo		Seaking, TA
Weapons Fit	2 x 20mm	2 x 20 mm	20mm gun	8SSM, 76mm 2 x 40mm	8 SSM 1 x 76mm	57mm, Chaff 2x20mm 2xSTWSII
WEIGHTS						
Structure (t)	257.5	408.3		267		800
Propulsion (t)	87.7	170.2		87		
Outfit (t)	61.4	94.99		129		
Auxiliary (t)	129.5	179.6		50		
Weapons (t)				40		
Fuel (t)	115.8	241.3		280		
FW/Stores etc (t)	30.17	41.76				
Margins (t)	61.6	111.05				
COST						£50m (1983)

DESIGN IDENTIFICATION	*13*	*14*	*15*	*16*	*17*	*18*
Vessel Role/Name	*ASW Frigate*	*Heavy Frigate*	*Crew Boat*	*Excursion Boat*	*Offshore Crew*	*Crew Change*
Designer/Builder	UCL	UCL	RMI Inc	RMI Inc	Aker	SSSCO
Date of Publication	1985	1985	1985	1985	1981	1980
Sources (References)	55	55	33	33	85	
DIMENSIONS						
Length Overall (m)	92	107	18.3	18.3	52	72.85
Length BP (m)						
Breadth Overall (m)	30	30	9.1	9.1	28	28.35
Depth to Main Deck (m)			4.27	4.27	16	
Depth to Wet Deck (m)			3.51	3.51		
Box Depth (m)			0.76	0.76		
Design Draught (m)	9	9.5	2.13	2.13	7.3	
Box Clearance (m)	4.3	4.6	1.38	1.38		
Displacement (t)	**5500**	**6500**	**57.9**	**57.9**	**1500**	**1865**
PERFORMANCE						
Maximum Speed (kts)	28	28	20+	20	26	35
Cruise Speed (kts)	18	18	18	12	20	
Range at Max (nm)						
Range at Cruise (nm)	4500 @ 18kt	5000 @ 18kt	375 @ 18kt	165 @ 18kt		
MACHINERY						
Prime Movers	4 x Spey GTE	4 x Spey GTE	2 x HSD	2 x HSD	2 x GT	
Location	In box	In box	On box	On box	In hulls	
Transmission	Electrical	Electrical to	Belt drive	Belt drive		
Gearing		AC motors	On motors	On motors		
Installed Power (hp)	64400	64400	1020	1020	28000	46000
Slow Speed Power	5340 Tyne GT	2x2680hp DG				
Propeller Type	generator	+ DC motor	CRP	CRP		
ELECTRICAL/SYSTEMS						
Auxiliary Machinery						
Fin Control			Automatic	Automatic		
STRUT ARRANGEMENT						
Strut Type	Long, haunch	Long, haunch	Long, flared	Long, flared	Twin	Twin
Strut Length (m)			16.78	16.78		
Strut Thickness (m)			Varying	Varying		
Rudder Arrangement	On overhang	On overhang	On overhang	On overhang		On overhang
LOWER HULL FORM						
Lower Hull Section	Circular	Circular	Circular	Circular		
Lower Hull Shape	Simple	Simple	Simple	Simple		
Hull Length (m)			16.13	16.13		
Hull Breadth (m)			1.5	1.5		
Hull Depth (m)			1.5	1.5		
STRUCTURE						
Hull Material			Aluminium	Aluminium		
Strut Material			Aluminium	Aluminium		
Box Material			Aluminium	Aluminium		
SS Material			Aluminium	Aluminium		
NATURAL PERIODS						
T roll (s)						
T pitch (s)						
T heave (s)						
PERSONNEL						
Complement	300	280	3	3		
Passengers			20	60	400	
USEFUL LOAD						
Payload (t)	3 Seaking, TA	3 Seaking, TA	5.4 + 20 pax	60 pax	400 pax+bagg	
Weapons Fit	76mm, Chaff 8 Exocet 2x30mm	76mm, Chaff 8 Harpoon 36 Seawolf				
WEIGHTS						
Structure (t)			22.8	27.6		
Propulsion (t)			8	8		
Outfit (t)			7	8.7		
Auxiliary (t)			8.1	7.7		
Weapons (t)						
Fuel (t)			4	1.3		
FW/Stores etc (t)			0.3	0.3		
Margins (t)						
COST	£130m (1983)	£145m (1983)				

DESIGN IDENTIFICATION	19	20	21	22	23	24
Vessel Role/Name	Oceanographic	Multi Purpose	Offshore Crew	Supply/Support	GSV	Pax Ferry
Designer/Builder	SSSCO	SSSCO	SSSCO	SSSCO	SSSCO	SSSCO
Date of Publication	1985	1985	1985	1985	1985	1985
Sources (References)	6	6	6	6	6	6
DIMENSIONS						
Length Overall (m)	75.29	19.5	40.23	90.53	66.14	47.55
Length BP (m)						
Breadth Overall (m)	28.96	10.67	16.76	40.84	25.6	19.8
Depth to Main Deck (m)						
Depth to Wet Deck (m)						
Box Depth (m)						
Design Draught (m)				10.6		
Box Clearance (m)						
Displacement (t)	**2534**	**60**	**230**	**5695**	**1514**	**280**
PERFORMANCE						
Maximum Speed (kts)	15.9	15.18	25	15.4	15.5	25
Cruise Speed (kts)						
Range at Max (nm)						
Range at Cruise (nm)						
MACHINERY						
Prime Movers						
Location		In hulls				
Transmission						
Gearing						
Installed Power (hp)	4446	600	4447	7577	3076	4640
Slow Speed Power						
Propeller Type						
ELECTRICAL/SYSTEMS						
Auxiliary Machinery						
Fin Control						
STRUT ARRANGEMENT						
Strut Type	Twin	Twin				
Strut Length (m)						
Strut Thickness (m)						
Rudder Arrangement						
LOWER HULL FORM						
Lower Hull Section	Circular					
Lower Hull Shape	Simple					
Hull Length (m)						
Hull Breadth (m)						
Hull Depth (m)						
STRUCTURE						
Hull Material						
Strut Material						
Box Material						
SS Material						
NATURAL PERIODS						
T roll (s)						
T pitch (s)						
T heave (s)						
ACCOMODATION						
Complement						
Passengers						
USEFUL LOAD						
Payload (t) / No. helos etc						
Weapons Fit/Special Items						
WEIGHTS						
Structure (t)						
Propulsion (t)						
Outfit (t)						
Auxiliary (t)						
Weapons (t)						
Fuel (t)						
FW/Stores etc (t)						
Margins (t)						
COST						

DESIGN IDENTIFICATION	25	26	27	28	29	30
Vessel Role/Name	Car Ferry	Support Ship	Crew Change	Military	V/STOL Carrier	Medium ASW
Designer/Builder	Wartsila	McClure	SSSCO	NUC	DTNSRDC	DTNSRDC
Date of Publication	1985	1973	1985	1971	1972	1974
Sources (References)	82	83	6, 90	73	75	74
DIMENSIONS						
Length Overall (m)		60.96	74.7	96.01	155.45	91.44
Length BP (m)			67.8			
Breadth Overall (m)		38.4	27.1	41.76	48.77	29.26
Depth to Main Deck (m)		26.21	15.2	16.46		
Depth to Wet Deck (m)		23.16	9.76	12.8		
Box Depth (m)		3.05	5.44	3.65		7.01 (2 decks)
Design Draught (m)		10.67/4.27	6.1	8.53/6.4		10.21
Box Clearance (m)		12.49	3.66	4.27		
Displacement (t)	**3000**	**2890**	**2032**	**3050**	**16053**	**5669**
PERFORMANCE						
Maximum Speed (kts)	16		38	35		25+
Cruise Speed (kts)	16	14	35	25, 10		
Range at Max (nm)				3000 @ 25kt		Relative values
Range at Cruise (nm)		9400 @ 14 kt	1000 @ 35kt	15000 @ 10kt		Baseline is 1.0
MACHINERY						
Prime Movers		Diesels	Gas turbines	2 x GT		Gas turbines
Location	On box	In hulls	In hulls	In hulls		In hulls
Transmission		Direct drive	Direct drive	Direct drive		Direct drive
Gearing						Planetary
Installed Power (hp)	4695	6000	54000	50000		
Slow Speed Power			2x3000hp DG	2 x GT#		
Propeller Type		In nozzles	CRP	CRP		
ELECTRICAL/SYSTEMS						
Auxiliary Machinery		2 x 250kW AC	2x1500hp DG	Same # 2xGT		
Fin Control			Manual/Auto			
STRUT ARRANGEMENT						
Strut Type	Long	Twin, raked	Twin	Twin, short	Short, flared	Short
Strut Length (m)		12.19, 12.19		19.81, 19.81		60.96
Strut Thickness (m)		3.05, 3.05		1.53, 1.53		2.652
Rudder Arrangement		Movable nozzle	On overhang	Flap on strut		
LOWER HULL FORM						
Lower Hull Section		Flat -circular		Circular	Elliptical	Circular
Lower Hull Shape	Simple	Simple		Simple		Simple
Hull Length (m)		60.96		96.01		91.44
Hull Breadth (m)		6.4		4.27		5.82
Hull Depth (m)		4.88		4.27		5.82
STRUCTURE						
Hull Material				Aluminium		Steel
Strut Material				Aluminium		Steel
Box Material				Aluminium		Steel/Al upper
SS Material				Aluminium		Aluminium?
NATURAL PERIODS						
T roll (s)						
T pitch (s)						
T heave (s)						
ACCOMODATION						
Complement			23	150 (316 max)		267
Passengers	500		400			
USEFUL LOAD						
Payload (t) / No. helos etc	500 pax +	650	240 + 400 pax	546 inc crew	18 helos plus	483 + 5 helos
Weapons Fit/Special Items	trailers/cars		Can land helo	Different Fits inc V/STOL	5 V/STOL	
WEIGHTS						
Structure (t)				1220		
Propulsion (t)		S, P, O & A		110		
Outfit (t)		are 1826t		91.5+116.2		
Auxiliary (t)				396		
Weapons (t)				72 + extras		In payload, as
Fuel (t)		203	200	460		is C&C weight
FW/Stores etc (t)			20			
Margins (t)						
COST						

DESIGN IDENTIFICATION	31	32	33	34	35	36
Vessel Role/Name	Medium ASW	Medium ASW	Medium ASW	Medium ASW	Small Escort	Small Escort
Designer/Builder	DTNSRDC	DTNSRDC	DTNSRDC	DTNSRDC	DTRC/Navsec	DTRC/Navsec
Date of Publication	1974	1974	1974	1974	1974	1974
Sources (References)	74	74	74	74	74	74
DIMENSIONS						
Length Overall (m)	93.88	91.44	93.88	91.44	59.13	65.84
Length BP (m)						
Breadth Overall (m)	29.26	29.26	29.26	29.26	28.65	28.65
Depth to Main Deck (m)						
Depth to Wet Deck (m)						
Box Depth (m)	7.01 (2 decks)	7.01 (2 decks)	7.01 (2 decks)	7.01 (2 decks)	7.01 (2 decks)	7.01 (2 decks)
Design Draught (m)	10.15	10.21	10.15	9.27	7.28	7.44
Box Clearance (m)						
Displacement (t)	**5730**	**5669**	**5730**	**4724**	**2093**	**2073**
PERFORMANCE						
Maximum Speed (kts)	23.75	25+	23.75	26.75	35 +	35 +
Cruise Speed (kts)						
Range at Max (nm)	See entry 30	See entry 30	See entry 30	See entry 30	See entry 37	See entry 37
Range at Cruise (nm)	Rel. Value 0.48	Rel. value 1.58	Rel. value 0.78	Rel. value 1.01	Rel. value 0.67	Rel. value 0.6
MACHINERY						
Prime Movers	Gas turbines	Gas turbines	Gas turbines	Gas turbines		
Location	In hulls	In hulls	In hulls	In hulls	In box	In box
Transmission	Direct drive	Direct drive	Direct drive	Direct drive	Bevel drive	Bevel drive
Gearing	Planetary	Planetary	Planetary	Planetary		
Installed Power (hp)						
Slow Speed Power						
Propeller Type						
ELECTRICAL/SYSTEMS						
Auxiliary Machinery						
Fin Control						
STRUT ARRANGEMENT						
Strut Type	Twin, short	Short	Twin, short	Short	Short	Twin, short
Strut Length (m)	24.38, 27.43	60.96	24.38, 27.43	54.86	47.55	15.85, 15.85
Strut Thickness (m)	2.99, 2.99	2.652	2.9, 2.99	2.652	1.98	1.98, 1.98
Rudder Arrangement						
LOWER HULL FORM						
Lower Hull Section	Circular	Circular	Circular	Circular	Circular	Circular
Lower Hull Shape	Simple	Simple	Simple	Simple	Simple	Simple
Hull Length (m)	93.88	91.44	93.88	91.44	59.13	65.84
Hull Breadth (m)	5.79	5.82	5.79	5.31	4.24	4.27
Hull Depth (m)	5.79	5.82	5.79	5.31	4.24	4.27
STRUCTURE						
Hull Material	Steel	Aluminium	Aluminium	Aluminium	Aluminium	Aluminium
Strut Material	Steel	Aluminium	Aluminium	Aluminium	Aluminium	Aluminium
Box Material	Steel/Al upper	Aluminium	Aluminium	Aluminium	Aluminium	Aluminium
SS Material	Aluminium	Aluminium	Aluminium	Aluminium	Aluminium	Aluminium
NATURAL PERIODS						
T roll (s)						
T pitch (s)						
T heave (s)						
ACCOMODATION						
Complement	267	267	267	267	118	118
Passengers						
USEFUL LOAD						
Payload (t) / No. helos etc	483 + 5 helos	483 + 5 helos	483 + 5 helos	483 + 5 helos	152 + 2 helos	152 + 2 helos
Weapons Fit/Special Items						
WEIGHTS						
Structure (t)						
Propulsion (t)						
Outfit (t)						
Auxiliary (t)						
Weapons (t)	In payload, as	In payload, as	In payload, as	In payload, as		
Fuel (t)	is C&C weight	is C&C weight	is C&C weight	is C&C weight		
FW/Stores etc (t)						
Margins (t)						
COST						

DESIGN IDENTIFICATION	37	38	39	40	41	42
Vessel Role/Name	Small Escort	Small Escort	Small Escort	Coast Defence	Coast Defence	STOL Support
Designer/Builder	DTRC/Navsec	DTRC/Navsec	DTRC/Navsec	NOSC/T. Lang	NOSC/T. Lang	NOSC/T. Lang
Date of Publication	1974	1974	1974	1974	1975	1974
Sources (References)	74	74	74			
DIMENSIONS						
Length Overall (m)	72.54	72.54	72.54			82.4
Length BP (m)						
Breadth Overall (m)	24.38	24.38	24.38			39
Depth to Main Deck (m)						20.73
Depth to Wet Deck (m)						13.72
Box Depth (m)	7.01 (2 decks)	7.01 (2 decks)	7.01 (2 decks)			7.01 (2 decks)
Design Draught (m)	6.92	7.32	7.32			9.45
Box Clearance (m)						4.27
Displacement (t)	**2123**	**2408**	**2438**	**508**	**1219**	**3048**
PERFORMANCE						
Maximum Speed (kts)	35 +	32.9	32.9	35	35	35
Cruise Speed (kts)				22	22	
Range at Max (nm)	Relative value	See entry 37	See entry 37			
Range at Cruise (nm)	Baseline is 1.0	Rel. value 0.97	Rel. value 0.97	1220 @ 22kt	2100 @ 22kt	
MACHINERY						
Prime Movers						
Location	In box	In box	In box			
Transmission	Bevel drive	Bevel drive	Bevel drive			
Gearing						
Installed Power (hp)						
Slow Speed Power						
Propeller Type						
ELECTRICAL/SYSTEMS						
Auxiliary Machinery						
Fin Control						
STRUT ARRANGEMENT						
Strut Type	Short	Short	Short	Twin, raked	Twin, raked	Twin, raked
Strut Length (m)	55.47	55.47	55.47			17.37, 17.37
Strut Thickness (m)	1.52	1.83	1.83			
Rudder Arrangement						Flap on struts
LOWER HULL FORM						
Lower Hull Section	Circular	Circular	Circular	Circular	Circular	Circular
Lower Hull Shape	Simple	Simple	Simple			Contoured ends
Hull Length (m)	72.54	72.54	72.54			80.36
Hull Breadth (m)	3.96	4.21	4.21			5.18
Hull Depth (m)	3.96	4.21	4.21			5.18
STRUCTURE						
Hull Material	Aluminium	Aluminium	Aluminium	Aluminium		Aluminium
Strut Material	Aluminium	Aluminium	Aluminium	Aluminium		Aluminium
Box Material	Aluminium	Aluminium	Aluminium	Aluminium		Aluminium
SS Material	Aluminium	Aluminium	Aluminium	Aluminium		Aluminium
NATURAL PERIODS						
T roll (s)						
T pitch (s)						
T heave (s)						
ACCOMODATION						
Complement	118	118	118			
Passengers						
USEFUL LOAD						
Payload (t) / No. helos etc	152 + 2 helos	152 + 2 helos	163 + 3 helos	66	152	
Weapons Fit/Special Items						
WEIGHTS						
Structure (t)				168 inc 15% margin		1006 inc 15% margin
Propulsion (t)						
Outfit (t)						
Auxiliary (t)						
Weapons (t)						
Fuel (t)						
FW/Stores etc (t)						
Margins (t)						
COST						

DESIGN IDENTIFICATION	43	44	45	46	47	48
Vessel Role/Name	STOL Support	Cruise Liner	Fast Ferry	AMCM	MCM	Optimum MCM
Designer/Builder	NOSC/T. Lang	Wartsila	Lang/SSSCO	USN/Kennell	USN/Kennell	USN/Kennell
Date of Publication	1974	1985	1985	1978	1978	1978
Sources (References)		57	6	91	91	91
DIMENSIONS						
Length Overall (m)		165	103	97.54	79.25	79.25
Length BP (m)						
Breadth Overall (m)		62	39.5	28.04	22.86	23.47
Depth to Main Deck (m)		34 to Boat Dk	25.8			
Depth to Wet Deck (m)						
Box Depth (m)						
Design Draught (m)				10.67	7.32	8.23
Box Clearance (m)						
Displacement (t)	**3556**		**3200**	**5869**	**2718**	**2718**
PERFORMANCE						
Maximum Speed (kts)	35					
Cruise Speed (kts)		16	25			
Range at Max (nm)						
Range at Cruise (nm)						
MACHINERY						
Prime Movers		2x2 diesels				
Location		In hulls				
Transmission		Direct drive				
Gearing		Combining gear				
Installed Power (hp)		16888				
Slow Speed Power						
Propeller Type						
ELECTRICAL/SYSTEMS						
Auxiliary Machinery						
Fin Control						
STRUT ARRANGEMENT						
Strut Type	Twin, raked	Single, haunch		Short	Short	Short
Strut Length (m)						
Strut Thickness (m)				3.05 Cw = 0.71	1.98 Cw = 0.85	2.93 Cw = 0.76
Rudder Arrangement	Flap on struts					
LOWER HULL FORM						
Lower Hull Section	Circular	Elliptical		Circular	Circular	Circular
Lower Hull Shape	Contoured ends	Simple		Simple/Cp 0.74	Simple/Cp 0.85	Simple/Cp 0.69
Hull Length (m)				97.54	79.25	79.25
Hull Breadth (m)				5.94	4.36	4.63
Hull Depth (m)				5.94	4.36	4.63
STRUCTURE						
Hull Material						
Strut Material						
Box Material						
SS Material						
NATURAL PERIODS						
T roll (s)						
T pitch (s)						
T heave (s)						
ACCOMODATION						
Complement						
Passengers			600			
USEFUL LOAD						
Payload (t) / No. helos etc			130 vehicles			
Weapons Fit/Special Items			plus 600 pax.			
WEIGHTS						
Structure (t)						
Propulsion (t)						
Outfit (t)						
Auxiliary (t)						
Weapons (t)						
Fuel (t)						
FW/Stores etc (t)						
Margins (t)						
COST						

DESIGN IDENTIFICATION	49	50	51	52	53	54
Vessel Role/Name	*"Ship A"*	*"Ship B"*	*"Escort C"*	*Fast Attack*	*Fast Attack*	*Fast Attack*
Designer/Builder	USN/Aronne	USN/Aronne	USN/Aronne	BAZAN	BAZAN	BAZAN
Date of Publication	1974	1974	1974	1985	1985	1985
Sources (References)	89	89	89	53	53	53
DIMENSIONS						
Length Overall (m)	85.95	85.95	85.95	33.2	33.2	33.2
Length BP (m)						
Breadth Overall (m)	27.43	28.96	27.43	15.1	18.56	
Depth to Main Deck (m)	20.73	20.12	21.18			
Depth to Wet Deck (m)	15.55	14.33	14.17			
Box Depth (m)	5.18	5.79	7.01			
Design Draught (m)	9.75	9.75	9.85	3.28	4.18	
Box Clearance (m)	5.79	4.57	4.32	3.5	3.5	
Displacement (t)	4064	4572	5334	335	470	480
PERFORMANCE						
Maximum Speed (kts)				33	33	33
Cruise Speed (kts)						
Range at Max (nm)				400 @ 33kt	500 @ 33kt	
Range at Cruise (nm)						
MACHINERY						
Prime Movers				2 x GT	2 x GT	2 x Diesels
Location						
Transmission						
Gearing						
Installed Power (hp)				10200	14340	
Slow Speed Power						
Propeller Type						
ELECTRICAL/SYSTEMS						
Auxiliary Machinery						
Fin Control						
STRUT ARRANGEMENT						
Strut Type	Short	Short	Short	Long	Long	Long
Strut Length (m)	68.58	68.88	54.86			
Strut Thickness (m)	2.44	2.44	2.65			
Rudder Arrangement				On overhang	On overhang	On overhang
LOWER HULL FORM						
Lower Hull Section	Circular	Circular	Circular	Circular	Circular	Circular
Lower Hull Shape	Simple	Simple	Simple	Simple	Simple	Simple
Hull Length (m)	85.95	85.95	85.95	33.2	33.2	
Hull Breadth (m)	5.33	5.33	5.64	2.3	2.77	
Hull Depth (m)	5.33	5.33	5.64	2.3	2.77	
STRUCTURE						
Hull Material				MS stiffs+HTS	MS stiffs+HTS	MS stiffs+HTS
Strut Material				MS+HTS plate	MS+HTS plate	MS+HTS plate
Box Material				MS,HTS(wtdk)	MS,HTS(wtdk)	MS,HTS(wtdk)
SS Material				Aluminium	Aluminium	Aluminium
NATURAL PERIODS						
T roll (s)						
T pitch (s)						
T heave (s)						
ACCOMODATION						
Complement						
Passengers						
USEFUL LOAD						
Payload (t) / No. helos etc						
Weapons Fit/Special Items				8 x SSM 1 x 76mm gun	8 x SSM 1 x 76mm gun	8 x SSM 1 x 76mm gun
WEIGHTS						
Structure (t)	Structural wts	Structural wts	Structural wts			180
Propulsion (t)	Steel 2136	Al. 1096	HTS 1662			93
Outfit (t)	HTS 1965	HTS/Al. 1476	HTS/Al. 1527			57
Auxiliary (t)	HY100 2068	HTS 1843	Al. 872			22
Weapons (t)						28
Fuel (t)						
FW/Stores etc (t)						
Margins (t)						
COST						

DESIGN IDENTIFICATION	55	56	57	58	59	60
Vessel Role/Name	Leisure Craft	ASW Frigate	ASW Frigate	ASW Frigate	ASW Frigate	Dive Support
Designer/Builder	Mitsui	DREA/swacem	DREA/swacem	DREA/swacem	DREA/swacem	Wartsila/Worley
Date of Publication	1985	1985	1985	1985	1985	1985
Sources (References)	42	81	81	81	81	70
DIMENSIONS						
Length Overall (m)	19.95	95.82	102.47	108.53	115.77	87
Length BP (m)	17					
Breadth Overall (m)	9	31.32	29.05	30.17	27.39	58
Depth to Main Deck (m)	5.75					29.35
Depth to Wet Deck (m)	3.43					22.6
Box Depth (m)	2.32					6.75
Design Draught (m)	2.2	8.82	8.6	9.01	8.88	15.85
Box Clearance (m)	1.23					6.25
Displacement (t)		**5029**	**5125**	**5189**	**5317**	**17490**
PERFORMANCE						
Maximum Speed (kts)	17	30	30	30	30	10
Cruise Speed (kts)	16					
Range at Max (nm)						
Range at Cruise (nm)						30 days +
MACHINERY						
Prime Movers	2 x HSD					6 x DGs
Location	In box					2x3MWazimuth
Transmission						and 6x1.32MW
Gearing	On motors					thruster units
Installed Power (hp)	1580	69711	75965	62464	63092	6 x 3326 hp
Slow Speed Power						
Propeller Type						2 azimuth units
ELECTRICAL/SYSTEMS						
Auxiliary Machinery	2 x 48kW AC					1x675kW gen DP system
Fin Control						
STRUT ARRANGEMENT						
Strut Type	Long	Short	Long	Short	Long	Twin
Strut Length (m)		72.83	93.42	82.49	105.82	
Strut Thickness (m)		2.74	2.74	2.74	2.74	
Rudder Arrangement	On overhang		On overhang		On overhang	Azimuth units
LOWER HULL FORM						
Lower Hull Section		Circular	Circular	Circular	Circular	
Lower Hull Shape	Simple	Simple	Simple	Contoured	Contoured	Simple
Hull Length (m)	17.5	95.82	95.82	108.53	108.53	87
Hull Breadth (m)		5.32	5.32	5.79	5.79	12
Hull Depth (m)	1.29	5.32	5.32	5.79	5.79	
STRUCTURE						
Hull Material	FRP					Steel
Strut Material	FRP					Steel
Box Material	FRP					Steel
SS Material	FRP					Steel
NATURAL PERIODS						
T roll (s)						
T pitch (s)						
T heave (s)						
ACCOMODATION						
Complement	6					120 total
Passengers	2, & 6 guests					
USEFUL LOAD						
Payload (t) / No. helos etc	8 pax	1438 inc fuel etc	1404 inc fuel etc	1354 inc fuel etc	1143 inc fuel etc	1000 VarDkLd
Weapons Fit/Special Items						2x100t & 1x50t cranes, 24 man sat. system, 2 bells, 2 moonpl
WEIGHTS						
Structure (t)		2087	2163	2351	2648	
Propulsion (t)		437	472	405	420	
Outfit (t)		1066 inc Aux.	1087 inc Aux	1079	1106	
Auxiliary (t)		In Outfit	In Outfit	In Outfit	In Outfit	
Weapons (t)						
Fuel (t)	12000 litres					1500m^3
FW/Stores etc (t)	1000 litres FW					300m^3
Margins (t)						
COST						

DESIGN IDENTIFICATION	61	62	63	64	65	66
Vessel Role/Name	Cargo Vessel	Military	CG Cutter	CG Cutter	Patrol Boat	Surveillance
Designer/Builder	RM I Inc.	RMI Inc.	Lockheed	Lockheed	Lockheed	Lockheed
Date of Publication	1983	1983	1986	1986	1986	1986
Sources (References)	94	94	78, 84	78, 84	78, 84	78, 84
DIMENSIONS						
Length Overall (m)	96.96	109.1	44.5	42.67	44.5	66.45
Length BP (m)						
Breadth Overall (m)	31.7	37.2	20.12	16.76	20.12	27.74
Depth to Main Deck (m)						
Depth to Wet Deck (m)						
Box Depth (m)						
Design Draught (m)		9.3				
Box Clearance (m)						
Displacement (t)	3400	5512	511	502	515	2200
PERFORMANCE						
Maximum Speed (kts)	37	40.1	25	20/25	25/30	11
Cruise Speed (kts)			11	8		3 (towing)
Range at Max (nm)		1000 @ 40kt				
Range at Cruise (nm)			4000 @ 11kt	3800 @ 8kt		12400 nm
MACHINERY						
Prime Movers				Gas turbine		
Location						
Transmission						
Gearing						
Installed Power (hp)	75000	131414				
Slow Speed Power	5000			Diesel		
Propeller Type						
ELECTRICAL/SYSTEMS						
Auxiliary Machinery						
Fin Control						
STRUT ARRANGEMENT						
Strut Type			Canted, single	Single, haunch	Single, haunch	
Strut Length (m)						
Strut Thickness (m)						
Rudder Arrangement			Stabilizers	On overhang	On overhang	
LOWER HULL FORM						
Lower Hull Section				Circular	Circular	
Lower Hull Shape			Curved	Simple	Simple	
Hull Length (m)						
Hull Breadth (m)						
Hull Depth (m)						
STRUCTURE						
Hull Material			Aluminium	Aluminium		
Strut Material			Aluminium	Aluminium		
Box Material			Aluminium	Aluminium		
SS Material			Aluminium	Aluminium		
NATURAL PERIODS						
T roll (s)						
T pitch (s)						
T heave (s)						
ACCOMODATION						
Complement			30	31	30	30
Passengers						
USEFUL LOAD						
Payload (t) / No. helos etc	370	1000-dubious				
Weapons Fit/Special Items						
WEIGHTS						
Structure (t)						
Propulsion (t)						
Outfit (t)						
Auxiliary (t)						
Weapons (t)						
Fuel (t)		1069				
FW/Stores etc (t)						
Margins (t)						
COST						

DESIGN IDENTIFICATION	67	68	69	70	71	72
Vessel Role/Name	OPT Ferry	Oceano/hydrog	Hydrog Survey	Workboat	Workboat	Frigate
Designer/Builder	Lockheed	Lockheed	Lockheed	DTNSRDC	DTNSRDC	NAVSEA
Date of Publication	1986	1986	1986	1975	1975	1985
Sources (References)	78, 84	78, 84	78, 84			71, 72
DIMENSIONS						Ev=23135m^3
Length Overall (m)	42.67	74.98	19.8	47.24	60.96	115.82
Length BP (m)						94.49
Breadth Overall (m)	16.76	28.04	9.14	16.764	17.98	27.43
Depth to Main Deck (m)				12.04	12.95	
Depth to Wet Deck (m)				8.69	9.6	
Box Depth (m)				3.35	3.35	
Design Draught (m)				5.03	5.91	10.67 max
Box Clearance (m)				3.66	3.69	
Displacement (t)	**525**	**3800**	**70**	**798**	**1307**	**7183**
PERFORMANCE						
Maximum Speed (kts)	27	16	20	15	20	25
Cruise Speed (kts)				15	20	
Range at Max (nm)						
Range at Cruise (nm)	430	8000	500 +			
MACHINERY						
Prime Movers						2 x GTE
Location						In box
Transmission						Electrical
Gearing						(65040hp total)
Installed Power (hp)						48500 propuls
Slow Speed Power						
Propeller Type						
ELECTRICAL/SYSTEMS						
Auxiliary Machinery						4x1.5MW DG
Fin Control						
STRUT ARRANGEMENT						
Strut Type		Single, haunch		Short	Short	Short, haunch
Strut Length (m)				34.14	39.89	94.5
Strut Thickness (m)				1.676	1.676	
Rudder Arrangement		On overhang				Cw=0.73
LOWER HULL FORM						
Lower Hull Section				Circular	Circular	Obround
Lower Hull Shape				Simple	Simple	Hi contoured
Hull Length (m)				47.24	60.96	115.82
Hull Breadth (m)				2.9	3.38	
Hull Depth (m)				2.9	3.38	Cp=0.68
STRUCTURE						
Hull Material						
Strut Material						
Box Material						
SS Material						
NATURAL PERIODS						
T roll (s)				19.5	20.7	
T pitch (s)				12.5	17.4	
T heave (s)				6.6	8.5	
ACCOMODATION						
Complement	7	50/64	2/4			
Passengers	300					
USEFUL LOAD						
Payload (t) / No. helos etc	300 pax + helo					69 mission load
Weapons Fit/Special Items						2xhelo,CIWS TA,Gun,SSM ECM,2TT,Sonr
WEIGHTS						
Structure (t)						2403
Propulsion (t)						462
Outfit (t)						452
Auxiliary (t)						1290
Weapons (t)						145
Fuel (t)						1060+71(helo)
FW/Stores etc (t)						111 misc loads
Margins (t)						702 (15% light)
COST						

DESIGN IDENTIFICATION	73	74	75	76	77	78
Vessel Role/Name	Geophysical	Geophysical	Geophysical	Dive Support	Rapid Interven	Dive Support
Designer/Builder	McClure	McClure	McClure	Mitsui	SSSCO/BS	SSSCO/BS
Date of Publication	1984	1984	1984			
Sources (References)	61	61	61	69	86	86
DIMENSIONS						
Length Overall (m)	74	55	51		74.5	93.3
Length BP (m)				67		
Breadth Overall (m)	32	32	31	28	27	40.1
Depth to Main Deck (m)				13.9	15.2	
Depth to Wet Deck (m)						
Box Depth (m)						
Design Draught (m)	4.6/8.5 max	4.3/8.5 max	3.7/7.0max	7.3		10.6
Box Clearance (m)	Vessels have variable draught					
Displacement (t)	**3570/4380**	**2990/3550**	**1549/1903**		**2100**	**6000**
PERFORMANCE						
Maximum Speed (kts)	15	14	12	18.6	25	16
Cruise Speed (kts)	15	14	12		16	16
Range at Max (nm)						
Range at Cruise (nm)	60 days	30 days	30 days			
MACHINERY						
Prime Movers	2xDGs	2xDGs	2 x diesels	8x1.12kW DG		
Location	In hulls	In hulls	In hulls	Electrical		
Transmission	DC converting	DC converting	Direct	5x2320kW		
Gearing	in box	in box				
Installed Power (hp)	7800	5000	2100	12000		
Slow Speed Power						
Propeller Type						
ELECTRICAL/SYSTEMS						
Auxiliary Machinery	9300 kW	5600 kW	520 kW	Integrated ?		
Fin Control						
STRUT ARRANGEMENT						
Strut Type				Long	Twin	Twin
Strut Length (m)				69		
Strut Thickness (m)						
Rudder Arrangement						
LOWER HULL FORM						
Lower Hull Section					Circular	Circular
Lower Hull Shape				Simple	Simple	Simple
Hull Length (m)						
Hull Breadth (m)						
Hull Depth (m)						
STRUCTURE						
Hull Material						
Strut Material						
Box Material						
SS Material						
NATURAL PERIODS						
T roll (s)						
T pitch (s)						
T heave (s)						
ACCOMODATION						
Complement				29		
Passengers				36 researchers		
USEFUL LOAD						
Payload (t) / No. helos etc				900t +36 pax		
Weapons Fit/Special Items						
WEIGHTS						
Structure (t)						
Propulsion (t)						
Outfit (t)						
Auxiliary (t)						
Weapons (t)						
Fuel (t)	1000	680	280			
FW/Stores etc (t)	40	200	30			
Margins (t)						
COST						

DESIGN IDENTIFICATION	79	80	81	82	83	84
Vessel Role/Name	Crew Change	Hi-Spd Ferry	Island Ferry	Island Ferry	Pax Ferry	Pax Ferry
Designer/Builder	SSSCO/BS	SSSCO/BS	SEACO	Fairey Marine	Mitsubishi	Pacific Marine
Date of Publication				1987	1986	1987
Sources (References)	86	86	67	68	103	36
DIMENSIONS						
Length Overall (m)	74.5	103	54.9	35.7	36.5	39.9
Length BP (m)						
Breadth Overall (m)	27.1	39.5	30.48	15	17.2	15.55
Depth to Main Deck (m)	15.2	26.8		5.8	6.2	
Depth to Wet Deck (m)	11.9					
Box Depth (m)	3.3					
Design Draught (m)	6.7		4.88	2.7	3.5	2.4-3.7
Box Clearance (m)	5.2					
Displacement (t)	**2100**	**3200**	**900**	**320**	**430**	**365**
PERFORMANCE						
Maximum Speed (kts)	38	20-25		14	22	
Cruise Speed (kts)	35	20-25	18	14		17
Range at Max (nm)						
Range at Cruise (nm)	500-1000/7day					1700 @ 17
MACHINERY						
Prime Movers			Diesels	Diesels		2 x diesels
Location			In hulls	In hulls		
Transmission				Direct		
Gearing						
Installed Power (hp)	52000					2700
Slow Speed Power						
Propeller Type						
ELECTRICAL/SYSTEMS						
Auxiliary Machinery						
Fin Control				Auto/manual		
STRUT ARRANGEMENT						
Strut Type	Twin	Twin	Twin, short	Long	Long	Twin
Strut Length (m)						
Strut Thickness (m)						
Rudder Arrangement						On stinger
LOWER HULL FORM						
Lower Hull Section	Circular	Circular	Circular	Square	Elliptical	Circular
Lower Hull Shape	Simple	Simple	Simple		Simple	Simple
Hull Length (m)			54.9	2.6		
Hull Breadth (m)			3.05	2.6		
Hull Depth (m)						
STRUCTURE						
Hull Material						Mild Steel
Strut Material						Mild Steel
Box Material						Mild Steel
SS Material						Mild Steel
NATURAL PERIODS						
T roll (s)						
T pitch (s)						
T heave (s)						
ACCOMODATION						
Complement						
Passengers	400	600		100		500
USEFUL LOAD						
Payload (t) / No. helos etc	40. + 400 pax	130 cars				500 pax.
Weapons Fit/Special Items		600 pax.		100 pax, + cars	600 pax	
WEIGHTS						
Structure (t)						
Propulsion (t)						
Outfit (t)						
Auxiliary (t)						
Weapons (t)						
Fuel (t)	200					
FW/Stores etc (t)	20					
Margins (t)						
COST						$ 2m (1987)

DESIGN IDENTIFICATION	85	86	87	88	89	90
Vessel Role/Name	Leisure	Crew Boat	Cruise Liner	AC Carrier	Patrol Boat	ASW Frigate
Designer/Builder	Mitsui	PAMESCO	Wartsila	DTNSRDC	US CG	UCL
Date of Publication	1986	1983	1983	1983	1982-86	1986
Sources (References)	54	63	57	87	58, 77	59
DIMENSIONS				Ev=68717m^3		EV=24500m^3
Length Overall (m)	22	24.38	163	140.8	42.4	107
Length BP (m)	19			128		
Breadth Overall (m)	10.2	13.26	53	44.8	18.3	28
Depth to Main Deck (m)	6.2			26.33		18.6
Depth to Wet Deck (m)				17.16		12.8
Box Depth (m)				9.17		5.8
Design Draught (m)	2.4	3.66	9 to 11	11.58	4.4	7.9
Box Clearance (m)				5.58		4.9
Displacement (t)	**195 GRT**	**160**		**15067**	**600**	**5470**
PERFORMANCE						
Maximum Speed (kts)	17		16	28	20	28
Cruise Speed (kts)	15	19	16	a) 20, b) 15	12 - 14	
Range at Max (nm)						
Range at Cruise (nm)	45hrs ?	530 @ 19kt		7500a, 9000b	3000@12-14kt	60 days patrol
MACHINERY						
Prime Movers	2 x diesels	2 x MTU diesel	2xPielstick	3LM2500 GTE		2x(GT, ACgen)
Location	In/on box		In hulls	(60MW) In box		In hulls
Transmission			Direct	Electrical		Direct+AC/DC
Gearing						CODLAG
Installed Power (hp)	1580	3120	16912	77000 propulsv		46667 propulsv
Slow Speed Power						9387 (DC mtrs)
Propeller Type				FP,80-85RPM		6m,FP,140rpm
ELECTRICAL/SYSTEMS						
Auxiliary Machinery	2 x 40 kW	2 x 40kW		3 x 4MW		4 x 1.5MW
Fin Control	Automatic	Manual				7m^2 fwd 21m^2 aft
STRUT ARRANGEMENT						
Strut Type	Long	Twin, short	Long	Long, canted	Long	Short
Strut Length (m)	17.68			126.17		92
Strut Thickness (m)				3.55		3.3 Cw=0.76
Rudder Arrangement	On overhang	On 'stinger'		On overhang		'Submarine'
LOWER HULL FORM						
Lower Hull Section	Elliptical	Square		Circular	Circular	Elliptical
Lower Hull Shape	Simple	Contoured		Contoured	Simple	Contoured
Hull Length (m)	17.3			124.59	36.5	107
Hull Breadth (m)				8.93/4.51	3	6.6
Hull Depth (m)				8.93/4.51	3	4.4 (Cp=0.74)
STRUCTURE						
Hull Material	FRP	Mild Steel	Mild Steel	Mild Steel		Mild Steel
Strut Material	FRP	Mild Steel	Mild Steel	Mild Steel		Mild Steel
Box Material	FRP	Aluminium	Mild Steel	Mild Steel		Mild Steel
SS Material	FRP	Aluminium	Mild Steel	Mild Steel		Mild Steel
NATURAL PERIODS						
T roll (s)						12-15
T pitch (s)						14-16
T heave (s)						9-11
ACCOMODATION						
Complement		3		690	30	206
Passengers		50	1500,704cabins			
USEFUL LOAD						
Payload (t) / No. helos etc Weapons Fit/Special Items		50 pax	1500 pax in 704 cabins 6700m^2 public rooms	17 aircraft (helo, VSTOL) VL SAM Phalanx CIWS	HH65aDolphin helo. 2x12.7mm MG grenade launchr	360t, inc 2 helo (EH101),76mm VL Seawolf, SEagl,Stingray
WEIGHTS						
Structure (t)		25.3Al,53.1MS		6297		Lightship 4372
Propulsion (t)		38.2		649		674
Outfit (t)		11.6		934		(S+P+O=2474)
Auxiliary (t)		3.2		2280		Electrical 390
Weapons (t)				267		Personnel 184
Fuel (t)		4000 US gall.		2455		Services 287
FW/Stores etc (t)		Lightship 131.4		304		Vari Load 791
Margins (t)				1113		Sol Ball 310
COST						£138.3m 1987

DESIGN IDENTIFICATION	91	92	93	94	95	96
Vessel Role/Name	*Workover*	*Ocean Survey*	*Oceanographic*	*Oceanographic*	*Oceanographic*	*Car Ferry*
Designer/Builder	Worley	David Kaysen			RaythonSSSCO	CETENA
Date of Publication	1984	1985	1985	1985	1982	1984
Sources (References)	70	88			62	60
DIMENSIONS		Ev=42758m^3				
Length Overall (m)	96.5	116.1	75.3	61.6		50
Length BP (m)		106.7			64.93	43
Breadth Overall (m)	47.8	31.7	29	31.7	26.52	25.5
Depth to Main Deck (m)	27.8	21.34				12.5
Depth to Wet Deck (m)		14.02			11.59	8.5
Box Depth (m)		7.32				4
Design Draught (m)	14.25 or 7	9.45	7.3	7.93	6.71	5
Box Clearance (m)		4.57			4.88	3.5
Displacement (t)	**13400**	**12786**	**2530**	**3270**	**1473**	**1250**
PERFORMANCE						
Maximum Speed (kts)	12				14	35
Cruise Speed (kts)		20@80%MCR				
Range at Max (nm)					5000 @ 14kt	440 @ 35kt
Range at Cruise (nm)		1500nm+34day				
MACHINERY						
Prime Movers		6x4000kW DG	DG	DG	4 x550kW DG	4 x LM500 GT
Location		In box				In hulls
Transmission		Electric- 2x2	Electrical	Electrical	84% electric	Direct
Gearing		motors in hulls				
Installed Power (hp)		17500 propuls	3488	6084	2953 total	20000
Slow Speed Power						
Propeller Type		FP contrartatng			Shrouded FP	195rpm3.45CP
ELECTRICAL/SYSTEMS		Integrated				
Auxiliary Machinery		4500kW			Integrated	3 x 120kW
Fin Control		Fixed fins			Automatic	
STRUT ARRANGEMENT						
Strut Type		Long, offsetCL	Twin	Twin	Twin, short	Long
Strut Length (m)		106.7			19.8, 19.8	
Strut Thickness (m)		3.33			1.98, 1.98	
Rudder Arrangement		On overhang			Spade from box	On overhang
LOWER HULL FORM						
Lower Hull Section		Rectangular			Circular	Obround
Lower Hull Shape		Bulged amid			Simple	Simple
Hull Length (m)		116.8				42.81
Hull Breadth (m)		9.39				4.5
Hull Depth (m)		7.87				3
STRUCTURE						
Hull Material		Steel	Steel	Mild Steel	Steel	Steel
Strut Material		Steel	Steel	Mild Steel	Steel	Steel
Box Material		Steel	Steel	Mild Steel	Aluminium	Steel
SS Material		Steel	Aluminium	Mild Steel	Aluminium	Aluminium
NATURAL PERIODS						
T roll (s)						
T pitch (s)						
T heave (s)						
ACCOMODATION						
Complement		58 plus	60	53	29	
Passengers		30USN,20scie			25 scientists	780
USEFUL LOAD						
Payload (t) / No. helos etc		20 scientists	900	920	25 scientists	780 pax
Weapons Fit/Special Items		30 USN pax. Widescan sonar			Comprehensive survey outfit	130 cars
WEIGHTS						
Structure (t)		4090				
Propulsion (t)		1390				
Outfit (t)		772				
Auxiliary (t)		1467				
Weapons (t)						
Fuel (t)		3692			228	50
FW/Stores etc (t)		52.8+127				
Margins (t)		1158				
COST						

DESIGN IDENTIFICATION	*97*	*98*	*99*	*100*	*101*	*102*
Vessel Role/Name	*Car Ferry*	*Pass Ferry*	*VISTOL*	*Fishing*	*Fishing*	*Pass. Ferry*
Designer/Builder	CETENA	HHI Korea	USN	SEACO	SEACO	FaireyMarintek
Date of Publication	1984	1988	1979	1978	1978	1988
Sources (References)	60	65	76	66	66	40
DIMENSIONS						
Length Overall (m)	36	19.2		29.26	34.14	36.5
Length BP (m)	32	17.2				
Breadth Overall (m)	20.5	9.2	39	15.85	18.9	
Depth to Main Deck (m)	12.3	4.5				
Depth to Wet Deck (m)		3.8				
Box Depth (m)		0.7				
Design Draught (m)	4.8	2.3	14.02			
Box Clearance (m)		1.5				
Displacement (t)	**900**	**71**	**30480**	**305**	**457**	
PERFORMANCE						
Maximum Speed (kts)	30	21.8	26	16	17	28
Cruise Speed (kts)				14	15	
Range at Max (nm)	440 @ 30kt					
Range at Cruise (nm)				2000 @ 14kt	4000 @ 15kt	
MACHINERY						
Prime Movers	2 x LM500 GT	2 x HSD	4 x GT			2xMTU16V396
Location	In hulls	On box				
Transmission		Bevel drive				
Gearing						
Installed Power (hp)	10000	2090	120000			4190
Slow Speed Power						
Propeller Type			4 propellers			FP
ELECTRICAL/SYSTEMS						
Auxiliary Machinery						
Fin Control						
STRUT ARRANGEMENT						
Strut Type	Long	Long		Short	Short	
Strut Length (m)		17.7				
Strut Thickness (m)		0.6 Cw = 0.787				
Rudder Arrangement	On overhang	On overhang		On strut	On strut	
LOWER HULL FORM						
Lower Hull Section	Obround	Circular		Circular	Circular	Semi-SWATH
Lower Hull Shape	Simple	Simpl,Cp0.822		Simple	Simple	arrangement
Hull Length (m)		17.2		29.26	34.14	of struts and
Hull Breadth (m)		1.6				hulls
Hull Depth (m)		1.6				
STRUCTURE						
Hull Material	Steel	Aluminium				
Strut Material	Steel	Aluminium				
Box Material	Steel	Aluminium				
SS Material	Aluminium	Aluminium				
NATURAL PERIODS						
T roll (s)						
T pitch (s)						
T heave (s)		5.3				
ACCOMODATION						
Complement			1585	8	12	
Passengers	400	150				500
USEFUL LOAD						
Payload (t) / No. helos etc	400 pax. and 60 cars	150 pax.	24 aircraft	142		500 pax.
Weapons Fit/Special Items						
WEIGHTS						
Structure (t)						
Propulsion (t)						
Outfit (t)						
Auxiliary (t)						
Weapons (t)						
Fuel (t)						
FW/Stores etc (t)						
Margins (t)						
COST						

DESIGN IDENTIFICATION	103	104	105	106	107	108
Vessel Role/Name	*Sonar Support*	*Sonar Support*	*Ocean Research*	*MultPrp OcRes*	*Tow-Salvage*	*Cheap Frigate*
Designer/Builder	YSL/UoG	MoD DGFMP	NAVSEA	NAVSEA	NAVSEA	NAVSEA
Date of Publication	1987	1987	May-86	1986	1986	1985
Sources (References)	79, 96	80, 96	56	56	56	56
DIMENSIONS	Ev=9229m^2	Ev=7885m^3				
Length Overall (m)	66	61.8				
Length BP (m)						
Breadth Overall (m)	26	25.2				
Depth to Main Deck (m)	14.3	13				
Depth to Wet Deck (m)	10.4	9.5				
Box Depth (m)	3.9	3.5				
Design Draught (m)	7.4	6.5				
Box Clearance (m)	3	3				
Displacement (t)	**2415**	**2330**	**2208**	**5119**	**6987**	**5055**
PERFORMANCE						
Maximum Speed (kts)	14.2	15.1				
Cruise Speed (kts)	8 and 3 (tow)	8 and 3 (tow)				
Range at Max (nm)	5000 @ 12kt	6560 @ 14kt				
Range at Cruise (nm)	7700 @ 8 kt	10200 @ 8kt				
MACHINERY						
Prime Movers	4 x 1MW DG	4 x 1.3MW DG	Diesel	Diesel+DG	Diesel	Diesel
Location	On box (in SS)	In box				
Transmission	Electric to DC	Electric to DC	Mechanical	Mech/Electrical	Mechanical	Mechanical
Gearing	mtrs 2x1.4MW	mtrs 2x1.5MW				
Installed Power (hp)	5364 total &	6770 total &	2400	12000	17000	24000
Slow Speed Power	3758 propulsiv	4027 propulsiv		1000 electrical		
Propeller Type	3.05m dia FP	3.42mFP,5bld				
ELECTRICAL/SYSTEMS						
Auxiliary Machinery	Integrated	Integrated				
		660kW SS load				
Fin Control	Fixed fins					
STRUT ARRANGEMENT						
Strut Type	Short	Short	Short	Short	Short	Short
Strut Length (m)	51	50.4				
Strut Thickness (m)	2.7	2.4				
	Cw = 0.75	Cw = 0.81				
Rudder Arrangement	On strut	Stabiliudders				
LOWER HULL FORM						
Lower Hull Section	Obround	Elliptical				
Lower Hull Shape	Simpl.Cp0.815	Coke, Cp0.592	Contoured		Contoured	Contoured
Hull Length (m)	66	61.8				
Hull Breadth (m)	4.7	6.8				
Hull Depth (m)	3.6 (radii 1.5)	4.4				
STRUCTURE						
Hull Material	Mild Steel	Mild Steel				
Strut Material	Mild Steel	Mild Steel				
Box Material	Mild Steel	Mild Steel				
SS Material	Mild Steel	Mild Steel				
NATURAL PERIODS						
T roll (s)	15	18				
T pitch (s)	19	14				
T heave (s)	8.8	9.7				
ACCOMODATION						
Complement	24	24	60	63	106	158
Passengers						
USEFUL LOAD						
Payload (t) / No. helos etc	VD Sonar 60t	VD Sonar 60t				
Weapons Fit/Special Items						
WEIGHTS						
Structure (t)	1056	1056				
Propulsion (t)	145	132				
Outfit (t)	148	196				
Auxiliary (t)	266	265				
Weapons (t)						
Fuel (t)	400	236				
FW/Stores etc (t)	65	60				
Margins (t)	270	325				
COST	£25.5m (1987)					

DESIGN IDENTIFICATION	109	110	111	112	113	114
Vessel Role/Name	Escrt HeliCarr	Heli Cruiser	Vari Role AC	Car Ferry	T-AGS	Pax Ferry
Designer/Builder	NAVSEA	NAVSEA	NAVSEA	IKO Concepts	NAVSEA	HHI/KIMM
Date of Publication	1986	1986	1986	1988	1988	1988
Sources (References)	56	56	56	99	100	98
DIMENSIONS						
Length Overall (m)	212			82	85.04	27.1
Length BP (m)						23.6
Breadth Overall (m)	32.3			25	31.27	12.4
Depth to Main Deck (m)	NB Can transit					5.3
Depth to Wet Deck (m)	Panama Canal					4.3
Box Depth (m)						1
Design Draught (m)				5		2.6
Box Clearance (m)	5.18					1.7
Displacement (t)	**24739**	**28042**	**35255**		**5425**	**132**
PERFORMANCE						
Maximum Speed (kts)					12	25.3
Cruise Speed (kts)					12	
Range at Max (nm)						
Range at Cruise (nm)					53 days	
MACHINERY						
Prime Movers	Gas turbines	GT gensets	Diesel		2x2MW DGs	2 x HSD
Location						On box
Transmission		Electrical			Electric to DC	Bevel drive
Gearing					motors (2 off)	1650:580
Installed Power (hp)	60000	135000	200000		5000 propulsive	2560
Slow Speed Power						
Propeller Type				Tractor thrusters		
ELECTRICAL/SYSTEMS						
Auxiliary Machinery					Integrated	
Fin Control						7m^2 aft, 2m^2
STRUT ARRANGEMENT						
Strut Type	Short	Short	Short	Single	Single, short	Single, long
Strut Length (m)	173					24.6
Strut Thickness (m)						0.8
Rudder Arrangement						On overhang
LOWER HULL FORM						
Lower Hull Section				Semi SWATH	Circular	Circular
Lower Hull Shape		Contoured		Contoured	Contoured	Simple
Hull Length (m)	212			82		23.6
Hull Breadth (m)						1.8
Hull Depth (m)						1.8
STRUCTURE						
Hull Material				Steel		Aluminium
Strut Material				Steel		Aluminium
Box Material				Steel		Aluminium
SS Material				Composite		Aluminium
NATURAL PERIODS						
T roll (s)						
T pitch (s)						
T heave (s)						
ACCOMODATION						
Complement	667 plus	1161	1250			
Passengers	2050 troops			400		254
USEFUL LOAD						
Payload (t) / No. helos etc				400 pax plus		254 pax
Weapons Fit/Special Items				260 cars or 24x18m trailers		
WEIGHTS						
Structure (t)						
Propulsion (t)						
Outfit (t)						
Auxiliary (t)						
Weapons (t)						
Fuel (t)						
FW/Stores etc (t)						
Margins (t)						
COST						$2-3m 1986

DESIGN IDENTIFICATION	115	116	117	118	119	120
Vessel Role/Name	Ferry	Crewboat	Patrol Boat	Research	Cruise	VISTOL
Designer/Builder	SSSCO	SSSCO	SSSCO	SSSCO	SSSCO	SSSCO
Date of Publication	1988	1988	1988	1988	1988	1988
Sources (References)	95	95	95	95	95	95
DIMENSIONS						
Length Overall (m)	30.5	22.5	46.9	75.3	75.3	91.4
Length BP (m)						
Breadth Overall (m)	16.1	16.1	17.7	29	29	32
Depth to Main Deck (m)						
Depth to Wet Deck (m)						
Box Depth (m)						
Design Draught (m)	3.4	3.4	4.3	7.3	7.3	7.9
Box Clearance (m)						
Displacement (t)	225	225	500	2500	2500	4500
PERFORMANCE						
Maximum Speed (kts)	28.5	28.5	22	17.3	17.2	35
Cruise Speed (kts)	25	25	20	16.4	16.4	25
Range at Max (nm)						
Range at Cruise (nm)	630	630	9600	16000	4300	5600
MACHINERY						
Prime Movers						
Location						
Transmission						
Gearing						
Installed Power (hp)	5195	5195	5400	6200	6200	60000
Slow Speed Power						
Propeller Type						
ELECTRICAL/SYSTEMS						
Auxiliary Machinery						
Fin Control						
STRUT ARRANGEMENT						
Strut Type	Twin	Twin	Twin	Twin	Twin	Twin
Strut Length (m)						
Strut Thickness (m)						
Rudder Arrangement	On overhang	On overhang			On overhang	
LOWER HULL FORM						
Lower Hull Section	Circular	Circular				
Lower Hull Shape	Simple	Simple			Contoured	
Hull Length (m)						
Hull Breadth (m)						
Hull Depth (m)						
STRUCTURE						
Hull Material						
Strut Material						
Box Material						
SS Material						
NATURAL PERIODS						
T roll (s)						
T pitch (s)						
T heave (s)						
ACCOMODATION						
Complement	10	8	26	25	100	150
Passengers	500	250		35	250	
USEFUL LOAD						
Payload (t) / No. helos etc	0	20	2x30mm, 1 helo	100	250 pax	500
Weapons Fit/Special Items	500 pax	250 pax	2 x Searider	35 scientists		
WEIGHTS						
Structure (t)						
Propulsion (t)						
Outfit (t)						
Auxiliary (t)						
Weapons (t)						
Fuel (t)						
FW/Stores etc (t)						
Margins (t)						
COST	$5m 1988	$4.5m 1988	$10m 1988	$36.5m 1988	$40.4m 1988	$60m 1988

DESIGN IDENTIFICATION	121	122	123	124	125	126
Vessel Role/Name	Pilot Tender	Cruise Liner	Passenger Ship	Helo Carrier	Harrier carrier	Corvette
Designer/Builder	Ocean Systems	Glasgow Univ	UCL	UCL	UCL	UCL
Date of Publication	1988	1988	1987	1982	1985	1986
Sources (References)	96	97	103	103	103	103
DIMENSIONS						
Length Overall (m)	30.5	144				
Length BP (m)		141	165	80	129	66
Breadth Overall (m)	15.5	62.5	40.5	34	38	24
Depth to Main Deck (m)		31.5				
Depth to Wet Deck (m)		21.5				
Box Depth (m)		10				
Design Draught (m)		16 or 9.6	10.5	11	10.8	7
Box Clearance (m)		5.5				
Displacement (t)	**245**	**41609/33137**	**39800**	**9250**	**14100**	**2245**
PERFORMANCE						
Maximum Speed (kts)		22.2	18	25	27	20
Cruise Speed (kts)		18				
Range at Max (nm)						
Range at Cruise (nm)		7800				
MACHINERY						
Prime Movers	Diesels	6 x MSD	Diesels	Gas turbines	Diesels + GTs	Diesels
Location		In box	In hulls	In hulls	In hulls	Box
Transmission		Electric	Direct	Direct	Direct	Bevel Drive
Gearing		2 motors				
Installed Power (hp)		70500				
Slow Speed Power						
Propeller Type						
ELECTRICAL/SYSTEMS						
Auxiliary Machinery						
Fin Control						
STRUT ARRANGEMENT						
Strut Type		Single, long				
Strut Length (m)		143	165	80	129	66
Strut Thickness (m)		5				
Rudder Arrangement		On overhang				
LOWER HULL FORM						
Lower Hull Section		Obround				
Lower Hull Shape		Simple				
Hull Length (m)		141	194	105	134	66
Hull Breadth (m)		16				
Hull Depth (m)		8				
STRUCTURE						
Hull Material	Steel	Steel				
Strut Material	Steel	Steel				
Box Material	Steel	Steel				
SS Material	Aluminium	Steel				
NATURAL PERIODS						
T roll (s)						
T pitch (s)						
T heave (s)						
ACCOMODATION						
Complement						
Passengers		1200				
USEFUL LOAD						
Payload (t) / No. helos etc		1200 pax				
Weapons Fit/Special Items		2000t inc stores pax, effects				
WEIGHTS						
Structure (t)		18504				
Propulsion (t)		2543				
Outfit (t)		6000				
Auxiliary (t)						
Weapons (t)						
Fuel (t)		2390				
FW/Stores etc (t)		1500 FW				
Margins (t)		8472 WB				
COST	$5.5m 1988	1.25*RylPrncss				

DESIGN IDENTIFICATION	*127*	*128*	*129*	*130*	*131*	*132*
Vessel Role/Name	*ASW Frigate*	*Ocean Research*	*Minehunter*	*STOL Carrier*		
Designer/Builder	UCL	UCL	UCL	UCL		
Date of Publication	1987	1987	1988	1988		
Sources (References)	103	103	103	103		
DIMENSIONS						
Length Overall (m)						
Length BP (m)	78	68	42	188		
Breadth Overall (m)	30.5	26.4	15.5	35		
Depth to Main Deck (m)						
Depth to Wet Deck (m)						
Box Depth (m)						
Design Draught (m)	7.6	7.6	4.6	11.4		
Box Clearance (m)						
Displacement (t)	5050	3300	925	26000		
PERFORMANCE						
Maximum Speed (kts)	25	12	15	28		
Cruise Speed (kts)						
Range at Max (nm)						
Range at Cruise (nm)						
MACHINERY						
Prime Movers	Diesel+AC, GT	Diesels	Diesels	Steam turbines		
Location			Box	In hulls		
Transmission		Electric	Bevel/belt drive	Direct		
Gearing		DC motor				
Installed Power (hp)						
Slow Speed Power						
Propeller Type						
ELECTRICAL/SYSTEMS						
Auxiliary Machinery						
Fin Control						
STRUT ARRANGEMENT						
Strut Type						
Strut Length (m)	78	68	42	188		
Strut Thickness (m)						
Rudder Arrangement						
LOWER HULL FORM						
Lower Hull Section						
Lower Hull Shape						
Hull Length (m)	90	84	52	196		
Hull Breadth (m)						
Hull Depth (m)						
STRUCTURE						
Hull Material						
Strut Material						
Box Material						
SS Material						
NATURAL PERIODS						
T roll (s)						
T pitch (s)						
T heave (s)						
ACCOMODATION						
Complement						
Passengers						
USEFUL LOAD						
Payload (t) / No. helos etc						
Weapons Fit/Special Items						
WEIGHTS						
Structure (t)						
Propulsion (t)						
Outfit (t)						
Auxiliary (t)						
Weapons (t)						
Fuel (t)						
FW/Stores etc (t)						
Margins (t)						
COST						

APPENDIX 2

SWATH SHIP DEADWEIGHT RATIOS BY *INITIAL*

Appendix 2 contains SWATH ship payload/displacement ratios produced by *INITIAL* as part of a typical parametric study. Tables A1 to A15 contain results from fifteen permutations of structural material and machinery plant. Data for aluminium, mild steel, and hybrid structures is presented in Tables A1 to A5, A6 to A10, A11 to A15 respectively. Within these primary groupings, gas turbines, high and medium speed diesels, diesel-electric and gas turbo electric propulsion options provide further subgroups.

For each of the fifteen groups thus defined, calculations were performed at six different operating ranges. These are 500, 1000, 2000, 4000, 6000, and 8000 nautical miles. In this context, range is defined as the distance which the vessel is required to cover at the specified design speed. Eleven different design speeds (from 8 to 36 knots) were examined for sixteen different payload requirements (from 10 to 1200 tonnes).

The Tables provide the percentage of ship displacement available for payload (as defined in Chapter 4) in each of these 15840 conditions. Thus, for example. Table A9 indicates that a mild steel SWATH ship with diesel electric propulsion, a range of 8000 nautical miles at 8 knots and a payload of 60 tonnes will be of 1500 tonnes displacement (payload displacement ratio of 4.01%).

The calculations consisted of determining the SWATH displacement required to support a specified payload at various operating speeds. The operating profile of the vessels in this particular survey was one of constant speed operation. There was therefore no distinction made between *maximum* and *cruise* speeds. Default calculations for the weight of stores (0.036Δ) and margins ($0.0755\ \text{WLIGHT}^{1.0747}$) were used in this study. The many other limitations present in *INITIAL* (such as lack of a space balance) must also be considered if applying this data.

TABLE A1- PAYLOAD AS A PERCENTAGE OF REQUIRED DISPLACEMENT
ALUMINIUM STRUCTURE, GAS TURBINE PROPULSION

RANGE 500nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	12.44	11.41	10.22	9.37	7.68	5.35	3.54	1.96	1.23	0.92	0.86
20t	16.46	15.33	14.02	14.54	11.65	8.69	6.11	3.22	2.13	1.61	1.64
30t	18.61	17.50	16.19	17.11	14.22	11.06	8.12	4.21	2.88	2.20	2.18
40t	20.01	18.93	17.66	18.87	16.06	12.87	9.75	5.03	3.53	2.73	2.56
50t	21.02	19.99	18.75	20.17	17.48	14.32	11.12	5.99	4.11	3.21	2.94
60t	21.82	20.81	20.75	21.20	18.62	15.53	12.29	6.87	4.64	3.66	3.31
100t	23.90	23.01	23.11	23.35	21.71	18.92	15.78	9.81	6.43	5.21	4.65
150t	25.50	25.69	24.54	24.47	24.05	21.60	18.69	12.62	8.21	6.82	6.08
200t	26.66	26.87	25.84	25.37	25.65	23.50	20.81	14.85	9.79	8.19	7.28
250t	27.62	27.83	26.89	26.18	26.41	24.97	22.48	16.69	11.44	9.41	8.27
300t	28.45	28.66	27.79	26.92	27.06	26.20	23.86	18.27	12.93	10.51	9.18
400t	29.88	30.09	29.32	28.25	28.25	28.19	26.12	20.90	15.52	12.40	10.83
600t	32.24	32.44	31.79	30.88	30.41	30.61	29.49	24.89	19.67	15.40	13.64
800t	34.23	34.42	33.86	33.06	32.33	32.42	32.09	27.95	22.97	17.92	16.03
1000t	36.52	36.19	35.68	34.96	34.09	34.09	34.27	30.50	25.76	20.64	18.14
1200t	38.11	37.81	37.34	36.67	35.78	35.66	35.87	32.70	28.18	23.07	20.06

RANGE 1000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	10.68	9.29	7.83	8.29	5.67	3.65	2.29	0.96	0.48	0.37	0.30
20t	14.51	12.95	11.27	12.45	9.17	6.30	4.17	1.85	0.95	0.73	0.59
30t	16.66	15.10	13.38	15.10	11.63	8.37	5.76	2.68	1.40	1.07	0.86
40t	18.11	16.57	14.87	16.98	13.50	10.05	7.13	3.45	1.84	1.40	1.13
50t	19.18	17.69	17.50	18.42	14.99	11.46	8.34	4.19	2.27	1.73	1.39
60t	20.02	18.58	19.53	19.56	16.22	12.67	9.41	4.88	2.69	2.04	1.63
100t	22.28	20.99	21.09	21.51	19.67	16.24	12.80	7.33	4.26	3.19	2.56
150t	24.03	24.45	22.75	22.51	22.36	19.21	15.82	9.84	6.04	4.42	3.61
200t	25.31	25.74	24.20	23.40	24.04	21.35	18.10	11.93	7.64	5.52	4.56
250t	26.36	26.78	25.37	24.22	24.64	23.04	19.94	13.73	9.11	6.51	5.43
300t	27.25	27.68	26.37	24.98	25.25	24.44	21.48	15.32	10.45	7.44	6.25
400t	28.79	29.20	28.04	26.48	26.42	26.70	24.00	18.01	12.87	9.10	7.75
600t	31.28	31.68	30.70	29.38	28.62	28.98	27.75	22.21	16.90	12.43	10.37
800t	33.87	33.74	32.88	31.71	30.60	30.78	30.61	25.48	20.21	15.38	12.64
1000t	36.07	35.57	34.79	33.72	32.41	32.47	32.93	28.21	23.05	18.01	14.68
1200t	37.69	37.22	36.51	35.52	34.25	34.06	34.45	30.56	25.54	20.38	16.54

RANGE 2000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	7.81	6.11	4.60	5.90	3.59	2.14	1.30	0.56	0.31	0.19	0.13
20t	11.21	9.18	7.26	9.56	6.27	3.94	2.48	1.10	0.61	0.38	0.27
30t	13.29	11.18	10.71	12.14	8.37	5.48	3.55	1.62	0.91	0.57	0.40
40t	14.76	12.65	13.70	14.09	10.10	6.84	4.54	2.13	1.20	0.76	0.53
50t	15.89	13.80	15.13	15.65	11.55	8.04	5.45	2.62	1.49	0.94	0.66
60t	16.80	14.74	15.62	16.90	12.80	9.11	6.30	3.09	1.78	1.13	0.79
100t	19.32	18.65	17.25	17.66	16.52	12.56	9.19	4.86	2.88	1.85	1.29
150t	21.33	22.14	19.57	18.61	19.60	15.67	12.03	6.82	4.18	2.73	1.90
200t	22.80	23.62	21.26	19.55	20.47	18.04	14.32	8.57	5.41	3.58	2.50
250t	23.99	24.80	22.62	20.44	21.01	19.95	16.24	10.15	6.57	4.40	3.07
300t	25.01	25.81	23.76	21.28	21.60	21.55	17.90	11.59	7.67	5.20	3.63
400t	26.72	27.51	25.67	23.36	22.83	23.95	20.66	14.14	9.71	6.73	4.70
600t	29.46	30.21	28.64	26.63	25.18	25.73	24.85	18.32	13.31	9.54	6.69
800t	33.37	32.42	31.03	29.22	27.29	27.55	28.07	21.71	16.42	12.10	8.62
1000t	35.20	34.35	33.08	31.41	29.40	29.30	30.15	24.58	19.17	14.44	10.49
1200t	36.87	36.08	34.91	33.36	31.47	30.95	31.60	27.10	21.64	16.62	12.27

RANGE 4000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	4.15	2.76	3.31	3.67	2.03	1.15	0.70	0.32	0.19	0.12	0.08
20t	6.63	4.70	5.88	6.45	3.77	2.22	1.37	0.63	0.38	0.25	0.16
30t	8.38	6.19	6.70	8.66	5.29	3.21	2.01	0.94	0.57	0.37	0.25
40t	9.73	7.41	7.41	9.04	6.65	4.13	2.63	1.25	0.75	0.49	0.33
50t	10.83	9.55	8.33	8.94	7.86	4.99	3.22	1.55	0.94	0.61	0.41
60t	11.76	11.18	9.27	9.07	8.96	5.80	3.80	1.84	1.12	0.73	0.49
100t	14.48	15.82	12.14	10.14	12.49	8.63	5.89	2.99	1.84	1.21	0.81
150t	16.77	18.18	14.65	11.52	12.53	11.48	8.17	4.34	2.72	1.80	1.22
200t	18.48	19.91	16.55	13.10	13.19	13.82	10.16	5.61	3.57	2.38	1.61
250t	19.87	21.30	18.11	14.70	13.99	15.78	11.92	6.81	4.40	2.95	2.01
300t	21.05	22.48	19.43	16.10	14.80	16.55	13.50	7.94	5.21	3.51	2.40
400t	23.04	24.45	21.63	18.45	16.34	17.38	16.27	10.05	6.75	4.61	3.17
600t	26.16	27.51	25.03	22.11	19.09	19.50	20.69	13.76	9.61	6.71	4.68
800t	31.57	29.96	27.71	24.99	22.05	21.58	23.01	16.94	12.22	8.70	6.15
1000t	33.53	32.06	29.98	27.43	24.60	23.52	24.55	19.75	14.63	10.59	7.57
1200t	35.29	33.93	31.99	29.57	26.84	25.32	26.09	22.27	16.86	12.38	8.95

RANGE 6000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	2.31	1.93	1.44	0.99	1.42	0.80	0.49	0.23	0.14	0.09	0.06
20t	4.02	3.74	2.67	1.69	2.71	1.57	0.97	0.46	0.29	0.19	0.13
30t	5.36	5.46	3.73	2.29	3.90	2.30	1.44	0.69	0.43	0.28	0.19
40t	6.48	6.90	4.67	2.81	4.98	3.00	1.89	0.92	0.57	0.38	0.26
50t	7.44	8.35	5.52	3.40	4.03	3.67	2.34	1.14	0.71	0.47	0.32
60t	8.28	9.71	6.29	3.96	4.21	4.31	2.77	1.36	0.85	0.56	0.38
100t	10.89	12.54	8.82	5.94	5.30	6.65	4.42	2.23	1.41	0.93	0.64
150t	13.22	15.00	11.21	7.99	6.61	8.91	6.29	3.28	2.10	1.39	0.95
200t	15.01	16.85	13.10	9.73	7.76	9.02	7.98	4.28	2.77	1.85	1.27
250t	16.49	18.35	14.69	11.23	8.81	9.65	9.54	5.25	3.42	2.29	1.58
300t	17.77	19.64	16.06	12.58	9.76	10.37	10.98	6.19	4.07	2.74	1.89
400t	19.91	21.78	18.38	14.90	11.80	11.80	13.55	7.96	5.33	3.62	2.51
600t	25.88	25.10	22.00	18.62	15.40	14.41	15.94	11.19	7.71	5.32	3.73
800t	29.88	27.73	24.86	21.61	18.37	16.71	17.74	14.08	9.95	6.96	4.91
1000t	31.94	29.96	27.27	24.16	20.95	18.77	19.52	16.70	12.06	8.54	6.10
1200t	33.78	31.94	29.39	26.39	23.23	20.65	21.21	19.10	14.05	10.07	7.25

RANGE 8000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	1.41	1.78	0.93	0.52	0.34	0.63	0.39	0.19	0.12	0.08	0.05
20t	2.58	3.35	1.77	1.01	0.65	1.23	0.77	0.37	0.24	0.16	0.11
30t	3.58	4.59	2.54	1.48	0.96	1.17	1.14	0.56	0.35	0.23	0.16
40t	4.46	5.65	3.25	1.94	1.25	1.46	1.51	0.74	0.47	0.31	0.21
50t	5.25	6.58	3.91	2.37	1.55	1.74	1.87	0.92	0.59	0.39	0.27
60t	5.96	7.41	4.52	2.80	1.84	2.01	2.23	1.10	0.71	0.47	0.32
100t	8.30	10.05	6.65	4.35	2.96	2.98	3.59	1.82	1.17	0.77	0.54
150t	10.52	12.46	8.80	6.05	4.24	4.05	5.19	2.69	1.74	1.16	0.81
200t	12.28	14.34	10.58	7.55	5.44	5.01	6.66	3.53	2.30	1.54	1.08
250t	13.77	15.89	12.11	8.91	6.55	5.90	7.63	4.35	2.86	1.91	1.34
300t	15.07	17.22	13.46	10.14	7.59	6.72	8.08	5.15	3.41	2.29	1.59
400t	17.28	19.46	15.78	12.32	9.50	8.22	9.23	6.69	4.48	3.03	2.12
600t	24.38	22.94	19.46	15.93	12.81	10.83	11.53	9.56	6.55	4.48	3.20
800t	28.29	25.70	22.41	18.90	15.64	13.11	13.61	12.19	8.51	5.89	4.22
1000t	30.43	28.04	24.90	21.46	18.13	15.23	15.52	14.61	10.39	7.26	5.18
1200t	32.34	30.10	27.10	23.72	20.37	17.36	17.28	16.87	12.19	8.60	6.17

TABLE A2- PAYLOAD AS A PERCENTAGE OF REQUIRED DISPLACEMENT
ALUMINIUM STRUCTURE, HIGH SPEED DIESEL PROPULSION

RANGE 500nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	20.18	18.37	16.28	14.04	10.93	7.71	6.32	3.94	3.49	1.78	0.92
20t	21.91	20.44	18.70	18.34	14.89	11.16	7.91	4.99	3.16	2.34	1.74
30t	22.86	21.57	20.03	20.63	17.19	13.58	9.89	5.90	3.82	2.69	2.48
40t	23.53	22.36	20.96	21.90	18.77	15.34	11.59	6.66	4.43	3.13	2.86
50t	24.05	22.97	21.67	22.84	19.96	16.68	12.97	7.32	4.97	3.56	3.02
60t	24.48	23.47	22.25	23.57	20.91	17.77	14.13	7.90	5.47	3.96	3.28
100t	25.74	24.91	25.03	25.23	23.45	20.78	17.47	10.79	7.13	5.36	4.38
150t	26.87	27.01	25.97	25.95	25.39	23.13	20.18	13.63	8.79	6.81	5.61
200t	27.78	27.93	27.02	26.66	26.77	24.79	22.13	15.84	10.17	8.06	6.70
250t	28.57	28.72	27.91	27.35	27.50	26.10	23.67	17.66	11.74	9.16	7.68
300t	29.28	29.44	28.70	28.02	28.10	27.20	24.95	19.20	13.23	10.16	8.58
400t	30.56	30.72	30.08	29.23	29.20	29.01	27.05	21.76	15.80	11.94	10.21
600t	32.76	32.91	32.40	31.63	31.20	31.32	30.21	25.62	19.91	14.92	13.00
800t	34.67	34.81	34.37	33.69	33.05	33.08	32.69	28.60	23.18	17.55	15.37
1000t	36.79	36.53	36.14	35.51	34.75	34.70	34.78	31.08	25.92	20.27	17.47
1200t	38.34	38.11	37.75	37.17	36.36	36.23	36.37	33.23	28.32	22.69	19.38

RANGE 1000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	17.63	15.34	12.93	10.59	8.33	5.47	3.35	1.27	0.67	0.42	0.31
20t	19.78	17.86	15.76	16.36	12.25	8.81	5.80	2.39	1.25	0.81	0.60
30t	20.96	19.26	17.37	18.60	14.71	11.16	7.72	3.42	1.77	1.18	0.88
40t	21.78	20.23	18.50	20.12	16.47	12.92	9.30	4.37	2.25	1.52	1.15
50t	22.41	20.98	19.36	21.25	17.82	14.33	10.63	5.24	2.70	1.85	1.42
60t	22.93	21.59	20.99	22.14	18.91	15.50	11.77	6.04	3.12	2.17	1.67
100t	24.43	23.32	23.53	23.91	21.88	18.82	15.21	8.79	4.77	3.32	2.61
150t	25.72	26.03	24.63	24.60	24.14	21.45	18.11	11.48	6.68	4.58	3.66
200t	26.74	27.05	25.84	25.35	25.70	23.33	20.24	13.65	8.37	5.69	4.62
250t	27.60	27.92	26.83	26.10	26.39	24.81	21.94	15.48	9.90	6.70	5.50
300t	28.38	28.70	27.70	26.82	27.01	26.04	23.35	17.06	11.29	7.63	6.32
400t	29.75	30.06	29.20	28.07	28.08	28.04	25.64	19.71	13.75	9.31	7.82
600t	32.06	32.35	31.67	30.68	30.11	30.34	29.08	23.78	17.79	12.58	10.44
800t	34.04	34.31	33.74	32.84	31.98	32.08	31.74	26.92	21.08	15.54	12.72
1000t	36.43	36.07	35.57	34.73	33.71	33.71	33.94	29.53	23.87	18.17	14.75
1200t	38.01	37.68	37.22	36.45	35.40	35.25	35.50	31.79	26.32	20.55	16.61

RANGE 2000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	13.36	10.65	8.20	8.83	5.47	3.48	2.05	0.79	0.37	0.21	0.15
20t	16.04	13.59	11.21	12.90	8.85	6.03	3.76	1.54	0.74	0.41	0.30
30t	17.56	15.31	13.06	15.44	11.26	8.02	5.23	2.25	1.09	0.61	0.45
40t	18.61	16.53	14.40	17.23	13.10	9.65	6.52	2.92	1.44	0.82	0.59
50t	19.42	17.47	17.30	18.61	14.57	11.02	7.66	3.56	1.79	1.02	0.74
60t	20.09	18.24	19.63	19.71	15.80	12.20	8.68	4.17	2.12	1.21	0.88
100t	21.97	20.42	20.60	21.21	19.25	15.73	11.97	6.36	3.41	1.99	1.44
150t	23.55	24.19	22.19	21.94	21.97	18.69	14.95	8.67	4.89	2.93	2.11
200t	24.76	25.39	23.64	22.82	23.56	20.85	17.24	10.65	6.27	3.83	2.76
250t	25.77	26.39	24.82	23.69	24.19	22.56	19.09	12.38	7.55	4.70	3.38
300t	26.65	27.27	25.83	24.49	24.80	23.98	20.66	13.92	8.75	5.54	3.99
400t	28.18	28.78	27.54	25.97	25.85	26.28	23.22	16.57	10.94	7.14	5.14
600t	30.70	31.26	30.27	28.87	27.95	28.37	27.07	20.77	14.70	10.08	7.25
800t	33.63	33.34	32.51	31.21	29.89	30.09	30.01	24.10	17.88	12.72	9.17
1000t	35.72	35.18	34.45	33.24	31.68	31.73	32.33	26.88	20.64	15.13	10.97
1200t	37.34	36.85	36.17	35.05	33.58	33.30	33.76	29.29	23.11	17.36	12.80

RANGE 4000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	7.58	5.26	3.65	5.43	3.12	1.91	1.12	0.46	0.23	0.14	0.09
20t	10.43	7.91	7.31	8.88	5.55	3.55	2.15	0.91	0.46	0.27	0.18
30t	12.20	9.69	10.07	11.37	7.51	4.98	3.10	1.34	0.69	0.41	0.27
40t	13.48	11.03	13.08	13.28	9.15	6.24	3.99	1.76	0.92	0.55	0.36
50t	14.49	12.11	13.40	14.83	10.55	7.37	4.82	2.18	1.14	0.68	0.45
60t	15.33	13.02	13.77	15.56	11.77	8.40	5.59	2.58	1.36	0.82	0.54
100t	17.72	18.06	15.72	15.82	15.48	11.73	8.29	4.11	2.23	1.35	0.90
150t	19.71	20.89	18.12	17.01	18.53	14.80	11.01	5.84	3.26	2.00	1.34
200t	21.21	22.38	19.89	18.25	19.18	17.16	13.24	7.41	4.26	2.65	1.77
250t	22.44	23.60	21.33	19.23	19.81	19.09	15.13	8.86	5.21	3.28	2.21
300t	23.50	24.64	22.54	20.19	20.35	20.72	16.78	10.20	6.13	3.89	2.64
400t	25.30	26.40	24.57	22.32	21.52	22.74	19.55	12.60	7.87	5.09	3.48
600t	28.17	29.20	27.73	25.64	23.83	24.40	23.82	16.64	11.03	7.37	5.12
800t	32.44	31.48	30.24	28.26	25.94	26.18	27.09	19.98	13.83	9.51	6.70
1000t	34.35	33.47	32.34	30.49	28.22	27.91	28.86	22.85	16.37	11.52	8.23
1200t	36.04	35.25	34.19	32.46	30.31	29.55	30.27	25.38	18.70	13.42	9.71

RANGE 6000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	4.41	2.86	3.45	3.87	2.17	1.31	0.77	0.33	0.17	0.11	0.07
20t	6.82	4.82	6.30	6.72	4.01	2.50	1.51	0.65	0.35	0.21	0.14
30t	8.48	6.31	7.13	8.96	5.60	3.58	2.21	0.97	0.52	0.32	0.21
40t	9.76	7.52	7.80	9.94	7.00	4.59	2.88	1.29	0.69	0.42	0.29
50t	10.80	9.59	8.58	9.67	8.24	5.51	3.52	1.60	0.86	0.53	0.36
60t	11.68	11.10	9.52	9.83	9.36	6.38	4.13	1.90	1.03	0.64	0.43
100t	14.28	15.81	12.41	11.23	12.93	9.34	6.35	3.08	1.70	1.05	0.71
150t	16.50	18.07	14.95	13.01	14.19	12.25	8.72	4.46	2.51	1.57	1.07
200t	18.18	19.76	16.88	14.14	14.82	14.60	10.77	5.75	3.30	2.08	1.42
250t	19.56	21.12	18.45	15.67	15.43	16.57	12.56	6.97	4.07	2.58	1.76
300t	20.74	22.29	19.79	17.03	16.12	18.08	14.16	8.12	4.82	3.08	2.11
400t	22.73	24.24	22.02	19.32	17.52	18.68	16.93	10.25	6.26	4.05	2.79
600t	25.87	27.30	25.47	22.87	20.09	20.56	21.33	13.97	8.95	5.93	4.14
800t	31.08	29.75	28.19	25.67	22.79	22.50	23.96	17.16	11.42	7.73	5.45
1000t	33.03	31.86	30.40	28.04	25.30	24.34	25.39	19.97	13.71	9.45	6.73
1200t	34.80	33.74	32.35	30.13	27.50	26.06	26.85	22.48	15.84	11.11	7.98

RANGE 8000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	2.72	1.97	1.78	3.01	1.67	1.00	0.60	0.26	0.14	0.09	0.06
20t	4.57	3.83	3.22	3.84	3.15	1.93	1.17	0.52	0.28	0.18	0.12
30t	5.99	5.57	4.44	4.27	4.47	2.81	1.73	0.78	0.43	0.27	0.18
40t	7.14	7.45	5.50	4.90	5.68	3.64	2.27	1.03	0.57	0.35	0.24
50t	8.11	8.82	6.44	5.51	6.78	4.42	2.79	1.28	0.71	0.44	0.30
60t	8.95	10.22	7.28	6.09	7.78	5.16	3.30	1.53	0.84	0.53	0.36
100t	11.55	13.30	9.99	7.94	9.25	7.78	5.18	2.50	1.40	0.88	0.60
150t	13.85	15.68	12.50	9.77	9.88	10.48	7.27	3.66	2.07	1.31	0.90
200t	15.62	17.48	14.46	11.60	10.73	12.73	9.12	4.76	2.74	1.74	1.20
250t	17.08	18.95	16.09	13.16	11.62	13.56	10.79	5.81	3.39	2.17	1.49
300t	18.34	20.20	17.49	14.52	12.48	13.84	12.31	6.82	4.02	2.59	1.79
400t	20.46	22.29	19.84	16.84	14.07	14.84	14.99	8.72	5.26	3.42	2.38
600t	25.75	25.55	23.48	20.50	17.29	17.07	19.11	12.12	7.61	5.03	3.53
800t	29.74	28.14	26.29	23.41	20.27	19.18	20.51	15.13	9.82	6.60	4.67
1000t	31.77	30.36	28.60	25.87	22.82	21.12	22.06	17.82	11.89	8.11	5.80
1200t	33.60	32.32	30.64	28.03	25.06	22.91	23.60	20.26	13.85	9.58	6.89

TABLE A3- PAYLOAD AS A PERCENTAGE OF REQUIRED DISPLACEMENT
ALUMINIUM STRUCTURE, MEDIUM SPEED DIESEL PROPULSION

RANGE 500nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	19.50	17.21	14.60	11.86	8.87	5.39	3.17	1.18	0.50	0.29	0.20
20t	21.34	19.46	17.22	17.29	12.80	8.67	5.55	2.25	0.97	0.57	0.40
30t	22.36	20.69	18.67	19.42	15.22	10.98	7.43	3.23	1.44	0.85	0.60
40t	23.06	21.54	19.68	20.85	16.94	12.74	8.99	4.13	1.89	1.11	0.79
50t	23.61	22.19	20.45	21.90	18.26	14.16	10.31	4.96	2.33	1.37	0.98
60t	24.06	22.73	21.08	22.74	19.31	15.34	11.45	5.74	2.75	1.62	1.16
100t	25.39	24.27	24.29	24.44	22.19	18.69	14.91	8.41	4.35	2.56	1.88
150t	26.56	26.66	25.26	25.09	24.40	21.36	17.84	11.06	6.14	3.63	2.72
200t	27.49	27.61	26.38	25.75	25.92	23.26	20.00	13.22	7.75	4.61	3.50
250t	28.30	28.44	27.32	26.41	26.54	24.75	21.72	15.04	9.21	5.54	4.25
300t	29.03	29.17	28.14	27.06	27.09	25.99	23.15	16.62	10.55	6.50	4.96
400t	30.33	30.48	29.57	28.28	28.17	28.01	25.48	19.28	12.95	8.30	6.28
600t	32.56	32.70	31.95	30.87	30.21	30.31	28.97	23.38	16.94	11.53	8.66
800t	34.48	34.63	33.97	33.02	32.10	32.08	31.65	26.56	20.21	14.38	10.78
1000t	36.72	36.36	35.77	34.90	33.84	33.73	33.85	29.20	23.01	16.94	12.70
1200t	38.28	37.95	37.41	36.61	35.53	35.29	35.40	31.49	25.47	19.26	14.47

RANGE 1000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	17.17	14.52	11.72	9.57	6.99	4.11	2.41	0.95	0.41	0.22	0.16
20t	19.38	17.12	14.60	15.29	10.70	6.95	4.37	1.82	0.82	0.43	0.31
30t	20.60	18.57	16.26	17.65	13.16	9.09	6.00	2.64	1.21	0.65	0.46
40t	21.44	19.57	17.41	19.27	14.97	10.79	7.40	3.41	1.60	0.86	0.61
50t	22.09	20.34	18.31	20.48	16.39	12.20	8.62	4.14	1.97	1.07	0.76
60t	22.62	20.97	20.61	21.44	17.54	13.40	9.71	4.82	2.34	1.28	0.91
100t	24.15	22.76	22.83	23.14	20.73	16.91	13.10	7.23	3.74	2.10	1.49
150t	25.46	25.73	23.97	23.73	23.21	19.78	16.11	9.71	5.34	3.08	2.18
200t	26.49	26.78	25.22	24.40	24.83	21.86	18.37	11.78	6.80	4.02	2.85
250t	27.37	27.67	26.25	25.08	25.35	23.49	20.19	13.57	8.15	4.92	3.49
300t	28.16	28.45	27.15	25.76	25.88	24.84	21.71	15.13	9.41	5.80	4.10
400t	29.54	29.83	28.69	27.10	26.96	27.03	24.20	17.81	11.69	7.46	5.28
600t	31.87	32.15	31.20	29.87	29.06	29.27	27.91	21.99	15.55	10.48	7.43
800t	33.86	34.13	33.30	32.13	31.00	31.05	30.75	25.25	18.77	13.18	9.38
1000t	36.37	35.90	35.15	34.09	32.79	32.73	33.00	27.98	21.56	15.63	11.17
1200t	37.95	37.52	36.84	35.86	34.59	34.32	34.54	30.34	24.03	17.89	12.97

RANGE 2000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	13.23	10.28	7.57	8.28	4.78	2.72	1.61	0.68	0.32	0.17	0.11
20t	15.91	13.20	10.49	12.30	7.93	4.88	3.03	1.32	0.63	0.35	0.22
30t	17.42	14.91	12.30	14.85	10.23	6.66	4.28	1.94	0.93	0.52	0.33
40t	18.47	16.11	14.47	16.68	12.04	8.16	5.42	2.53	1.23	0.69	0.44
50t	19.28	17.05	16.98	18.09	13.51	9.46	6.44	3.10	1.53	0.86	0.54
60t	19.94	17.81	19.10	19.23	14.75	10.61	7.38	3.65	1.82	1.03	0.65
100t	21.81	19.99	19.96	20.45	18.30	14.14	10.50	5.64	2.94	1.70	1.08
150t	23.39	23.97	21.60	21.00	21.15	17.21	13.45	7.80	4.26	2.51	1.61
200t	24.59	25.19	23.06	21.73	22.46	19.49	15.77	9.68	5.50	3.29	2.13
250t	25.60	26.20	24.25	22.48	22.92	21.31	17.68	11.34	6.66	4.06	2.64
300t	26.48	27.07	25.27	23.23	23.46	22.82	19.30	12.84	7.76	4.80	3.15
400t	28.01	28.59	27.00	24.93	24.58	25.22	21.99	15.45	9.81	6.24	4.14
600t	30.53	31.08	29.75	27.99	26.83	27.20	26.03	19.65	13.38	8.90	6.06
800t	33.76	33.16	32.00	30.44	28.89	29.03	29.11	23.01	16.46	11.34	7.88
1000t	35.68	35.01	33.96	32.54	30.82	30.78	31.31	25.83	19.18	13.60	9.62
1200t	37.30	36.69	35.72	34.42	32.82	32.43	32.84	28.29	21.61	15.71	11.29

RANGE 4000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	7.76	5.23	3.78	5.27	2.84	1.60	0.97	0.44	0.22	0.13	0.08
20t	10.58	7.83	7.24	8.68	5.10	3.01	1.87	0.86	0.44	0.26	0.17
30t	12.33	9.56	10.32	11.15	6.96	4.27	2.71	1.28	0.65	0.38	0.25
40t	13.59	10.87	12.81	13.06	8.53	5.41	3.51	1.69	0.86	0.51	0.33
50t	14.58	11.93	13.03	14.59	9.90	6.45	4.26	2.08	1.07	0.64	0.42
60t	15.39	12.81	13.33	14.98	11.09	7.41	4.98	2.47	1.28	0.76	0.50
100t	17.73	17.90	15.26	14.88	14.78	10.60	7.50	3.94	2.10	1.26	0.83
150t	19.68	20.81	17.60	15.74	17.25	13.63	10.11	5.62	3.09	1.87	1.24
200t	21.15	22.28	19.35	16.72	17.53	16.02	12.29	7.16	4.04	2.48	1.65
250t	22.36	23.48	20.76	17.68	18.09	17.98	14.17	8.57	4.95	3.07	2.05
300t	23.41	24.51	21.96	18.98	18.74	19.66	15.82	9.88	5.84	3.65	2.45
400t	25.18	26.26	23.97	21.22	20.12	21.19	18.63	12.26	7.51	4.79	3.23
600t	28.01	29.04	27.09	24.69	22.71	23.19	22.98	16.26	10.57	6.95	4.77
800t	32.36	31.32	29.59	27.42	25.03	25.21	26.25	19.59	13.31	9.00	6.26
1000t	34.34	33.30	31.73	29.73	27.50	27.14	27.94	22.45	15.81	10.93	7.70
1200t	36.03	35.08	33.62	31.77	29.68	28.94	29.56	24.98	18.10	12.77	9.10

RANGE 6000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	4.61	2.87	3.43	3.83	2.01	1.13	0.70	0.33	0.17	0.10	0.07
20t	7.03	4.79	6.25	6.66	3.74	2.18	1.36	0.65	0.34	0.21	0.14
30t	8.69	6.25	6.89	8.89	5.25	3.15	2.00	0.97	0.51	0.31	0.21
40t	9.95	7.42	7.43	9.40	6.59	4.05	2.62	1.28	0.68	0.41	0.28
50t	10.97	9.54	8.31	8.91	7.79	4.90	3.21	1.59	0.85	0.52	0.34
60t	11.84	11.06	9.22	8.90	8.88	5.70	3.78	1.90	1.01	0.62	0.41
100t	14.38	15.85	12.01	9.86	12.20	8.49	5.87	3.07	1.67	1.03	0.69
150t	16.54	18.07	14.46	11.24	12.12	11.31	8.14	4.45	2.47	1.53	1.03
200t	18.18	19.72	16.33	12.90	12.86	13.63	10.12	5.74	3.25	2.02	1.37
250t	19.53	21.07	17.86	14.51	13.73	15.54	11.88	6.95	4.01	2.52	1.70
300t	20.69	22.21	19.16	15.90	14.60	16.11	13.46	8.10	4.75	3.00	2.04
400t	22.64	24.14	21.35	18.25	16.25	17.16	16.22	10.23	6.17	3.95	2.70
600t	25.72	27.16	24.73	21.92	19.15	19.54	20.62	13.94	8.83	5.79	4.00
800t	31.11	29.59	27.41	24.82	22.14	21.82	23.00	17.13	11.28	7.56	5.27
1000t	33.06	31.69	29.68	27.26	24.73	23.91	24.79	19.93	13.55	9.25	6.51
1200t	34.81	33.55	31.69	29.41	27.00	25.85	26.53	22.45	15.68	10.87	7.74

RANGE 8000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	2.87	1.98	1.71	3.01	1.56	0.88	0.55	0.27	0.14	0.09	0.06
20t	4.76	3.87	3.10	2.91	2.96	1.72	1.09	0.53	0.29	0.18	0.12
30t	6.19	5.63	4.28	3.33	4.23	2.51	1.60	0.79	0.43	0.26	0.18
40t	7.33	7.17	5.29	3.84	5.38	3.26	2.11	1.05	0.57	0.35	0.24
50t	8.30	8.90	6.19	4.33	6.43	3.98	2.60	1.31	0.71	0.44	0.30
60t	9.13	10.30	7.00	4.78	6.91	4.66	3.07	1.56	0.85	0.53	0.36
100t	11.68	13.39	9.60	6.62	6.87	7.12	4.86	2.54	1.40	0.88	0.60
150t	13.92	15.72	12.00	8.78	8.08	9.71	6.86	3.72	2.09	1.31	0.89
200t	15.65	17.49	13.89	10.58	9.25	11.05	8.65	4.83	2.75	1.73	1.19
250t	17.07	18.92	15.46	12.13	10.34	11.55	10.28	5.90	3.41	2.16	1.48
300t	18.30	20.15	16.81	13.50	11.34	12.25	11.77	6.92	4.05	2.58	1.77
400t	20.38	22.20	19.09	15.85	13.15	13.71	14.42	8.84	5.29	3.41	2.36
600t	25.71	25.41	22.63	19.58	16.73	16.47	18.00	12.27	7.65	5.02	3.49
800t	29.80	27.98	25.44	22.57	19.78	18.93	20.00	15.29	9.86	6.58	4.62
1000t	31.82	30.17	27.82	25.10	22.40	21.15	21.96	17.99	11.94	8.09	5.75
1200t	33.63	32.11	29.91	27.32	24.71	23.17	23.83	20.44	13.91	9.55	6.82

TABLE A4- PAYLOAD AS A PERCENTAGE OF REQUIRED DISPLACEMENT
ALUMINIUM STRUCTURE, DIESEL ELECTRIC PROPULSION

RANGE 500nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	7.42	5.04	3.49	4.39	2.66	1.69	1.12	0.56	0.33	0.22	0.18
20t	10.84	8.01	7.00	7.54	4.84	3.19	2.16	1.11	0.65	0.43	0.36
30t	13.00	10.08	10.22	9.95	6.68	4.53	3.12	1.64	0.97	0.64	0.53
40t	14.57	11.65	11.91	11.88	8.25	5.74	4.03	2.15	1.29	0.85	0.71
50t	15.78	12.92	12.78	12.79	9.63	6.83	4.87	2.64	1.60	1.06	0.88
60t	16.77	13.98	13.54	13.41	10.84	7.84	5.66	3.13	1.90	1.26	1.05
100t	19.52	18.25	16.12	15.31	14.62	11.17	8.44	4.92	3.08	2.07	1.72
150t	21.70	21.67	18.76	17.13	17.21	14.30	11.24	6.92	4.46	3.05	2.52
200t	23.28	23.31	20.68	18.63	18.55	16.74	13.53	8.71	5.75	3.99	3.30
250t	24.55	24.62	22.20	19.90	19.65	18.73	15.48	10.32	6.97	4.90	4.04
300t	25.62	25.72	23.47	21.00	20.62	20.42	17.17	11.79	8.12	5.77	4.76
400t	27.41	27.54	25.57	23.31	22.37	22.47	20.00	14.39	10.25	7.44	6.12
600t	30.22	30.38	28.75	26.80	25.30	25.22	24.31	18.65	13.97	10.50	8.62
800t	33.58	32.67	31.26	29.52	27.75	27.52	27.61	22.08	17.15	13.24	10.88
1000t	35.63	34.64	33.37	31.79	29.98	29.56	29.66	24.99	19.95	15.74	12.95
1200t	37.30	36.40	35.25	33.79	32.10	31.42	31.47	27.52	22.45	18.04	14.86

RANGE 1000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	6.60	4.41	3.63	4.06	2.44	1.54	1.01	0.50	0.29	0.19	0.15
20t	9.85	7.15	7.03	7.06	4.47	2.92	1.96	0.99	0.58	0.38	0.29
30t	11.96	9.12	9.74	9.40	6.21	4.17	2.84	1.46	0.86	0.56	0.44
40t	13.51	10.64	10.77	11.06	7.72	5.31	3.67	1.93	1.14	0.75	0.59
50t	14.72	11.88	11.65	11.72	9.05	6.35	4.46	2.38	1.42	0.93	0.73
60t	15.72	12.93	12.41	12.32	10.24	7.31	5.20	2.81	1.69	1.12	0.87
100t	18.52	17.88	15.19	14.21	13.97	10.53	7.83	4.46	2.75	1.84	1.43
150t	20.77	20.91	17.87	16.08	16.25	13.61	10.53	6.32	4.00	2.71	2.12
200t	22.41	22.60	19.83	17.63	17.58	16.05	12.77	8.01	5.19	3.56	2.78
250t	23.72	23.95	21.39	18.89	18.67	18.05	14.69	9.54	6.32	4.38	3.42
300t	24.83	25.08	22.70	20.12	19.64	19.75	16.37	10.95	7.39	5.18	4.04
400t	26.68	26.95	24.85	22.46	21.39	21.60	19.21	13.47	9.39	6.71	5.24
600t	29.57	29.86	28.13	26.03	24.34	24.30	23.58	17.66	12.93	9.55	7.47
800t	33.41	32.20	30.69	28.79	26.80	26.60	26.83	21.08	16.01	12.13	9.52
1000t	35.28	34.20	32.85	31.11	29.13	28.64	28.85	23.99	18.74	14.51	11.42
1200t	36.97	36.00	34.75	33.15	31.29	30.51	30.64	26.53	21.21	16.71	13.21

RANGE 2000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	5.23	3.41	3.31	3.54	2.09	1.31	0.85	0.41	0.24	0.15	0.11
20t	8.14	5.73	6.42	6.27	3.88	2.50	1.65	0.82	0.47	0.31	0.22
30t	10.12	7.49	7.68	8.27	5.45	3.60	2.40	1.21	0.71	0.46	0.32
40t	11.62	8.90	8.70	8.97	6.84	4.61	3.13	1.60	0.94	0.61	0.43
50t	12.82	10.08	9.57	9.61	8.08	5.55	3.82	1.98	1.17	0.76	0.54
60t	13.82	11.08	10.40	10.20	9.21	6.43	4.47	2.35	1.39	0.91	0.65
100t	16.68	17.02	13.54	12.16	12.70	9.44	6.85	3.77	2.28	1.51	1.07
150t	19.03	19.46	16.25	14.15	14.41	12.42	9.35	5.40	3.34	2.24	1.60
200t	20.76	21.24	18.27	15.69	15.66	14.82	11.49	6.90	4.36	2.95	2.12
250t	22.15	22.66	19.89	17.05	16.72	16.82	13.35	8.30	5.34	3.64	2.63
300t	23.32	23.85	21.25	18.49	17.71	18.31	15.00	9.60	6.28	4.32	3.13
400t	25.28	25.82	23.51	20.89	19.49	19.83	17.83	11.96	8.06	5.64	4.12
600t	28.32	28.86	26.93	24.56	22.47	22.50	22.26	15.98	11.29	8.12	6.03
800t	32.58	31.28	29.60	27.42	24.99	24.79	25.32	19.33	14.16	10.43	7.86
1000t	34.58	33.36	31.82	29.81	27.53	26.86	27.23	22.23	16.75	12.59	9.61
1200t	36.31	35.20	33.78	31.90	29.74	28.74	28.99	24.79	19.12	14.62	11.28

RANGE 4000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	3.36	2.13	2.12	2.71	1.62	1.00	0.64	0.31	0.18	0.12	0.08
20t	5.60	3.80	3.53	3.71	3.07	1.94	1.25	0.61	0.35	0.23	0.16
30t	7.28	5.78	4.87	4.60	4.38	2.82	1.85	0.91	0.53	0.34	0.24
40t	8.62	7.61	6.03	5.39	5.58	3.66	2.42	1.21	0.70	0.46	0.32
50t	9.73	9.16	7.05	6.09	6.67	4.44	2.97	1.50	0.87	0.57	0.40
60t	10.68	10.98	7.97	6.74	7.59	5.19	3.51	1.78	1.05	0.68	0.48
100t	13.54	14.36	10.89	8.89	9.38	7.84	5.49	2.90	1.72	1.13	0.80
150t	15.99	16.90	13.55	10.72	10.79	10.58	7.67	4.21	2.55	1.69	1.20
200t	17.83	18.79	15.60	12.63	12.01	12.84	9.60	5.45	3.35	2.24	1.59
250t	19.32	20.31	17.28	14.29	13.13	14.07	11.32	6.63	4.13	2.77	1.99
300t	20.59	21.59	18.72	15.73	14.16	14.86	12.88	7.74	4.89	3.31	2.37
400t	22.71	23.71	21.10	18.16	15.99	16.36	15.62	9.82	6.36	4.35	3.14
600t	25.99	26.97	24.75	21.95	19.05	19.04	19.94	13.49	9.09	6.35	4.64
800t	31.24	29.55	27.56	24.92	22.09	21.39	22.15	16.65	11.60	8.26	6.09
1000t	33.25	31.74	29.89	27.42	24.69	23.49	24.02	19.46	13.92	10.08	7.50
1200t	35.04	33.67	31.94	29.60	26.98	25.40	25.77	21.97	16.08	11.82	8.88

RANGE 6000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	2.25	1.87	1.39	1.08	1.33	0.82	0.52	0.25	0.14	0.09	0.07
20t	3.95	3.70	2.59	1.97	2.52	1.59	1.02	0.49	0.29	0.19	0.13
30t	5.31	5.50	3.66	2.75	3.28	2.33	1.51	0.74	0.43	0.28	0.20
40t	6.46	7.06	4.62	3.43	3.91	3.04	1.98	0.98	0.57	0.37	0.26
50t	7.45	8.31	5.48	3.99	4.47	3.72	2.45	1.22	0.71	0.47	0.33
60t	8.32	9.25	6.28	4.51	4.84	4.37	2.90	1.46	0.85	0.56	0.40
100t	11.04	12.17	8.92	6.51	6.22	6.73	4.61	2.38	1.41	0.93	0.66
150t	13.47	14.72	11.44	8.70	7.71	9.05	6.53	3.49	2.09	1.38	0.98
200t	15.35	16.66	13.45	10.54	8.99	9.88	8.28	4.55	2.76	1.83	1.31
250t	16.89	18.24	15.14	12.12	10.14	10.76	9.87	5.57	3.42	2.28	1.63
300t	18.22	19.58	16.59	13.51	11.17	11.60	11.33	6.55	4.06	2.72	1.95
400t	20.44	21.81	19.04	15.91	13.01	13.17	13.95	8.40	5.31	3.60	2.59
600t	25.80	25.24	22.83	19.71	16.62	15.94	17.03	11.74	7.69	5.29	3.83
800t	29.88	27.94	25.70	22.73	19.67	18.33	19.07	14.71	9.91	6.93	5.06
1000t	31.96	30.22	28.12	25.29	22.29	20.45	20.96	17.38	12.00	8.50	6.27
1200t	33.82	32.23	30.23	27.53	24.59	22.38	22.72	19.81	13.98	10.03	7.45

RANGE 8000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	1.57	1.70	1.05	0.66	0.63	0.69	0.44	0.21	0.12	0.08	0.06
20t	2.87	3.42	1.99	1.28	1.16	1.36	0.87	0.42	0.24	0.16	0.11
30t	3.97	4.70	2.86	1.87	1.63	2.00	1.28	0.63	0.37	0.24	0.17
40t	4.94	5.80	3.65	2.43	2.06	2.62	1.69	0.83	0.49	0.32	0.23
50t	5.79	6.77	4.39	2.96	2.46	3.20	2.10	1.04	0.61	0.40	0.28
60t	6.56	7.63	5.08	3.47	2.84	3.76	2.49	1.24	0.73	0.48	0.34
100t	9.07	10.38	7.43	5.30	4.16	4.91	3.99	2.04	1.21	0.79	0.57
150t	11.41	12.88	9.79	7.24	5.55	6.03	5.72	3.00	1.79	1.19	0.85
200t	13.27	14.82	11.72	8.92	6.76	7.07	7.31	3.94	2.37	1.57	1.13
250t	14.82	16.42	13.37	10.40	7.85	8.02	8.79	4.84	2.94	1.96	1.41
300t	16.17	17.80	14.81	11.73	9.02	8.91	10.12	5.71	3.51	2.34	1.68
400t	18.44	20.09	17.27	14.04	11.13	10.53	11.85	7.38	4.61	3.10	2.23
600t	25.14	23.64	21.08	17.79	14.69	13.31	14.14	10.45	6.72	4.58	3.35
800t	28.58	26.44	24.01	20.82	17.66	15.69	16.24	13.23	8.72	6.02	4.42
1000t	30.73	28.80	26.48	23.40	20.23	17.80	18.16	15.77	10.62	7.43	5.44
1200t	32.64	30.87	28.65	25.67	22.53	19.71	19.93	18.11	12.44	8.79	6.47

TABLE A5- PAYLOAD AS A PERCENTAGE OF REQUIRED DISPLACEMENT
ALUMINIUM STRUCTURE, GAS TURBO ELECTRIC PROPULSION

RANGE 500nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	8.10	5.86	4.29	5.06	3.23	2.12	1.45	0.76	0.47	0.39	0.35
20t	11.65	9.07	7.04	8.49	5.74	3.93	2.76	1.49	0.92	0.76	0.69
30t	13.85	11.23	10.45	11.02	7.78	5.50	3.94	2.18	1.36	1.13	1.02
40t	15.41	12.84	13.13	12.99	9.49	6.88	5.02	2.84	1.79	1.48	1.34
50t	16.61	14.12	14.39	14.56	10.94	8.11	6.02	3.48	2.21	1.83	1.65
60t	17.58	15.17	15.13	15.28	12.20	9.21	6.94	4.08	2.62	2.16	1.95
100t	20.26	18.70	17.41	17.14	16.01	12.74	10.04	6.28	4.18	3.43	3.09
150t	22.37	22.44	19.96	18.83	19.07	15.93	13.03	8.64	5.94	4.84	4.37
200t	23.90	24.02	21.79	20.22	20.34	18.33	15.39	10.66	7.55	6.11	5.55
250t	25.12	25.27	23.23	21.42	21.40	20.26	17.35	12.44	9.02	7.28	6.63
300t	26.15	26.32	24.44	22.47	22.34	21.88	19.02	14.02	10.39	8.36	7.63
400t	27.88	28.08	26.43	24.54	24.00	24.27	21.78	16.75	12.83	10.30	9.47
600t	30.62	30.83	29.47	27.88	26.81	26.89	25.91	21.07	16.93	13.62	12.62
800t	33.63	33.05	31.88	30.48	29.16	29.11	29.04	24.46	20.30	16.69	15.31
1000t	35.80	34.98	33.94	32.68	31.24	31.09	31.31	27.29	23.19	19.44	17.68
1200t	37.46	36.72	35.77	34.61	33.28	32.89	33.06	29.73	25.72	21.91	19.81

RANGE 1000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	6.90	4.82	3.71	4.48	2.75	1.76	1.17	0.60	0.37	0.27	0.23
20t	10.21	7.70	7.14	7.66	4.99	3.30	2.25	1.18	0.72	0.53	0.47
30t	12.35	9.72	10.15	10.09	6.85	4.67	3.25	1.73	1.08	0.79	0.69
40t	13.89	11.26	11.82	12.02	8.45	5.91	4.18	2.27	1.42	1.04	0.92
50t	15.10	12.50	12.66	13.12	9.83	7.02	5.05	2.79	1.76	1.29	1.14
60t	16.09	13.54	13.39	13.65	11.06	8.04	5.87	3.30	2.10	1.53	1.35
100t	18.86	18.09	15.93	15.37	14.83	11.40	8.69	5.17	3.38	2.47	2.18
150t	21.06	21.35	18.54	17.06	17.56	14.54	11.51	7.24	4.88	3.56	3.16
200t	22.66	23.00	20.43	18.46	18.70	16.97	13.82	9.08	6.27	4.57	4.08
250t	23.95	24.31	21.94	19.66	19.71	18.95	15.76	10.72	7.56	5.54	4.95
300t	25.03	25.41	23.20	20.76	20.63	20.62	17.45	12.21	8.79	6.51	5.78
400t	26.85	27.24	25.28	23.06	22.31	22.77	20.26	14.84	11.03	8.33	7.32
600t	29.70	30.09	28.46	26.54	25.15	25.33	24.54	19.12	14.89	11.61	10.07
800t	33.19	32.39	30.95	29.25	27.54	27.55	27.82	22.54	18.15	14.50	12.48
1000t	35.35	34.37	33.08	31.53	29.76	29.54	29.94	25.43	21.00	17.10	14.66
1200t	37.04	36.14	34.96	33.52	31.88	31.36	31.67	27.94	23.53	19.47	16.64

RANGE 2000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	5.02	3.32	3.32	3.63	2.12	1.30	0.85	0.42	0.26	0.18	0.13
20t	7.85	5.59	6.51	6.40	3.94	2.49	1.65	0.83	0.52	0.35	0.27
30t	9.81	7.30	7.70	8.56	5.52	3.58	2.41	1.24	0.77	0.53	0.40
40t	11.29	8.68	8.66	9.32	6.92	4.60	3.13	1.63	1.03	0.70	0.53
50t	12.47	9.83	9.48	9.82	8.17	5.53	3.82	2.02	1.28	0.88	0.66
60t	13.46	11.50	10.29	10.30	9.30	6.41	4.47	2.40	1.52	1.05	0.79
100t	16.31	16.90	13.38	11.98	12.88	9.42	6.84	3.84	2.49	1.73	1.29
150t	18.66	19.33	16.03	13.71	14.30	12.39	9.35	5.50	3.64	2.55	1.91
200t	20.38	21.09	18.01	15.15	15.39	14.78	11.48	7.03	4.74	3.36	2.51
250t	21.76	22.50	19.60	16.59	16.39	16.79	13.34	8.44	5.79	4.13	3.09
300t	22.94	23.69	20.95	18.03	17.35	18.38	14.99	9.75	6.79	4.89	3.66
400t	24.89	25.65	23.17	20.43	19.08	19.74	17.82	12.13	8.69	6.35	4.76
600t	27.94	28.68	26.55	24.11	22.01	22.27	22.24	16.17	12.09	9.07	6.81
800t	32.56	31.10	29.20	26.98	24.56	24.52	25.40	19.54	15.08	11.56	8.74
1000t	34.48	33.17	31.44	29.38	27.11	26.56	27.21	22.44	17.77	13.86	10.63
1200t	36.21	35.01	33.42	31.49	29.33	28.42	28.91	25.00	20.20	16.00	12.43

RANGE 4000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	2.76	1.96	1.62	1.51	1.46	0.86	0.55	0.27	0.17	0.12	0.08
20t	4.73	3.80	2.98	2.42	2.78	1.68	1.08	0.54	0.35	0.23	0.16
30t	6.25	5.50	4.15	3.16	3.99	2.46	1.60	0.81	0.52	0.35	0.25
40t	7.49	7.13	5.18	3.80	5.07	3.20	2.11	1.08	0.69	0.47	0.33
50t	8.54	9.01	6.11	4.38	5.53	3.91	2.60	1.34	0.86	0.58	0.41
60t	9.45	10.38	6.94	4.90	5.73	4.59	3.07	1.60	1.03	0.70	0.49
100t	12.22	13.35	9.65	6.78	6.92	7.04	4.86	2.60	1.70	1.16	0.82
150t	14.65	15.89	12.18	9.02	8.34	9.61	6.86	3.80	2.51	1.73	1.22
200t	16.49	17.79	14.16	10.88	9.61	10.97	8.67	4.94	3.30	2.28	1.62
250t	17.99	19.32	15.80	12.48	10.74	11.71	10.30	6.03	4.07	2.83	2.01
300t	19.28	20.62	17.21	13.89	11.77	12.49	11.80	7.07	4.83	3.38	2.41
400t	21.43	22.78	19.57	16.30	13.60	14.01	14.47	9.03	6.28	4.44	3.18
600t	26.35	26.09	23.22	20.11	17.10	16.74	18.15	12.53	9.00	6.47	4.70
800t	30.78	28.71	26.08	23.14	20.17	19.13	20.10	15.60	11.51	8.41	6.17
1000t	32.81	30.93	28.49	25.69	22.79	21.26	21.98	18.35	13.83	10.25	7.59
1200t	34.63	32.89	30.60	27.93	25.10	23.20	23.74	20.83	16.01	12.01	8.98

RANGE 6000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	1.65	1.75	1.02	0.59	0.47	0.66	0.42	0.21	0.14	0.09	0.06
20t	2.99	3.58	1.95	1.14	0.89	1.29	0.83	0.42	0.27	0.18	0.13
30t	4.12	4.90	2.79	1.68	1.29	1.90	1.23	0.62	0.40	0.27	0.19
40t	5.10	6.03	3.56	2.19	1.66	2.48	1.62	0.83	0.54	0.36	0.26
50t	5.96	7.01	4.27	2.67	2.02	2.90	2.01	1.03	0.67	0.45	0.32
60t	6.74	7.89	4.93	3.14	2.35	3.05	2.38	1.23	0.80	0.54	0.38
100t	9.25	10.65	7.21	4.85	3.56	4.04	3.83	2.02	1.33	0.90	0.64
150t	11.58	13.15	9.48	6.69	4.87	5.20	5.51	2.98	1.98	1.34	0.95
200t	13.41	15.07	11.34	8.30	6.12	6.25	7.06	3.90	2.61	1.78	1.26
250t	14.95	16.66	12.93	9.74	7.33	7.22	8.49	4.80	3.24	2.22	1.58
300t	16.27	18.02	14.32	11.03	8.45	8.11	9.81	5.67	3.85	2.65	1.89
400t	18.51	20.28	16.70	13.31	10.50	9.73	11.03	7.33	5.05	3.50	2.50
600t	25.40	23.79	20.44	17.04	13.99	12.51	13.37	10.39	7.33	5.15	3.71
800t	29.10	26.55	23.40	20.07	16.93	14.91	15.53	13.16	9.49	6.75	4.91
1000t	31.23	28.88	25.91	22.67	19.50	17.04	17.50	15.69	11.53	8.30	6.08
1200t	33.12	30.93	28.11	24.95	21.79	18.98	19.32	18.03	13.47	9.79	7.22

RANGE 8000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	1.07	1.39	0.71	0.42	0.28	0.25	0.34	0.17	0.11	0.08	0.05
20t	2.01	2.58	1.38	0.83	0.55	0.49	0.68	0.34	0.23	0.15	0.11
30t	2.85	3.61	2.01	1.22	0.81	0.72	1.01	0.51	0.34	0.23	0.16
40t	3.61	4.53	2.60	1.60	1.08	0.95	1.33	0.68	0.45	0.30	0.22
50t	4.31	5.36	3.16	1.97	1.33	1.17	1.66	0.85	0.56	0.38	0.27
60t	4.95	6.12	3.69	2.33	1.59	1.39	1.97	1.02	0.67	0.45	0.32
100t	7.13	8.61	5.59	3.69	2.57	2.22	2.85	1.68	1.11	0.75	0.54
150t	9.27	10.98	7.58	5.22	3.72	3.16	3.75	2.49	1.66	1.12	0.80
200t	11.02	12.87	9.27	6.60	4.80	4.04	4.60	3.28	2.20	1.49	1.06
250t	12.51	14.45	10.76	7.86	5.83	4.86	5.39	4.05	2.73	1.86	1.32
300t	13.82	15.82	12.09	9.03	6.79	5.63	6.14	4.80	3.26	2.22	1.59
400t	18.21	18.13	14.40	11.13	8.59	7.07	7.52	6.25	4.29	2.94	2.13
600t	24.46	21.74	18.12	14.66	11.76	9.61	9.96	8.97	6.28	4.35	3.17
800t	27.52	24.59	21.11	17.62	14.51	11.99	12.11	11.49	8.18	5.73	4.15
1000t	29.73	27.01	23.66	20.18	16.96	14.25	14.06	13.83	10.00	7.07	5.14
1200t	31.69	29.13	25.90	22.46	19.18	16.33	15.85	16.03	11.75	8.37	6.20

TABLE A6- PAYLOAD AS A PERCENTAGE OF REQUIRED DISPLACEMENT
MILD STEEL STRUCTURE, GAS TURBINE PROPULSION

RANGE 500nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	10.15	9.20	8.13	8.36	6.19	4.22	2.71	1.06	0.44	0.20	0.10
20t	13.44	12.40	11.20	11.97	9.44	6.89	4.71	2.00	0.87	0.41	0.19
30t	15.17	14.14	12.93	14.09	11.53	8.79	6.27	2.83	1.27	0.60	0.29
40t	16.27	15.27	14.09	15.51	13.02	10.23	7.54	3.59	1.65	0.79	0.38
50t	17.05	16.08	16.65	16.55	14.16	11.38	8.60	4.27	2.02	0.98	0.48
60t	17.64	16.70	17.05	17.33	15.06	12.32	9.50	4.90	2.37	1.16	0.57
100t	19.08	18.24	18.06	18.15	17.39	14.90	12.12	6.97	3.65	1.86	0.93
150t	20.02	20.23	19.15	18.63	18.95	16.80	14.20	8.90	5.00	2.66	1.36
200t	20.60	20.83	19.85	18.97	19.16	18.05	15.63	10.38	6.15	3.39	1.78
250t	21.02	21.25	20.35	19.24	19.30	18.94	16.69	11.56	7.14	4.06	2.18
300t	21.34	21.57	20.73	19.57	19.42	19.63	17.52	12.54	8.02	4.68	2.56
400t	21.81	22.05	21.30	20.25	19.66	19.88	18.76	14.09	9.50	5.80	3.28
600t	23.08	22.68	22.05	21.16	20.09	20.08	20.32	16.23	11.75	7.65	4.58
800t	23.47	23.12	22.56	21.77	20.74	20.33	20.52	17.69	13.41	9.15	5.72
1000t	23.79	23.47	22.97	22.25	21.31	20.59	20.66	18.78	14.72	10.41	6.74
1200t	24.06	23.77	23.30	22.64	21.77	20.85	20.83	19.65	15.79	11.49	7.66

RANGE 1000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	8.54	7.28	6.00	6.75	4.52	2.83	1.72	0.65	0.29	0.14	0.07
20t	11.63	10.22	8.70	10.19	7.35	4.91	3.14	1.26	0.57	0.28	0.14
30t	13.35	11.92	10.36	12.37	9.34	6.54	4.34	1.83	0.84	0.41	0.21
40t	14.49	13.08	13.50	13.90	10.84	7.86	5.38	2.36	1.11	0.55	0.27
50t	15.31	13.93	14.64	15.05	12.03	8.95	6.29	2.86	1.36	0.68	0.34
60t	15.94	14.60	15.00	15.66	13.00	9.89	7.09	3.33	1.61	0.81	0.41
100t	17.52	17.94	16.14	16.09	15.64	12.60	9.60	4.97	2.55	1.31	0.67
150t	18.59	19.04	17.45	16.48	17.11	14.75	11.76	6.63	3.60	1.91	0.99
200t	19.28	19.73	18.28	16.80	17.12	16.21	13.32	7.99	4.53	2.46	1.31
250t	19.76	20.22	18.88	17.13	17.18	17.29	14.52	9.13	5.37	2.99	1.61
300t	20.14	20.60	19.35	17.70	17.28	17.95	15.49	10.11	6.14	3.49	1.90
400t	20.71	21.16	20.04	18.55	17.51	17.87	16.96	11.71	7.48	4.41	2.47
600t	22.53	21.90	20.95	19.67	18.08	17.99	18.59	14.03	9.63	6.01	3.52
800t	22.97	22.42	21.58	20.43	19.00	18.25	18.57	15.68	11.30	7.36	4.48
1000t	23.31	22.82	22.06	21.01	19.70	18.55	18.69	16.94	12.66	8.54	5.35
1200t	23.61	23.16	22.45	21.49	20.27	18.86	18.86	17.96	13.80	9.57	6.17

RANGE 2000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	5.96	4.51	3.64	4.77	2.83	1.63	0.94	0.36	0.17	0.08	0.04
20t	8.63	6.85	7.03	7.76	4.95	3.00	1.80	0.70	0.33	0.17	0.09
30t	10.25	8.38	9.72	9.87	6.62	4.18	2.58	1.03	0.50	0.25	0.13
40t	11.39	9.49	10.24	11.44	7.99	5.21	3.29	1.35	0.66	0.33	0.18
50t	12.25	10.35	10.63	11.68	9.14	6.12	3.95	1.66	0.82	0.41	0.22
60t	12.92	11.05	10.96	11.64	10.12	6.94	4.56	1.96	0.97	0.50	0.26
100t	14.70	15.52	12.92	11.81	12.96	9.52	6.63	3.07	1.57	0.81	0.43
150t	15.98	16.84	14.46	12.21	12.89	11.78	8.62	4.28	2.28	1.20	0.65
200t	16.81	17.68	15.49	12.90	12.78	13.43	10.18	5.36	2.94	1.57	0.85
250t	17.43	18.30	16.25	13.78	12.85	14.08	11.45	6.31	3.56	1.93	1.06
300t	17.90	18.77	16.84	14.48	12.98	13.80	12.51	7.16	4.14	2.27	1.26
400t	18.63	19.48	17.73	15.56	13.31	13.63	14.21	8.64	5.21	2.94	1.65
600t	21.46	20.42	18.91	17.00	14.81	13.84	14.59	10.96	7.04	4.15	2.41
800t	21.98	21.06	19.72	17.99	15.97	14.25	14.56	12.72	8.57	5.24	3.12
1000t	22.38	21.56	20.33	18.74	16.87	14.84	14.76	14.13	9.87	6.22	3.79
1200t	22.73	21.97	20.84	19.36	17.60	15.67	15.05	15.30	11.01	7.12	4.43

RANGE 4000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	2.86	1.95	1.74	2.96	1.57	0.85	0.48	0.18	0.09	0.05	0.03
20t	4.63	3.76	3.06	2.65	2.93	1.64	0.94	0.36	0.19	0.09	0.05
30t	5.90	5.56	4.12	2.78	4.12	2.37	1.38	0.54	0.28	0.14	0.08
40t	6.88	7.29	4.99	3.03	5.16	3.05	1.81	0.72	0.37	0.19	0.10
50t	7.66	8.82	5.74	3.41	4.68	3.68	2.21	0.89	0.46	0.23	0.13
60t	8.32	9.54	6.38	3.90	3.96	4.27	2.60	1.06	0.55	0.28	0.16
100t	10.17	11.56	8.32	5.49	3.99	6.32	4.03	1.71	0.90	0.46	0.26
150t	11.63	13.10	9.94	6.96	4.60	5.02	5.56	2.47	1.32	0.69	0.39
200t	12.64	14.14	11.11	8.09	5.57	4.98	6.86	3.19	1.73	0.91	0.52
250t	13.40	14.92	12.00	9.00	6.39	5.19	7.10	3.86	2.13	1.13	0.64
300t	14.01	15.53	12.72	9.76	7.10	5.46	6.40	4.48	2.52	1.35	0.77
400t	16.85	16.46	13.85	10.99	8.29	6.09	6.31	5.64	3.25	1.77	1.02
600t	19.43	17.71	15.39	12.73	10.08	7.77	6.92	7.61	4.59	2.57	1.51
800t	20.09	18.56	16.45	13.97	11.41	9.09	7.62	9.24	5.79	3.33	1.98
1000t	20.60	19.22	17.26	14.93	12.47	10.18	8.28	9.99	6.88	4.04	2.44
1200t	21.03	19.75	17.93	15.72	13.36	11.10	9.18	10.01	7.87	4.72	2.88

RANGE 6000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	1.43	1.69	0.88	0.42	0.22	0.13	0.33	0.13	0.07	0.03	0.02
20t	2.51	3.31	1.64	0.81	0.43	0.25	0.17	0.25	0.13	0.07	0.04
30t	3.39	4.40	2.30	1.17	0.63	0.37	0.25	0.37	0.19	0.10	0.06
40t	4.12	5.29	2.89	1.52	0.83	0.49	0.33	0.49	0.26	0.13	0.08
50t	4.74	6.04	3.42	1.84	1.02	0.61	0.41	0.61	0.32	0.17	0.10
60t	5.28	6.68	3.90	2.15	1.20	0.73	0.49	0.73	0.39	0.20	0.12
100t	6.93	8.59	5.47	3.23	1.89	1.17	0.80	1.20	0.64	0.33	0.19
150t	8.34	10.16	6.91	4.33	2.66	1.69	1.17	1.76	0.95	0.50	0.29
200t	9.37	11.27	8.01	5.26	3.34	2.18	1.52	2.29	1.25	0.66	0.38
250t	11.14	12.12	8.89	6.04	3.96	2.63	1.86	2.80	1.55	0.82	0.48
300t	12.90	12.80	9.64	6.73	4.51	3.06	2.19	3.28	1.83	0.98	0.57
400t	16.31	13.87	10.82	7.88	5.50	3.84	2.81	3.06	2.39	1.29	0.76
600t	17.54	15.32	12.51	9.61	7.09	5.19	3.92	3.77	3.45	1.90	1.13
800t	18.32	16.32	13.71	10.91	8.35	6.33	4.90	4.48	4.42	2.48	1.49
1000t	18.92	17.10	14.65	11.95	9.40	7.31	5.79	5.15	5.33	3.05	1.84
1200t	19.42	17.73	15.42	12.82	10.30	8.17	6.59	5.78	6.18	3.59	2.19

RANGE 8000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	0.77	1.16	0.51	0.24	0.13	0.08	0.06	0.04	0.05	0.03	0.02
20t	1.43	2.11	0.97	0.47	0.26	0.16	0.11	0.09	0.10	0.05	0.03
30t	2.00	2.91	1.40	0.70	0.38	0.23	0.16	0.13	0.15	0.08	0.05
40t	2.51	3.60	1.80	0.91	0.50	0.31	0.22	0.18	0.20	0.11	0.06
50t	2.96	4.20	2.17	1.12	0.62	0.39	0.27	0.22	0.25	0.13	0.08
60t	3.37	4.73	2.51	1.32	0.74	0.46	0.33	0.26	0.30	0.16	0.09
100t	4.71	6.40	3.71	2.06	1.19	0.76	0.54	0.42	0.50	0.26	0.16
150t	6.81	7.87	4.89	2.87	1.71	1.11	0.79	0.60	0.75	0.40	0.23
200t	8.69	8.96	5.85	3.58	2.20	1.44	1.04	0.77	0.99	0.52	0.31
250t	10.64	9.82	6.66	4.21	2.65	1.77	1.29	0.92	1.23	0.65	0.39
300t	12.36	10.53	7.35	4.78	3.08	2.08	1.52	1.08	1.46	0.78	0.46
400t	14.52	11.65	8.49	5.78	3.86	2.67	1.98	1.36	1.92	1.03	0.62
600t	15.78	13.22	10.20	7.37	5.19	3.73	2.84	1.88	2.79	1.53	0.92
800t	16.66	14.33	11.45	8.62	6.31	4.66	3.62	2.34	3.61	2.01	1.22
1000t	17.34	15.18	12.45	9.65	7.27	5.51	4.35	2.77	4.38	2.48	1.51
1200t	17.90	15.89	13.27	10.53	8.12	6.27	5.03	3.24	4.49	2.94	1.80

TABLE A7- PAYLOAD AS A PERCENTAGE OF REQUIRED DISPLACEMENT
MILD STEEL STRUCTURE, HIGH SPEED DIESEL PROPULSION

RANGE 500nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	16.50	14.84	12.97	10.99	8.79	5.86	3.61	1.29	0.47	0.19	0.09
20t	17.97	16.61	15.03	15.42	12.09	8.90	5.97	2.35	0.91	0.38	0.18
30t	18.74	17.54	16.13	17.02	13.99	10.86	7.69	3.29	1.33	0.57	0.27
40t	19.24	18.16	16.87	18.05	15.28	12.26	9.02	4.13	1.73	0.75	0.36
50t	19.61	18.61	17.41	18.78	16.24	13.33	10.10	4.88	2.11	0.93	0.45
60t	19.90	18.96	19.40	19.34	16.98	14.18	11.00	5.56	2.47	1.10	0.53
100t	20.66	19.88	19.76	19.84	18.85	16.46	13.52	7.73	3.78	1.77	0.87
150t	21.21	21.37	20.40	20.01	20.13	18.09	15.45	9.70	5.14	2.54	1.28
200t	21.58	21.75	20.90	20.22	20.35	19.13	16.74	11.17	6.30	3.24	1.67
250t	21.86	22.03	21.27	20.42	20.43	19.89	17.69	12.33	7.29	3.89	2.05
300t	22.08	22.25	21.56	20.58	20.48	20.46	18.43	13.29	8.16	4.49	2.41
400t	22.43	22.60	22.00	21.11	20.60	20.74	19.53	14.78	9.62	5.58	3.10
600t	23.43	23.10	22.61	21.84	20.91	20.85	20.94	16.81	11.83	7.40	4.35
800t	23.75	23.47	23.04	22.35	21.40	21.03	21.15	18.20	13.46	8.88	5.45
1000t	24.02	23.77	23.38	22.76	21.89	21.24	21.26	19.23	14.74	10.13	6.44
1200t	24.26	24.04	23.68	23.10	22.30	21.45	21.39	20.05	15.79	11.20	7.34

RANGE 1000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	14.16	12.12	10.01	9.21	6.65	4.30	2.53	0.88	0.33	0.14	0.07
20t	16.00	14.26	12.39	13.41	9.86	6.95	4.42	1.67	0.65	0.28	0.14
30t	16.97	15.41	13.71	15.27	11.89	8.80	5.90	2.38	0.96	0.42	0.21
40t	17.60	16.18	14.61	16.52	13.32	10.21	7.12	3.04	1.26	0.56	0.28
50t	18.07	16.75	16.97	17.42	14.40	11.32	8.14	3.65	1.55	0.69	0.34
60t	18.44	17.20	17.81	18.11	15.26	12.24	9.01	4.21	1.83	0.83	0.41
100t	19.40	18.37	18.23	18.40	17.50	14.76	11.59	6.10	2.86	1.34	0.68
150t	20.09	20.43	19.14	18.59	19.00	16.64	13.67	7.92	3.99	1.95	1.00
200t	20.56	20.90	19.77	18.86	19.12	17.87	15.11	9.34	4.97	2.51	1.31
250t	20.90	21.25	20.24	19.08	19.15	18.77	16.19	10.51	5.85	3.05	1.62
300t	21.18	21.52	20.60	19.36	19.17	19.46	17.04	11.48	6.64	3.55	1.91
400t	21.61	21.95	21.15	20.01	19.28	19.55	18.33	13.05	8.01	4.48	2.48
600t	22.98	22.53	21.90	20.89	19.60	19.58	19.92	15.26	10.16	6.10	3.53
800t	23.34	22.96	22.40	21.49	20.28	19.74	19.97	16.80	11.80	7.46	4.49
1000t	23.63	23.30	22.79	21.97	20.86	19.96	20.04	17.96	13.12	8.64	5.37
1200t	23.90	23.60	23.12	22.36	21.34	20.19	20.15	18.89	14.23	9.68	6.18

RANGE 2000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	10.34	8.03	6.01	7.12	4.32	2.67	1.51	0.52	0.21	0.09	0.05
20t	12.59	10.44	8.41	10.49	7.05	4.65	2.79	1.02	0.41	0.18	0.09
30t	13.82	11.83	10.70	12.58	8.99	6.21	3.89	1.48	0.60	0.28	0.14
40t	14.66	12.79	13.38	14.05	10.47	7.48	4.85	1.92	0.80	0.37	0.19
50t	15.28	13.52	14.54	15.16	11.64	8.54	5.70	2.34	0.99	0.46	0.24
60t	15.77	14.10	14.67	15.66	12.61	9.45	6.46	2.74	1.17	0.54	0.28
100t	17.06	17.72	15.58	15.49	15.26	12.13	8.87	4.17	1.88	0.89	0.47
150t	18.00	18.67	16.86	15.85	16.57	14.27	10.99	5.66	2.69	1.31	0.70
200t	18.62	19.30	17.70	16.25	16.61	15.75	12.55	6.92	3.43	1.71	0.92
250t	19.09	19.76	18.33	16.58	16.52	16.85	13.77	7.99	4.12	2.10	1.14
300t	19.46	20.13	18.82	17.13	16.52	17.30	14.76	8.92	4.76	2.48	1.35
400t	20.04	20.68	19.56	17.97	16.65	17.04	16.28	10.48	5.91	3.18	1.77
600t	22.11	21.43	20.55	19.09	17.27	16.99	17.67	12.81	7.83	4.47	2.57
800t	22.53	21.96	21.16	19.87	18.22	17.17	17.51	14.51	9.39	5.61	3.32
1000t	22.87	22.39	21.64	20.46	18.94	17.43	17.53	15.83	10.70	6.64	4.03
1200t	23.17	22.74	22.04	20.95	19.53	17.82	17.65	16.91	11.82	7.57	4.70

RANGE 4000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	5.43	3.63	3.46	4.35	2.45	1.44	0.80	0.28	0.11	0.05	0.03
20t	7.64	5.60	6.87	7.16	4.35	2.67	1.53	0.55	0.23	0.11	0.06
30t	9.02	6.93	8.03	9.19	5.90	3.75	2.21	0.81	0.34	0.16	0.09
40t	10.00	7.94	8.33	10.07	7.19	4.70	2.84	1.07	0.45	0.22	0.12
50t	10.76	9.43	8.72	9.64	8.29	5.56	3.43	1.32	0.56	0.27	0.15
60t	11.38	11.03	9.45	9.57	9.24	6.33	3.98	1.56	0.67	0.32	0.18
100t	13.06	14.26	11.51	10.15	11.60	8.80	5.88	2.48	1.09	0.53	0.29
150t	14.33	15.55	13.12	10.79	11.38	11.01	7.76	3.51	1.60	0.79	0.44
200t	15.19	16.42	14.23	11.83	11.14	12.63	9.26	4.44	2.08	1.05	0.58
250t	15.84	17.06	15.06	12.69	11.15	12.33	10.50	5.28	2.54	1.30	0.73
300t	16.36	17.56	15.73	13.39	11.25	11.95	11.56	6.05	2.99	1.54	0.87
400t	17.16	18.33	16.74	14.47	11.83	11.69	13.21	7.41	3.82	2.01	1.15
600t	20.42	19.37	18.04	15.94	13.51	11.85	12.48	9.62	5.31	2.91	1.69
800t	20.97	20.09	18.86	16.95	14.70	12.27	12.36	11.35	6.61	3.75	2.21
1000t	21.40	20.64	19.49	17.73	15.62	13.29	12.51	12.77	7.76	4.53	2.72
1200t	21.77	21.11	20.01	18.37	16.37	14.14	12.75	13.97	8.79	5.27	3.21

RANGE 6000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	2.92	1.83	1.96	3.10	1.68	0.97	0.53	0.19	0.08	0.04	0.02
20t	4.63	3.83	3.20	3.78	3.11	1.84	1.04	0.37	0.16	0.08	0.04
30t	5.83	5.57	4.29	3.83	4.35	2.65	1.52	0.56	0.24	0.12	0.07
40t	6.76	7.17	5.19	4.26	5.44	3.38	1.98	0.73	0.31	0.16	0.09
50t	7.50	8.72	5.95	4.68	6.38	4.07	2.42	0.91	0.39	0.19	0.11
60t	8.12	9.53	6.61	5.09	6.54	4.70	2.84	1.08	0.47	0.23	0.13
100t	9.90	11.45	8.61	6.23	5.78	6.85	4.35	1.75	0.77	0.39	0.22
150t	11.31	12.92	10.29	7.73	5.76	7.65	5.95	2.53	1.14	0.58	0.33
200t	12.31	13.93	11.49	8.85	6.15	6.52	7.30	3.25	1.50	0.76	0.44
250t	13.07	14.69	12.43	9.74	6.98	6.34	8.44	3.92	1.84	0.95	0.55
300t	13.68	15.30	13.19	10.48	7.70	6.38	8.22	4.56	2.18	1.13	0.65
400t	16.85	16.22	14.38	11.65	8.88	6.67	7.23	5.72	2.83	1.49	0.86
600t	18.83	17.48	15.81	13.29	10.62	8.09	7.22	7.69	4.02	2.18	1.28
800t	19.48	18.35	16.78	14.46	11.90	9.37	7.61	9.32	5.11	2.84	1.69
1000t	19.99	19.02	17.53	15.36	12.91	10.42	8.13	9.99	6.10	3.47	2.09
1200t	20.42	19.58	18.15	16.10	13.74	11.30	8.99	9.50	7.02	4.08	2.48

RANGE 8000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	1.67	1.77	1.14	0.64	1.28	0.73	0.40	0.14	0.06	0.03	0.02
20t	2.87	3.45	2.08	1.21	0.62	1.41	0.79	0.28	0.12	0.06	0.04
30t	3.81	4.96	2.89	1.73	0.91	2.04	1.16	0.42	0.18	0.09	0.05
40t	4.58	5.89	3.59	2.20	1.18	2.64	1.52	0.56	0.24	0.12	0.07
50t	5.23	6.65	4.22	2.63	1.44	3.20	1.87	0.70	0.30	0.15	0.09
60t	5.78	7.30	4.78	3.03	1.69	3.72	2.21	0.83	0.36	0.19	0.11
100t	7.47	9.19	6.56	4.37	2.59	1.53	3.46	1.36	0.60	0.31	0.18
150t	8.89	10.73	8.16	5.66	3.54	2.17	1.86	1.98	0.89	0.46	0.27
200t	9.93	11.81	9.37	6.68	4.35	2.76	2.07	2.57	1.18	0.61	0.36
250t	10.74	12.64	10.33	7.52	5.06	3.29	2.31	3.13	1.46	0.76	0.44
300t	12.90	13.31	11.13	8.24	5.69	3.78	2.54	3.67	1.73	0.91	0.53
400t	16.26	14.34	12.28	9.40	6.76	4.65	3.16	4.67	2.26	1.20	0.71
600t	17.32	15.76	13.83	11.10	8.42	6.11	4.33	4.61	3.26	1.77	1.05
800t	18.07	16.75	14.91	12.34	9.69	7.29	5.34	4.42	4.19	2.32	1.39
1000t	18.65	17.52	15.75	13.31	10.72	8.28	6.22	4.70	5.06	2.85	1.72
1200t	19.13	18.15	16.44	14.12	11.59	9.14	7.01	5.05	5.88	3.36	2.05

TABLE A8- PAYLOAD AS A PERCENTAGE OF REQUIRED DISPLACEMENT
MILD STEEL STRUCTURE, MEDIUM SPEED DIESEL PROPULSION

RANGE 500nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	15.86	13.79	11.46	9.45	7.08	4.20	2.40	0.81	0.29	0.12	0.06
20t	17.44	15.71	13.67	14.20	10.31	6.81	4.22	1.55	0.57	0.24	0.11
30t	18.26	16.72	14.86	15.98	12.30	8.66	5.67	2.23	0.85	0.35	0.17
40t	18.80	17.38	15.66	17.14	13.70	10.06	6.87	2.85	1.11	0.47	0.23
50t	19.20	17.87	17.29	17.98	14.76	11.19	7.88	3.43	1.37	0.58	0.28
60t	19.51	18.26	18.66	18.63	15.60	12.11	8.76	3.97	1.62	0.70	0.34
100t	20.32	19.26	18.97	18.95	17.77	14.66	11.35	5.80	2.55	1.14	0.56
150t	20.90	21.03	19.71	19.02	19.22	16.57	13.45	7.57	3.58	1.66	0.82
200t	21.30	21.44	20.27	19.16	19.24	17.82	14.92	8.98	4.50	2.15	1.08
250t	21.59	21.75	20.68	19.32	19.25	18.74	16.03	10.14	5.33	2.62	1.34
300t	21.82	21.99	21.00	19.58	19.28	19.43	16.90	11.12	6.08	3.07	1.59
400t	22.19	22.36	21.49	20.23	19.41	19.51	18.21	12.70	7.39	3.91	2.08
600t	23.34	22.89	22.15	21.09	19.77	19.61	19.79	14.94	9.49	5.39	2.99
800t	23.67	23.28	22.63	21.70	20.45	19.83	19.89	16.50	11.13	6.67	3.83
1000t	23.95	23.59	23.01	22.16	21.03	20.09	20.04	17.70	12.46	7.79	4.62
1200t	24.20	23.87	23.34	22.56	21.51	20.35	20.17	18.65	13.57	8.79	5.36

RANGE 1000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	13.74	11.38	8.94	8.87	5.54	3.18	1.81	0.64	0.23	0.10	0.05
20t	15.63	13.57	11.32	12.50	8.56	5.40	3.28	1.23	0.46	0.20	0.10
30t	16.62	14.76	12.67	14.46	10.56	7.09	4.52	1.78	0.69	0.30	0.15
40t	17.28	15.56	14.18	15.79	12.03	8.44	5.58	2.30	0.90	0.39	0.19
50t	17.76	16.15	16.91	16.76	13.16	9.54	6.50	2.79	1.12	0.49	0.24
60t	18.14	16.61	17.12	17.51	14.08	10.47	7.32	3.25	1.32	0.58	0.29
100t	19.12	18.40	17.47	17.50	16.52	13.14	9.84	4.86	2.11	0.95	0.48
150t	19.84	20.14	18.49	17.53	17.98	15.22	11.99	6.49	3.00	1.40	0.71
200t	20.31	20.63	19.16	17.69	17.86	16.62	13.54	7.82	3.81	1.83	0.94
250t	20.67	20.99	19.65	17.87	17.83	17.66	14.72	8.94	4.55	2.23	1.16
300t	20.95	21.28	20.03	18.33	17.86	18.30	15.67	9.90	5.23	2.63	1.38
400t	21.38	21.72	20.61	19.09	18.03	18.22	17.12	11.48	6.45	3.37	1.81
600t	22.91	22.32	21.40	20.12	18.50	18.33	18.68	13.79	8.45	4.71	2.62
800t	23.27	22.76	21.95	20.82	19.39	18.61	18.76	15.44	10.04	5.89	3.38
1000t	23.57	23.12	22.38	21.36	20.06	18.94	18.94	16.71	11.37	6.95	4.10
1200t	23.84	23.42	22.75	21.81	20.61	19.23	19.05	17.74	12.49	7.90	4.77

RANGE 2000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	10.22	7.69	5.46	6.67	3.76	2.08	1.18	0.44	0.17	0.07	0.04
20t	12.45	10.06	7.73	9.98	6.27	3.74	2.23	0.85	0.33	0.15	0.08
30t	13.68	11.44	10.54	12.09	8.12	5.11	3.15	1.25	0.49	0.22	0.11
40t	14.51	12.39	13.26	13.59	9.57	6.27	3.99	1.63	0.65	0.29	0.15
50t	15.13	13.10	13.96	14.73	10.74	7.27	4.74	2.00	0.81	0.37	0.19
60t	15.61	13.67	14.04	14.90	11.71	8.15	5.43	2.35	0.96	0.44	0.23
100t	16.89	17.49	14.98	14.48	14.45	10.81	7.69	3.62	1.56	0.72	0.37
150t	17.82	18.46	16.26	14.56	15.22	13.04	9.78	4.98	2.25	1.07	0.56
200t	18.44	19.09	17.10	14.80	15.01	14.62	11.36	6.15	2.89	1.40	0.74
250t	18.90	19.55	17.73	15.43	14.98	15.75	12.62	7.17	3.50	1.72	0.92
300t	19.27	19.92	18.22	16.06	15.06	15.72	13.66	8.07	4.07	2.04	1.09
400t	19.83	20.47	18.96	17.01	15.33	15.60	15.28	9.59	5.11	2.64	1.44
600t	22.06	21.23	19.95	18.29	16.36	15.84	16.37	11.92	6.89	3.76	2.11
800t	22.48	21.76	20.64	19.17	17.44	16.30	16.53	13.65	8.38	4.77	2.74
1000t	22.83	22.18	21.18	19.84	18.27	16.73	16.68	15.02	9.65	5.70	3.35
1200t	23.12	22.54	21.62	20.39	18.94	17.24	16.80	16.14	10.76	6.56	3.93

RANGE 4000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	5.55	3.57	3.44	4.22	2.21	1.19	0.68	0.26	0.11	0.05	0.03
20t	7.75	5.48	6.66	6.99	3.98	2.25	1.32	0.52	0.21	0.10	0.05
30t	9.10	6.77	7.63	9.00	5.44	3.20	1.92	0.77	0.31	0.15	0.08
40t	10.06	7.73	7.81	9.32	6.68	4.05	2.49	1.01	0.42	0.20	0.11
50t	10.81	9.42	8.33	8.70	7.74	4.83	3.02	1.25	0.52	0.25	0.13
60t	11.40	11.12	9.03	8.46	8.67	5.54	3.52	1.48	0.62	0.30	0.16
100t	13.03	14.17	11.00	8.55	9.77	7.89	5.28	2.36	1.01	0.49	0.27
150t	14.25	15.44	12.54	9.52	9.22	10.08	7.07	3.35	1.49	0.73	0.40
200t	15.08	16.28	13.60	10.70	9.35	10.72	8.54	4.25	1.94	0.96	0.53
250t	15.71	16.91	14.40	11.61	9.63	10.36	9.77	5.07	2.38	1.19	0.66
300t	16.20	17.40	15.04	12.36	9.94	10.32	10.82	5.82	2.80	1.41	0.79
400t	16.97	18.15	16.01	13.53	11.06	10.60	11.77	7.16	3.59	1.85	1.04
600t	20.42	19.16	17.33	15.14	12.90	11.49	11.94	9.33	5.01	2.69	1.54
800t	20.95	19.86	18.24	16.27	14.21	12.15	12.03	11.06	6.27	3.47	2.02
1000t	21.38	20.40	18.93	17.13	15.23	13.17	12.19	12.48	7.39	4.21	2.48
1200t	21.74	20.86	19.50	17.83	16.07	14.02	12.44	13.64	8.40	4.91	2.94

RANGE 6000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	3.05	1.95	1.74	3.06	1.55	0.83	0.48	0.19	0.08	0.04	0.02
20t	4.77	3.81	3.03	2.29	2.89	1.60	0.94	0.37	0.15	0.08	0.04
30t	5.96	5.56	4.06	2.48	4.07	2.31	1.38	0.55	0.23	0.11	0.06
40t	6.87	7.17	4.91	2.79	5.08	2.98	1.80	0.73	0.31	0.15	0.08
50t	7.60	8.72	5.62	3.31	3.63	3.60	2.20	0.91	0.38	0.19	0.11
60t	8.20	9.57	6.25	3.78	3.46	4.18	2.59	1.08	0.46	0.23	0.13
100t	9.92	11.43	8.12	5.34	3.90	6.15	4.00	1.74	0.75	0.37	0.21
150t	11.28	12.86	9.69	6.79	4.65	5.04	5.52	2.52	1.12	0.56	0.31
200t	12.22	13.84	10.82	7.91	5.64	5.35	6.81	3.24	1.47	0.74	0.42
250t	12.94	14.57	11.69	8.82	6.48	5.77	7.12	3.91	1.81	0.92	0.52
300t	13.53	15.15	12.40	9.59	7.21	6.20	7.05	4.54	2.14	1.09	0.62
400t	16.77	16.05	13.51	10.81	8.45	6.96	7.47	5.70	2.77	1.44	0.83
600t	18.85	17.25	15.04	12.58	10.31	8.25	7.40	7.66	3.95	2.11	1.23
800t	19.49	18.09	16.10	13.84	11.70	9.53	7.77	9.30	5.03	2.75	1.62
1000t	19.99	18.74	16.92	14.82	12.81	10.58	8.21	9.79	6.01	3.37	2.00
1200t	20.41	19.27	17.59	15.63	13.74	11.46	9.08	9.38	6.92	3.96	2.38

RANGE 8000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	1.75	1.81	1.05	0.51	0.28	0.64	0.37	0.15	0.06	0.03	0.02
20t	2.97	3.51	1.93	0.98	0.55	1.23	0.73	0.29	0.12	0.06	0.04
30t	3.91	5.06	2.68	1.41	0.82	0.68	1.07	0.43	0.18	0.09	0.05
40t	4.67	5.97	3.33	1.81	1.07	0.87	1.41	0.57	0.25	0.12	0.07
50t	5.31	6.72	3.90	2.19	1.31	1.05	1.74	0.71	0.31	0.15	0.09
60t	5.85	7.36	4.42	2.54	1.54	1.22	2.05	0.85	0.37	0.18	0.11
100t	7.48	9.20	6.06	3.75	2.39	1.84	2.36	1.39	0.61	0.31	0.18
150t	8.84	10.69	7.52	4.97	3.32	2.32	2.84	2.02	0.90	0.46	0.26
200t	9.83	11.73	8.63	5.96	4.13	2.93	2.59	2.62	1.19	0.61	0.35
250t	10.59	12.52	9.51	6.80	4.85	3.49	2.74	3.19	1.47	0.76	0.44
300t	13.03	13.16	10.24	7.52	5.49	3.99	2.94	3.73	1.74	0.90	0.52
400t	16.34	14.15	11.40	8.72	6.61	4.90	3.34	4.74	2.28	1.19	0.70
600t	17.37	15.51	13.04	10.50	8.38	6.39	4.52	5.47	3.28	1.76	1.03
800t	18.09	16.46	14.21	11.82	9.76	7.59	5.54	4.80	4.22	2.30	1.37
1000t	18.66	17.19	15.11	12.86	10.89	8.59	6.44	5.00	5.09	2.83	1.70
1200t	19.13	17.79	15.86	13.73	11.85	9.46	7.24	5.32	5.91	3.34	2.02

TABLE A9- PAYLOAD AS A PERCENTAGE OF REQUIRED DISPLACEMENT
MILD STEEL STRUCTURE, DIESEL ELECTRIC PROPULSION

RANGE 500nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	5.67	3.76	3.49	3.56	2.11	1.30	0.82	0.37	0.19	0.11	0.06
20t	8.39	6.04	6.37	6.13	3.83	2.44	1.58	0.72	0.37	0.21	0.13
30t	10.11	7.63	7.47	7.44	5.29	3.46	2.29	1.07	0.55	0.31	0.19
40t	11.35	8.85	8.31	8.09	6.53	4.38	2.94	1.40	0.73	0.42	0.26
50t	12.29	9.82	9.00	8.62	7.61	5.21	3.55	1.72	0.90	0.52	0.32
60t	13.04	11.21	9.79	9.04	8.56	5.97	4.13	2.03	1.08	0.62	0.38
100t	15.05	15.01	12.15	10.42	10.42	8.45	6.11	3.19	1.74	1.01	0.63
150t	16.51	16.56	13.98	11.64	11.34	10.72	8.07	4.45	2.50	1.48	0.93
200t	17.46	17.57	15.21	12.75	11.99	12.14	9.63	5.56	3.22	1.93	1.23
250t	18.16	18.29	16.12	13.77	12.56	12.60	10.92	6.55	3.88	2.37	1.52
300t	18.70	18.86	16.83	14.59	13.05	12.98	12.00	7.44	4.51	2.79	1.80
400t	19.50	19.69	17.90	15.84	13.88	13.60	13.72	8.96	5.64	3.58	2.34
600t	21.97	20.77	19.28	17.49	15.54	14.61	14.63	11.34	7.56	5.00	3.36
800t	22.52	21.49	20.19	18.60	16.83	15.44	15.29	13.13	9.15	6.24	4.30
1000t	22.94	22.04	20.87	19.43	17.80	16.13	15.85	14.55	10.48	7.36	5.16
1200t	23.30	22.48	21.41	20.09	18.57	16.92	16.36	15.72	11.64	8.36	5.97

RANGE 1000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	4.97	3.23	3.42	3.30	1.92	1.17	0.73	0.32	0.16	0.09	0.05
20t	7.52	5.30	5.40	5.62	3.53	2.22	1.42	0.63	0.32	0.18	0.11
30t	9.18	6.79	6.46	6.43	4.90	3.16	2.06	0.93	0.47	0.26	0.16
40t	10.38	7.95	7.28	7.03	6.09	4.02	2.65	1.23	0.62	0.35	0.21
50t	11.32	9.40	8.17	7.52	7.13	4.81	3.22	1.51	0.77	0.43	0.27
60t	12.08	11.06	8.98	7.96	8.05	5.53	3.75	1.79	0.92	0.52	0.32
100t	14.12	14.24	11.32	9.39	9.43	7.92	5.61	2.82	1.50	0.85	0.52
150t	15.62	15.84	13.16	10.58	10.24	10.14	7.48	3.98	2.17	1.26	0.78
200t	16.62	16.88	14.42	11.90	10.89	11.15	9.00	5.01	2.80	1.65	1.03
250t	17.35	17.64	15.36	12.93	11.46	11.55	10.27	5.93	3.40	2.02	1.27
300t	17.92	18.23	16.10	13.75	11.95	11.89	11.35	6.77	3.96	2.39	1.51
400t	18.77	19.11	17.22	15.03	12.77	12.48	12.81	8.23	5.00	3.08	1.98
600t	21.54	20.25	18.67	16.73	14.65	13.49	13.55	10.55	6.79	4.35	2.86
800t	22.12	21.02	19.62	17.88	15.97	14.32	14.16	12.34	8.30	5.49	3.69
1000t	22.57	21.59	20.33	18.75	16.97	15.08	14.72	13.77	9.59	6.52	4.46
1200t	22.94	22.06	20.90	19.44	17.78	15.98	15.24	14.96	10.72	7.46	5.19

RANGE 2000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	3.82	2.41	2.45	2.80	1.64	0.98	0.60	0.25	0.12	0.07	0.04
20t	6.03	4.10	3.77	3.78	3.04	1.88	1.17	0.50	0.24	0.13	0.08
30t	7.54	5.74	4.93	4.48	4.27	2.70	1.70	0.74	0.36	0.20	0.12
40t	8.68	7.39	5.96	5.08	5.36	3.45	2.21	0.98	0.48	0.26	0.16
50t	9.59	8.98	6.84	5.62	6.13	4.15	2.70	1.21	0.60	0.33	0.20
60t	10.33	10.42	7.59	6.09	6.45	4.81	3.16	1.43	0.71	0.39	0.24
100t	12.39	12.82	9.84	7.46	7.35	7.02	4.81	2.29	1.17	0.65	0.39
150t	13.96	14.48	11.68	9.07	8.11	8.70	6.53	3.27	1.71	0.96	0.59
200t	15.02	15.58	12.98	10.37	8.77	9.04	7.96	4.16	2.22	1.26	0.78
250t	15.81	16.40	13.97	11.39	9.34	9.37	9.18	4.97	2.71	1.56	0.96
300t	16.43	17.04	14.75	12.22	9.83	9.67	10.18	5.72	3.18	1.85	1.15
400t	17.38	17.99	15.95	13.52	11.07	10.27	10.71	7.06	4.06	2.41	1.51
600t	20.71	19.25	17.49	15.31	13.01	11.31	11.33	9.26	5.63	3.45	2.21
800t	21.34	20.09	18.52	16.53	14.38	12.21	11.94	11.00	6.99	4.41	2.87
1000t	21.83	20.73	19.29	17.46	15.43	13.34	12.52	12.44	8.18	5.30	3.51
1200t	22.23	21.25	19.91	18.20	16.29	14.27	13.06	13.60	9.25	6.13	4.11

RANGE 4000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	2.30	1.86	1.33	0.90	1.15	0.74	0.44	0.18	0.08	0.04	0.03
20t	3.89	3.63	2.42	1.55	1.77	1.43	0.86	0.35	0.17	0.09	0.05
30t	5.09	5.20	3.36	2.08	2.04	2.08	1.27	0.52	0.25	0.13	0.08
40t	6.05	6.64	4.17	2.64	2.33	2.68	1.66	0.69	0.33	0.18	0.11
50t	6.85	7.51	4.88	3.16	2.60	3.26	2.03	0.86	0.41	0.22	0.13
60t	7.52	8.25	5.51	3.63	2.85	3.75	2.40	1.02	0.49	0.27	0.16
100t	9.50	10.38	7.51	5.22	3.69	3.99	3.73	1.65	0.81	0.44	0.27
150t	11.10	12.08	9.27	6.73	4.59	4.40	5.19	2.39	1.19	0.65	0.40
200t	12.23	13.26	10.57	7.90	5.59	4.86	5.82	3.09	1.56	0.86	0.53
250t	13.09	14.15	11.59	8.86	6.44	5.28	5.83	3.74	1.92	1.07	0.65
300t	13.78	14.86	12.42	9.67	7.18	5.67	5.97	4.36	2.27	1.28	0.78
400t	16.90	15.93	13.68	10.96	8.43	6.35	6.33	5.49	2.94	1.68	1.04
600t	19.10	17.38	15.34	12.81	10.30	8.03	7.15	7.43	4.18	2.45	1.53
800t	19.83	18.36	16.48	14.12	11.69	9.39	7.89	9.00	5.31	3.18	2.01
1000t	20.40	19.10	17.35	15.13	12.79	10.50	8.55	9.43	6.33	3.87	2.48
1200t	20.86	19.70	18.05	15.96	13.70	11.45	9.36	9.61	7.27	4.53	2.93

RANGE 6000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	1.44	1.70	0.90	0.51	0.28	0.18	0.35	0.14	0.06	0.03	0.02
20t	2.55	3.05	1.69	0.97	0.54	0.35	0.68	0.27	0.13	0.07	0.04
30t	3.46	4.12	2.39	1.41	0.80	0.50	1.00	0.40	0.19	0.10	0.06
40t	4.23	5.01	3.02	1.81	1.05	0.65	1.30	0.54	0.25	0.14	0.08
50t	4.89	5.77	3.59	2.19	1.28	0.78	0.83	0.67	0.31	0.17	0.10
60t	5.47	6.42	4.11	2.55	1.51	0.92	0.93	0.79	0.38	0.20	0.12
100t	7.25	8.41	5.83	3.80	2.35	1.48	1.31	1.30	0.62	0.34	0.20
150t	8.79	10.08	7.44	5.05	3.26	2.11	1.72	1.89	0.92	0.50	0.30
200t	9.91	11.28	8.68	6.08	4.06	2.69	2.09	2.46	1.21	0.67	0.41
250t	10.79	12.20	9.68	6.94	4.77	3.23	2.41	3.01	1.50	0.83	0.51
300t	13.08	12.94	10.47	7.68	5.40	3.72	2.71	3.53	1.78	0.99	0.60
400t	16.38	14.10	11.71	8.91	6.49	4.62	3.27	4.47	2.32	1.30	0.80
600t	17.58	15.67	13.44	10.74	8.22	6.11	4.49	4.64	3.35	1.92	1.19
800t	18.40	16.76	14.65	12.07	9.56	7.34	5.54	4.96	4.30	2.51	1.57
1000t	19.03	17.59	15.59	13.13	10.64	8.37	6.47	5.38	5.19	3.08	1.94
1200t	19.55	18.26	16.35	13.99	11.56	9.27	7.29	5.81	6.02	3.62	2.31

RANGE 8000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	0.93	1.23	0.64	0.35	0.19	0.11	0.07	0.11	0.05	0.03	0.02
20t	1.72	2.24	1.23	0.68	0.38	0.22	0.14	0.22	0.10	0.06	0.03
30t	2.40	3.09	1.77	0.99	0.56	0.33	0.21	0.33	0.15	0.08	0.05
40t	3.00	3.82	2.26	1.29	0.73	0.44	0.28	0.20	0.21	0.11	0.07
50t	3.53	4.47	2.72	1.58	0.90	0.54	0.35	0.25	0.26	0.14	0.08
60t	4.01	5.04	3.15	1.85	1.07	0.65	0.41	0.30	0.31	0.17	0.10
100t	5.55	6.84	4.61	2.82	1.69	1.05	0.68	0.47	0.51	0.28	0.17
150t	6.95	8.42	6.05	3.85	2.40	1.52	1.00	0.68	0.76	0.41	0.25
200t	8.92	9.59	7.17	4.73	3.03	1.96	1.31	0.87	1.00	0.55	0.33
250t	10.81	10.51	8.06	5.48	3.61	2.37	1.60	1.05	1.24	0.68	0.42
300t	12.58	11.27	8.80	6.15	4.14	2.77	1.89	1.22	1.47	0.81	0.50
400t	14.85	12.47	10.01	7.28	5.08	3.49	2.43	1.55	1.93	1.08	0.66
600t	16.14	14.13	11.76	9.03	6.63	4.76	3.41	2.13	2.81	1.59	0.99
800t	17.04	15.29	13.02	10.34	7.87	5.84	4.29	2.65	3.63	2.09	1.31
1000t	17.73	16.19	13.99	11.40	8.91	6.77	5.09	3.12	4.39	2.58	1.62
1200t	18.29	16.92	14.80	12.29	9.81	7.61	5.82	3.56	4.72	3.05	1.93

TABLE A10- PAYLOAD AS A PERCENTAGE OF REQUIRED DISPLACEMENT
MILD STEEL STRUCTURE, GAS-TURBO ELECTRIC PROPULSION

RANGE 500nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	6.27	4.44	3.58	4.12	2.57	1.64	1.09	0.52	0.29	0.17	0.11
20t	9.11	6.95	6.84	6.92	4.57	3.04	2.06	1.02	0.57	0.35	0.21
30t	10.87	8.64	8.95	8.98	6.20	4.25	2.95	1.49	0.85	0.51	0.32
40t	12.11	9.89	9.80	9.92	7.55	5.32	3.75	1.94	1.11	0.68	0.42
50t	13.05	10.87	10.49	10.45	8.69	6.26	4.49	2.37	1.37	0.84	0.53
60t	13.79	11.67	11.06	10.88	9.68	7.10	5.16	2.78	1.62	1.00	0.63
100t	15.75	15.80	13.30	12.14	12.42	9.75	7.42	4.26	2.57	1.62	1.03
150t	17.14	17.27	15.05	13.25	13.25	12.06	9.54	5.81	3.64	2.34	1.51
200t	18.04	18.22	16.21	14.07	13.87	13.74	11.16	7.12	4.60	3.01	1.97
250t	18.69	18.90	17.05	15.03	14.37	14.65	12.46	8.24	5.46	3.63	2.41
300t	19.20	19.42	17.71	15.80	14.82	14.99	13.53	9.22	6.25	4.22	2.83
400t	19.95	20.19	18.68	16.96	15.56	15.55	15.20	10.85	7.64	5.29	3.63
600t	22.18	21.19	19.94	18.49	16.89	16.44	16.65	13.26	9.86	7.12	5.05
800t	22.70	21.85	20.77	19.49	18.06	17.17	17.23	15.00	11.58	8.63	6.29
1000t	23.11	22.36	21.40	20.24	18.94	17.79	17.73	16.34	12.97	9.91	7.39
1200t	23.45	22.77	21.90	20.84	19.65	18.34	18.18	17.41	14.13	11.03	8.38

RANGE 1000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	5.23	3.56	3.45	3.63	2.18	1.34	0.86	0.39	0.22	0.13	0.08
20t	7.84	5.75	6.30	6.23	3.95	2.53	1.65	0.77	0.43	0.25	0.15
30t	9.51	7.29	7.35	7.75	5.42	3.57	2.38	1.14	0.63	0.37	0.23
40t	10.72	8.47	8.16	8.28	6.68	4.51	3.06	1.49	0.84	0.50	0.30
50t	11.66	9.41	8.81	8.73	7.77	5.36	3.69	1.83	1.04	0.62	0.37
60t	12.41	11.12	9.63	9.09	8.72	6.13	4.28	2.16	1.23	0.73	0.45
100t	14.41	14.69	11.94	10.30	10.71	8.63	6.30	3.37	1.98	1.20	0.74
150t	15.88	16.23	13.72	11.38	11.39	10.90	8.28	4.69	2.84	1.75	1.09
200t	16.84	17.24	14.93	12.51	11.95	12.50	9.85	5.84	3.63	2.27	1.43
250t	17.54	17.96	15.82	13.51	12.45	12.87	11.14	6.85	4.36	2.76	1.76
300t	18.09	18.53	16.52	14.32	12.89	13.14	12.22	7.76	5.04	3.24	2.08
400t	18.91	19.36	17.56	15.54	13.64	13.63	13.95	9.30	6.26	4.12	2.69
600t	21.64	20.45	18.93	17.18	15.30	14.52	14.84	11.69	8.30	5.68	3.82
800t	22.20	21.17	19.85	18.28	16.56	15.27	15.37	13.47	9.95	7.02	4.85
1000t	22.64	21.72	20.53	19.11	17.52	15.92	15.87	14.88	11.33	8.19	5.79
1200t	23.00	22.17	21.08	19.77	18.29	16.73	16.35	16.03	12.50	9.24	6.65

RANGE 2000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	3.64	2.32	2.45	2.94	1.66	0.98	0.60	0.26	0.14	0.08	0.05
20t	5.78	3.95	3.69	3.97	3.09	1.87	1.17	0.51	0.28	0.16	0.09
30t	7.26	5.70	4.85	4.48	4.33	2.69	1.70	0.76	0.42	0.24	0.14
40t	8.37	7.34	5.86	4.95	5.42	3.44	2.21	1.00	0.55	0.31	0.19
50t	9.26	9.11	6.71	5.37	6.33	4.14	2.70	1.24	0.69	0.39	0.23
60t	9.99	10.52	7.45	5.74	6.56	4.79	3.16	1.47	0.82	0.47	0.28
100t	12.02	12.69	9.62	6.95	7.01	7.00	4.81	2.35	1.34	0.77	0.46
150t	13.57	14.32	11.40	8.66	7.68	8.75	6.52	3.35	1.95	1.14	0.68
200t	14.62	15.41	12.65	9.93	8.29	8.85	7.95	4.25	2.53	1.49	0.90
250t	15.40	16.22	13.60	10.94	8.82	9.08	9.17	5.08	3.08	1.83	1.12
300t	16.01	16.85	14.36	11.76	9.32	9.34	10.20	5.84	3.61	2.17	1.33
400t	16.95	17.79	15.52	13.06	10.66	9.89	10.68	7.20	4.58	2.81	1.75
600t	20.58	19.03	17.06	14.85	12.58	10.90	11.16	9.42	6.29	3.98	2.54
800t	21.22	19.86	18.11	16.09	13.96	11.89	11.76	11.17	7.75	5.05	3.29
1000t	21.71	20.49	18.90	17.02	15.02	13.03	12.36	12.61	9.02	6.02	3.99
1200t	22.12	21.01	19.53	17.78	15.88	13.98	12.93	13.82	10.14	6.91	4.66

RANGE 4000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	1.82	1.79	1.05	0.54	0.30	0.63	0.37	0.15	0.08	0.05	0.03
20t	3.16	3.41	1.95	1.05	0.59	0.55	0.73	0.31	0.17	0.09	0.05
30t	4.21	4.89	2.72	1.51	0.87	0.75	1.08	0.46	0.25	0.14	0.08
40t	5.06	5.87	3.41	1.94	1.14	0.93	1.42	0.60	0.33	0.18	0.11
50t	5.78	6.69	4.02	2.34	1.39	1.10	1.75	0.75	0.42	0.23	0.13
60t	6.41	7.39	4.56	2.72	1.64	1.26	2.07	0.90	0.50	0.27	0.16
100t	8.26	9.44	6.33	4.03	2.54	1.82	2.53	1.46	0.82	0.45	0.27
150t	9.80	11.11	7.92	5.33	3.51	2.40	2.64	2.12	1.21	0.67	0.40
200t	10.91	12.28	9.12	6.39	4.35	2.99	3.01	2.75	1.59	0.88	0.53
250t	11.76	13.17	10.07	7.28	5.10	3.58	3.37	3.35	1.95	1.09	0.66
300t	13.28	13.88	10.86	8.04	5.76	4.12	3.71	3.91	2.31	1.30	0.79
400t	16.81	14.98	12.10	9.29	6.90	5.08	4.33	4.96	3.00	1.71	1.04
600t	18.58	16.45	13.85	11.14	8.68	6.68	5.39	6.78	4.26	2.49	1.54
800t	19.35	17.45	15.06	12.49	10.05	7.97	6.39	7.47	5.40	3.23	2.03
1000t	19.94	18.21	16.00	13.55	11.16	9.06	7.42	7.88	6.44	3.93	2.49
1200t	20.42	18.83	16.76	14.42	12.09	10.00	8.32	8.38	7.40	4.60	2.95

RANGE 6000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	0.98	1.30	0.60	0.30	0.17	0.10	0.07	0.11	0.06	0.03	0.02
20t	1.79	2.36	1.15	0.59	0.33	0.21	0.14	0.22	0.12	0.07	0.04
30t	2.48	3.24	1.64	0.86	0.49	0.31	0.21	0.33	0.18	0.10	0.06
40t	3.09	3.99	2.10	1.13	0.65	0.41	0.28	0.34	0.24	0.13	0.08
50t	3.62	4.65	2.53	1.38	0.80	0.50	0.35	0.41	0.30	0.16	0.10
60t	4.10	5.23	2.92	1.62	0.95	0.60	0.42	0.48	0.36	0.19	0.12
100t	5.64	7.04	4.27	2.50	1.51	0.98	0.70	0.75	0.60	0.32	0.19
150t	7.02	8.61	5.58	3.45	2.16	1.42	1.02	1.05	0.89	0.48	0.29
200t	9.00	9.77	6.64	4.27	2.75	1.85	1.34	1.33	1.17	0.64	0.39
250t	10.98	10.67	7.51	4.99	3.29	2.25	1.65	1.60	1.45	0.79	0.48
300t	12.77	11.41	8.25	5.63	3.79	2.63	1.94	1.85	1.72	0.95	0.58
400t	15.46	12.57	9.47	6.74	4.69	3.33	2.50	2.32	2.25	1.25	0.76
600t	16.73	14.18	11.25	8.46	6.20	4.58	3.54	3.18	3.25	1.84	1.14
800t	17.60	15.30	12.54	9.78	7.43	5.66	4.46	3.94	4.19	2.42	1.50
1000t	18.28	16.16	13.55	10.86	8.47	6.60	5.30	4.64	5.06	2.97	1.86
1200t	18.83	16.86	14.38	11.76	9.37	7.45	6.08	5.16	5.88	3.50	2.21

RANGE 8000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	0.56	0.84	0.38	0.19	0.11	0.07	0.05	0.03	0.05	0.03	0.02
20t	1.07	1.57	0.73	0.37	0.21	0.14	0.10	0.06	0.10	0.05	0.03
30t	1.52	2.21	1.06	0.55	0.31	0.20	0.15	0.10	0.14	0.08	0.05
40t	1.94	2.78	1.38	0.72	0.42	0.27	0.20	0.13	0.19	0.10	0.06
50t	2.32	3.29	1.68	0.89	0.52	0.34	0.25	0.16	0.24	0.13	0.08
60t	2.67	3.76	1.96	1.05	0.62	0.40	0.29	0.19	0.29	0.15	0.09
100t	4.57	5.28	2.97	1.67	1.00	0.66	0.49	0.31	0.48	0.26	0.16
150t	6.66	6.69	4.02	2.36	1.45	0.97	0.72	0.46	0.71	0.38	0.23
200t	8.76	7.77	4.91	2.99	1.88	1.27	0.95	0.60	0.94	0.51	0.31
250t	10.61	8.64	5.66	3.56	2.28	1.56	1.17	0.74	1.16	0.64	0.39
300t	12.03	9.37	6.33	4.08	2.66	1.84	1.39	0.88	1.39	0.76	0.46
400t	13.63	10.54	7.45	5.01	3.37	2.38	1.82	1.13	1.82	1.01	0.62
600t	15.02	12.21	9.17	6.53	4.61	3.36	2.62	1.64	2.65	1.49	0.92
800t	15.97	13.40	10.46	7.76	5.67	4.24	3.36	2.13	2.84	1.96	1.22
1000t	16.71	14.32	11.49	8.79	6.60	5.04	4.05	2.61	2.98	2.42	1.51
1200t	17.32	15.08	12.36	9.68	7.43	5.78	4.71	3.06	3.25	2.86	1.80

TABLE A11- PAYLOAD AS A PERCENTAGE OF REQUIRED DISPLACEMENT
ADVANCED STRUCTURE, GAS TURBINE PROPULSION

RANGE 500nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	10.65	9.68	8.59	8.76	6.52	4.47	2.90	1.16	0.52	0.33	0.19
20t	14.10	13.05	11.82	12.54	9.93	7.29	5.03	2.18	0.99	0.63	0.37
30t	15.93	14.88	13.66	14.76	12.13	9.30	6.69	3.10	1.45	0.91	0.54
40t	17.11	16.09	14.89	16.26	13.70	10.82	8.04	3.93	1.89	1.16	0.71
50t	17.94	16.96	17.04	17.36	14.90	12.04	9.17	4.68	2.31	1.40	0.87
60t	18.58	17.63	18.06	18.22	15.86	13.05	10.14	5.37	2.72	1.63	1.02
100t	20.19	19.34	19.23	19.35	18.38	15.83	12.98	7.66	4.19	2.43	1.60
150t	21.30	21.52	20.42	20.01	20.19	17.94	15.28	9.82	5.76	3.31	2.24
200t	22.05	22.27	21.29	20.52	20.75	19.36	16.89	11.50	7.11	4.23	2.82
250t	22.62	22.85	21.94	20.95	21.06	20.41	18.11	12.87	8.29	5.08	3.35
300t	23.09	23.31	22.48	21.33	21.34	21.25	19.10	14.02	9.35	5.88	3.84
400t	23.85	24.08	23.33	22.29	21.87	22.14	20.64	15.88	11.15	7.32	4.73
600t	25.34	25.24	24.62	23.74	22.87	22.93	22.77	18.58	13.98	9.75	6.42
800t	26.53	26.18	25.64	24.86	23.84	23.70	23.95	20.55	16.16	11.78	8.06
1000t	27.32	27.01	26.51	25.81	24.88	24.45	24.60	22.11	17.95	13.51	9.55
1200t	28.04	27.76	27.30	26.66	25.80	25.17	25.25	23.42	19.46	15.04	10.91

RANGE 1000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	9.00	7.72	6.39	7.09	4.77	3.01	1.85	0.73	0.34	0.18	0.10
20t	12.27	10.82	9.27	10.69	7.75	5.22	3.37	1.40	0.67	0.36	0.20
30t	14.09	12.63	11.03	12.97	9.85	6.95	4.67	2.03	0.99	0.53	0.30
40t	15.30	13.86	13.84	14.59	11.44	8.35	5.78	2.63	1.30	0.71	0.40
50t	16.18	14.78	15.63	15.81	12.70	9.53	6.76	3.18	1.61	0.88	0.50
60t	16.86	15.50	16.03	16.72	13.73	10.53	7.63	3.71	1.90	1.05	0.60
100t	18.62	18.26	17.21	17.36	16.57	13.45	10.36	5.56	3.01	1.70	0.98
150t	19.88	20.32	18.70	17.93	18.63	15.81	12.74	7.45	4.26	2.48	1.45
200t	20.73	21.17	19.71	18.42	18.82	17.46	14.50	9.01	5.38	3.21	1.91
250t	21.38	21.82	20.48	18.87	19.06	18.70	15.87	10.33	6.40	3.90	2.35
300t	21.91	22.35	21.10	19.44	19.31	19.70	17.00	11.48	7.34	4.56	2.78
400t	22.77	23.20	22.08	20.59	19.85	20.31	18.77	13.39	9.00	5.79	3.62
600t	25.11	24.48	23.54	22.27	20.90	21.02	21.27	16.28	11.72	7.95	5.17
800t	26.05	25.50	24.67	23.54	22.13	21.81	22.25	18.44	13.91	9.81	6.60
1000t	26.87	26.38	25.63	24.61	23.31	22.61	22.88	20.17	15.75	11.46	7.92
1200t	27.61	27.17	26.48	25.53	24.33	23.37	23.53	21.63	17.33	12.94	9.15

RANGE 2000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	6.36	4.86	3.55	5.02	3.00	1.74	1.03	0.41	0.21	0.12	0.07
20t	9.20	7.37	6.98	8.16	5.24	3.21	1.96	0.80	0.41	0.23	0.14
30t	10.93	9.01	10.15	10.37	7.02	4.48	2.81	1.18	0.61	0.35	0.21
40t	12.15	10.20	11.23	12.05	8.47	5.59	3.59	1.55	0.81	0.46	0.27
50t	13.07	11.14	11.66	12.92	9.69	6.57	4.31	1.91	1.01	0.57	0.34
60t	13.81	11.90	12.04	12.91	10.73	7.45	4.98	2.25	1.20	0.69	0.41
100t	15.78	16.58	13.94	13.21	13.80	10.24	7.26	3.54	1.95	1.13	0.68
150t	17.26	18.10	15.69	13.79	14.69	12.72	9.47	4.96	2.82	1.66	1.01
200t	18.27	19.12	16.90	14.36	14.76	14.56	11.22	6.22	3.65	2.18	1.34
250t	19.05	19.90	17.83	15.34	14.98	15.99	12.67	7.35	4.43	2.69	1.66
300t	19.69	20.53	18.59	16.22	15.27	16.35	13.89	8.37	5.16	3.17	1.98
400t	20.72	21.54	19.79	17.61	15.92	16.48	15.89	10.16	6.53	4.11	2.59
600t	24.07	23.03	21.54	19.63	17.44	17.26	18.29	13.04	8.90	5.83	3.78
800t	25.09	24.19	22.86	21.14	19.14	18.18	18.78	15.31	10.93	7.39	4.91
1000t	25.98	25.17	23.96	22.38	20.52	19.10	19.44	17.19	12.70	8.82	5.98
1200t	26.78	26.03	24.92	23.45	21.71	19.97	20.16	18.79	14.27	10.14	7.00

RANGE 4000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	3.14	2.00	2.28	3.11	1.68	0.92	0.54	0.22	0.12	0.07	0.04
20t	5.08	3.87	3.39	4.86	3.12	1.78	1.05	0.44	0.24	0.14	0.09
30t	6.46	5.65	4.55	4.12	4.39	2.57	1.54	0.65	0.36	0.21	0.13
40t	7.53	7.39	5.52	4.28	5.51	3.31	2.01	0.86	0.48	0.28	0.18
50t	8.40	8.94	6.34	4.54	6.51	4.00	2.47	1.07	0.60	0.35	0.22
60t	9.12	10.17	7.06	4.81	7.12	4.64	2.90	1.28	0.72	0.42	0.27
100t	11.21	12.57	9.25	6.31	6.05	6.89	4.50	2.07	1.18	0.70	0.44
150t	12.89	14.33	11.11	8.04	6.57	8.81	6.23	3.00	1.75	1.04	0.66
200t	14.10	15.57	12.49	9.40	7.19	8.14	7.72	3.87	2.30	1.38	0.88
250t	15.05	16.53	13.57	10.51	7.81	8.26	9.03	4.70	2.83	1.71	1.09
300t	15.83	17.31	14.47	11.47	8.72	8.56	10.19	5.47	3.34	2.04	1.31
400t	17.10	18.56	15.93	13.03	10.27	9.29	10.71	6.91	4.33	2.68	1.73
600t	22.09	20.38	18.06	15.39	12.69	10.75	11.31	9.41	6.15	3.91	2.56
800t	23.28	21.76	19.66	17.17	14.58	12.15	12.31	11.53	7.80	5.07	3.36
1000t	24.28	22.90	20.97	18.64	16.14	13.[illegible]4	13.32	13.37	9.32	6.17	4.15
1200t	25.17	23.90	22.10	19.89	17.49	15.13	14.29	15.00	10.72	7.22	4.91

RANGE 6000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	1.63	1.79	1.01	0.51	0.29	0.64	0.37	0.16	0.09	0.05	0.03
20t	2.86	3.50	1.88	0.98	0.56	1.24	0.73	0.31	0.18	0.11	0.07
30t	3.85	4.87	2.65	1.43	0.83	0.67	1.08	0.46	0.27	0.16	0.10
40t	4.67	5.85	3.32	1.85	1.09	0.86	1.42	0.62	0.36	0.21	0.14
50t	5.38	6.68	3.93	2.24	1.34	1.04	1.76	0.77	0.45	0.27	0.17
60t	6.00	7.40	4.49	2.62	1.58	1.21	2.08	0.92	0.53	0.32	0.20
100t	7.91	9.55	6.31	3.95	2.49	1.83	3.30	1.50	0.88	0.53	0.34
150t	9.58	11.36	8.01	5.32	3.51	2.51	2.95	2.20	1.31	0.79	0.51
200t	10.83	12.68	9.34	6.48	4.42	3.12	3.41	2.88	1.73	1.05	0.68
250t	11.84	13.73	10.44	7.48	5.25	3.76	3.88	3.52	2.14	1.30	0.85
300t	12.69	14.59	11.37	8.37	6.01	4.37	4.33	4.15	2.54	1.55	1.01
400t	17.04	15.99	12.91	9.88	7.36	5.51	5.18	5.33	3.32	2.05	1.34
600t	20.26	18.04	15.22	12.26	9.60	7.49	6.66	7.47	4.81	3.02	2.00
800t	21.58	19.58	16.97	14.12	11.43	9.18	7.96	9.37	6.19	3.95	2.64
1000t	22.68	20.86	18.41	15.67	13.00	10.68	9.13	11.05	7.50	4.86	3.27
1200t	23.64	21.96	19.65	17.01	14.37	12.01	10.20	11.88	8.72	5.73	3.89

RANGE 8000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	0.92	1.32	0.61	0.31	0.18	0.12	0.10	0.12	0.07	0.04	0.03
20t	1.70	2.40	1.17	0.62	0.37	0.24	0.19	0.25	0.15	0.09	0.06
30t	2.38	3.30	1.69	0.91	0.54	0.36	0.29	0.37	0.22	0.13	0.09
40t	2.99	4.08	2.17	1.19	0.72	0.48	0.38	0.49	0.29	0.17	0.11
50t	3.53	4.77	2.61	1.46	0.89	0.60	0.47	0.61	0.36	0.22	0.14
60t	4.02	5.38	3.03	1.72	1.06	0.72	0.56	0.73	0.43	0.26	0.17
100t	5.63	7.31	4.48	2.69	1.71	1.17	0.92	1.20	0.72	0.43	0.28
150t	7.15	9.04	5.94	3.77	2.46	1.72	1.34	1.77	1.07	0.65	0.42
200t	9.16	10.36	7.14	4.71	3.16	2.24	1.74	2.33	1.41	0.86	0.56
250t	11.01	11.43	8.16	5.56	3.82	2.74	2.13	2.87	1.75	1.07	0.70
300t	13.00	12.32	9.05	6.34	4.44	3.23	2.50	3.39	2.09	1.28	0.84
400t	16.37	13.79	10.57	7.71	5.58	4.14	3.23	4.39	2.75	1.69	1.12
600t	18.56	15.98	12.91	9.96	7.55	5.81	4.63	5.45	4.01	2.51	1.67
800t	19.99	17.64	14.73	11.78	9.24	7.29	5.91	6.47	5.21	3.30	2.21
1000t	21.17	19.01	16.24	13.33	10.72	8.63	7.11	7.44	6.36	4.07	2.74
1200t	22.21	20.19	17.54	14.69	12.05	9.86	8.23	8.37	7.45	4.82	3.27

TABLE A12- PAYLOAD AS A PERCENTAGE OF REQUIRED DISPLACEMENT
ADVANCED STRUCTURE, HIGH SPEED DIESEL PROPULSION

RANGE 500nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	17.30	15.61	13.68	11.65	9.25	6.20	4.00	1.73	0.65	0.28	0.16
20t	18.83	17.45	15.83	16.15	12.70	9.40	6.35	2.66	1.16	0.55	0.31
30t	19.65	18.43	17.00	17.82	14.70	11.47	8.18	3.60	1.59	0.79	0.46
40t	20.20	19.09	17.78	18.90	16.06	12.95	9.60	4.51	1.98	1.02	0.60
50t	20.61	19.58	18.36	19.69	17.07	14.08	10.75	5.33	2.42	1.24	0.74
60t	20.93	19.97	20.37	20.29	17.86	15.00	11.71	6.07	2.84	1.44	0.88
100t	21.82	21.03	20.98	21.08	19.91	17.45	14.44	8.47	4.35	2.21	1.39
150t	22.53	22.69	21.70	21.41	21.36	19.27	16.57	10.67	5.94	3.18	1.98
200t	23.06	23.22	22.36	21.76	21.92	20.49	18.04	12.34	7.30	4.07	2.51
250t	23.48	23.65	22.88	22.12	22.18	21.40	19.16	13.68	8.48	4.90	3.01
300t	23.85	24.02	23.31	22.42	22.39	22.12	20.05	14.80	9.53	5.67	3.47
400t	24.48	24.65	24.04	23.16	22.81	22.98	21.44	16.60	11.32	7.08	4.36
600t	25.51	25.67	25.18	24.43	23.66	23.67	23.39	19.20	14.11	9.48	6.15
800t	26.82	26.54	26.12	25.44	24.51	24.37	24.53	21.08	16.25	11.49	7.75
1000t	27.56	27.31	26.93	26.32	25.47	25.07	25.16	22.59	18.01	13.21	9.21
1200t	28.25	28.03	27.68	27.11	26.33	25.75	25.78	23.85	19.50	14.73	10.54

RANGE 1000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	14.92	12.82	10.64	9.37	7.02	4.55	2.71	0.97	0.39	0.18	0.10
20t	16.83	15.05	13.13	14.05	10.39	7.37	4.73	1.84	0.77	0.37	0.20
30t	17.85	16.27	14.52	16.01	12.51	9.33	6.31	2.63	1.13	0.55	0.30
40t	18.53	17.09	15.47	17.32	14.02	10.82	7.61	3.36	1.48	0.72	0.40
50t	19.05	17.70	17.35	18.27	15.17	12.00	8.71	4.03	1.82	0.90	0.50
60t	19.45	18.19	18.92	19.02	16.09	12.98	9.65	4.65	2.15	1.07	0.60
100t	20.55	19.51	19.45	19.67	18.51	15.70	12.44	6.76	3.37	1.74	0.98
150t	21.42	21.75	20.43	20.01	20.25	17.78	14.73	8.81	4.71	2.52	1.46
200t	22.04	22.37	21.23	20.43	20.72	19.19	16.36	10.44	5.90	3.27	1.91
250t	22.53	22.87	21.84	20.83	20.97	20.24	17.61	11.79	6.96	3.97	2.36
300t	22.96	23.29	22.36	21.14	21.15	21.09	18.62	12.93	7.92	4.64	2.79
400t	23.67	23.99	23.19	22.07	21.56	21.88	20.20	14.81	9.61	5.87	3.63
600t	25.30	25.11	24.48	23.49	22.44	22.51	22.40	17.59	12.34	8.05	5.19
800t	26.42	26.04	25.49	24.60	23.41	23.21	23.51	19.63	14.50	9.93	6.62
1000t	27.19	26.86	26.36	25.55	24.47	23.92	24.10	21.26	16.30	11.58	7.95
1200t	27.90	27.61	27.14	26.40	25.40	24.62	24.70	22.63	17.85	13.06	9.18

RANGE 2000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	10.99	8.59	6.48	7.49	4.57	2.85	1.63	0.59	0.25	0.13	0.07
20t	13.34	11.13	9.02	11.02	7.45	4.96	3.01	1.14	0.50	0.25	0.15
30t	14.65	12.60	10.59	13.21	9.50	6.61	4.20	1.67	0.74	0.38	0.22
40t	15.54	13.63	13.68	14.76	11.06	7.97	5.24	2.17	0.97	0.50	0.29
50t	16.21	14.41	15.64	15.93	12.31	9.11	6.16	2.65	1.21	0.62	0.37
60t	16.75	15.04	15.80	16.81	13.33	10.08	6.98	3.10	1.43	0.75	0.44
100t	18.19	18.20	16.66	16.83	16.18	12.97	9.61	4.73	2.30	1.22	0.72
150t	19.31	19.97	18.12	17.30	18.13	15.33	11.95	6.44	3.31	1.80	1.08
200t	20.10	20.77	19.14	17.88	18.35	16.99	13.71	7.89	4.23	2.36	1.42
250t	20.73	21.38	19.92	18.29	18.50	18.26	15.10	9.15	5.09	2.89	1.76
300t	21.25	21.90	20.57	18.90	18.66	19.26	16.25	10.25	5.90	3.41	2.10
400t	22.12	22.74	21.60	20.04	19.09	19.62	18.08	12.13	7.36	4.40	2.75
600t	24.72	24.03	23.14	21.72	20.06	20.18	20.66	15.02	9.85	6.21	4.00
800t	25.64	25.07	24.29	23.01	21.38	20.90	21.40	17.23	11.92	7.83	5.17
1000t	26.47	25.97	25.25	24.09	22.59	21.66	21.96	19.02	13.70	9.31	6.29
1200t	27.22	26.78	26.11	25.03	23.64	22.41	22.56	20.54	15.26	10.67	7.35

RANGE 4000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	5.89	3.98	3.59	4.58	2.60	1.54	0.87	0.33	0.15	0.08	0.05
20t	8.26	6.10	6.77	7.54	4.62	2.87	1.68	0.64	0.30	0.16	0.10
30t	9.73	7.55	9.11	9.67	6.26	4.03	2.43	0.95	0.44	0.24	0.15
40t	10.79	8.64	9.38	11.28	7.64	5.06	3.12	1.25	0.59	0.32	0.20
50t	11.61	9.51	9.73	11.06	8.81	5.98	3.76	1.55	0.73	0.40	0.25
60t	12.28	11.28	10.23	10.92	9.83	6.81	4.37	1.83	0.87	0.48	0.30
100t	14.15	15.33	12.50	11.47	12.85	9.50	6.47	2.92	1.42	0.79	0.49
150t	15.62	16.83	14.33	12.49	13.36	11.93	8.57	4.14	2.09	1.18	0.73
200t	16.67	17.87	15.62	13.23	13.30	13.77	10.27	5.25	2.73	1.55	0.97
250t	17.49	18.68	16.63	14.28	13.46	15.04	11.69	6.27	3.34	1.92	1.21
300t	18.17	19.34	17.46	15.15	13.73	14.80	12.91	7.20	3.93	2.28	1.45
400t	19.28	20.41	18.78	16.55	14.35	14.85	14.92	8.87	5.04	2.99	1.91
600t	23.08	22.01	20.71	18.61	16.19	15.58	16.64	11.63	7.05	4.34	2.82
800t	24.15	23.24	22.05	20.16	17.92	16.49	17.06	13.86	8.83	5.60	3.70
1000t	25.06	24.28	23.17	21.43	19.33	17.39	17.68	15.74	10.43	6.79	4.55
1200t	25.89	25.20	24.15	22.53	20.55	18.32	18.36	17.37	11.88	7.91	5.37

RANGE 6000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	3.24	2.06	2.65	3.27	1.79	1.05	0.59	0.23	0.11	0.06	0.04
20t	5.12	3.87	3.54	5.68	3.32	2.00	1.16	0.45	0.22	0.12	0.08
30t	6.43	5.69	4.73	5.03	4.64	2.87	1.69	0.67	0.32	0.18	0.12
40t	7.44	7.33	5.72	5.27	5.80	3.67	2.21	0.89	0.43	0.24	0.15
50t	8.26	8.75	6.56	5.66	6.83	4.41	2.69	1.10	0.53	0.30	0.19
60t	8.95	10.35	7.30	6.07	7.74	5.10	3.16	1.31	0.64	0.36	0.23
100t	10.94	12.48	9.53	7.20	8.23	7.46	4.86	2.12	1.05	0.60	0.38
150t	12.59	14.17	11.44	8.86	8.07	9.75	6.66	3.07	1.56	0.90	0.57
200t	13.78	15.38	12.85	10.21	8.44	10.03	8.19	3.96	2.05	1.19	0.76
250t	14.72	16.31	13.97	11.30	8.90	9.73	9.53	4.79	2.52	1.48	0.95
300t	15.51	17.09	14.90	12.23	9.38	9.80	10.71	5.57	2.99	1.76	1.14
400t	17.52	18.33	16.40	13.74	10.92	10.27	12.07	7.02	3.89	2.32	1.51
600t	21.54	20.16	18.52	16.00	13.30	11.46	12.15	9.52	5.55	3.40	2.23
800t	22.72	21.55	20.03	17.71	15.13	12.61	12.88	11.64	7.09	4.44	2.94
1000t	23.73	22.71	21.28	19.12	16.65	14.11	13.71	13.48	8.50	5.43	3.64
1200t	24.62	23.72	22.36	20.32	17.96	15.47	14.55	15.11	9.82	6.39	4.32

RANGE 8000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	1.90	1.82	1.28	0.91	1.37	0.79	0.45	0.18	0.09	0.05	0.03
20t	3.26	3.67	2.34	1.52	2.59	1.53	0.89	0.35	0.17	0.10	0.06
30t	4.31	5.35	3.25	2.04	3.11	2.23	1.31	0.53	0.26	0.15	0.10
40t	5.17	6.49	4.04	2.60	2.78	2.88	1.71	0.70	0.34	0.20	0.13
50t	5.90	7.33	4.75	3.11	2.67	3.50	2.11	0.87	0.43	0.25	0.16
60t	6.54	8.05	5.38	3.58	2.80	4.08	2.49	1.03	0.51	0.30	0.19
100t	8.47	10.18	7.40	5.18	3.49	6.12	3.90	1.68	0.85	0.49	0.32
150t	10.14	11.95	9.25	6.74	4.50	4.61	5.46	2.46	1.26	0.74	0.48
200t	11.39	13.24	10.67	8.00	5.55	4.99	6.84	3.20	1.66	0.98	0.64
250t	12.39	14.25	11.83	9.05	6.48	5.45	7.51	3.91	2.06	1.22	0.80
300t	13.24	15.10	12.80	9.96	7.31	5.90	7.05	4.59	2.45	1.46	0.95
400t	16.94	16.46	14.40	11.49	8.75	6.75	7.28	5.85	3.20	1.93	1.26
600t	20.08	18.47	16.58	13.83	11.07	8.61	8.34	8.12	4.64	2.84	1.88
800t	21.37	19.99	18.21	15.62	12.91	10.37	9.43	10.09	5.98	3.73	2.49
1000t	22.45	21.25	19.55	17.10	14.45	11.89	10.44	11.85	7.24	4.59	3.08
1200t	23.40	22.34	20.71	18.38	15.80	13.23	11.39	13.40	8.43	5.42	3.67

TABLE A13- PAYLOAD AS A PERCENTAGE OF REQUIRED DISPLACEMENT
ADVANCED STRUCTURE, MEDIUM SPEED DIESEL PROPULSION

RANGE 500nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	16.65	14.54	12.14	9.67	7.47	4.46	2.57	0.90	0.34	0.16	0.09
20t	18.30	16.53	14.45	14.88	10.85	7.22	4.52	1.72	0.68	0.31	0.17
30t	19.17	17.59	15.71	16.74	12.95	9.17	6.07	2.47	1.00	0.47	0.25
40t	19.75	18.31	16.56	17.96	14.42	10.67	7.35	3.16	1.32	0.62	0.34
50t	20.19	18.84	17.20	18.86	15.54	11.86	8.44	3.80	1.62	0.77	0.42
60t	20.53	19.26	19.76	19.55	16.43	12.84	9.38	4.40	1.92	0.92	0.51
100t	21.48	20.41	20.20	20.22	18.78	15.59	12.18	6.44	3.03	1.50	0.84
150t	22.23	22.35	21.02	20.46	20.48	17.70	14.51	8.45	4.28	2.20	1.24
200t	22.77	22.91	21.73	20.76	20.88	19.13	16.16	10.06	5.39	2.86	1.63
250t	23.22	23.37	22.29	21.07	21.06	20.20	17.43	11.40	6.40	3.49	2.02
300t	23.60	23.75	22.76	21.37	21.25	21.06	18.46	12.55	7.32	4.10	2.40
400t	24.25	24.41	23.53	22.28	21.67	21.82	20.07	14.44	8.96	5.23	3.14
600t	25.30	25.47	24.74	23.69	22.58	22.53	22.32	17.25	11.63	7.26	4.53
800t	26.74	26.35	25.72	24.79	23.56	23.26	23.39	19.32	13.79	9.05	5.82
1000t	27.49	27.14	26.57	25.74	24.62	24.00	24.05	20.98	15.59	10.64	7.03
1200t	28.19	27.87	27.34	26.58	25.55	24.73	24.70	22.38	17.15	12.07	8.18

RANGE 1000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	14.49	12.06	9.54	8.99	5.85	3.38	1.94	0.71	0.28	0.13	0.07
20t	16.45	14.35	12.04	13.11	9.03	5.75	3.53	1.37	0.56	0.27	0.15
30t	17.50	15.61	13.46	15.17	11.14	7.54	4.86	1.99	0.83	0.40	0.22
40t	18.20	16.45	14.44	16.56	12.69	8.97	6.00	2.57	1.09	0.53	0.30
50t	18.73	17.09	17.23	17.60	13.89	10.14	6.99	3.12	1.35	0.66	0.37
60t	19.15	17.59	18.24	18.40	14.86	11.14	7.87	3.64	1.60	0.79	0.45
100t	20.28	18.96	18.70	18.81	17.49	14.02	10.61	5.46	2.56	1.29	0.74
150t	21.16	21.46	19.78	19.01	19.39	16.30	12.98	7.31	3.65	1.90	1.10
200t	21.79	22.10	20.62	19.32	19.58	17.89	14.72	8.84	4.65	2.49	1.45
250t	22.30	22.62	21.26	19.66	19.72	19.09	16.08	10.15	5.56	3.05	1.79
300t	22.73	23.05	21.80	20.09	19.90	20.05	17.19	11.28	6.41	3.59	2.13
400t	23.45	23.77	22.67	21.15	20.36	20.64	18.94	13.18	7.95	4.62	2.80
600t	25.26	24.91	23.99	22.72	21.35	21.34	21.40	16.05	10.51	6.49	4.06
800t	26.36	25.85	25.05	23.93	22.50	22.12	22.37	18.21	12.62	8.16	5.25
1000t	27.13	26.68	25.96	24.95	23.66	22.92	23.05	19.95	14.42	9.67	6.38
1200t	27.85	27.44	26.78	25.85	24.66	23.71	23.73	21.41	15.99	11.06	7.45

RANGE 2000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	10.87	8.25	5.91	7.02	3.98	2.22	1.28	0.50	0.21	0.10	0.06
20t	13.21	10.75	8.34	10.49	6.64	4.00	2.41	0.97	0.41	0.21	0.12
30t	14.51	12.21	10.78	12.70	8.59	5.46	3.42	1.43	0.62	0.31	0.18
40t	15.40	13.22	13.87	14.28	10.12	6.70	4.32	1.86	0.81	0.42	0.24
50t	16.06	13.99	15.09	15.48	11.36	7.77	5.14	2.28	1.01	0.52	0.30
60t	16.59	14.61	15.19	16.20	12.40	8.72	5.89	2.68	1.20	0.62	0.36
100t	18.03	18.15	16.06	15.89	15.34	11.59	8.37	4.14	1.95	1.02	0.60
150t	19.14	19.76	17.53	16.13	16.93	14.04	10.68	5.72	2.82	1.51	0.90
200t	19.93	20.56	18.55	16.52	16.88	15.80	12.46	7.08	3.64	1.98	1.19
250t	20.55	21.18	19.34	17.02	17.01	17.17	13.90	8.28	4.41	2.45	1.48
300t	21.07	21.69	19.99	17.81	17.24	18.05	15.10	9.35	5.14	2.89	1.76
400t	21.93	22.54	21.03	19.07	17.80	18.23	17.02	11.19	6.48	3.76	2.32
600t	24.67	23.84	22.57	20.91	18.99	19.01	19.66	14.09	8.82	5.37	3.39
800t	25.60	24.88	23.77	22.31	20.57	19.94	20.34	16.32	10.81	6.85	4.42
1000t	26.42	25.78	24.79	23.46	21.88	20.88	21.09	18.16	12.55	8.22	5.41
1200t	27.17	26.60	25.68	24.46	23.01	21.78	21.84	19.72	14.09	9.49	6.36

RANGE 4000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	6.02	3.92	3.54	4.45	2.35	1.29	0.75	0.31	0.14	0.07	0.05
20t	8.37	5.99	6.99	7.36	4.23	2.43	1.46	0.61	0.28	0.15	0.09
30t	9.82	7.39	8.78	9.48	5.79	3.45	2.12	0.91	0.41	0.22	0.14
40t	10.86	8.45	8.94	11.03	7.10	4.37	2.74	1.19	0.55	0.30	0.18
50t	11.66	9.29	9.19	10.28	8.24	5.21	3.32	1.47	0.68	0.37	0.23
60t	12.32	11.23	9.82	9.99	9.23	5.99	3.88	1.75	0.82	0.44	0.27
100t	14.14	15.26	12.01	10.09	11.84	8.54	5.83	2.79	1.34	0.73	0.45
150t	15.56	16.72	13.77	10.75	11.27	10.94	7.84	3.97	1.96	1.09	0.67
200t	16.58	17.75	15.03	12.06	11.47	12.77	9.49	5.05	2.57	1.44	0.90
250t	17.38	18.54	16.01	13.17	11.87	13.05	10.90	6.04	3.15	1.79	1.12
300t	18.04	19.19	16.81	14.09	12.31	13.08	12.12	6.95	3.71	2.13	1.33
400t	19.12	20.25	18.10	15.59	13.21	13.53	14.16	8.59	4.77	2.79	1.76
600t	23.08	21.82	19.99	17.79	15.49	14.80	15.60	11.32	6.71	4.06	2.61
800t	24.13	23.04	21.43	19.44	17.33	16.09	16.54	13.54	8.44	5.25	3.42
1000t	25.05	24.07	22.61	20.79	18.84	17.25	17.41	15.42	10.01	6.39	4.22
1200t	25.87	24.98	23.64	21.96	20.14	18.20	18.10	17.05	11.44	7.47	4.99

RANGE 6000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	3.38	2.03	2.48	3.23	1.66	0.90	0.53	0.23	0.11	0.06	0.04
20t	5.27	3.88	3.37	5.61	3.09	1.74	1.04	0.45	0.21	0.12	0.07
30t	6.58	5.67	4.51	3.84	4.34	2.51	1.53	0.67	0.32	0.18	0.11
40t	7.57	7.32	5.45	3.98	5.45	3.23	2.00	0.88	0.42	0.24	0.15
50t	8.38	8.74	6.25	4.25	6.42	3.91	2.45	1.10	0.52	0.29	0.18
60t	9.05	10.40	6.95	4.53	6.22	4.55	2.89	1.31	0.63	0.35	0.22
100t	10.99	12.48	9.06	6.16	5.71	6.76	4.48	2.11	1.03	0.58	0.37
150t	12.57	14.13	10.88	7.87	6.43	8.05	6.20	3.06	1.53	0.87	0.55
200t	13.72	15.30	12.22	9.22	7.17	7.93	7.68	3.94	2.01	1.15	0.73
250t	14.63	16.21	13.29	10.33	7.87	8.29	8.99	4.77	2.48	1.43	0.91
300t	15.39	16.96	14.17	11.28	8.79	8.75	10.12	5.56	2.94	1.71	1.09
400t	17.51	18.17	15.61	12.86	10.37	9.71	10.83	7.00	3.82	2.26	1.45
600t	21.57	19.97	17.73	15.23	12.85	11.50	12.06	9.50	5.47	3.31	2.15
800t	22.73	21.33	19.33	17.03	14.78	12.84	13.03	11.61	6.99	4.32	2.84
1000t	23.73	22.47	20.65	18.51	16.39	14.28	13.86	13.45	8.39	5.30	3.51
1200t	24.61	23.47	21.78	19.78	17.77	15.63	14.69	15.08	9.70	6.23	4.17

RANGE 8000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	1.99	1.85	1.20	0.61	1.28	0.70	0.42	0.18	0.09	0.05	0.03
20t	3.37	3.51	2.20	1.17	0.83	1.36	0.82	0.36	0.17	0.10	0.06
30t	4.43	5.43	3.05	1.68	1.15	1.98	1.21	0.54	0.26	0.15	0.10
40t	5.29	6.59	3.79	2.16	1.45	2.57	1.59	0.71	0.35	0.20	0.13
50t	6.01	7.42	4.45	2.61	1.73	3.13	1.96	0.88	0.43	0.25	0.16
60t	6.63	8.13	5.04	3.03	1.98	2.67	2.32	1.05	0.52	0.30	0.19
100t	8.51	10.21	6.94	4.50	3.00	3.15	3.65	1.72	0.85	0.49	0.32
150t	10.13	11.93	8.67	5.98	4.18	3.97	5.14	2.51	1.27	0.73	0.47
200t	11.33	13.18	10.00	7.21	5.22	4.72	6.11	3.26	1.67	0.98	0.63
250t	12.29	14.17	11.08	8.26	6.14	5.41	6.33	3.97	2.07	1.21	0.78
300t	13.11	14.99	12.00	9.17	6.98	6.05	6.76	4.66	2.46	1.45	0.94
400t	16.89	16.31	13.51	10.73	8.45	7.20	7.71	5.94	3.22	1.92	1.25
600t	20.14	18.26	15.76	13.13	10.85	8.92	8.81	8.22	4.66	2.83	1.86
800t	21.40	19.75	17.48	15.00	12.77	10.69	9.86	10.21	6.01	3.71	2.45
1000t	22.47	20.98	18.88	16.55	14.40	12.22	10.86	11.97	7.28	4.57	3.04
1200t	23.41	22.05	20.10	17.89	15.81	13.57	11.79	13.52	8.47	5.40	3.62

TABLE A14- PAYLOAD AS A PERCENTAGE OF REQUIRED DISPLACEMENT
ADVANCED STRUCTURE, DIESEL ELECTRIC PROPULSION

RANGE 500nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	6.05	4.04	3.54	3.74	2.23	1.39	0.89	0.42	0.23	0.14	0.09
20t	8.93	6.47	6.75	6.44	4.06	2.61	1.72	0.82	0.45	0.28	0.18
30t	10.76	8.18	8.21	8.29	5.60	3.71	2.49	1.22	0.67	0.41	0.27
40t	12.07	9.48	9.11	9.00	6.92	4.70	3.20	1.59	0.89	0.55	0.37
50t	13.08	10.52	9.85	9.57	8.07	5.59	3.87	1.96	1.10	0.68	0.46
60t	13.89	11.38	10.51	10.06	9.08	6.41	4.50	2.32	1.31	0.81	0.55
100t	16.09	16.02	13.08	11.57	11.66	9.10	6.68	3.64	2.11	1.33	0.90
150t	17.74	17.77	15.12	12.99	12.81	11.59	8.86	5.11	3.06	1.96	1.34
200t	18.87	18.96	16.54	14.04	13.34	13.49	10.62	6.41	3.94	2.56	1.76
250t	19.73	19.85	17.63	15.24	14.37	14.49	12.08	7.57	4.77	3.14	2.18
300t	20.43	20.57	18.50	16.23	15.02	15.05	13.34	8.62	5.55	3.70	2.58
400t	21.53	21.69	19.88	17.79	16.15	16.02	15.39	10.46	6.99	4.76	3.37
600t	24.53	23.32	21.82	20.02	18.04	17.58	17.69	13.40	9.46	6.70	4.86
800t	25.58	24.55	23.24	21.64	19.85	18.91	18.91	15.70	11.55	8.43	6.24
1000t	26.48	25.57	24.40	22.95	21.31	20.07	19.97	17.59	13.35	9.99	7.53
1200t	27.28	26.46	25.39	24.07	22.54	21.12	20.92	19.21	14.95	11.42	8.74

RANGE 1000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	5.32	3.49	3.37	3.47	2.04	1.26	0.80	0.37	0.20	0.12	0.08
20t	8.03	5.71	6.04	6.03	3.74	2.38	1.55	0.73	0.39	0.24	0.16
30t	9.80	7.31	7.17	7.28	5.20	3.40	2.25	1.07	0.58	0.35	0.24
40t	11.09	8.56	8.06	7.94	6.46	4.33	2.90	1.41	0.77	0.47	0.31
50t	12.09	9.57	8.80	8.49	7.57	5.17	3.52	1.74	0.96	0.59	0.39
60t	12.91	11.20	9.68	8.96	8.56	5.95	4.11	2.06	1.14	0.70	0.47
100t	15.15	15.25	12.23	10.53	10.68	8.54	6.16	3.26	1.86	1.15	0.78
150t	16.85	17.04	14.30	11.95	11.78	10.99	8.25	4.61	2.70	1.70	1.15
200t	18.03	18.27	15.75	13.18	12.59	12.84	9.96	5.82	3.50	2.23	1.53
250t	18.92	19.19	16.87	14.39	13.32	13.54	11.41	6.92	4.25	2.75	1.89
300t	19.65	19.94	17.77	15.39	13.97	14.07	12.65	7.92	4.97	3.25	2.25
400t	20.81	21.12	19.20	16.98	15.10	15.00	14.72	9.69	6.30	4.21	2.95
600t	24.12	22.81	21.22	19.27	17.15	16.55	16.76	12.57	8.63	5.98	4.27
800t	25.20	24.08	22.69	20.94	19.01	17.89	17.94	14.86	10.63	7.59	5.52
1000t	26.12	25.14	23.88	22.29	20.50	19.07	18.98	16.77	12.39	9.06	6.70
1200t	26.94	26.06	24.90	23.44	21.76	20.12	19.94	18.40	13.95	10.41	7.82

RANGE 2000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	4.13	2.63	2.87	3.02	1.74	1.06	0.66	0.30	0.16	0.09	0.06
20t	6.49	4.47	4.32	4.55	3.24	2.02	1.28	0.59	0.31	0.19	0.12
30t	8.12	5.87	5.37	5.31	4.54	2.91	1.88	0.87	0.46	0.28	0.19
40t	9.35	7.57	6.47	5.93	5.70	3.73	2.44	1.14	0.62	0.37	0.25
50t	10.32	9.28	7.42	6.49	6.73	4.49	2.98	1.42	0.76	0.46	0.31
60t	11.13	10.95	8.24	7.00	7.53	5.19	3.49	1.68	0.91	0.56	0.37
100t	13.40	13.81	10.72	8.66	8.79	7.61	5.32	2.69	1.49	0.92	0.61
150t	15.18	15.67	12.79	10.12	9.72	9.96	7.24	3.85	2.19	1.36	0.92
200t	16.43	16.97	14.29	11.63	10.55	11.06	8.87	4.92	2.86	1.79	1.21
250t	17.39	17.95	15.46	12.85	11.29	11.58	10.26	5.90	3.49	2.22	1.51
300t	18.18	18.75	16.41	13.86	11.95	12.06	11.48	6.81	4.11	2.63	1.80
400t	19.43	20.01	17.93	15.49	13.10	12.96	13.45	8.45	5.27	3.43	2.37
600t	23.31	21.83	20.07	17.86	15.53	14.55	14.87	11.19	7.35	4.94	3.47
800t	24.45	23.19	21.61	19.62	17.44	15.92	16.01	13.44	9.19	6.34	4.52
1000t	25.42	24.30	22.87	21.03	18.99	17.13	17.05	15.34	10.84	7.65	5.52
1200t	26.27	25.28	23.95	22.24	20.31	18.26	18.02	16.99	12.33	8.87	6.49

RANGE 4000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	2.53	1.91	1.47	1.13	1.34	0.80	0.49	0.21	0.11	0.07	0.04
20t	4.27	3.72	2.68	1.98	2.49	1.55	0.96	0.42	0.22	0.13	0.09
30t	5.59	5.49	3.71	2.69	3.06	2.26	1.41	0.63	0.33	0.20	0.13
40t	6.64	7.21	4.60	3.23	3.55	2.92	1.85	0.83	0.44	0.27	0.18
50t	7.51	8.16	5.39	3.69	3.82	3.55	2.27	1.04	0.55	0.33	0.22
60t	8.26	8.96	6.10	4.14	4.08	4.14	2.68	1.23	0.66	0.40	0.27
100t	10.47	11.33	8.33	5.97	5.09	6.14	4.18	2.00	1.09	0.66	0.44
150t	12.30	13.26	10.33	7.74	6.13	6.60	5.83	2.91	1.61	0.99	0.66
200t	13.63	14.63	11.84	9.14	7.01	7.17	7.27	3.76	2.11	1.31	0.88
250t	14.67	15.70	13.05	10.30	7.79	7.72	8.53	4.57	2.60	1.62	1.10
300t	15.54	16.58	14.06	11.30	8.73	8.27	9.27	5.33	3.08	1.93	1.31
400t	16.93	17.97	15.69	12.94	10.33	9.26	9.86	6.74	4.00	2.54	1.74
600t	21.75	19.99	17.96	15.40	12.83	10.96	11.14	9.21	5.71	3.72	2.57
800t	23.00	21.49	19.63	17.25	14.77	12.39	12.35	11.31	7.28	4.84	3.38
1000t	24.05	22.72	20.99	18.76	16.38	14.02	13.46	13.15	8.73	5.90	4.16
1200t	24.98	23.78	22.16	20.05	17.76	15.43	14.49	14.78	10.07	6.92	4.93

RANGE 6000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	1.62	1.79	1.01	0.60	0.41	0.65	0.39	0.17	0.09	0.05	0.04
20t	2.87	3.37	1.90	1.15	0.77	1.24	0.77	0.33	0.18	0.11	0.07
30t	3.89	4.54	2.69	1.66	1.09	1.41	1.14	0.50	0.26	0.16	0.11
40t	4.75	5.52	3.40	2.14	1.39	1.59	1.49	0.66	0.35	0.21	0.14
50t	5.50	6.36	4.05	2.59	1.66	1.80	1.84	0.82	0.44	0.27	0.18
60t	6.15	7.09	4.64	3.02	1.91	2.00	2.18	0.98	0.52	0.32	0.21
100t	8.18	9.32	6.60	4.51	2.96	2.75	3.46	1.61	0.87	0.53	0.36
150t	9.96	11.23	8.45	6.02	4.12	3.55	4.59	2.36	1.29	0.79	0.53
200t	11.30	12.64	9.91	7.28	5.15	4.24	4.87	3.07	1.70	1.05	0.71
250t	12.38	13.75	11.11	8.35	6.07	4.86	5.28	3.76	2.10	1.30	0.88
300t	13.28	14.67	12.13	9.29	6.90	5.42	5.71	4.41	2.50	1.56	1.06
400t	16.93	16.15	13.75	10.88	8.36	6.43	6.53	5.65	3.26	2.06	1.40
600t	20.28	18.32	16.09	13.34	10.73	8.48	8.01	7.87	4.72	3.03	2.08
800t	21.63	19.93	17.85	15.23	12.63	10.27	9.31	9.82	6.09	3.97	2.75
1000t	22.75	21.25	19.28	16.79	14.23	11.83	10.46	11.56	7.37	4.87	3.40
1200t	23.74	22.39	20.51	18.13	15.62	13.20	11.51	12.99	8.57	5.75	4.04

RANGE 8000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	1.08	1.38	0.74	0.43	0.25	0.17	0.20	0.14	0.07	0.04	0.03
20t	1.99	2.51	1.42	0.84	0.50	0.34	0.38	0.28	0.15	0.09	0.06
30t	2.77	3.47	2.03	1.22	0.74	0.50	0.55	0.42	0.22	0.13	0.09
40t	3.46	4.29	2.61	1.59	0.97	0.65	0.71	0.56	0.29	0.18	0.12
50t	4.08	5.02	3.14	1.94	1.20	0.80	0.86	0.69	0.37	0.22	0.15
60t	4.63	5.66	3.63	2.28	1.42	0.95	1.00	0.83	0.44	0.27	0.18
100t	6.43	7.71	5.33	3.49	2.26	1.52	1.53	1.36	0.73	0.45	0.30
150t	8.10	9.54	7.02	4.78	3.20	2.21	2.11	2.00	1.08	0.67	0.45
200t	9.40	10.94	8.39	5.89	4.06	2.86	2.63	2.62	1.44	0.89	0.60
250t	11.25	12.06	9.54	6.86	4.85	3.47	3.11	3.21	1.78	1.10	0.75
300t	13.18	13.00	10.49	7.73	5.58	4.05	3.56	3.79	2.12	1.32	0.90
400t	16.27	14.53	12.06	9.23	6.89	5.13	4.38	4.89	2.79	1.75	1.19
600t	18.89	16.80	14.44	11.62	9.09	7.03	5.81	6.91	4.06	2.59	1.77
800t	20.33	18.50	16.25	13.51	10.91	8.67	7.05	8.52	5.27	3.40	2.35
1000t	21.52	19.89	17.74	15.08	12.46	10.13	8.18	9.23	6.42	4.19	2.91
1200t	22.55	21.09	19.01	16.44	13.84	11.44	9.38	9.98	7.52	4.97	3.47

TABLE A15- PAYLOAD AS A PERCENTAGE OF REQUIRED DISPLACEMENT
ADVANCED STRUCTURE, GAS-TURBO ELECTRIC PROPULSION

RANGE 500nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	6.67	4.75	3.65	4.32	2.71	1.75	1.17	0.58	0.34	0.21	0.17
20t	9.67	7.42	6.94	7.27	4.83	3.25	2.23	1.14	0.66	0.43	0.34
30t	11.53	9.22	9.73	9.44	6.55	4.54	3.18	1.67	0.98	0.63	0.50
40t	12.85	10.56	10.63	10.84	7.99	5.68	4.05	2.17	1.29	0.84	0.66
50t	13.85	11.61	11.37	11.41	9.21	6.69	4.85	2.65	1.60	1.04	0.82
60t	14.65	12.47	11.99	11.89	10.26	7.59	5.59	3.11	1.89	1.24	0.98
100t	16.79	16.83	14.26	13.31	13.40	10.46	8.06	4.78	3.01	2.00	1.57
150t	18.38	18.50	16.22	14.59	14.69	13.00	10.40	6.54	4.27	2.90	2.26
200t	19.46	19.62	17.57	15.59	15.49	14.86	12.22	8.05	5.41	3.75	2.90
250t	20.27	20.46	18.58	16.52	16.15	16.32	13.70	9.35	6.45	4.54	3.50
300t	20.93	21.14	19.40	17.46	16.75	16.99	14.93	10.50	7.40	5.28	4.06
400t	21.98	22.20	20.67	18.93	17.79	17.87	16.91	12.44	9.10	6.66	5.09
600t	24.74	23.74	22.48	21.02	19.46	19.32	19.59	15.43	11.89	9.05	6.90
800t	25.76	24.91	23.83	22.54	21.10	20.55	20.70	17.68	14.13	11.07	8.55
1000t	26.64	25.89	24.93	23.77	22.46	21.64	21.70	19.50	16.00	12.83	10.11
1200t	27.43	26.76	25.88	24.82	23.62	22.62	22.60	21.02	17.61	14.39	11.53

RANGE 1000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	5.59	3.84	3.50	3.82	2.31	1.44	0.94	0.45	0.26	0.16	0.11
20t	8.36	6.18	6.70	6.55	4.18	2.71	1.80	0.88	0.51	0.32	0.21
30t	10.14	7.84	8.11	8.54	5.75	3.83	2.59	1.29	0.76	0.48	0.32
40t	11.44	9.10	8.98	9.24	7.08	4.84	3.33	1.69	1.00	0.64	0.42
50t	12.44	10.11	9.68	9.73	8.24	5.75	4.02	2.08	1.24	0.79	0.52
60t	13.25	10.96	10.35	10.16	9.26	6.58	4.66	2.46	1.47	0.95	0.63
100t	15.45	15.71	12.88	11.50	12.05	9.29	6.89	3.84	2.37	1.55	1.03
150t	17.11	17.45	14.88	12.77	12.92	11.78	9.09	5.37	3.41	2.26	1.53
200t	18.25	18.63	16.28	13.80	13.65	13.67	10.85	6.70	4.37	2.94	2.01
250t	19.12	19.53	17.34	14.99	14.31	14.87	12.32	7.89	5.27	3.59	2.47
300t	19.83	20.25	18.21	15.97	14.91	15.30	13.57	8.96	6.11	4.22	2.93
400t	20.95	21.38	19.56	17.52	15.97	16.12	15.60	10.83	7.64	5.39	3.81
600t	24.22	23.02	21.49	19.73	17.82	17.55	18.02	13.78	10.23	7.49	5.44
800t	25.28	24.25	22.92	21.35	19.61	18.81	19.08	16.07	12.39	9.33	6.93
1000t	26.19	25.28	24.08	22.66	21.06	19.94	20.06	17.95	14.24	10.97	8.31
1200t	27.01	26.18	25.09	23.77	22.29	20.95	20.97	19.55	15.85	12.44	9.59

RANGE 2000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	3.94	2.54	2.92	3.09	1.77	1.05	0.66	0.30	0.18	0.11	0.07
20t	6.24	4.32	4.29	4.91	3.28	2.02	1.28	0.60	0.35	0.22	0.14
30t	7.83	5.67	5.27	5.44	4.60	2.90	1.88	0.89	0.52	0.33	0.21
40t	9.03	7.54	6.38	5.92	5.77	3.71	2.44	1.17	0.69	0.43	0.28
50t	9.99	9.09	7.31	6.37	6.81	4.47	2.97	1.45	0.86	0.54	0.35
60t	10.79	10.77	8.11	6.79	7.69	5.18	3.48	1.72	1.03	0.65	0.42
100t	13.04	13.67	10.52	8.15	8.55	7.58	5.32	2.75	1.67	1.06	0.70
150t	14.80	15.52	12.54	9.71	9.36	9.93	7.24	3.94	2.45	1.57	1.05
200t	16.04	16.80	13.99	11.20	10.14	11.05	8.86	5.02	3.18	2.07	1.38
250t	16.99	17.78	15.12	12.40	10.84	11.42	10.25	6.01	3.88	2.55	1.72
300t	17.77	18.57	16.05	13.41	11.48	11.83	11.47	6.93	4.55	3.01	2.04
400t	19.02	19.82	17.53	15.04	12.59	12.66	13.48	8.59	5.81	3.91	2.68
600t	23.19	21.63	19.65	17.42	15.12	14.21	14.79	11.36	8.04	5.58	3.91
800t	24.34	22.98	21.22	19.19	17.03	15.56	15.86	13.62	9.99	7.11	5.07
1000t	25.31	24.09	22.49	20.62	18.59	16.76	16.89	15.52	11.71	8.52	6.17
1200t	26.17	25.06	23.59	21.84	19.91	17.95	17.87	17.17	13.26	9.82	7.22

RANGE 4000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	2.03	1.81	1.18	0.64	0.54	0.69	0.42	0.19	0.11	0.07	0.05
20t	3.51	3.61	2.19	1.22	0.96	1.34	0.82	0.37	0.22	0.14	0.09
30t	4.67	5.35	3.06	1.77	1.33	1.96	1.22	0.56	0.33	0.21	0.14
40t	5.62	6.42	3.83	2.27	1.65	2.54	1.60	0.74	0.44	0.27	0.18
50t	6.43	7.32	4.52	2.75	1.95	3.08	1.97	0.92	0.55	0.34	0.23
60t	7.12	8.09	5.14	3.19	2.22	2.93	2.33	1.09	0.66	0.41	0.27
100t	9.22	10.38	7.15	4.74	3.17	3.42	3.67	1.78	1.09	0.68	0.45
150t	11.01	12.29	9.00	6.30	4.38	4.19	5.18	2.60	1.61	1.01	0.67
200t	12.33	13.66	10.42	7.59	5.45	4.89	6.33	3.38	2.12	1.33	0.89
250t	13.37	14.74	11.57	8.69	6.40	5.52	6.47	4.12	2.61	1.65	1.11
300t	14.24	15.62	12.54	9.64	7.25	6.11	6.80	4.83	3.09	1.97	1.33
400t	17.28	17.04	14.13	11.25	8.75	7.15	7.57	6.15	4.02	2.59	1.75
600t	21.25	19.10	16.48	13.73	11.17	9.02	9.06	8.50	5.75	3.78	2.59
800t	22.54	20.63	18.23	15.63	13.10	10.87	10.40	10.53	7.33	4.92	3.41
1000t	23.62	21.89	19.67	17.19	14.71	12.47	11.61	12.33	8.79	6.00	4.20
1200t	24.56	22.97	20.89	18.53	16.12	13.88	12.72	13.94	10.15	7.03	4.97

RANGE 6000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	1.13	1.46	0.70	0.38	0.23	0.15	0.16	0.14	0.08	0.05	0.03
20t	2.07	2.64	1.34	0.74	0.45	0.30	0.30	0.28	0.17	0.10	0.07
30t	2.87	3.63	1.93	1.08	0.66	0.45	0.45	0.42	0.25	0.15	0.10
40t	3.57	4.47	2.47	1.41	0.87	0.59	0.59	0.55	0.34	0.21	0.14
50t	4.19	5.21	2.96	1.73	1.08	0.73	0.72	0.69	0.42	0.26	0.17
60t	4.75	5.87	3.43	2.03	1.28	0.87	0.86	0.82	0.50	0.31	0.21
100t	6.54	7.93	5.03	3.14	2.05	1.42	1.35	1.35	0.83	0.51	0.34
150t	8.19	9.76	6.61	4.35	2.92	2.07	1.92	1.99	1.23	0.76	0.51
200t	9.47	11.13	7.89	5.40	3.73	2.69	2.43	2.60	1.63	1.01	0.68
250t	11.35	12.24	8.98	6.34	4.48	3.27	2.92	3.20	2.02	1.26	0.85
300t	13.12	13.16	9.92	7.18	5.17	3.83	3.37	3.78	2.40	1.51	1.02
400t	16.47	14.66	11.49	8.65	6.44	4.88	4.22	4.88	3.15	1.99	1.35
600t	19.45	16.88	13.90	11.01	8.58	6.74	5.71	6.89	4.56	2.94	2.00
800t	20.86	18.54	15.74	12.90	10.38	8.36	7.01	8.57	5.90	3.85	2.64
1000t	22.03	19.90	17.26	14.49	11.93	9.81	8.20	9.44	7.16	4.73	3.28
1200t	23.05	21.07	18.57	15.87	13.31	11.13	9.42	10.33	8.35	5.59	3.90

RANGE 8000nm AT DESIGN SPEEDS OF

PAYLOAD	8kt	10kt	12kt	14kt	16kt	18kt	20kt	24kt	28kt	32kt	36kt
10t	0.69	0.97	0.46	0.25	0.16	0.11	0.08	0.11	0.07	0.04	0.03
20t	1.30	1.81	0.90	0.50	0.31	0.21	0.16	0.23	0.14	0.08	0.06
30t	1.85	2.54	1.31	0.74	0.46	0.32	0.24	0.34	0.21	0.13	0.08
40t	2.36	3.20	1.70	0.97	0.61	0.43	0.32	0.45	0.28	0.17	0.11
50t	2.82	3.80	2.07	1.19	0.76	0.53	0.40	0.56	0.34	0.21	0.14
60t	3.25	4.34	2.42	1.41	0.90	0.63	0.48	0.67	0.41	0.25	0.17
100t	4.72	6.12	3.67	2.25	1.47	1.04	0.80	1.10	0.68	0.42	0.28
150t	6.91	7.80	4.99	3.19	2.13	1.53	1.18	1.59	1.02	0.63	0.42
200t	8.93	9.11	6.11	4.04	2.76	2.01	1.56	1.97	1.35	0.83	0.56
250t	10.66	10.20	7.09	4.82	3.36	2.46	1.93	2.33	1.67	1.04	0.70
300t	12.39	11.12	7.96	5.54	3.92	2.91	2.29	2.68	2.00	1.24	0.84
400t	15.80	12.64	9.45	6.84	4.98	3.76	2.98	3.35	2.63	1.65	1.12
600t	17.79	14.94	11.82	9.02	6.85	5.32	4.30	4.56	3.84	2.44	1.66
800t	19.30	16.68	13.67	10.82	8.47	6.73	5.52	5.66	5.00	3.21	2.20
1000t	20.54	18.12	15.22	12.37	9.91	8.02	6.67	6.67	6.11	3.97	2.74
1200t	21.63	19.35	16.57	13.73	11.21	9.21	7.75	7.62	7.17	4.71	3.26

APPENDIX 3

SAMPLE WEIGHT EQUATION CALCULATION

In order to illustrate the 'weight equation' approach of Chapter 4, a typical design situation may be considered.

A *type ship* SWATH has a payload (P) of 1035t, a designed maximum speed (V) of 28 knots and 9000nm endurance (E) at a cruise speed (U) of 15 knots. Structure is mild steel throughout, and propulsion is gas turbo-electric.

The weights for a *similar* ship having a payload of 1300t, maximum speed of 25 knots, and a range of 9000nm at 15 knots (N.B. no change) may be determined using the weight equation.

$\partial P/P$	=	[(1300/1035)-1.0]100.0	=	25.6%
$\partial V/V$	=	(25-28)100.0	=	-10.7%
∂U	=	(15.0-15.0)100.0	=	0.0%
∂E	=	(9000-9000)100.0	=	0.0%

Using the indices specific to a gas turbo-electric powered SWATH constructed of mild steel, the calculation has the form shown in Table A3.1

Table A3.1 Tabular Calculation of SWATH Data by Weight Equation

Column	1	2	3	4	5	6	7
Item	Weight in Type Ship	Weight as a % of Δ	Index of Δ	Product 2 x 3	Weights increase	New % Weight	New Weights
Structure	6297	41.79	1.029	43.00	1.0374	43.353	6532
Machinery	649	4.31	0.406	1.75	0.8193	3.531	532
Auxiliary	2280	15.13	0.981	14.84	1.0357	15.670	2361
Outfit	934	6.20	0.881	5.46	1.0320	6.398	964
Store/Margin	1417	9.40	0.000	0.000	0.0000	9.400	1417
Fuel	2455	16.30	0.598	9.75	1.0217	16.654	2509
Payload	1035	6.87	-	-	-	8.629	1300
Δ	15067	100.00		74.80		103.635	15615

In order to develop the table beyond column 4, the calculation to determine $\partial\Delta/\Delta$ must first be performed.

$$\partial\Delta/\Delta = \frac{0.256(6.87/100) + -0.107(1.827*4.31/100) + 0.0(1.691*16.3/100) + 0.0\,(1.00*16.3/100)}{1 - 0.748}$$

$$= 0.3636$$

which may then be used to examine the way in which the individual weights increase.

Group	Multiplying Function	Multiplier
Structure	1.0+(1.029*0.03636)	=1.0374
Machinery	1.0+(0.406*0.03636)+(1.827* -0.107)	=0.8193
Auxiliary	1.0+(0.981*0.03636)	=1.0357
Outfit	1.0+(0.881*0.03636)	=1.0320
Stores/Margin	1.0+(0.000*0.03636)	=0.0000
Fuel	1.0+(0.598*0.03636)+(1.691*0.0)+(1.0* -0.0)	=1.0217

The above values are returned to column 5 of Table A3.1, where they are multiplied by the contents of column 2 to give new percentage weights. These are summed to give the *new* displacement as a percentage of the *type* displacement.

The new displacement is therefore 1.036*15067 = **15615 tonnes**

APPENDIX 4

HYDROSTATIC CALCULATIONS

This appendix describes the calculation procedures in module *HYD*. The nomenclature employed to describe SWATH geometry is that used throughout the thesis.

Hydrostatic Calculations

Buoyancy

Hull volume $\nabla_H = 2 \int_0^{LOA} A_H(x)\, dx$

where $A_H(x) = {}^{\pi}/_4[d(x)\, b(x)]$ for circular or elliptical hulls

or $A_H(x) = [d(x)\, b(x)] + [(\pi - 4)\, r(x)^2]$ for 'obround' hulls

Strut volume $\nabla_S = 2 \int_0^{LOA} A_S(x)\, dx$

where $A_S(x) = t(x)\, [\, T - 0.5\, (\, D_H + d(x)\,)\,] \; = t(x)\, [\, CS - 0.5\, d(x)\,]$

Where the strut mets the upper hull surface, a portion of sectional area is neglected if one considers only hull and strut as contributing to sectional area. Because this intersection volume can contribute as much as 4% of the full load displacement, it is as important to account for this as it is to include appendage volume.

Intersection volume $\nabla_I = 2 \int_0^{LOA} A_I(x)\, dx$

where A_I is the shaded area in Figure A4.1

and $A_I(x) = 0.25\, d(x)^2\, [(2 - \cos\theta)({}^{t(x)}/_{d(x)}) - \theta]$

and $\theta = \arcsin\, [{}^{t(x)}/_{d(x)}]$

Appendage (fin) volume ∇_F is calculated from the currently active values of thickness and chord using the assumption of elliptical sections.

Total immersed volume $\nabla_T = \nabla_H + \nabla_S + \nabla_I + \nabla_F$

This result is also checked by integration of the total areas ($A_T = A_H + A_S + A_I$) at each section

Total immersed volume, $\nabla_T = 2 \int_0^{LOA} A_T(x)\, dx$

Longitudinal moment of buoyancy $M_{\nabla T} = 2 \int_0^{LOA} x\, A_T(x)\, dx$

Longitudinal centre of buoyancy, LCB $x_{LCB} = M_{\nabla T} / \nabla_T$

The height of the centre of buoyancy is calculated by an approximation.

$$KB = \left[0.5\, D_H\, \nabla_H + (0.98\, D_H\, \nabla_I) + 0.5[T - 0.5\,(D_H + d(x))]\nabla_S + 0.5\, D_H\, \nabla_F\right] / \nabla_T$$

Waterplane Properties

Waterplane area $A_W = 2 \int_0^{LOA} t(x)\, dx$

Moment of waterplane area about origin $M_{AW} = 2 \int_0^{LOA} x\, t(x)\, dx$

Waterplane centroid $x_{LCF} = M_{AW} / A_W$

Longitudinal moment of waterplane inertia about LCF $I_L = 2 \int_0^{LOA} (x^2 - x_{LCF}^2)\, t(x)\, dx$

Transverse waterplane moment of inertia $I_T = {}^2/_3 \int_0^{LOA} t(x)^3\, dx + A_W\, ({}^{BHC}/_2)^2$

Initial Stability

By definition, longitudinal metacentric radius, $BM_L = {}^{I_L}/_{\nabla_T}$

Transverse metacentric radius, $BM_T = {}^{I_T}/_{\nabla_T}$

Automated method for hull design

It is sometimes desirable to develop a systematic series of simple SWATH hullforms. This requires the ability to generate designs having specified values of displacement, waterplane area, LCB, LCF, GM_L, GM_T, hull length, maximum hull sectional area, strut length and thickness. This may be achieved in the following manner.

A number of coefficients may be derived from the area (A_W), first (M_{AW}) and second (I_L) moments of the waterplane, the hull volume (∇_H), moment ($M_{\nabla H}$) and maximum sectional area (A_{Hmax}), and leading dimensions T_S, L_S, L_H.

$C_W = A_W/(2L_ST_S)$

$C_{LCF} = M_{AW}/(A_WL_S)$ for M_{AW} about strut midlength position

$C_{IW} = I_L/(A_WL_S^2)$ for I_L about strut midlength position

$C_p = \nabla_H/(2L_HA_{Hmax})$

$C_{LCB} = M_{\nabla H}/(A_{Hmax}L_H^2)$ for $M_{\nabla H}$ about body midlength position

It has been shown [41,42] that strut thickness and lower hull sectional area functions may be represented as finite sums of Chebychev series.

$$t(x) = 2\sum_{m=1}^{M}[A_{sm}\cos(2m-1)\alpha + B_{sm}\sin(2m\alpha)]$$ for x relative to the strut midlength

$$A_H(x) = \sum_{m=1}^{M}[A_{bm}\cos(2m-1)\alpha + B_{bm}\sin(2m\alpha)]$$ for x relative to the body midlength

where $\alpha = \sin^{-1} x$

$A_{s1} = 4\, C_W/\pi$

$A_{s2} = A_{s1}(1 - 16\, C_{IW})$

$A_{s3} = 1 - A_{s1} - A_{s2}$

$A_{b1} = 4\, C_p/\pi$

$A_{b2} = 1 - A_{b1}$

$B_{b1} = 4\, A_{b1}\, C_{LCB}$

$B_{s2} = B_{s3} = A_{b3} = B_{b2} = B_{b3}$

Thus, the two series may be written in terms of C_W, C_{LCF}, C_{IW}, C_p, C_{LCB} which are known for given values of A_W, M_{AW}, I_L, ∇_H, $M_{\nabla H}$, T_S, L_S, A_{Hmax}, and L_H

In turn, the latter group of variables may be expressed in terms of the more recognizable quantities of displacement, A_W, LCB, LCF, GM_L and GM_T (for known KG), hull length (L_H) and maximum sectional area (A_{Hmax}), and the setback (SS) and dimensions of the strut (L_S, T_S).

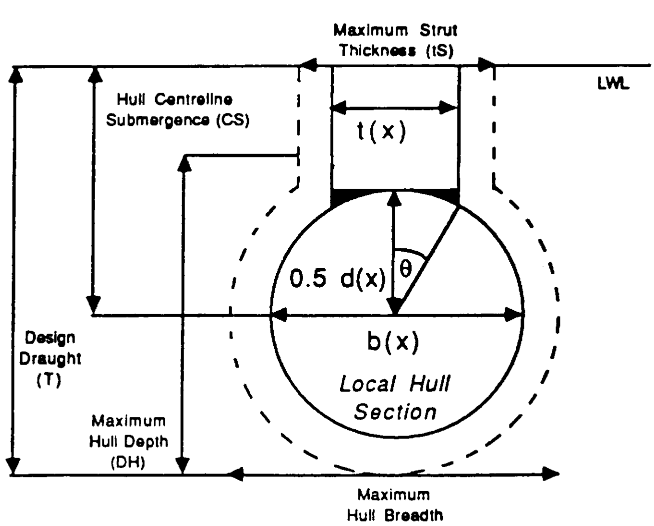
All but one (usually SS) of these variables may be used as fixed input requirements in an automated hull generation method. For a series of values of the free variable, the strut thickness and sectional area Chebyshev series may be evaluated at all values of x. If these functions show non negative values at all values of x, then an acceptable pair of series and value of the free variable has been found. Since the strut properties are then known, the hull centreline separation required to give GM_T may be determined.

References

41. Nagley, T.J. and Reed, A.M., "Documentation for SWATH Ship Resistance Optimisation Program (*SWATHO*) User's and Maintenance Manual", DTNSRDC Report SPD-0927-03, September, 1981

42. McCreight, K.K., "Assessing the Seaworthiness of SWATH Ships", SNAME Annual Meeting, New York, November 1987

Figure A4.1 Computation of Hull-Strut Intersection Volume



APPENDIX 5

MARINE ENGINE DATABASE

Appendix 5 contains details of the marine engines used in the machinery design program described in Chapter 8. The data is presented in tabular format, as indicated below.

293 medium speed (350 - 1000 RPM) inline diesels	Table A5.1
114 medium speed (350 - 1000 RPM) 'vee' diesels	Table A5.2
72 high speed (1000+ RPM) inline diesels	Table A5.3
183 high speed (1000+ RPM) 'vee' diesels	Table A5.4

Each table contains 10 columns, listing the following information for each engine;

1) design RPM
2) maximum continuous rating (metric HP)
3) weight (in kg)
4) length (in mm)
5) breadth (in mm)
6) depth (in mm)
7) specific fuel consumption at MCR (in g/kW/hr)
8) cost (in £, 1986)
9) code denoting country of origin (see Table A5.5)
10) code denoting manufacturer (see Table A5.6)

TABLE A5.1

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800,  2040,  18500,  5030,  1853,  3394, 193,      0    ,  6,  8
800,  3060,  26000,  5125,  1853,  6120, 193,      0    ,  6,  8
800,  4080,  35500,  7208,  1853,  7198, 193,      0    ,  6,  8
800,  4590,  38000,  7700,  1853,  7630, 193,      0    ,  6,  8
750,  1800,  17000,  4820,  1830,  2970, 199,      0    ,  8, 10
750,  2400,  21000,  6010,  1930,  3120, 199,      0    ,  8, 10
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600,  2013,  15600,  4070,  1870,  2670, 196,      0    ,  5,  1
600,  2416,  18000,  4570,  1870,  2945, 195,      0    ,  5,  1
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600,  1140,  10700,  3652,  1755,  2655, 199,      0    ,  7,  2
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425, 15400, 222000, 12182,  3905,  6685, 178,      0    ,  7,  4
425, 17300, 250000, 13212,  3905,  6685, 178,      0    ,  7,  4
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750,   425,   9000,  3605,  1290,  1950, 243,      0    ,  7,  4
750,   500,   7300,  3140,  1290,  2325, 243,      0    ,  7,  4
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750,   600,   7600,  3140,  1290,  2325, 243,      0    ,  7,  4
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999	1224	8100	3804	1270	2130	0	0	4	22
825	1100	14000	4140	1530	2420	0	0	4	22
825	1420	0	4876	1529	2417	0	0	4	22
775	1800	18500	5280	1690	3080	0	0	4	22
775	2400	22000	6240	1690	3200	0	0	4	22
775	2700	24000	7085	1690	3240	0	0	4	22
750	3300	36000	6290	1970	3885	0	0	4	22
750	3850	39000	6830	1970	3885	0	0	4	22
750	4400	44000	7400	1970	3980	0	0	4	22
750	4950	47000	7940	1970	3980	0	0	4	22
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999	3083	24500	5880	2070	3410	203	0	1	28
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600	5840	0	7250	2590	3710	0	0	1	28
600	6570	0	7940	2590	3710	0	0	1	28
600	3960	40920	5666	2428	4264	206	0	1	28
600	5280	51800	6931	2428	4264	206	0	1	28
600	5940	0	0	2428	4264	206	0	1	28
500	3850	46230	6359	2428	4264	206	0	1	28
999	1107	7354	3286	1288	2460	204	0	1	28
999	1329	9816	3613	1288	2437	204	0	1	28
999	1771	12620	4403	1288	2476	200	0	1	28
999	1994	13028	4937	1288	2579	200	0	1	28
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999	1220	20660	4410	1410	2571	215	0	1	28
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380	1950	22700	4675	1816	2271	0	0	13	42
330	2300	28100	5675	2048	2326	0	0	13	42
360	3800	43500	6273	2674	2628	0	0	13	42
350	2050	16000	3925	1845	1824	0	0	13	42
500	4200	48000	5580	2575	3550	0	0	11	44
500	4620	49000	5650	2575	3550	0	0	11	44
375	1500	20500	4014	1984	2960	0	0	13	59
300	1700	24500	4163	2046	3265	0	0	13	59
290	2000	28500	4430	2209	3463	0	0	13	59
275	2300	35000	4780	2312	3628	0	0	13	59
255	2800	48000	5225	2531	4013	0	0	13	59
227	3400	60000	5710	2750	4372	0	0	13	59
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720	2000	19500	5130	1850	3250	0	0	13	47
600	2202	26500	6045	1560	2970	0	0	13	47
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630	3000	29000	7030	1970	3295	0	0	13	47
450	3600	58400	7275	2075	3770	0	0	13	47
360	1600	24300	5240	1830	3300	0	0	13	47
360	1800	24300	5240	1830	3300	0	0	13	47
310	2200	30400	5180	1825	3605	0	0	13	47
300	3000	48300	6095	2220	3770	0	0	13	47
600	3000	26500	5240	1500	2930	0	0	1	36
450	6000	82000	7460	2345	3980	0	0	3	38
750	2400	15400	3865	1355	2610	0	0	3	38
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520	3900	34700	7076	1840	3063	0	0	3	38
520	4482	50000	7310	2070	3515	0	0	3	38
450	4500	53200	7308	2512	2586	0	0	3	38
450	4500	50000	6570	1540	3730	0	0	10	54
450	5220	58000	7040	1750	4150	0	0	10	54
510	5400	60000	7040	1750	4150	0	0	10	54
650	1800	15500	4667	1504	2658	0	0	13	49
650	2400	20900	6231	1575	2651	0	0	13	49
450	8820	108000	7396	3005	5550	0	0	11	44
425	9000	101000	8230	3327	4937	0	0	2	45
400	8250	122000	9030	3880	6095	0	0	3	38
350	9900	149000	9465	3200	2026	0	0	3	38

600,	545,	7200,	2505,	1620,	2655,	0,	0,	7,	2
600,	1140,	10700,	3652,	1755,	2655,	0,	0,	7,	2
500,	180,	5600,	2602,	980,	1745,	0,	0,	4,	17
500,	260,	6100,	2602,	1045,	1880,	0,	0,	4,	17
425,	240,	9700,	3481,	1330,	2155,	0,	0,	4,	17
425,	575,	13000,	4051,	1430,	2430,	0,	0,	4,	17
425,	810,	15000,	4521,	1510,	2515,	0,	0,	4,	17
425,	1080,	18600,	5208,	1470,	2620,	0,	0,	4,	17
395,	1000,	21600,	6278,	1470,	2620,	0,	0,	4,	17
440,	1200,	14500,	3400,	1200,	1920,	0,	0,	13,	55
460,	1400,	17000,	3850,	1220,	2090,	0,	0,	13,	55
450,	950,	10000,	3028,	1020,	1801,	0,	0,	13,	55
500,	1000,	10000,	3028,	1020,	1801,	0,	0,	13,	55
600,	550,	12300,	4130,	1660,	2700,	0,	0,	17,	56
600,	700,	13500,	4425,	1640,	2250,	0,	0,	17,	56
375,	960,	13600,	4425,	1640,	2250,	0,	0,	17,	56
375,	980,	25200,	5900,	2050,	3650,	0,	0,	17,	56
375,	1670,	32800,	7670,	2370,	3620,	0,	0,	17,	56
750,	1510,	9500,	3445,	1470,	2923,	0,	0,	2,	29
514,	2475,	29000,	5130,	1910,	3140,	0,	0,	2,	29
400,	1000,	13000,	4160,	1610,	1855,	0,	0,	13,	42
400,	1200,	13000,	4160,	1610,	1855,	0,	0,	13,	42
395,	1500,	17500,	3920,	1610,	2250,	0,	0,	13,	42
400,	600,	11500,	3874,	1080,	2446,	0,	0,	13,	57
400,	650,	11700,	3874,	1080,	2446,	0,	0,	13,	57
400,	750,	11700,	3874,	1080,	2446,	0,	0,	13,	57
400,	800,	12500,	3874,	1020,	2540,	0,	0,	13,	57
400,	900,	12500,	3874,	1020,	2540,	0,	0,	13,	57
400,	1050,	13500,	3992,	1120,	2613,	0,	0,	13,	57
400,	1300,	13500,	3992,	1120,	2613,	0,	0,	13,	57
395,	1300,	15500,	4325,	1120,	2865,	0,	0,	13,	57
395,	1400,	16500,	3995,	1220,	2932,	0,	0,	13,	57
395,	1400,	16500,	4340,	1190,	2920,	0,	0,	13,	57
900,	650,	6400,	3330,	1530,	2125,	0,	0,	13,	47
900,	800,	8000,	3715,	1245,	2280,	0,	0,	13,	47
900,	1000,	11500,	4055,	1440,	2505,	0,	0,	13,	47
900,	1100,	11500,	4085,	1440,	2160,	0,	0,	13,	47
720,	1200,	13800,	4520,	1405,	2765,	0,	0,	13,	47
720,	1400,	16200,	4750,	1540,	2775,	0,	0,	13,	47
420,	600,	9700,	4090,	1350,	2410,	0,	0,	13,	47
410,	850,	11900,	4140,	1510,	2585,	0,	0,	13,	47
400,	850,	14600,	4015,	1465,	2835,	0,	0,	13,	47
400,	1200,	15800,	4475,	1465,	2835,	0,	0,	13,	47
390,	1400,	18700,	4700,	1675,	2954,	0,	0,	13,	47
750,	1080,	9200,	3540,	1380,	2340,	0,	0,	1,	36
900,	600,	6000,	3347,	1134,	2029,	0,	0,	13,	49
900,	800,	7300,	3422,	1075,	2026,	0,	0,	13,	49
800,	1000,	9000,	4402,	1453,	2330,	0,	0,	13,	49
750,	1200,	8400,	4085,	1260,	2244,	0,	0,	13,	49
700,	1500,	12400,	4630,	1313,	2649,	0,	0,	13,	49
480,	1600,	22300,	4095,	1330,	2200,	0,	0,	13,	55
500,	1600,	26000,	4300,	1370,	2395,	0,	0,	13,	55
540,	2000,	31000,	4787,	1400,	2600,	0,	0,	13,	55
600,	2300,	34000,	5025,	1500,	2760,	0,	0,	13,	55
600,	2800,	42000,	5215,	1560,	2845,	0,	0,	13,	55
760,	4000,	66000,	6888,	1860,	3390,	0,	0,	13,	55
550,	1600,	21000,	3705,	1260,	2285,	0,	0,	13,	55
600,	1900,	27000,	4055,	1400,	2470,	0,	0,	13,	55
660,	2300,	36000,	4750,	1510,	2745,	0,	0,	13,	55
720,	2700,	46000,	5220,	1680,	2982,	0,	0,	13,	55
740,	2800,	46500,	5220,	1680,	3030,	0,	0,	13,	55
800,	3300,	60000,	6155,	1850,	3288,	0,	0,	13,	55
500,	2200,	34500,	5930,	2305,	3800,	0,	0,	17,	56
750,	3305,	24000,	5195,	2110,	925,	0,	0,	2,	29
650,	3604,	29000,	6348,	2249,	1005,	0,	0,	2,	29
825,	1650,	11700,	3780,	1270,	2830,	0,	0,	5,	58
825,	2200,	15700,	4540,	1370,	2940,	0,	0,	5,	58

825	2475	17400	4920	1300	2940	0	0	5	58
750	3000	26500	4650	1740	4000	0	0	5	58
750	4500	39500	6210	1740	4310	0	0	5	58
300	1800	26000	4739	1360	2997	0	0	13	57
280	2000	30000	5285	1470	3175	0	0	13	57
280	2200	30000	5285	1470	3175	0	0	13	57
260	2400	35000	5515	1600	3395	0	0	13	57
260	2600	35000	5515	1600	3395	0	0	13	57
240	2800	45000	5434	1710	3832	0	0	13	57
240	3300	50000	5577	1820	3946	0	0	13	57
220	4000	70000	6610	2000	4453	0	0	13	57
220	4500	70000	6110	2000	4453	0	0	13	57
180	6000	130000	7767	2400	5768	0	0	13	57
315	3200	43000	5056	1500	3003	0	0	13	53
225	4700	75500	6230	1880	4065	0	0	13	53
228	6700	134000	8890	2070	4314	0	0	13	53
900	1620	7900	3603	1740	2155	0	0	2	44
500	1800	18000	5050	1787	3280	0	0	2	44
600	2700	20000	5167	1962	3480	0	0	2	44
750	3996	33000	5833	1900	3498	0	0	2	44
450	4680	45000	6510	2134	4125	0	0	2	44
500	5010	51000	6638	2422	4255	0	0	2	44
720	1890	12800	4020	1325	2490	201	0	1	36
750	2576	17200	4750	1325	2490	201	0	1	36
999	2305	12800	4020	1325	2490	208	0	1	36
999	3080	17200	4750	1325	2490	208	0	1	36

TABLE A5.2

750	3600	26000	6370	2200	3030	199	0	8	10
750	4800	34000	6890	2200	3200	199	0	8	8
800	6120	42000	6771	2555	3653	193	0	6	8
800	8160	50000	7891	2615	3823	193	0	6	8
800	9180	58000	8503	2723	3974	193	0	6	9
900	2250	12000	3340	1730	2820	196	0	6	9
900	3380	17200	4420	1950	2840	196	0	6	9
900	4500	21700	5325	1980	2840	196	0	6	2
600	1900	16300	4165	2000	2901	199	0	7	2
600	2280	18900	4651.	2063	2970	199	0	7	2
600	2665	22000	5101	2129	2969	199	0	7	2
600	3045	27600	5551	2129	2969	199	0	7	2
600	3425	30000	6115	2036	2907	199	0	7	2
600	3800	33500	6555	2036	2907	199	0	7	2
600	3221	18000	3685	2070	2940	192	0	5	1
600	4027	21600	4198	2070	3030	192	0	5	1
600	4832	25300	4578	1900	3250	190	0	5	1
600	6443	32700	4846	1900	3710	188	0	5	1
600	10100	98000	6930	4400	4095	187	0	7	4
600	13500	130000	8650	4400	4095	187	0	7	4
600	15200	140000	9350	4400	4095	187	0	7	4
999	4560	25700	4855	1990	3145	197	0	7	4
825	2040	12000	3340	1730	2820	204	0	1	13
825	3060	17200	4420	1950	2840	204	0	1	13
825	4080	21700	5325	1980	2840	204	0	1	13
825	1768	10700	3315	1800	2285	210	0	1	13
825	2638	14200	4225	1800	2285	210	0	1	13
825	3536	17900	5065	1800	2285	210	0	1	13
900	2100	13600	3304	1710	2408	0	0	13	12
900	2800	18000	4115	1710	2730	0	0	13	12
750	2800	22000	4200	2350	3000	0	0	13	12
720	3700	28000	5245	2350	3140	0	0	13	12
600	4200	41000	5170	3130	3415	0	0	13	12
600	6000	52000	6500	3130	3945	0	0	13	12
750	5280	42600	6400	2750	3370	0	591000	1	15
750	7040	54450	7810	2750	4020	0	787500	1	15
750	2124	21620	4407	2016	2677	207	237600	1	15
750	2832	30250	5359	2016	2677	207	316500	1	15
999	1630	10900	3350	1510	2600	199	0	14	21
999	1900	12300	3700	1510	2750	199	0	14	21
999	2180	13500	4050	1510	2750	199	0	14	21
999	2450	15200	4400	1510	2750	199	0	14	21
999	3600	21000	4350	2000	2850	202	0	14	21
999	4800	27500	6050	2000	3100	202	0	14	21
999	5400	30000	6500	2000	3100	202	0	14	21
750	3000	31600	4775	1900	3300	0	0	14	21
750	4000	39100	5900	2400	3580	0	0	14	21
750	4500	43000	6410	2400	3580	0	0	14	21
750	3600	32200	4910	1900	3640	0	0	14	21
750	4800	39900	5930	2400	3700	0	0	14	21
750	5400	43900	6930	2400	3710	0	0	14	21
750	6600	50000	6050	2950	3900	197	0	14	21
750	7700	57000	6650	2950	3900	197	0	14	21
750	8800	65000	7250	3000	3950	197	0	14	21
750	9900	72000	7800	3000	3950	197	0	14	21
600	9900	92000	7650	3050	4600	187	0	14	21
600	11500	104000	8400	3050	4600	187	0	14	21
600	13200	117000	9350	3050	4750	187	0	14	21
600	14850	129000	10150	3050	4750	187	0	14	21
450	10550	129000	7500	4000	5500	0	0	14	21
450	12660	150000	8300	4000	5500	0	0	14	21
450	14770	168000	9100	4000	5500	0	0	14	21
450	16880	189000	9900	4000	5500	0	0	14	21
450	18990	208000	10800	4000	5700	0	0	14	21
450	7500	85000	7400	3480	3950	0	0	14	21
450	8750	99000	8750	3530	4200	0	0	14	21

450	10000	110000	9450	3530	4200	0	0	14	21
450	11250	121000	10150	3530	4200	0	0	14	21
450	10550	129000	7500	4000	5350	0	0	14	21
450	12660	150000	8300	4000	5350	0	0	14	21
450	14770	168000	9100	4000	5350	0	0	14	21
450	16880	189000	10000	4000	5500	0	0	14	21
450	18990	208000	10800	4000	5500	0	0	14	21
999	1630	10900	3820	1510	2600	0	0	4	22
999	1900	12300	4170	1510	2745	0	0	4	22
999	2180	13500	4520	1510	2745	0	0	4	22
999	2450	15200	4870	1510	2745	0	0	4	22
775	3600	27000	5560	2015	3022	0	0	4	22
775	4800	33000	6600	2090	3070	0	0	4	22
999	4692	34500	4850	2656	3317	203	0	1	28
999	6166	38600	5870	2706	3427	203	0	1	28
600	7920	78100	7223	3658	4518	206	0	1	28
500	7700	92130	8125	3658	4518	206	0	1	28
600	10560	102450	8925	3658	4518	206	0	1	28
600	8760	0	7550	4880	4010	0	0	1	28
600	11680	0	9250	4880	4010	0	0	1	28
700	3000	25400	6049	2360	2850	0	0	13	49
815	3300	21600	4760	2300	3330	0	0	5	58
825	4950	29000	6205	2320	3330	0	0	5	58
175	11500	218000	8890	2040	4560	0	0	13	53
530	13500	142000	10290	4440	4815	0	0	13	60
720	3600	42300	6965	2475	3085	0	0	13	47
750	3096	19500	4800	1830	2310	0	0	1	36
750	3864	21200	4785	1830	2395	0	0	1	36
470	11400	113000	8200	3710	4141	0	0	3	38
400	15000	200000	9655	4480	5885	0	0	3	38
600	3800	33500	6555	2100	2900	0	0	7	2
900	1050	10800	5062	1676	2749	0	0	12	61
900	1500	13500	5932	1676	2840	0	0	12	61
900	1950	18200	6913	1676	2840	0	0	12	61
900	1525	11600	6126	1676	3208	0	0	12	61
900	2550	14900	7072	1676	3361	0	0	12	61
900	3400	19000	8053	1676	3361	0	0	12	61
900	4000	21300	8898	1676	3564	0	0	12	61
800	2305	14900	7072	1719	3361	0	0	12	61
800	3070	19000	8053	1719	3361	0	0	12	61
800	3600	21200	8898	1719	3564	0	0	12	61
900	2800	16600	7163	1719	3439	0	0	12	61
900	3600	19800	8120	1719	3439	0	0	12	61
900	4300	22700	9053	1719	3642	0	0	12	61
900	4344	21230	4785	1830	2400	201	0	1	36
999	6144	0	0	1830	2400	201	0	1	36
999	4610	21230	4785	1830	2400	208	0	1	36
999	6160	25820	5600	1830	2400	208	0	1	36

TABLE A5.3

1200,	225,	2970,	2179,	1073,	1555,	238,	0 ,	1,	11
1200,	300,	3060,	2179,	1073,	1555,	238,	0 ,	1,	11
1200,	335,	3310,	2179,	1073,	1555,	233,	0 ,	1,	11
1200,	300,	3660,	2635,	1073,	1555,	238,	0 ,	1,	11
1200,	400,	3780,	2635,	1073,	1555,	238,	0 ,	1,	11
1200,	440,	3840,	2635,	1073,	1555,	228,	0 ,	1,	11
1500,	1012,	4440,	2873,	1613,	1918,	0 ,	188000,	1,	7
1200,	896,	6500,	2770,	1445,	2460,	199,	0 ,	6,	8
1200,	1428,	9300,	3442,	1445,	2460,	199,	0 ,	6,	8
1200,	1904,	11300,	4177,	1445,	2460,	199,	0 ,	6,	8
1800,	400,	1720,	1692,	895,	1342,	217,	0 ,	3,	5
1800,	330,	1650,	1692,	895,	1342,	214,	0 ,	3,	5
1800,	180,	1640,	1492,	900,	1085,	234,	0 ,	3,	5
1800,	225,	1610,	1692,	840,	1222,	228,	0 ,	3,	5
2300,	345,	1100,	1460,	810,	1160,	0 ,	0 ,	3,	6
1650,	480,	2800,	1935,	1230,	1780,	0 ,	0 ,	3,	6
1650,	550,	2800,	1935,	1230,	1780,	0 ,	0 ,	3,	6
1250,	1630,	10000,	3550,	1600,	2780,	0 ,	0 ,	3,	6
1250,	2180,	13000,	4300,	1900,	2700,	0 ,	0 ,	3,	6
2000,	340,	1050,	1484,	900,	1055,	225,	0 ,	7,	3
2000,	300,	1050,	1484,	900,	1055,	220,	0 ,	7,	3
1900,	224,	980,	1484,	900,	1055,	223,	0 ,	7,	3
1900,	188,	930,	1352,	940,	1106,	232,	0 ,	7,	3
1900,	169,	920,	1352,	818,	1106,	238,	0 ,	7,	3
2100,	132,	710,	1272,	893,	1022,	242,	0 ,	7,	3
2100,	125,	610,	1170,	926,	913,	230,	0 ,	7,	3
2200,	97,	590,	1170,	784,	937,	244,	0 ,	7,	3
1200,	300,	3200,	2230,	1130,	1867,	0 ,	0 ,	13,	12
1200,	400,	3350,	2400,	1240,	1880,	0 ,	0 ,	13,	12
1500,	62,	820,	1054,	743,	1555,	0 ,	7955,	1,	14
1500,	127,	1370,	1617,	806,	1302,	0 ,	11820,	1,	14
1500,	150,	1370,	1618,	807,	1122,	0 ,	12830,	1,	14
1500,	170,	1680,	1925,	806,	1312,	0 ,	15515,	1,	14
1500,	182,	1320,	1618,	806,	1236,	0 ,	13365,	1,	14
1500,	200,	1680,	1714,	806,	1237,	0 ,	16805,	1,	14
1150,	230,	3740,	2469,	870,	1723,	0 ,	24175,	1,	14
1600,	250,	1640,	1441,	900,	1161,	0 ,	17345,	1,	14
1600,	310,	1660,	1441,	1001,	1161,	0 ,	18475,	1,	14
1800,	324,	1135,	1745,	752,	1128,	210,	0,	8,	23
1200,	1420,	11700,	3910,	1800,	2540,	0,	0,	15,	36
1000,	2400,	0,	4925,	1495,	1850,	0,	0,	15,	50
1100,	1335,	10600,	3910,	1800,	2540,	0,	0,	16,	52
1000,	2475,	15600,	3600,	1700,	2590,	0,	0,	10,	32
1000,	3330,	19000,	4420,	1700,	2590,	0,	0,	10,	32
1000,	1500,	8680,	3350,	1210,	2650,	0,	0,	15,	33
1000,	1620,	11900,	3500,	1225,	1860,	0,	0,	13,	53
1000,	1626,	11400,	3500,	1225,	1860,	0,	0,	13,	53
1000,	1440,	9200,	3540,	1380,	2340,	0,	0,	1,	36
1475,	954,	3400,	3120,	910,	1700,	0,	0,	3,	38
1000,	1800,	10500,	3590,	1300,	2385,	0,	0,	3,	38
1000,	2400,	11700,	3865,	1405,	2690,	0,	0,	3,	38
1000,	840,	6400,	2780,	792,	1890,	0,	0,	10,	54
1000,	1620,	11400,	3500,	906,	2310,	0,	0,	10,	54
1000,	1800,	11900,	3500,	906,	2310,	0,	0,	10,	54
1800,	350,	2020,	2221,	930,	1780,	0,	0,	1,	41
1800,	425,	2390,	2357,	1080,	1996,	0,	0,	1,	41
1800,	500,	3040,	2706,	1135,	2013,	0,	0,	1,	41
2000,	224,	1430,	1665,	862,	1374,	0,	0,	2,	29
1800,	465,	1600,	1796,	1112,	1459,	0,	0,	2,	29
1650,	639,	2200,	1847,	1143,	1582,	0,	0,	2,	29
1800,	857,	2150,	1856,	1143,	1582,	0,	0,	2,	29
1000,	386,	7000,	2575,	1360,	1990,	0,	0,	2,	29
1000,	979,	7500,	3065,	1525,	2275,	0,	0,	2,	29
1000,	1050,	6200,	3234,	1240,	2342,	0,	0,	2,	29
1000,	1612,	7700,	3345,	1370,	2570,	0,	0,	2,	29
1000,	1350,	7200,	2886,	1340,	1300,	0,	0,	13,	42

1200,	1632,	7800,	3440,	1200,	1960,	0,	0,	11,	44
2000,	522,	1570,	1660,	1095,	1416,	0,	0,	13,	46
1950,	330,	1850,	1770,	975,	1270,	0,	0,	13,	47
1450,	550,	3850,	2505,	1200,	1710,	0,	0,	13,	47
1215,	816,	6770,	3112,	1670,	2268,	0,	0,	12,	48
1300,	550,	3600,	2697,	1670,	1678,	0,	0,	13,	49

TABLE A5.4

1200,	2856,	15400,	4010,	1980,	2570,	199,	0 ,	6,	8
1200,	3808,	18000,	4852,	1980,	2755,	199,	0 ,	6,	8
1500,	1350,	4620,	2333,	1613,	2273,	0 ,	211000,	1,	7
1500,	2025,	6260,	3015,	1613,	2343,	0 ,	255000,	1,	7
1500,	2700,	8400,	3454,	1613,	2375,	0 ,	347000,	1,	7
1500,	3040,	9180,	3715,	1613,	2273,	0 ,	370000,	1,	7
1800,	800,	2700,	2660,	1250,	1295,	208,	0 ,	3,	5
2820,	700,	1250,	1508,	855,	1187,	0 ,	0 ,	3,	5
1800,	450,	2620,	1852,	1190,	1330,	224,	0 ,	3,	5
2800,	440,	1840,	1439,	900,	939,	214,	0 ,	3,	5
1800,	300,	1850,	1401,	1190,	1305,	226,	0 ,	3,	5
1800,	600,	2690,	2000,	1090,	1330,	214,	0 ,	3,	5
1800,	800,	2810,	2100,	1250,	1295,	208,	0 ,	3,	5
2800,	385,	1710,	1439,	864,	939,	221,	0 ,	3,	5
2800,	264,	1200,	1440,	820,	1038,	224,	0 ,	3,	5
2800,	197,	750,	1000,	843,	916,	236,	0 ,	3,	5
2800,	248,	820,	1000,	900,	916,	225,	0 ,	3,	5
2375,	1200,	3400,	3030,	1280,	1708,	200,	0 ,	3,	5
2300,	340,	1400,	1330,	1085,	1205,	0 ,	0 ,	3,	6
2300,	540,	1850,	1825,	1085,	1205,	0 ,	0 ,	3,	6
1500,	330,	2250,	1970,	1200,	1820,	0 ,	0 ,	3,	6
1500,	630,	4300,	2630,	1500,	1855,	0 ,	0 ,	3,	6
2300,	460,	1400,	1330,	1085,	1205,	0 ,	0 ,	3,	6
2300,	690,	1850,	1825,	1085,	1145,	0 ,	0 ,	3,	6
2300,	815,	2450,	2500,	1200,	1100,	0 ,	0 ,	3,	6
1650,	345,	2250,	1970,	1200,	1820,	0 ,	0 ,	3,	6
1500,	660,	4300,	2630,	1500,	1855,	0 ,	0 ,	3,	6
1500,	780,	4450,	2630,	1500,	1855,	0 ,	0 ,	3,	6
1650,	960,	4750,	2760,	1585,	1970,	0 ,	0 ,	3,	6
1650,	1100,	4750,	2760,	1585,	1970,	0 ,	0 ,	3,	6
1500,	1430,	4740,	2800,	1580,	2300,	0 ,	0 ,	3,	6
1500,	1830,	7650,	3000,	1725,	2000,	0 ,	0 ,	3,	6
1500,	2200,	6500,	3300,	1700,	2200,	0 ,	0 ,	3,	6
1500,	3000,	8800,	3580,	1700,	2200,	0 ,	0 ,	3,	6
1250,	2180,	13000,	4300,	1900,	2700,	0 ,	0 ,	3,	6
1250,	3260,	12100,	3760,	2200,	2700,	0 ,	0 ,	3,	6
1250,	4350,	22000,	5000,	2200,	2650,	0 ,	0 ,	3,	6
1250,	5440,	24000,	5600,	2300,	2900,	0 ,	0 ,	3,	6
2420,	1275,	2100,	2200,	1200,	1400,	0 ,	0 ,	3,	6
1610,	1650,	4740,	2800,	1580,	2300,	0 ,	0 ,	3,	6
1610,	1940,	6600,	3100,	1580,	2300,	0 ,	0 ,	3,	6
1800,	3300,	6500,	3300,	1700,	2200,	0 ,	0 ,	3,	6
1800,	4400,	8800,	3580,	1700,	2200,	0 ,	0 ,	3,	6
1700,	5280,	9800,	3800,	1700,	2200,	0 ,	0 ,	3,	6
1700,	6600,	12000,	4580,	1700,	2500,	0 ,	0 ,	3,	6
1610,	4550,	10400,	4370,	1700,	2200,	0 ,	0 ,	3,	6
1480,	5060,	14000,	3760,	2200,	2700,	0 ,	0 ,	3,	6
1480,	6770,	19000,	4400,	2200,	2650,	0 ,	0 ,	3,	6
1395,	5935,	16000,	4100,	2300,	2800,	0 ,	0 ,	3,	6
1395,	7920,	21000,	4700,	2300,	2950,	0 ,	0 ,	3,	6
1480,	8400,	24000,	5600,	2300,	2900,	0 ,	0 ,	3,	6
1395,	9900,	26000,	5900,	2300,	2950,	0 ,	0 ,	3,	6
1650,	600,	1900,	1620,	1425,	1320,	0 ,	0 ,	2,	18
1650,	800,	2400,	1920,	1440,	1420,	0 ,	0 ,	2,	18
1650,	1200,	3350,	2450,	1520,	1640,	0 ,	0 ,	2,	18
1650,	665,	2060,	1720,	1460,	1420,	0 ,	0 ,	2,	18
1650,	890,	2570,	1950,	1440,	1420,	0 ,	0 ,	2,	18
1650,	1330,	3570,	2550,	1510,	1510,	0 ,	0 ,	2,	18
1650,	1780,	4800,	3020,	1580,	1700,	0 ,	0 ,	2,	18
2180,	650,	1850,	1620,	1400,	1280,	0 ,	0 ,	2,	19
2180,	870,	2310,	1850,	1400,	1280,	0 ,	0 ,	2,	19
2180,	1305,	3210,	2450,	1450,	1440,	0 ,	0 ,	2,	19
1745,	650,	1900,	1620,	1425,	1320,	0 ,	0 ,	2,	19
1745,	870,	2400,	1920,	1440,	1420,	0 ,	0 ,	2,	19
1745,	1305,	3350,	2450,	1520,	1640,	0 ,	0 ,	2,	19
1940,	780,	2060,	1720,	1460,	1420,	0 ,	0 ,	2,	19

1940	1050	2570	1950	1440	1420	0	0	2	19
1940	1560	3570	2550	1510	1510	0	0	2	19
1940	2095	4800	3020	1580	1700	0	0	2	19
1710	2215	5230	2445	1640	2325	0	0	2	19
1710	2970	6700	3160	1640	2305	0	0	2	19
1710	3715	9000	3800	1640	2320	0	0	2	19
1400	2300	6520	3122	1707	2256	0	0	2	19
1455	3130	10900	3460	1600	2455	0	0	2	19
1455	4170	13710	4150	1600	2550	0	0	2	19
1455	5210	16280	4840	1600	2645	0	0	2	19
1160	3300	11400	3460	1660	2505	0	0	2	19
1160	4400	14350	4150	1660	2600	0	0	2	19
1160	5500	17050	4840	1660	2695	0	0	2	19
1160	4420	13100	3720	1660	2720	0	0	2	19
1160	5890	16250	4410	1660	2810	0	0	2	19
1160	7635	20000	5100	1660	2905	0	0	2	19
2100	320	1100	1865	1240	830	0	0	4	22
1800	450	1200	1760	1250	1350	0	0	4	22
2100	370	1300	1490	1240	1345	0	0	4	22
1800	520	1300	2020	1255	1475	0	0	4	22
2000	600	2210	1817	1174	1638	232	0	11	25
2100	420	2100	1817	1174	1243	224	0	11	25
2200	400	1590	1325	1205	1222	0	0	11	25
1800	465	1905	1735	1194	1270	0	0	12	26
1800	478	3357	2921	1245	1473	0	0	12	26
1800	626	3520	2921	1245	1473	0	0	12	26
1800	640	2722	1626	1626	1787	0	0	12	27
1800	700	5693	3277	1473	1880	0	0	12	26
1800	915	6618	3277	1676	1829	0	0	12	26
1800	930	7258	4064	1473	1803	0	0	12	26
1800	940	6677	3277	1676	1829	0	0	12	26
1800	1215	5330	2692	1626	1702	0	0	12	27
1800	1280	5421	2692	1626	1727	0	0	12	27
2200	665	1850	1620	1400	1280	0	0	2	20
2200	885	2310	1850	1400	1280	0	0	2	20
2200	1330	3210	2450	1450	1440	0	0	2	20
1975	815	2060	1720	1460	1420	0	0	2	20
1975	1090	2570	1950	1440	1420	0	0	2	20
1975	1630	3570	2550	1510	1510	0	0	2	20
1975	2180	4800	3300	1580	2060	0	0	2	20
1790	2300	5200	2345	1640	2405	0	0	2	20
1790	3070	6750	3220	1640	2305	0	0	2	20
1790	3840	9080	3800	1640	2320	0	0	2	20
1790	2555	5230	2545	1640	2325	0	0	2	20
1790	3410	6700	3160	1640	2305	0	0	2	20
1790	4265	9000	3800	1640	2320	0	0	2	20
1790	3755	7620	3380	1640	2505	0	0	2	20
1790	4685	9980	3830	1750	2575	0	0	2	20
1400	2305	6520	3122	1707	2256	0	0	2	20
1410	3320	10900	3460	1600	2455	0	0	2	20
1410	4425	13710	4150	1600	2550	0	0	2	20
1410	5535	16280	4840	1600	2645	0	0	2	20
1220	3510	11400	3460	1660	2505	0	0	2	20
1220	4680	14350	4150	1660	2600	0	0	2	20
1220	5850	17050	4840	1660	2695	0	0	2	20
1220	4990	13900	3720	1660	2720	0	0	2	20
1220	6655	17050	4410	1660	2810	0	0	2	20
1220	8325	20500	5100	1660	2905	0	0	2	20
1800	421	1325	1340	1201	1197	207	0	8	23
1800	383	1250	1314	1201	1165	207	0	8	23
2100	476	1165	1430	1215	1040	217	0	2	24
2100	549	1215	1915	1500	1120	216	0	2	24
2100	465	1165	1430	1215	1040	222	0	2	24
2100	354	1115	1480	1080	990	220	0	2	24
2100	438	1050	1220	890	990	215	0	2	24
2100	367	1020	1220	890	990	218	0	2	24
1000	3240	12000	4000	1840	2467	0	0	2	45

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2000,   370,  2929, 2236, 1347, 1595, 0,    0, 13, 46
1600,  1340,  6000, 3168, 1406, 1870, 0,    0, 13, 46
1100,  4000, 17000, 4500, 1700, 2455, 0,    0, 13, 46
1800,   376,  1490, 1445, 1152, 1293, 0,    0, 12, 48
1215,  1632,  9500, 3615, 1879, 2583, 0,    0, 12, 48
1200,  1900, 10000, 3770, 1737, 2435, 0,    0,  7, 51
1000,  3396, 19500, 4800, 1830, 2310, 0,    0,  1, 36
1000,  1620, 12500, 3500, 1700, 2700, 0,    0, 12, 31
1200,  3730, 20600, 5410, 1680, 3150, 0,    0, 12, 31
1100,  4194, 24800, 6270, 1680, 3280, 0,    0, 12, 31
1800,   670,  2460, 2120, 1560, 1620, 0,    0, 10, 32
1800,   960,  4630, 2310, 1700, 1800, 0,    0, 10, 32
1800,  1500,  6530, 2850, 1700, 2060, 0,    0, 10, 32
1800,  2000,  8040, 3540, 1700, 2130, 0,    0, 10, 32
1000,  2475, 15600, 3600, 1700, 2590, 0,    0, 10, 32
1000,  3330, 19000, 4420, 1700, 2590, 0,    0, 10, 32
1225,   640,  5280, 2350, 1600, 2240, 0,    0, 10, 32
1225,   970,  6670, 2970, 1600, 2240, 0,    0, 10, 32
1225,  1380,  7780, 3535, 1600, 2240, 0,    0, 10, 32
1000,  4000, 20900, 5725, 2140, 3645, 0,    0, 15, 33
3000,   450,   880, 1416,  970,  940, 0,    0, 11, 34
3000,   750,   800, 1416,  720,  950, 0,    0, 11, 34
1900,   800,  2100, 1534, 1480, 1400, 0,    0, 11, 34
1900,  1050,  2600, 1787, 1420, 1458, 0,    0, 11, 34
1900,  1600,  3600, 2425, 1457, 1623, 0,    0, 11, 34
1900,  2100,  5200, 3090, 1380, 1695, 0,    0, 11, 34
2100,   800,  2010, 1637, 1170, 1443, 0,    0,  1, 35
1000,  4560, 21200, 4785, 1830, 2395, 0,    0,  1, 36
2200,   450,  1710, 1843, 1139, 1201, 0,    0, 13, 37
1475,  1464,  4400, 1925, 1575, 1865, 0,    0,  3, 38
1500,  2000,  5300, 2580, 1575, 2225, 0,    0,  3, 38
1500,  2200,  7750, 3180, 1620, 1932, 0,    0,  9, 39
1500,  1470,  5900, 2540, 1620, 1920, 0,    0,  9, 39
1500,  2940, 10500, 4130, 1710, 1920, 0,    0,  9, 39
2010,   935,  1300, 1909, 1210, 1354, 0,    0, 11, 40
2010,  1375,  1460, 2147, 1210, 1310, 0,    0, 11, 40
2020,  1350,  1640, 2305, 1352, 1303, 0,    0, 11, 40
2020,  1650,  1660, 2305, 1400, 1303, 0,    0, 11, 40
1800,   675,  3930, 3044, 1317, 2011, 0,    0,  1, 41
1800,   800,  5220, 3578, 1355, 1939, 0,    0,  1, 41
1800,   840,  6000, 3863, 1355, 1909, 0,    0,  1, 41
1800,  1250,  6310, 3343, 1355, 1909, 0,    0,  1, 41
2100,   186,   825, 1030,  865, 1135, 0,    0,  2, 29
2100,   340,   940, 1390,  865, 1135, 0,    0,  2, 29
1800,  1006,  2980, 2120, 1510, 1402, 0,    0,  2, 29
1650,  1700,  4850, 2704, 1554, 1715, 0,    0,  2, 29
1000,   771, 10300, 3000, 2000, 2240, 0,    0,  2, 29
1000,  1350,  7200, 2886, 1340, 1300, 0,    0, 13, 42
1050,  3000, 17000, 4064, 1727, 2921, 0,    0, 12, 43
1500,  1260,  5500, 2000, 1770, 1570, 0,    0, 11, 44
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Table A5.5 Identification Code for Country of Origin of Marine Engines

Code	*Country*
1	United Kingdom
2	Federal Republic of Germany
3	France
4	Denmark
5	Norway
6	Finland
7	Netherlands
8	Sweden
9	Austria
10	Switzerland
11	Italy
12	USA
13	Japan
14	Germany/Denmark
15	Belgium
16	Unknown
17	Czechslovakia

Table A5.6 Identification Code for Marine Engine Manufacturers

Code	*Manufacturer*
1	Wichmann
2	Bolnes
3	DAF
4	Stork Werkspoor
5	Baudouin
6	SACM Mulhouse/UNI Diesel
7	Paxman
8	Wartsila
9	Nohab
10	Lindholmen
11	Kelvin
12	Daihatsu
13	British Polar
14	Gardner
15	WH Allen
16	Mirrlees Blackstone
17	Callesen
18	MTU (Continuous Operation)
19	MTU (Cruise Rating)
20	MTU (Special Purpose)
21	MAN/B+W
22	Alpha Diesel
23	Saab Scania
24	Mercedes Benz
25	Iveco Aifo
26	Detroit Diesel Allison (with gearbox)
27	Detroit Diesel Allison (without gearbox)
28	Mirrlees Blackstone
29	Deutz MWM
30	Anglo Belgian Corporation
31	Alco Power Inc
32	Caterpillar
33	Cockerill Industries
34	Isotta Fraschini
35	Perkins Engines
36	Ruston Diesels
37	Izuzu Marine Engineering
38	SEMT Pielstick
39	Simmering Graz Pauker

Table A5.6 (continued) Identification Code for Marine Engine Manufacturers

Code	*Manufacturer*
40	CRM
41	Cummins Engine Co
42	Fuji Diesel
43	General Electric Company
44	Grande Motori Trieste
45	Krupp MaK
46	Mitsubishi Heavy Industries
47	Niigata Engineering Co
48	Waukesha Engine Division
49	Yanmar Diesel Engine Co
50	Anglo Belgian Corporation
51	Brons Industrie
52	Bombadier
53	Ito Engineering Co Ltd
54	Sulzer Brothers Ltd
55	Akasaka Diesels
56	CKD Prague
57	Hanshin Engine Works
58	Bergen Diesel
59	Makita Diesel Co
60	Mitsui Engineering and Shipbuilding Co
61	General Motors

APPENDIX 6

LOWER HULL DESIGN PROCEDURE

This appendix details the calculation procedure employed in the design of circular hulls for SWATH ships. This method is based on the work of Bose [2], which also incorporates the effects of end load and bending moment by means of a parabolic interaction equation. This appendix describes only the pressure vessel design procedure, and the user is referred to [2] for further details of the overall technique.

Stresses due to Pressure Loading

An iterative procedure is employed to develop scantlings resulting in allowable material stresses. The calculations for failure stresses for a cylindrical element under pressure are made according to BS 5500 [1,3]

This calculation is composed of three stages
a) calculation of interframe failure pressure P_C
b) calculation of total elastic stress in frame flange
c) calculation of frame tripping stress

a) Interframe Failure Pressure

In order to use the design curve given in Figure 3.6(3) of BS 5500 [3], it is necessary to calculate the ratio P_M/P_{C5}

P_M is the von Mises minimum shell buckling pressure, given by Windenburg as

$$P_M = \frac{2.6E(h/2R)^{5/2}}{L/2R - 0.45(h/2R)^{1/2}}$$

The pressure (P_{C5}) to cause interframe shell yield is given by

$P_{C5} = Pb/(1 - \gamma G)$

where

$-\gamma G = [(1 - \nu/2)A\,G]/[(1 + \beta)(A + b\,h)]$

$\beta = [2\,h\,N]/[\alpha(A + b\,h)]$

$A = Af\,(R/R_g)^2$

$\alpha L = 1.285\,L/[\sqrt{(Rh)}]$

G and N are functions of αL

The ratio of P_C/P_{C5} and hence P_C may be found from the BS 5500 curve, which is approximated by

$$P_C/P_{C5} = -0.0030 + 0.7273(P_M/P_{C5}) - 0.2357(P_M/P_{C5})^2 + 0.0348(P_M/P_{C5})^3 - 0.0019(P_M/P_{C5})^4$$
for $P_M/P_{C5} \leq 6$
$$P_C/P_{C5} = 0.76 + 0.03(P_M/P_{C5})$$
for $P_M/P_{C5} > 6$

b) Total Elastic Stress in Frames

The procedure employed to calculate the total elastic stress in the flange of the frames assumes that the maximum permissible out-of-circularity (C_n) occurs in the worst possible mode (n), and at a loading of twice the design pressure P_D.

i.e. $\sigma_{fbr} = \sigma_f + \sigma_{fbn}$
$$\sigma_f = [pR^2 (1 - \nu/2)/hRf]\ [1 + A/(bh + 2Nh/\alpha)]^{-1}$$
where $p = 2P_D$
$$\sigma_{fbn} = [p/(P_n - p)]\ [(Ee_f/R^2)C_n]$$
$$P_n = [(n^2 - 1)E\ I_c]/[R^3\ L_s] + \{(Eh/R)/[(n^2 - 1 + \lambda^2/2)(n^2/\lambda^2 + 1)^2]\}$$
where $\lambda = \pi R/L$
and σ_{fbn} is taken for the mode (n) giving the highest stress level.
I_c is calculated using the effective plating breadths given in Table 3.6 of BS 5500

c) Frame Tripping Stress

In this calculation, the frame is assumed to be free to rotate at the toe. From energy considerations, the stress required for tripping is found from

$$\sigma_t = (E\ I_z)/(A\ R\underline{z})$$

Buckling and instability of stiffeners is considered by employing frame proportions within the limits suggested by BS 5500.

$h_w/t_w \leq 20$ for webs of flanged stiffeners
$h_w/t_w \leq 16$ for flat bar welded stiffeners
$h_w/t_w \leq 10$ for flat bar tack-welded (free to rotate) stiffeners
$b_F/t_F \leq 5$ for stiffener flanges

Nomenclature for Appendix 6

P_n	overall buckling pressure for the n^{th} mode
P_M	von Mises shell buckling pressure
Pb	$\sigma_y h/R$ 'boiler' pressure
P_D, P_C	design pressure, collapse pressure
P_{C5}	pressure for mean hoop stress in shell midway between frames to equal yield stress
R	hull radius
h	shell thickness
L	unsupported span, length between bulkheads
I_c	combined second moment of area of ring frames and effective shell plate
I_z	combined second moment of area of ring frames about own axis of symmetry
L_s	ring frame spacing
Af	ring frame sectional area
A	modified ring frame area, $A = Af\,(R/R_g)^2$
b	width of ring frame in contact with shell
Rf	radius from hull axis to flange of ring frame
Rg	radius from hull axis to neutral axis of ring frame
e_f	distance of frame flange from neutral axis of effective shell and frame
Cn	allowable out of circularity in frame flange in n^{th} mode
n	number of collapsed waves in circumferential direction
σ_t	stress to cause frame tripping
σ_{fbn}	out of circularity stress in frame flange in n^{th} mode
σ_{fb}	out of circularity stress in frame flange
σ_f	mean hoop stress in frame flange

References

1. Faulkner, D., "Structural Design of Pressure Hulls", Ocean Engineering IV Lecture Notes, Department of Naval Architecture and Ocean Engineering, University of Glasgow, 1978

2. Bose, N., "A Computer Program to Obtain Preliminary Structural Scantlings and Steel Weights for Circular Hulled Semi-Submersibles with Bracing", Department of Naval Architecture and Ocean Engineering Report Number NAOE-HL-80-22, University of Glasgow, 1980

3. *Specification for Unfired Fusion Welded Pressure Vessels*, British Standards Institute, 1976, BS 5500

APPENDIX 7

EQUATIONS FOR ESTIMATING THREE DIGIT NES163 WEIGHTS

This appendix lists equations derived from a regression analysis of a number of NATO combatant and auxiliary ship designs. These have been used in the program *EMPIREWT* described in Chapter 10.

All weights are in metric tonnes, all linear dimensions are in metres, and all powers are in kilowatts.

1 HULL

10	**Hull structure**	
100	Hull plating	
101	Hull longitudinal and transverse framing	
102	Inner bottom plating	
103	Hull structural walkways/sponsons	No equations are developed for items 100 to 106
104	Hull armour and protection	
105	Sonar domes forming part of hull structure	
106	Inserts and Pads	
11	**Superstructure**	
110	Superstructure plating	
111	Superstructure longitudinal and transverse framing	
112	Superstructure decks and flats	
113	Superstructure bulkheads	
114	Superstructure hangar	No equations are developed for items 110 to 118
115	Superstructure structural sponsons	
116	Superstructure armour and protection	
117	Unallocated	
118	Ramp for V/STOL aircraft	
12	**Structural Bulkheads (exc. Superstructure 11)**	
120	Main transverse bulkheads	No equations are developed for items 120 to 121
121	Main longitudinal bulkheads	
122	Other structural bulkheads	4.80e-3*(Enclosed Volume)
123	Funnel, structural trunks and enclosures	6.667e-4*(Enclosed Volume)
124	Bulkhead armour and protection	
125	Inserts and Pads	No equations are developed for items 124 to 125
13	**Structural Decks (exc. Superstructure 11)**	
130	Main decks	
131	Minor decks and flats	
132	Deck armour and protection	No equations are developed for items 130 to 134
133	Deck Pillars	
134	False Floors	
14	**Doors, Hatches and Scuttles**	
140	Bridge windows, sidelights and scuttles	0.42677+[3.9164e-4*(Full Load Displacement)]
141	Watertight and gastight doors and hatches	1.25e-3*(Enclosed Volume)
142	Escape hatches and scuttles	0.912+[4.4475e-4*(Enclosed Volume)]
143	Manholes	0.954+[1.6095e-4*(Enclosed Volume)]
144	Blow off plates	
146	Non WT Doors	
15	**Seats, Supports and Masts**	
150	Unallocated	
151	Seats and supports for Group 1 items	$0.017824*[(\text{Enclosed Volume})^{0.518}]$
152	Seats and supports for Group 2 items	$0.23498*[(\text{Group 2 Weight})^{0.887}]$
153	Seats and supports for Group 3 items	1.532+[0.04672*(Group 3 Weight)]
154	Seats and supports for Group 4 items, masts	0.08244*(Group 4 Weight)
155	Seats and supports for Group 5 items	$5.259*[(\text{Group 5 Weight})^{0.173}]$
156	Seats and supports for Group 6 items	$0.020*[(\text{Group 6 Weight})^{0.984}]$
157	Seats and supports for Group 7 items	$0.671*[(\text{Group 7 Weight})^{0.635}]$
158	Seats and supports for Group 8 items	

16 Control Surfaces	
160 Rudders and skegs	$0.03538*[LBP*(Draft)]$
161 Stabilisers (fixed)	
162 Unallocated	
163 Hydrofoils	
164 Bilge keels	$0.934+1.541e\text{-}4*[LOA*(Beam\ mld)*(Depth\ mld)]^{\dagger}$
165 Stabilising tanks	

17 Structural Castings and Forgings	
170 Shaft brackets	$0.7361*[LBP*(Draft)]^{0.519}$ †
171 Forgings and castings	$5.104e\text{-}8*[(Enclosed\ Volume)^{1.9338}]$
172 Sea chests	$1.0857e\text{-}4*[(Full\ Load\ Displacement)^{1.230}]$
173 Anchor hawse pipes and navel pipes	$2.2955e\text{-}3*[(Full\ Load\ Displacement)^{0.852}]$
174 Stern tubes	$1.7797e\text{-}2*[(Full\ Load\ Displacement)^{0.567}]$
175 Sea tubes	$2.2155e\text{-}5*[(Full\ Load\ Displacement)^{1.452}]$
177 Built in Tanks	

18 Buoyancy and Ballast Units	
180 Buoyancy units	No equations are developed for items 180 to 181
181 Ballast units	

19 Fastenings	
190 Welding	$4.989e\text{-}3*[(Group\ 1\ Weight)^{1.119}]$
191 Riveting	
192 Bolting	$0.11361*[(Group\ 1\ Weight)^{0.4214}]$

Note † Not applicable to SWATH ships

<u>2 PROPULSION</u>

20 Propulsion Power Plant (Nuclear)	
200 Reactor	
201 Steam generator	
202 Primary circuit steam	
203 Primary circuit service system	No equations are developed for items 200 to 207
204 Reactor plant auxiliary system	
205 Reactor plant control and instrumentation	
206 Primary shielding	
207 Secondary shielding	

21 Propulsion Power Plant (non-Nuclear)	
210 Main boilers	
211 Main boiler systems control and instrumentation	
212 Main electrical storage batteries	No equations are developed for items 210 to 215
213 Main electrical storage battery system, switchgear, control	
214 Gas generators (if separate from power turbine)	
215 Gas generator systems, control and instrumentation	

22 Propulsion Units and Control Equipment	
220 Steam turbines	
221 Gas turbines	No equations are developed for items 220 to 224
222 Propulsion diesel engines	
223 Electric propulsion generator sets and motors	
224 Propulsion unit control equipment (when integral with unit)	
225 Clutches, gearing, flexible coupling and turning gear	$0.5045*[(Total\ Propulsive\ Power)^{0.4639}]$
226 Machinery space lifting gear	$1.7253e\text{-}4*(Total\ Propulsive\ Power)$
227 Insulation	

23 Main Condensers and Air Ejectors	
230 Main condensers	
231 Air ejectors	No equations are developed for items 230 to 232
232 Insulation lagging and liners	

24 Shafting, Bearings and Propulsors	
240 Shafting	$3.017e\text{-}2*[(LOA*\sqrt{(\text{Maximum Propusive Power})})^{0.7626}]$
241 Propulsors, inc. bow thrusters & activated rudders	$0.1544*[(\text{Maximum Propulsive Power})^{0.4866}]$
242 Shaft bearings, bulkhead glands, seals, etc	$0.10521*[(\text{Weight of Sub-subgroup 240})^{1.125}]$
243 Torsionmeters and brakes	$0.420+[1.988e\text{-}3*(\text{Group 2 Weight})]$
244 Pitch Control Systems	$2.9265*\{[LOA*(\text{Maximum Propulsive Power})/10^6]^{0.8731}\}$
25 Combustion Air Supply and Exhaust Systems	
250 Supply fans or blowers	
251 Supply system (downtakes)	$7.0298e\text{-}6*\{[(\text{Depth mld})*(\sqrt{\text{Total Propulsive Power}})]^{1.8923}\}$
252 Exhaust system (uptakes)	$1.0445e\text{-}4*\{[(\text{Depth mld})*(\sqrt{\text{Total Propulsive Power}})]^{1.6918}\}$
26 Steam Systems	
260 Main superheated steam system	
261 Auxiliary superheated steam system	
262 Saturated steam system	No equations are developed for items 260 to 264
263 Steam exhaust system	
264 Steam drain system	
27 Circulating, Cooling, & Feed Water & Condensate Systems	
270 Main circulating water system to condensers	
271 Cooling water system for propulsion units	$4.0507e\text{-}2*(\text{Group 2 Weight})$
272 Feed water system for propulsion units	
273 Condensate system for propulsion units	
28 Fuel Oil Service Systems	
280 Combustion fuel oil service to propulsion units	$3.6759e\text{-}4*[LOA*(\sqrt{\text{Total Propulsive Power}})]$
29 Lub Oil Systems	
290 Lub oil system to propulsion units	$1.4002e\text{-}2*(LOA^{1.408})$

3 ELECTRICAL

30 Electrical Main Supply Power Generation	
300 Steam turbine generator sets	
301 Gas turbine generators	
302 Diesel generator sets	$7.0708e\text{-}2*[(\text{Electrical Power})^{0.87487}]$
31 Power Distribution Equipment	
310 Main supply equipment	$3.0e\text{-}4*(\text{Electrical Power})$
311 Distribution equipment	$2.244e\text{-}3*[(\text{Electrical Power})^{1.0836}]$
312 General service conversion equipment	$1.292+1.1836e\text{-}3*(\text{Elec Pwr}) - 4.433e\text{-}7*(\text{Elec Pwr})^2+2.717e\text{-}10*(\text{Elec Pwr})^3$
313 Portable apparatus system (equipment)	$0.235+[5.418e\text{-}4*(\text{Electrical Power})]$
314 Emergency supply system	
32 Power Distribution Cabling	
320 Cabling	$4.35+1.4661e\text{-}4*[(\text{Electrical Power})*LOA]$
321 Glands and cable support equipment	$1.289+2.2997e\text{-}5*\{[\text{Electrical Power}]*[LOA+(\text{Beam mld})+(\text{Depth mld})]\}$
33 Lighting Systems	
330 General lighting systems	$8.2177e\text{-}4*[(\text{Enclosed Volume})^{0.9666}]$
331 Emergency lighting system	$2.3711e\text{-}4*[(\text{Enclosed Volume})^{0.8549}]$
332 Ceremonial lighting system	
333 Secondary lighting system	

4 CONTROL AND COMMUNICATIONS

40 Navigation Systems	
400 Gyro and other compasses	1.462+3.0425e-4*(Full Load Displacement)
401 SINS	
402 Nav aids and direction finding equipment	2.0e-4*(Full Load Displacement)
403 Logs	0.295+1.284e-5*(Full Load Displacement)
404 Wind speed and direction indicating system	6.673e-7*[LOA*(Beam mld)*(Depth mld)]$^{1.2189}$
405 Navigation radar	0.321+1.668e-6*[LOA*(Beam mld)*(Depth mld)]
406 Viewing devices	3.9348e-6*[LOA*(Beam mld)*(Depth mld)]$^{1.082}$
407 Chronometers	0.168+7.147e-6*(Full Load Displacement)
408 Plotting and chart tables	0.385+9.869e-5*(Full Load Displacement)
409 Navigation lights, etc	0.622+1.274e-5*[LOA*(Beam mld)*(Depth mld)]
41 Internal Communications	
410 Broadcasts	0.501+1.1952e-4*(Enclosed Volume)
411 RICE equipment, ventilated suit systems, telephones	1.609-[8.924e-5*(Enclosed Volume)]+[5.441e-9*(Enclosed Volume)^{2}]
412 Sound reproduction equipment (SRE)	0.298+2.242e-5*(Enclosed Volume)
413 Voice and pneumatic tubes	
414 Television, radio and cinema equipment	2.9061e-3*(Total Complement)
415 Alarms and warnings	0.782+4.734e-5*(Enclosed Volume)
416 NBCD warning systems	0.502+3.0367e-6*(Enclosed Volume)
417 Engine telegraph & propeller orders	1.8339e-11*[(Total Propulsive Power)$^{2.3172}$]
418 Rudder angle indicators	
42 Ship and Main Machinery Control System	
420 Ship control console	0.819+2.8401e-5*[LOA*(Beam mld)*(Depth mld)]
421 Systems consoles	3.961+1.157e-5*[LOA*(Beam mld)*(Depth mld)]
422 Command console	
423 Rudder control system	5.5639*[10$^{(4.4494e-4*LOA*Draft)}$]
424 Unallocated	
425 Moveable stabilisers and control system	5.1384e-4*(Full Load Displacement)$^{1.3074}$, $\leq$ 85.0t
426 Hydrofoil control system	
427 Tank stabilisation systems (Active and Passive)	
428 Machinery control system	6.6776e-2*[($\sqrt{}$Total Propulsive Power)$^{0.96153}$]
43 Weapon Control System	
430 Surface/air weapon control systems	6.182+4.551e-2*(Group 7 Weight)
431 Surface/surface weapon control systems	0.673+5.889e-3*(Group 7 Weight)
432 Surface/anti-submarine weapon control systems	2.4803e-4*[(Group 7 Weight)$^{2.2645}$]
433 Submerged launched (non-air flight) systems	
434 Submerged launched (air flight) systems	
435 Weapon and surveillance radars	3.615+(2.0314e-2*LOA)
436 Sonars	13.995+0.29336*(Group 7 Weight)
437 Centralised weapon control systems	2.329+5.6297e-4*(Full Load Displacement)
438 Electronic warfare systems (EW)	0.330+1.0839e-4*(Full Load Displacement)
439 Optical Sights	
435 Radar Office	
44 Ship's Protective System	
440 Degaussing system	3.9476e-5*[(Enclosed Volume)$^{1.2453}$]
441 Cathodic protection system	0.438+2.28e-4*(Group 1 Weight)
442 Zinc protectors	0.500
443 SIRS	
45 External Communication Systems	
450 Radio communication systems	0.0667*(Group 4 Weight)
451 Underwater telephone and echo sounders	0.200
452 Visual signalling equipment	0.782
453 Sirens and whistles	0.29585e-2*[10$^{(1.1468e-4*(Full Load Displacement))}$]
454 Satellite communication systems	4.000

5 AUXILIARY SYSTEMS

50	**Air Conditioning, Ventilation, Refrigeration Systems**	
500	Air conditioning plants	9.3587e-3*(Enclosed Volume)$^{0.815}$
501	Chilled and tepid water systems	9.8847e-5*[LOA*(Total Complement)]$^{1.172}$
502	Air conditioning & mechanical ventilation systems (ex MMS-508)	2.6679e-3*(Enclosed Volume)
503	Free standing air conditioning units & electric space heaters	2.000
504	Natural ventilation systems (ex MMS-508)	0.08*(Total Complement)
505	Refrigeration plant and equipment	2.085+2.2686e-7*[(Enclosed Volume)*(Total Complement)]
506	Unallocated	
507	Unallocated	
508	Air conditioning and ventilation systems in MMS	5.925+1.9601e-8*[(Enclosed Volume)*(Total Propulsive Power)]
51	**Fuel Systems (excluding Aircraft Systems)**	
510	Main Fuel filling, heating and transfer systems	2.270+2.108e-6*[LOA+Bmld+Dmld]*[Fuel Weight]
511	Auxiliary fuel systems	6.500 (if LOA>110m)
512	Tank cleaning systems	
52	**Sea and Fresh Water Systems**	
520	Sea water system	1.2905e-4*[LOA+(Beam mld)+(Depth mld)]$^{2.4188}$
521	Sea water fire fighting system	5.833e-4*(Enclosed Volume)
522	Flooding and spraying systems	4.6567e-4*[(Full Load Displacement)$^{1.0563}$]
523	Prewetting system	2.1629e-4*[LOA*(Beam mld)]$^{1.1915}$
524	Ballasting, trimming and drainage systems	11.0+1.5e-3*(Full Load Displacement) for SWATH 2.00+1.5e-3*(Full Load Displacement) for monohulls
525	Sea water/fresh water cooling system	4.0156e-3*[(Group 2 Weight)$^{1.2064}$]
526	Distilling plant system	6.6276e-2*[(Total Complement)$^{0.9398}$]
527	Fresh water system	2.791+2.0802e-2*(Total Complement)
53	**Air and Gas Systems**	
530	HP air system	1.1308e-4*[(Enclosed Volume)*(Total Propulsive Power)]$^{0.5973}$
531	LP air system	3.7729e-4*[LOA$^{1.895}$]
532	Air breathing system	4.000
533	Control air systems	
534	Salvage air systems	
535	Recompression chamber	
536	Special air service system (AGOUTI)	
537	Gas fire extinguishing systems	1.020+[7.1114e-2*LOA]
54	**Hydraulic Systems (excluding Aircraft Systems)**	
540	Hydraulic systems	3.5e-4*(Enclosed Volume)
55	**Aircraft Systems**	
550	Unallocated	
551	Aircraft handling systems (ex 552, 553, 554)	5.200+0.6*(Number of Aircraft)
552	Aircraft lifts	
553	Arresting gear and barriers	
554	Catapults and jet blast deflectors	
555	Aircraft gas producing systems	
556	Aircraft liquid systems	1.720+1.285e-3*[(Number of Aircraft)*LOA*(Beam mld)]
557	Unallocated	
558	Aircraft electrical systems	2.000
56	**Waste Disposal Systems**	
560	Sewage disposal systems	0.856+2.5107e-6*[(Total Complement)*(LOA+Bmld+Dmld)]
561	Waste water disposal system	1.0586e-9*[(Total Complmenet)*(Enclosed Volume)]$^{1.3622}$
562	Garbage disposal system	-0.773+2.017e-2*(Total Complement) (if complement > 40)
563	Oil slick dispersal	
57	**Auxiliary Steam, Exhaust Steam and Steam Drain System**	
570	Auxiliary steam generators and systems	4.3077e-2*[(Enclosed Volume)$^{0.5693}$]
571	Exhaust steam systems	0.391+5.739e-5*(Total Propulsive Power)

58	**Lub Oil Systems (excluding 290 and 556)**	
580	Main lub oil filling and transfer system	4.6995e-6*[LOA+(Beam mld)+(Depth mld)]$^{2.7075}$
581	Auxiliary lub oil systems	-4.327+3.5361e-2*[LOA+Bmld+Dmld] (if [LOA+Bmld+Dmld] > 122.5m)

6 OUTFIT AND FURNISHINGS

60	**Hull Fittings**	
600	Anchors, cables, winches, bollards, fairleads, cleats etc	1.0273e-2*[LOA*Bmld*Dmld]$^{0.8403}$
601	Guardrails, stanchions, rigging, awnings	1.9192e-2*[LOA*(Beam mld)]$^{0.7999}$
602	Ladders and fittings	2.308+4.7856e-4*(Enclosed Volume)
603	Non-structural walkways	3.6373e-2*[LOA*(Beam mld)]$^{0.80812}$
604	Miscellaneous fittings	0.17814*[(Enclosed Volume)$^{0.13154}$]
61	**Boats and Lifesaving Equipment**	
610	Powered and non-powered boats	3.5559e-2*(Total Complement)
611	Davits and handling equipment for boats	0.852+3.8466e-3*[(Total Complement)*(Depth mld)]
612	Liferafts, lifejackets, stowages, floats etc	0.19726*[(Total Complement)$^{0.51133}$]
62	**Minor bulkheads, Partitions, Deck and Bulkhead Coverings (Main Hull)**	
620	Minor bulkheads and doors	2.0833e-3*(Enclosed Volume)
621	Partitions and linings (decorative)	3.2134*[(Total Complement)$^{0.23472}$]
622	External and internal paint	0.32692*[(Group 1 Weight)$^{0.64198}$]
623	Deck coverings	2.2356e-3*[(Enclosed Volume)$^{0.98278}$]
624	Deck treads and tread plates	2.7818e-5*[(LOA*(Beam mld)]$^{1.5082}$
625	Acoustic insulation	4.0e-8*[(Enclosed Volume)*(Total Propulsive Power)]
626	Thermal insulation	3.207+2.1813e-3*(Enclosed Volume)
627	Deck, bulkhead and hull damping	
628	Deck coverings in superstructure	
63	**Furnishings & fittings in Storerooms& Stowages (excluding Stores and Spare Gear - Group 8)**	
630	Furnishings and fittings in named Naval Stores	2.669+4.9825e-2*(Total Complement)
631	Furnishings and fittings in Victualling Stores (including MEDICAL AND NAAFI CANTEEN STORES)	4.3001e-2*(Total Complement)
632	Spare gear stowage throughout Ship	0.611+8.8823e-5*(Enclosed Volume)
633	Furnishings and fittings in all other stores	
64	**Furnishings for Living Spaces**	
640	Furnishings for officer's accomodation	0.87222*(Number of Officers)
641	Furnishings for crew's accomodation	1.7533*[(Number of Crew)$^{0.5}$]
642	Furnishings for heads and bathrooms	0.198+1.2e-2*(Total Complement)
65	**Furnishings for Offices, Medical Spaces etc**	
650	Furnishings for offices (ex air offices - 657)	-0.645+0.2126*(Number of Officers) (if no. Officers > 3)
651	Furnishings for sick bay and dental surgeries	0.53415*[10$^{(1.3343e-3*(Total\ Complement))}$]
652	Furnishings for emergency operating theatre	
653	First aid equipment throughout ship	
654	Furnishings for health physics laboratory	
655	Furnishings for operations spaces	6.7195e-3*[(Group 4 Weight)$^{1.4703}$]
656	Furnishings for amenity spaces	1.434*[10$^{(1.6812e-3*(Total\ Complement))}$]
657	Furnishings for air offices	
658	Furnishings for lobbies and passageways	-2.1219+2.3277e-2*[LOA+(Beam mld)+(Depth mld)]
66	**Equipment for Galleys, Laundries and Workshops**	
660	Equipment for galleys, pantries and other food preparation spaces	3.1163e-2*[(Total Complement)$^{1.0705}$]
661	Water coolers, DAR's, ice cream machines etc	
662	Equipment for laundry and drying rooms	1.3614e-2*(Total Complement)
663	Equipment for workshops and repair spaces (excluding air - 664)	-9.158+[6.9465e-2*(Total Complement)] (if complement > 130)
664	Equipment for air workshops and repair spaces	

67 Minor Bulkheads, Partitions, Deck & Bulkhead Coverings in the Superstructure

670 Minor bulkheads and doors
671 Partitions and linings (decorative)
672 External and internal paint — Items 670 to 677 included in subgroup 62
673 Deck coverings
674 Deck treads and tread plates
675 Acoustic insulation
676 Thermal thermal/acoustic insulation
677 Deck and bulkhead damping

68 Portable Fire Fighting, Damage Control, NBC Equipment and Escape Equipment

680 Portable firefighting equipment — 4.020+4.707e-5*(Enclosed Volume)
681 Damage control equipment — -0.137+1.3128e-6*[(Total Complment)*(Enclosed Volume)]
682 NBC equipment
683 Escape equipment

69 Load Handling and Replenishment at Sea (RAS) Equipment

690 RAS mast, high points and tripods — -0.583+2.777e-4*[LOA*Bmld*Dmld] (if [LOA*Bmld*Dmld] > 2100)
691 Stores handling and RAS strike down equipment — 0.326+1.7636e-4*[LOA*(Bmld)*(Dmld)]
692 Cranes and other non portable lifting appliances — -22.0+2.2372e-2*[LOA*(Beam mld)] (if [LOA*Bmld] > 1000)
693 Portable lifting equipment

<u>7 ARMAMENT</u> — No equations have been developed for Group 7 items

70 Surface/Air Armament

700 Mountings and launchers
701 Ammunition and missile handling systems
702 Ammunition and missile stowages

71 Surface/Surface Armament (Guided Missiles)

710 Mountings and launchers
711 Missile handling systems
712 Missile stowages

72 Surface/Anti Submarine Armament

720 Mountings and launchers
721 Ammunition and missile handling systems
722 Ammunition and missile stowages

73 Submerged Launched (Non-Air Flight) Armament

730 Mountings and launchers
731 Weapon handling systems
732 Weapon stowages

74 Submerged Launched (Air Flight) Armament

740 Mountings and launchers
741 Weapon handling systems
742 Weapon stowages

75 Air Launched Armament

750 Weapon handling systems
751 Weapon stowages

76 Minehunting, Minelaying and Minesweeping Equipment

760 Minehunting equipment
761 Minelaying equipment
762 Minesweeping equipment

77 Rockets, Small Arms and Pyrotechnics

770 Rocket flare and decoy launchers
771 Small arms
772 Pyrotechnics

8 VARIABLE LOAD

No equations have been developed for Group 8 items

80 Officers, Crew and Effects
800 Officers, crew and effects
801 Commando officers, men and effects

81 Ammunitions
810 Surface/air weapons
811 Surface/surface weapons
812 Surface/anti-submarine weapons
813 Submerged launched (non-air flight) weapons
814 Submerged launched (air flight) weapons
815 Air launched weapons
816 Mines and mine disposal weapons
817 Rockets, flares, pyrotechnics and small arms (exc air)
818 Commando fuel and ammunitions

82 Aircraft
820 Fixed wing
821 Non fixed wing

83 Military Vehicles
830 Armoured fighting vehicles
831 Military transport
832 Staff cars, landrovers etc

84 Victualling and Medical Stores
840 Dry provisions
841 Mess and galley gear
842 Loan clothing
843 NAAFI/CANTEEN Stores
844 Refrigerated stores
845 Bedding
846 Medical stores
847 Cash clothing
848 CO's, Wardroom. Trophies and Sports Gear Store

85 Naval Stores and Spare Gear
850 Stores in named Naval Stores
851 Machinery spaces
852 Stationery and office machinery
853 Oils and greases
854 Flammables, acids, paints and gases
855 Rigging warrant items

86 Weapon Stores
860 Air stores
861 Army stores
862 Electronic stores
863 Weapon control stores
864 Gunnery stores

87 Operating Fluids
870 Unallocated
871 Operating fluids for Group 1 (free flooding liquids)
872 Operating fluids for Group 2
873 Operating fluids for Group 3
874 Operating fluids for Group 4
875 Operating fluids for Group 5
876 Operating fluids for Group 6
877 Operating fluids for Group 7

88 Stowed Liquids

880 Liquids in fresh water tanks
881 Liquids in sea water tanks (trim and compensating tanks)
882 Liquids in fuel oil tanks
883 Liquids in reserve and main feed water tanks
884 Liquids in lub oil tanks (exc air - 889)
885 Liquids in hydraulic oil tanks
886 Liquids in pure water tanks (nuclear, battery) and detergent tanks
887 Liquids in sanitary tanks
888 Liquids in aviation fuel tanks
889 Liquids in aviation lub oil tanks

89 Cargo

890 Solid Cargo
891 Liquid Cargo
892 Passengers and Effects

APPENDIX 8

STATISTICAL TERMS EMPLOYED IN CHAPTER 10

The sample *mean* or *expected value* on a set containing N samples of x is

$$\bar{x} = E[x] = {}^{1}/_{N} \sum_{i=1}^{N} x_i$$

The *variance* is the basic measure of the dispersion in certainty, and is calculated using the sum of the squared deviations from the sample mean

Chapter 10 employs the *biased estimator* of sample variance

$$S_x^2 = 1/_N \sum_{i=1}^{N} (x_i - \bar{x})^2$$

The *unbiased* estimator is given by

$$S_x^2 = {}^{1}/_{(N-1)} \sum_{i=1}^{N} (x_i - \bar{x})^2$$

Except where the sample set is small, the difference between the biased and unbiased estimator is negligible

The *standard deviation* is the square root of the variance. The *coefficient of variation* (COV) is the ratio of the standard deviation to a suitable normalising basis, usually the mean.

Chapter 10 assumes *normal* (*Gaussian*) probability distributions. This distribution is dependent on only two parameters, the mean and variance. In practice this is by far the most commonly encountered distribution. This is true for a number of reasons, foremost being the *central limit* set of mathematical theorems. Informally, and in general terms, these state that any process which can be conceived of as the sum of many small independent random variables will tend towards a normal distribution.

The estimation of ship weights from the sum of many sub-subgroups (which may be viewed as random variables) is a problem adhering to the conditions of the central limit theorem.

The theory of functions of random variables provides the following results.

If $y = \sum x_i$ where x_i are independent random variables, then

$$E[y] = \sum E[x_i]$$

$$V[y] = \sum V[x_i]$$

which states that the mean and variance of y may be obtained from the sum of the individual means and variances of x_i. This is fundamental to the methods used in Chapter 10 to provide variances in ship weight estimates.

The mean and variance of the constituent weights (sub-subgroups) may be used to obtain the mean and variance of the composite parts (groups). This allows the standard deviation for the total weight to be derived, and the *confidence limits* to be defined.

With 99.7% confidence,	the weight will fall within 3 standard deviations of the expected value
With 95.5% confidence,	the weight will fall within 2 standard deviations of the expected value
With 68.0% confidence,	the weight will fall within 1 standard deviation of the expected value

APPENDIX 9

WARSHIP SPACE REQUIREMENTS

This Appendix details the expressions used in Chapter 10 to estimate the deck area and volume required in a warship design.

Reference is made to 'Category numbers'. These are intended to represent varying levels of capability and sophistication in the projected design, and are described below.

Category 1 - NATO standard destroyer/large frigate, complex weapons fit (e.g. Type 22)
Category 2 - NATO standard destroyer/large frigate, simpler weapons fit than above
Category 3 - Large frigate, standards slightly reduced from NATO
Category 4 - NATO standard small frigate (e.g. Type 21)
Category 5 - Light frigate, commercial standards (e.g. VT Mark 5)
Category 6 - Corvette, commercial standards

Where the equations listed below refer to 'Category numbers' it is to be understood that this variable may have a maximum value of 6 and a minimum of 1.

Group 1 - Aviation (part of PAYLOAD)

Hangaring and Maintenance areas for;

Lynx -	85.0 + 90(No. helos) m^2
Sea King -	290.0(No. helos) m^2

Group 2 - Main Armament, Group 3 - Secondary Armament (part of PAYLOAD)

Requirements input to design process

Group 4 - Sonar, Group 5 - Radar (part of PAYLOAD)

Requirements input to design process

Group 6 - Operations Spaces (part of PAYLOAD)

Either obtained from requirements input to design process OR

Operations Room -	136.6 - 12.1(Category No.) m^2
Electronic Warfare Spaces -	54.2 - 11.8 (Category No.) m^2
Ship Control Centre -	48.9 - 5.1 (Category No.) m^2
Gyro Room -	10.0 m^2

Group 7 - Communications (part of PAYLOAD)

Either obtained from requirements input to design process OR

Main Communications Spaces -	108.3 - 13.3 (Category No.) m^2
SRE/Telephones -	16.5 - 2.2 (Category No.) m^2

Group 8 - Navigation Spaces

Bridge and Chartroom -	52.0 m^2

Group 9 - Machinery Spaces

Machinery Rooms -	(No. decks) * (Mchy space plan area) m^2
Uptakes, downtakes -	k_9 (No. decks) * (Mchy space plan area) m^2
COGOG Ships $k_9 = 0.20$	
CODOG Ships $k_9 = 0.17$	
Diesel Ships $k_9 = 0.10$	
Steering Gear -	$5.64 + 2.14\,\Delta^{1/3}$ m^2
Miscellaneous -	(Sum of Above Machinery Areas)

For SWATHs, estimate machinery rooms, and uptakes and downtakes as volumes from compartment lengths and sectional areas

Group 10 - Electrical

Switchboard Room -	45.0 - 3.86 (Category No.) m^2
Electrical Distribution Spaces -	65.0 - 9.14 (Category No.) m^2
Conversion/Generator Rooms -	74.0 - 9.71 (Category No.) m^2
Battery Rooms -	28.3 - 4.29 (Category No.) m^2

Group 11 - Offices

General Offices -	95.0 - 11.6 (Category No.) m^2
Air Office -	7.5 m^2 for air capable ship

Group 12 - Workshops

Workshops -	104.7 - 13.0 (Category No.) m^2

Group 13 - Stores

Stores (full RN standard) -	0.008 (Total complement x days at sea) m^2 OR
Stores (acceptable minimum) -	0.011 (Total complement x days at sea) m^2
Naval and Spare Gear Stores -	1.20 (Total complement) m^2

Group 14 - Accommodation

Officers Spaces -	36.2 + 7.17 (No. officers) m^2
Senior Rates Spaces -	3.2 (No. senior rates) m^2
Senior Rates WC/Showers -	8.4 + 0.3 (No. senior rates) m^2
Junior Rates Mess -	2.34 (No. junior rates) m^2
Junior Rates Showers -	6.5 + 0.09 (No. junior rates) m^2
Junior Rates WCs -	1.3 + 0.17 (No. junior rates) m^2
Galley -	11.0 + 0.2 (Total complement) m^2
Scullery -	14.9 - 1.35 (Category No.) m^2
Laundry -	0.11 (Total complement) m^2
Canteen -	31.5 - 4.45 (Category No.) m^2
Sickbay -	36.3 - 4.24 (Category No.) m^2

Group 15 - Ventilation and Air Conditioning

Ventilation and Air Conditioning - k_{15}(Sum of Groups 1-8, 10-14) m^2

k_{15} = 0.080, for 1980s NBCD philosophy

k_{15} = 0.048, for 1970s NBCD philosophy

Group 16 - Lobbies and Passageways

Lobbies, passageways - k_{16}(Sum of Groups 1-8, 10-14) m^2

k_{16} = 0.25, for 'maximum' width

k_{16} = 0.18, for 'minimum' width

Group 17 - Miscellaneous

NBCD Cleansing Station -	27.2 - 3.2 (Category No.) m^2
Sewage Treatment -	0.15 (Total Complement) m^2
Others -	0.015 (Sum of Groups 1-8, 10-14) m^2

Group 18 - Fuel

Dieso -	Fuel Weight/0.84 m^3
Avcat -	AVCAT Weight/0.80 m^3

Group 19 - Fresh Water

Ocean Going Ships FW -	0.273 (Total Complement) m^3
Coastal Ships FW -	0.227 (Total Complement) m^3

Group 20 Trimming/Ballast

Ballast Tankage -	Ballast Weight/1.025 m^3