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ABSTRACT

An increased emphasis during the 1970's on the design and construction of small combatant ships has led to a rapid development of alternative ships. This thesis presents a comparative analysis of several of these small combatants. The analysis uses design statistics to identify and examine the principal factors which influence small warship design.

The evaluation of the designs presented in this thesis leads to the interpretation of small combatants as low-cost ships with limited missions. It is, therefore, submitted that the design of such ships should be kept simple and functional, in order to emphasize basic performance for a minimal monetary investment.

A COMPARATIVE ANALYSIS OF SMALL COMBATANT SHIPS

by

PAUL EDWARD SULLIVAN

B.S., U.S. Naval Academy
(1974)

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
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A COMPARATIVE ANALYSIS OF SMALL COMBATANT SHIPS

by

PAUL EDWARD SULLIVAN

Submitted to the Department of Ocean Engineering
on May 9, 1980 in partial fulfillment
of the requirements for the degrees of
Ocean Engineer and Master of Science in
Naval Architecture and Marine Engineering

ABSTRACT

An increased emphasis during the 1970's on the design and construction of small combatant ships has led to a rapid development of alternative ships. This thesis presents a comparative analysis of several of these small combatants. The analysis uses design statistics to identify and examine the principal factors which influence small warship design.

The evaluation of the designs presented in this thesis leads to the interpretation of small combatants as low-cost ships with limited missions. It is, therefore, submitted that the design of such ships should be kept simple and functional, in order to emphasize basic performance for a minimal monetary investment.

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CHAPTER I

INTRODUCTION

1.1 Purpose

The escalation of shipbuilding costs, the institution of the 200 mile territorial limit, and the entry of "third world" nations into modest naval construction programs have had the combined effect of placing increased emphasis on small naval ships as an attractive alternative to larger, more costly combatants. Consequently, there has been rapid proliferation of new designs, as commercial shipbuilders compete for the expanding market.

The developments in the field of small ships warrant an investigation into the various alternative configurations which now exist. It is the purpose of this study to initiate such an investigation by a comparative analysis of several conventionally-hulled small combatants. This comparison employs a simple procedure for the evaluation of the design features of each ship, and for the identification of those aspects which are critical to the design of small naval ships.

1.2 Rationale for Ship Selection

The ships to be studied are as follows:

. FFG-7 (U.S.A.)

. CPIC (U.S.A.)

. PG-84 (U.S.A.)

. PGG (U.S.A.)

- . PCG (U.S.A.)
- . PC-1 (U.S.A.)
- . SPICA II (Sweden)
- . RESHEF (Israel)

The thrust of this study is to cover ship designs which span the range of time, size, and nationality. Therefore, a normal range of displacement from 200 to 800 tons has been selected, and current designs from both European countries and the United States are included. Additionally, three other ships are added for reasons of completeness. The first, FFG-7, is used as a basis for comparison of the small ships with the more familiar naval frigate. Finally, two patrol craft which are outside the nominal displacement range are included. CPIC, a 72 ton planing craft, and PC-1, a far-term, high-technology planing ship of 1,100 tons are added. They are intended to demonstrate what happens beyond each end of the selected size range.

A more complete study would result from inclusion of more foreign ships, and from expansion of the ship size range. However. such an undertaking is limited by data availability. The choice of ships for this study has been influenced by access to the information required for a complete analysis.

1.3 Study Aims

The primary concern of the study is the identification and exploration of the naval architectural features which exert the most influence on small combatant design. Once identified (Chapter V), these features form the basis for conclusions about the following areas, which are treated in Chapter VI.

1. Impact of mission requirements
2. Scale effects with size
3. Design lanes
4. Trends over time
5. National preference in design practice

In addition to these concepts, the advantages and disadvantages of small combatants (vs. larger naval ships) are discussed in Chapter VI. As a final illustration of the importance of certain design features, the five ships which fall in the displacement range (200-800 tons) are evaluated relative to each other, using the critical features as criteria for comparison.

The conclusions reached in Chapter VI are summarized and consolidated in Chapter VII. This review of results is then used as a basis for recommendations for further study, and for the future of small combatants in the U.S. Navy.

CHAPTER II

METHODOLOGY

2.1 Definition of Study Approach

The method used for comparative ship analysis is well-established by references 15, 21, 22, and 25. The first step of the analytical procedure involves a familiarization with the type of ship being studied. Then, a brief look is taken at each specific ship, as illustrated in Chapter III.

With the background information firmly established, the next step is to assemble the collection of data which forms the basis for the study. Using this information base, a standard set of design indices (listed in section 2.3) is computed for each ship. The indices, in turn, are grouped into functional areas for examination, and for identification of the most critical design parameters (Chapters IV and V). The final step is the consolidation of data into statements of trends and conclusions, outlined in Chapter VI.

The basis for this methodology is the statistical base mentioned above, which includes ship design parameters such as performance data, weights, and space usage.

2.2 Weight and Space Classification Systems

The weight and space usage data for each ship is classified according to the U.S. Navy standard weight and space calculation systems.[11, 12]

2.2.1 WEIGHT CLASSIFICATION (FIGURE 2.1)

The Navy system groups the various weight items into seven categories, which are formed according to functional area. The sum of these weight groups comprises lightship weight. Full load displacement is obtained by adding to lightship weight the sum of all the loads.

A more detailed listing of the components in each weight group is provided by reference 11.

2.2.2 SPACE CLASSIFICATION (FIGURE 2.2)

The U.S. Navy space classification system divides the utilization of space into three areas: (1) mission; (2) personnel; and (3) ship operation. The mission area (volume group 100) includes all weapons, command, and electronics spaces. The personnel group (volume group 200) consists of berthing, messing, and human support spaces. The ship operation area (volume group 300) covers everything not included in the first two groups.

Note that the sum of the three groups gives total enclosed volume, including superstructure.

2.3 Design Indices

The design indices used to compare the ships fall into two categories, indices by type and indices by function. A description of each category follows.

FIGURE 2.1

U.S. NAVY WEIGHT CLASSIFICATION SYSTEM

Group	Function
1	Hull Structure
2	Main Propulsion
3	Electrical
4	Command and Surveillance
5	Auxiliaries
6	Outfit and Furnishings
7	Armament
Loads	Crew and Effects
	Potable Water
	Ammunition
	Fuel Oil
	Lubricating Oil
	Stores
	Aircraft, Aircraft Stores, Ammunition, and Fuel

FIGURE 2.2

U.S. NAVY SPACE CLASSIFICATION SYSTEM

Category		Typical Space
1.0	MILITARY MISSION PERFORMANCE	
1.1	Communications, detection and Evaluation	CIC, Computer Room, Radar Room, Sonar Room
1.2	Weapons	Magazines, Fire Control, Electronics Room
1.3	Aviation	Hangar, Aviation Shops, Stores, JP-5 Tanks
1.4	Special Missions	Flag Spaces
2.0	SHIP'S PERSONNEL	
2.1	Living	Berthing Areas, Lounges, Mess Decks
2.2	Supporting Functions	Galley, Medical Facilities, Administrative Offices
2.3	Stowage	Locker Rooms, Potable Water Tanks, Reefer, Dry Prov. Strm.
3.0	SHIP OPERATIONS	
3.1	Control	Pilothouse, I.C., Gyro Room
3.2	Main Propulsion	Main & Aux. Mchy Rms., Uptakes, Shaft Alley
3.3	Auxiliary Systems	Fan Rooms, Pump Rooms, Steering Gear Room
3.4	Maintenance	Shops
3.5	Stowage	Storerooms
3.6	Tankage	Fuel Oil, Lube Oil, Tanks
3.7	Passageways & Access	Passageways
3.8	Unassigned	Voids

2.3.1 INDICES BY TYPE (See Appendix A)

Indices by type are grouped according to the kind of design features they portray. Weight and volume fractions are examples of allocation of designer's resources. Indices listed under densities illustrate the efficiency with which particular weight items have been integrated into the smallest possible space. Specific ratios refer to the amount of a resource (weight or volume) which has been dedicated to each man, horsepower, etc. They measure the design standard applied to each major functional area. Capacity/ship size ratios measure the overall amount of men, horsepower, launchers, or electric power for each ton of displacement. Overall indices include performance standards and anything not covered by other index types.

Weight, volume, and deck space are all examined in Chapter IV.

2.3.2 INDICES BY FUNCTIONAL AREA (See Appendix A)

The most convenient way to analyze a ship is by each functional group, such as propulsion, structure, or personnel. Thus, indices pertaining to a single concept can be examined at once. This is the approach taken for most of the study, as illustrated in Chapter V.

It should be noted that when grouping indices by area, many indices discussed by type (section 2.3.1 above) are necessarily included. Thus, some overlap between type and function is expected.

2.4 Governing Relationships for Allocation Fractions

Having enumerated and defined each index, it is necessary to digress enough to mention a fundamental interdependency between certain types of indices. These relationships are used to express the weight or volume fraction dedicated to a function by using the two governing design indices as follows:

(Allocation Fraction)=(Design Standard)(Mission Requirement)

The design standard is represented by a specific ratio and the mission requirement is reflected by a capacity/ship size ratio. An example of this relationship is main propulsion weight fraction:

$$W_2/\Delta = (W_2/SHP)(SHP/\Delta)$$

In this case, the group 200 weight fraction is dictated by the main propulsion weight specific ratio (design standard) and by mission speed or powering requirement reflected by main propulsion ship size ratio. A requirement for ruggedness in the design can drive W_2/SHP up, while a mission which dictates higher speed will raise SHP/Δ.

The implication of this interplay between specific ratios and capacity size ratios is profound. It surfaces for each weight and volume fraction, and it helps to explain the magnitude of that fraction. It also demonstrates when parameters are stressed in the design in order to meet particular mission requirements.

2.5 Sources and Error

Current design data for modern small combatants is very hard to obtain. Much of the needed information is classified. In addition, the marketability of small ships as a commercial venture places many unclassified statistics in the category of builders proprietary information. Thus, data gathering is restricted to the few builders' weight statements available and to use of drawings, equipment descriptions, and performance parameters published in the open literature.

As a result of the above problems, some of the data in this study is not as accurate as might be desired. Data on all U.S. ships is from builder weight statements and unclassified drawings and descriptions. Thus, it is, for the most part, sound. However, the data for the two European designs is based on published small-scale drawings, and a weight estimate routine which relies on known machinery weights, steel thickness, etc. These figures are, therefore, good estimates, but estimates nonetheless. The author has made every effort to point out the less reliable information wherever it appears.

Caution is advised in the acceptance of these numbers if accuracy of more than 10% is required to establish a point.

Another caution, concerning volume fractions, is in order. The volumes for most of the ships in this study have been measured directly from drawings. Thus, some inaccuracy of measurement must be expected. But more important is the assignment of a space to a particular volume group. This process is subject to interpretation, especially if two or more functions are served by the same space. These two problems with volume certainly do not render the figures useless. However, it must be remembered that some degree of error is present, and that it must be kept in mind as conclusions are drawn from the data.

There are other areas in which estimates have been used where unclassified material is unavailable. These are noted in the tables where appropriate. They are best described as accurate, conservative approximations based on data for similar ships, or on design curves from literature.

CHAPTER III

INTRODUCTION TO SMALL COMBATANTS

3.1 History of Small Combatant Evolution

The small combatant of the 1970's can be thought of as a descendant of the PT Boat of World War II. Development of this type of ship has occurred principally during the 1960's and early 1970's, after a long period of low-level activity. The recent trends in design have been those of increasing size and sophistication, better seakeeping, and longer range. The most significant aspect of evolution has been the addition of missile systems, initiated on OSA and KOMAR class patrol boats by the Soviet Union in the late 1950's. Large offensive missiles and gun systems of up to 76mm have had the most impact on the displacement increase. (See section 6.4 for trends with time.)

Small combatant evolution in the free world cannot properly be discussed without including the individual shipbuilders. The charts included in this section (Figures 3.1 and 3.1A) are segregated by country, but they could as easily be broken down by builder. In the United States, Peterson and Tacoma have been intimately involved in the line beginning with PG-84. Boeing and Grumman are responsible for the hydrofoil development sequence.

The European nations follow a similar pattern. In the United Kingdom, Vosper Thornycroft is the premier patrol

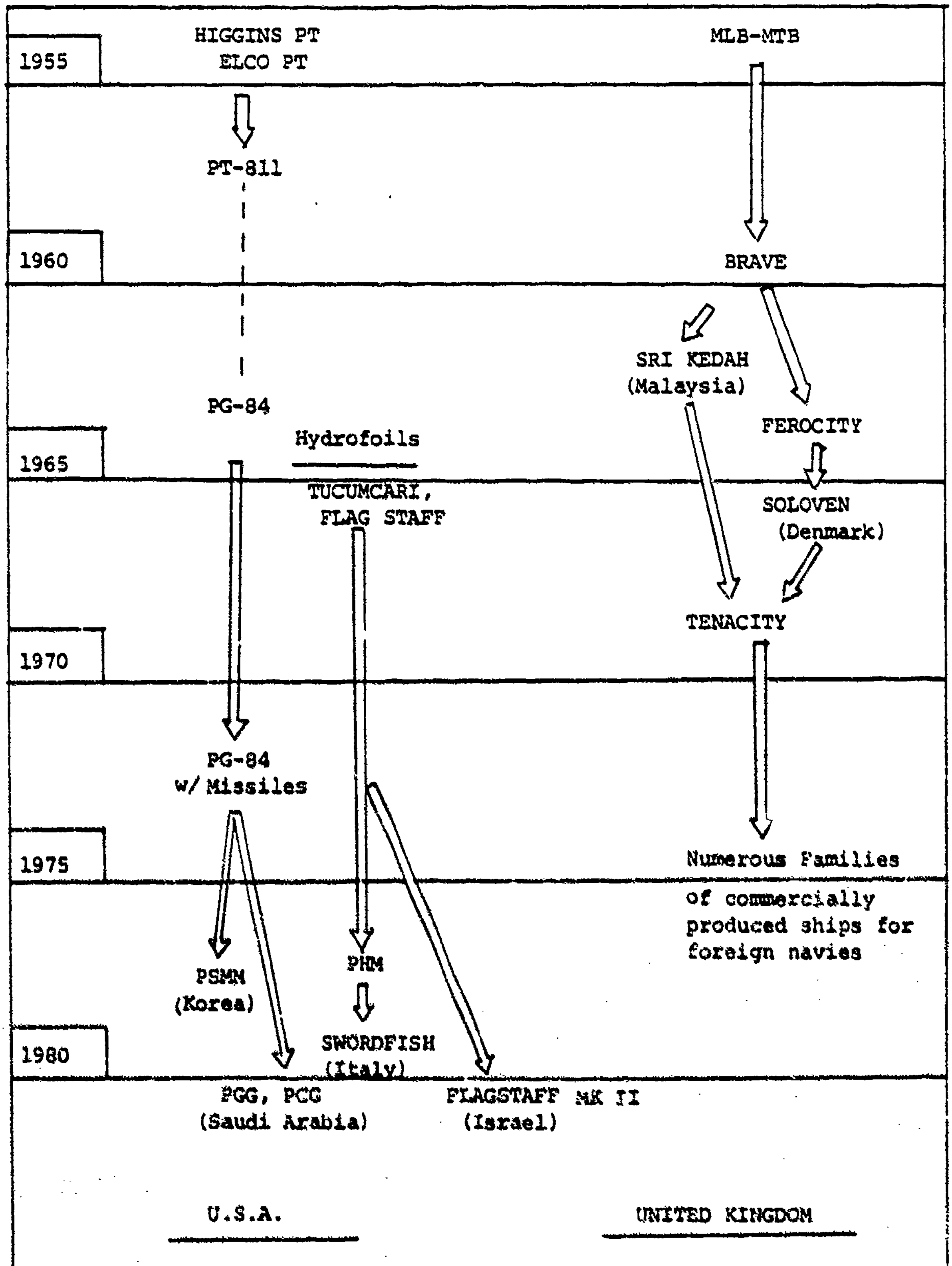


FIGURE 3.1 U.S., U.K. - EVOLUTION OF SMALL COMBATANT FAMILIES

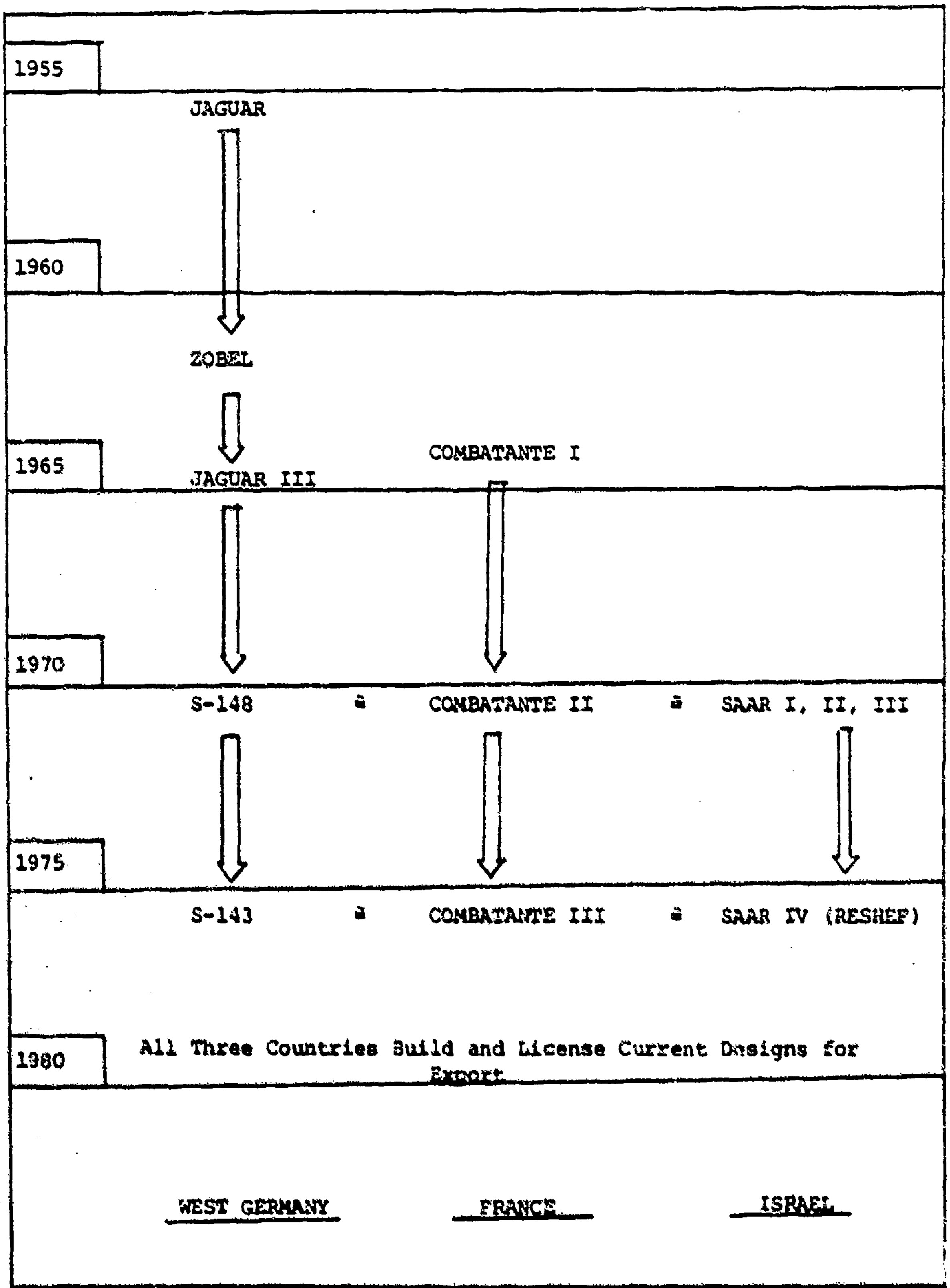


FIGURE 3.1A EUROPE - SMALL COMBATANT FAMILIES

craft builder, although it has recently been joined in the commercial market by Brooke. These two companies are building numerous craft for foreign military sales. In Germany, Lurssen is the long-standing builder, followed closely by Blohm and Voss. The French designs have intermingled with the German and have been built by CMN. Israel Shipyards has picked up the same designs, and has introduced further refinements.

Development in the Soviet Union is harder to trace, but it has been similar to that in the West. The Soviets have evolved from the Komar class, which is a PT boat with missiles, to the 800 plus ton Nanuchka which is a formidable, well-armed seagoing platform. Along the way, several classes of hydrofoils have also been produced.

The emergence of the small warship into a position of significance has paralleled the development of the cruise missile. The sinking of an Israeli destroyer by a missile-armed patrol craft in 1967 provides sufficient evidence of the potential of small platforms for missiles. Most small combatants now built have a ship-to-ship missile battery as the primary system. With this policy established, emphasis is shifting to self-defense, seakeeping, and operation in an electronic warfare environment.

3.2 Current Naval Strength Trends

It is worthwhile to examine the strength levels of the world's navies in order to determine the percentage of naval ships which can be classified as small combatants. A survey of the naval strength appendix from a recent Jane's Fighting Ships[28] is included in this section (Figure 3.2). This survey is based only on the fifty-odd largest navies listed in that appendix. Hence, it does not account for large numbers of small combatants present in the smaller naval inventories.

The numbers are based on the following definitions:

(a) Small Combatants: corvettes (500-1100 tons); fast attack craft (below 500 tons, speed greater than 25 knots).

(b) Total Combatants: includes aircraft carriers, all submarines, cruisers, destroyers, frigates, corvettes, fast attack craft, minelayers, minesweepers, landing ships, patrol craft (speed less than 25 knots), and landing craft.

The table in Figure 3.2 shows that in the largest navies, small combatants have risen as a fraction of numbers of hulls from 24 to 30 percent of the total. It must be remembered that the figure would be much smaller if it were calculated by tons instead of hulls. However, there is a clear trend to an increasing proportion of naval strength.

The second table in this section (Figure 3.3) shows the United States and the Soviet Union. This table is based on an inventory from the regular pages of Jane's Fighting Ships:

FIGURE 3.2

SMALL COMBATANT POPULATION TRENDS (50 MAJOR NAVIES)

1970-1971	Number of small combatants	1778
	Percent of combatants	23.8
	Percent of naval ships	16.4
	Countries included	55
1972-1973	Number of small combatants	1974
	Percent of combatants	27.4
	Percent of naval ships	18.3
	Countries included	53
1975-1976	Number of small combatants	2320
	Percent of combatants	30.5
	Percent of naval ships	23.9
	Countries included	51
1977-1978	Number of small combatants	2328
	Percent of combatants	30.3
	Percent of naval ships	23.6
	Countries included	51
1978-1979	Number of small combatants	2305
	Percent of combatants	30.4
	Percent of naval ships	23.1
	Countries included	51

FIGURE 3.3

U.S. vs U.S.S.R. - SMALL COMBATANT POPULATION

(Base Year: 1978-1979)

		Tons	Hulls
United States (*)	Small Combatants	1,254	8
	Combatants	3,812,108	545
	Naval Ships		647
Soviet Union	Small Combatants	166,250	364
	Combatants	3,241,260	1,582
	Naval Ships		2,130

PERCENTAGES OF SMALL COMBATANTS

	% of Combatants (by Disp.)	% by Hulls	
		Combatants	Naval Ships
United States	.034%	1.5%	1.2%
Soviet Union	5.130%	23.0%	17.1%

*Including hydrofoils and USCG high and medium endurance cutters.

1978-1979.[28] The obvious conclusion to be reached from this table is that the United States places a much lower priority on small warships than does the Soviet Union. The inequality of emphasis becomes even more apparent if it is recalled that large numbers of small combatants have been installed in the Soviet sattelite navies. The reason for the difference is a basic disparity in naval missions. The U.S. Navy is a power projection organization which has no mission for a small, short-range ship. Coastal defense of the U.S. would presumably be undertaken by the Coast Guard, which uses ships of 1,000 tons or more for this role. In contrast, the Soviet Union has traditionally had a defensive navy with emphasis on coastal defense. The Soviets have only recently (1970's) expanded the role of their navy to include sea control. Consequently, they have a much higher inventory of small combatant ships.

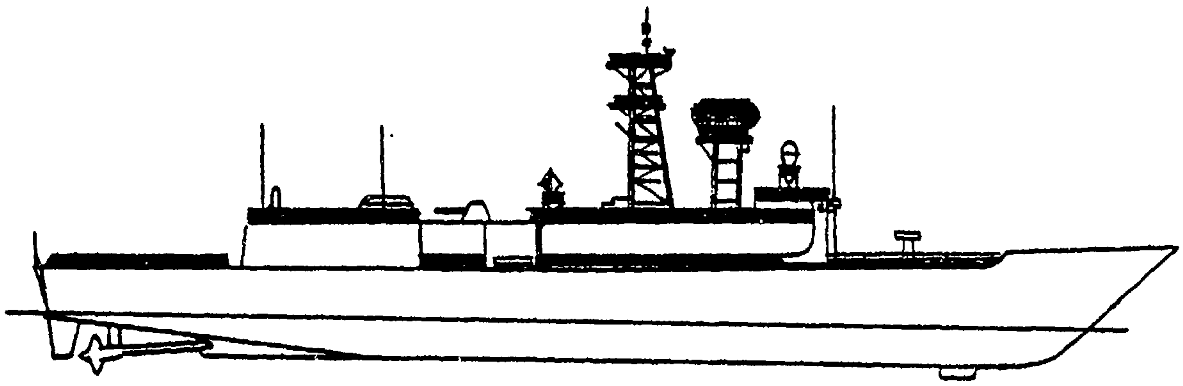
3.3 Gross Ship Description

This section is comprised of a brief description of each ship included in the study. It is for a general familiarization with the ships. The profile drawings give an idea of the ship appearance. (See Figures 3.4 through 3.11)

3.4 Size Comparison

The ship size chart (Figure 3.12) shows all ships in this study drawn to the same scale. The profiles show how much

FIGURE 3.4 FFG-7 CLASS



Country: U.S.A.

Builder: Bath Iron Works, Todd

Year Delivered: 1977

L.O.A.: 440 Feet

Displacement: 3782 tons, full load

Speed: 29 Knots

Range: 4500 NM @ 20 KT

Complement: 185

Propulsion: 2 G.E. LM 2500 Gas Turbines
40,00 SHP
Single, Controllable Reversible Pitch Propeller

Weapons: 1 MK 13 GMLS
1 MK 75 76 mm Gun
1 CIWS
2 MK 32 Triple Torpedo Tubes
2 LAMPS MK III Helicopters

Sensors: AN/SPS - 49
AN/SPS - 55
MK 92 FCS
AN/SQ5-56 Sonar

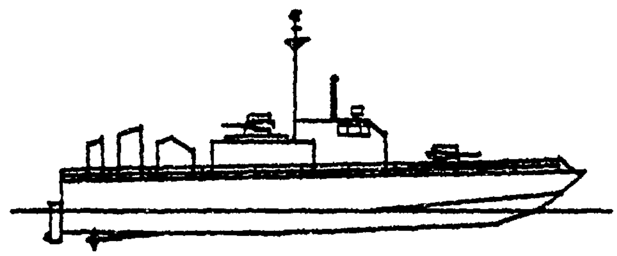


FIGURE 3.5 CPIC CLASS

Country:	U.S.A. (for South Korea)	L.O.A.:	99.9 Feet
Builder	Tacoma	Displacement:	72.5 Tons Full Load
Year Delivered:	1976	Speed:	45 Knots
		Complement:	11

Propulsion: 3 AVCO-LYCOMING Gas Turbines - 6,000 SHP
V-Drive and 3 CRP Propellers
2 Volvo Diesel Outdrives - 370 SHP

Weapons: 1 (2) Emerlec 30 MM Twin
2 Twin M60 Machine Guns
2 40 MM Grenade Launchers

Sensors: MK 93 GFCS

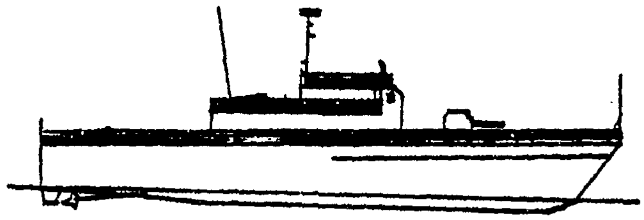


FIGURE 3.6 PG-84 CLASS

Country:	U.S.A.	L.O.A.:	164.5 Feet
Builder:	Tacoma, Peterson	Displacement:	242 Tons Full Load
Year Delivered:	1964	Speed:	40+ Knots
		Range:	1700 NM @ 16 Knots
		Complement:	24

Propulsion: 1 GE LM1500 Gas Turbine - 13,500 SHP
2 Cummins Diesels - 1650 SHP
2 CRP (CODOG)

Weapons: 1 3"/50 Gun
1 40 MM Gun
2 Twin .50 Cal Machine Guns

Sensors: 1 MK 63 FCS

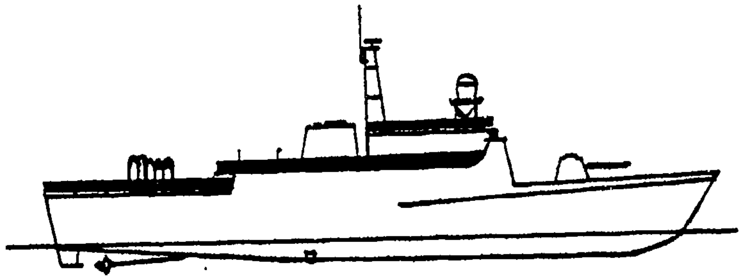


FIGURE 3.7 PGG CLASS

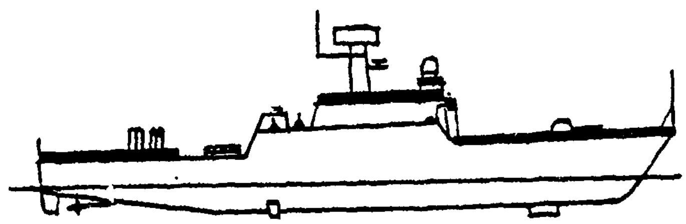
Country:	U.S.A. (for Saudi Arabia)	L.O.A.:	190.5 Feet
		Displacement:	390 Tons Full Load
Builder:	Tacoma	Speed:	38 Knots
Year Delivered:	1980	Complement:	32

Propulsion: CODOG 1 LM2500 23,000 SHP
2 GM Diesels - 2850 SHP
2 CRP Propellers

Weapons:
4 Harpoon
1 MK 75 76 MM
2 Twin 20 MM Machine Guns
1 81 MM Mortar
2 40 MM Mortar

Sensors:
AN/SPS 55
MK 92 FCS

FIGURE 3.8 PCG CLASS



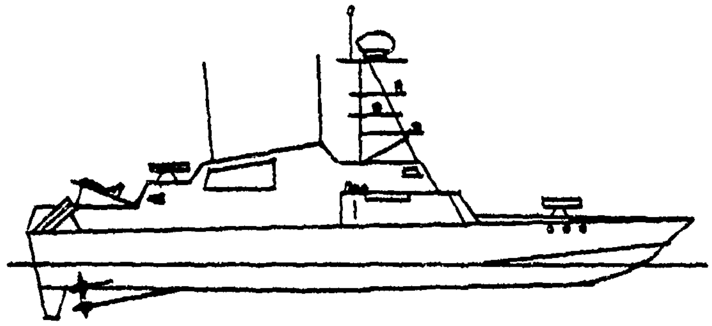
Country:	U.S.A. (for Saudi Arabia)	L.O.A.:	245.5 Feet
Builder:	Peterson	Displacement:	797 Tons Full Load
Year Delivered:	1980	Speed:	30 Knots
		Complement:	58

Propulsion: CODOG: 1 GE LM2500 Gas Turbine - 23,000 SHP
2 GM Diesels - 2930 SHP
2 CRP Propellers

Weapons:
4 Harpoon
1 MK 75 76 MM
2 Twin 20 MM Machine Guns
1 81 MM Mortar
2 40 MM Mortars
2 MK 32 Triple Torpedo Tubes

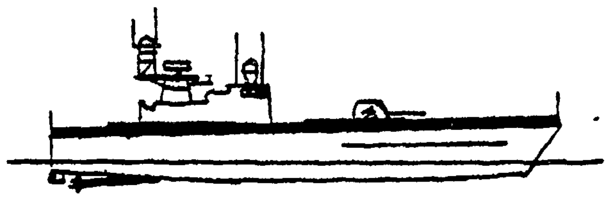
Sensors:
AN/SPS 40 B
AN/SPS 55
MK 92 FCS
AN/SQS-56 Sonar

FIGURE 3.9 PC-1 CLASS



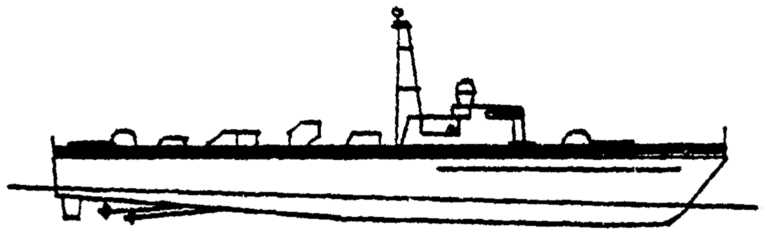
Country:	U.S.A.
Builder:	None
Delivered:	Far Term Design
L.O.A.:	250.1 Feet
Displacement:	1109 Tons Full Load
Speed:	45+ Knots
Range:	4000+ NM @ 16 Knots
Complement:	75
Weapons:	Advanced Systems
Sensors:	Far Term

FIGURE 3.10 SPICA II CLASS



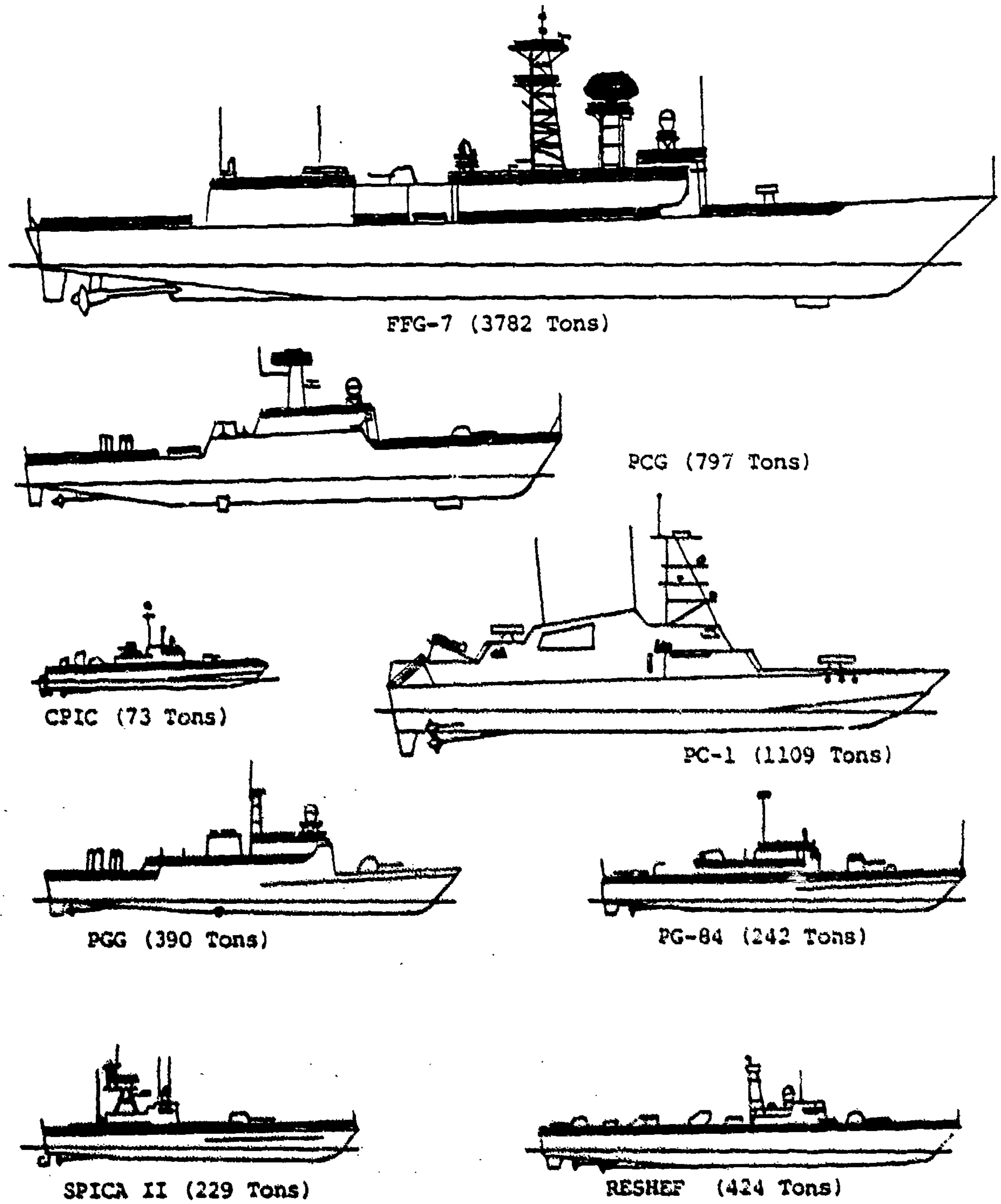
Country:	Sweden
Builder:	Karlskrona
Year Delivered:	1973
L.O.A.:	143 Feet
Displacement:	229 Tons Full Load
Speed:	40.5 Knots
Range:	Not Available
Complement:	32
Propulsion:	3 Rolls Royce Gas Turbines - 12,900 SHP 3 Shafts with V Drive and Fully-Cavitating CRP Propellers
Weapons:	1 57 MM BOFORS 6 21-Inch Torpedo Tubes Mine Rails
Sensors:	Philips Teleindustry 9LV200 FCS

FIGURE 3.11 RESHEF CLASS



Country:	Israel
Builder:	Israel Shipyards
Year Delivered:	1973
L.O.A.:	190.6 Feet
Displacement:	424 Full Load (Based on Estimate)
Speed:	32 Knots
Range:	2500 NM @ 20 Knots
Complement:	44
Propulsion:	4 MTU Diesels - 13,500 SHP
	4 Shafts
Weapons:	2 76 MM Guns
	6 Gabrielle Missiles
	4 RBOC
	2 Twin 40 MM (Removed)
Sensors:	ORION 250 FCS

FIGURE 3.12 SMALL COMBATANTS - SIZE COMPARISON



Scale: 3.5 MM = 10 Ft.

smaller the small ships are than a frigate. It is evident that CPIC is really too small to be considered as more than a fast patrol boat. Of particular note is the unique appearance of the European ships, SPICA II and RESHEF. Also of interest is the contrast between PCG and PC-1, which are radically differing designs of about the same overall length.

CHAPTER IV

OVERALL COMPARISON OF SHIPS

With completion of the review of the basic characteristics for each ship, the analysis begins with this chapter. The overall design features and weight, volume, and deck space allocation fractions are discussed, with the intention of identifying design differences which will be reviewed and explained in following chapters. This chapter treats only overall design characteristics, and can thus be thought of as a first-level analysis.

4.1 Gross Characteristics

The table in Figure 4.1 tabulates the major characteristics of each ship. This table, along with the drawings in Chapter III, should provide a good basis for noting overall differences between ships

The ships are listed in three basic groups. At the left are FFG-7 and CPIC, the large and small baseline ships. In the center are four U.S. designs, arranged by date. They range from 1964 to far-term (future). At the right are two European ships.

4.1.1 FFG-7

This large "yardstick" is much bigger than the other ships. Its length, displacement, and internal volume show this. FFG-7 is the newest U.S. frigate and it represents the

FIGURE 4.1

TABLE OF GROSS CHARACTERISTICS

SHIP	FFG-7	CPIC	PG-84	PGG	PCG	PC-1	SPICA II	RESHEF
L.O.A. (ft)	445	99.9	164.5	190.5	245.5	250.1	143.0	190.6
Δ_{FL} (Tons)	3782	72.5	241.9	390	796.6	1109	229	424
Volume (FT^3)	531,132	11,720	43,656	75,369	117,442	223,992	29,127	52,262
V_{MAX} (KT)	29	45	40+	38	30	45+	40.5	32
Range (NM)	4500 @ 20 KT	500+ @ 16 KT	1700 @ 16 KT	2000+ @ 16 KT	3000+ @ 16 KT	5000+ @ 16 KT	1500 @ 16 KT	2500 @ 20 KT
SHP_{CRUISE}	40,000	370	1650	2850	2930	3520	12,900	13,500
SHP_{BOOST}	---	6,000	13,700	20,000	20,000	105,000	---	---
Plant	Gas Turbine	CODOG	CODOG	CODOG	CODOG	CODOG	Gas Turbine	Diesel
Accomodations	185	11	24	32	58	75	32	44
Stores (Day)	30	2.5	14	14	14	n/a	n/a	10
Year	1977	1976	1964	1980	1980	(1990)	1973	1973
PAYLOAD								
Missiles	MK 13 GMLS	None	None[1]	Harpoon[4]	Harpoon[4]	AAW SUW ASW	None[2]	Gabrielle[6]
Torpedo Tubes	2 MK 32	None	None	None	2 MK 32	21 in[6]	21 in[6]	None[3]
Aircraft	2 Lamps	None	None	None	None	RPV	None	None
Guns	76 mm	Twin[1] 30 mm	3"/50	76 mm[5]	76 mm[5]	None	57 mm	2 76 mm
	CIWS	4x 50 cal	40 mm	2 Twin 20 mm	2 Twin 20 mm			2 Twin[5] 40 mm
			2 Twin .50 Cal.	81 mm Mortar	81 mm Mortar			
				2 40 mm Mortar	2 40 mm Mortar			

[1]Designed for 2; [2]Installed in later versions; [3]Can be installed-alternative configuration; [4]Removed; [5]Space & weight for CIWS

most recent design standards for a delivered ship. It is a single-screw design, and is the first gas turbine-powered frigate for the U.S. It is designed for reduced manning and high habitability. This ship has a vastly different mission from those of the smaller designs. The payload, range, and stores endurance show FFG-7 to be an escort ship built for extended steaming, in open ocean situations. Speed in excess of 30 knots is de-emphasized for such missions, and as a result, the ship is slower than all others in the study.

4.1.2 CPIC

This small baseline ship is a short range, high speed patrol craft designed for coastal missions. Its sophisticated all-gun armament, shallow draft, and high speed make CPIC ideally suited for clandestine insertion and small patrol boat actions.

4.1.3 PG-84

The oldest U.S. small combatant, PG-84, is the first U.S. Navy ship to use a gas turbine for propulsion. It is a short-mission ship with a fast reaction time. It does, however, have added cruising range on the diesels. Use of an aluminum hull can be considered inventive for PG-84's era. The armament of this ship consists entirely of gun systems.

4.1.4 PGG

This small combatant designed and built in the United

States, will be delivered to Saudi Arabia. It resembles an enlarged PG-84 class ship, with a modernized weapons and electronics suite, and with a more modern propulsion plant. PGG's increased range, payload, and seakeeping ability elevate it from a coastal gunboat to a ship which can venture to sea in weather of up to sea state 4. PGG has a newer turbine and more electric generation capacity than PG-84, and it is fin-stabilized. The offensive capability of four Harpoon missiles gives PGG long-range surface-to-surface missions, while its smaller guns allow it to be used for coastal interdiction.

4.1.5 PCG

Another ship built in the U.S. for Saudi Arabia, PCG carries the PGG hull form to almost 800 tons. This ship has all of the same weapons as PGG, but it also has an anti-submarine warfare suite of two MK32 triple torpedo tubes and the AN/SQS-56 sonar. Thus, the thrust of this ship tends toward coastal submarine defense. With the emphasis on ASW, the speed requirement is lessened to 30 knots, allowing the use of the same propulsion plant as in PGG.

4.1.6 PC-1

This design study applies advanced technology to a large planing ship. This 1,100 ton design is an example of what might be expected in the late 1990's. It is very fast, very powerful, and has a long rage when cruising on diesels. It employs an arsenal of futuristic weapons, including remotely piloted vehicles, missile-launched torpedos and sonar buoys, and Harpoon. PC-1 design data and indices must be taken as standards not yet achievable, but as real possibilities in the future.

4.1.7 SPICA II

This is a Swedish ship of about the same displacement as PG-84. It has similar speed, but here the similarity ends. As a newer design than PG-84, SPICA II has a more modern gun and better electronics. It also has a very large torpedo armament. Not mentioned in the table is the installation of mine rails. SPICA II differs from the other ships in appearance, with a small deckhouse set far aft. This ship is intended for action in the restricted waters around Scandanavia, as its armament implies.

4.1.8 RESHEF

This Israeli ship is a derivative of many German and French ships built in the last 10 years. It has a steel hull, a small deckhouse, and a very low profile. This ship has a good offensive armament, with a sophisticated electronics suite. Much of the hull is dedicated to a large combat operations area. RESHEF is built for medium range missions at high speed in the Mediterranean Sea. Its top speed is lower than the other ships of similar size, but it has a better range than the others at speed. RESHEF is the only ship in the study powered by high-speed diesels.

4.2 Weight Comparison

The graph in Figure 4.2 shows the lightship weight breakdown by percent. Figure 4.3 shows the weight breakdown for the ships from 200 to 800 tons on an absolute scale.

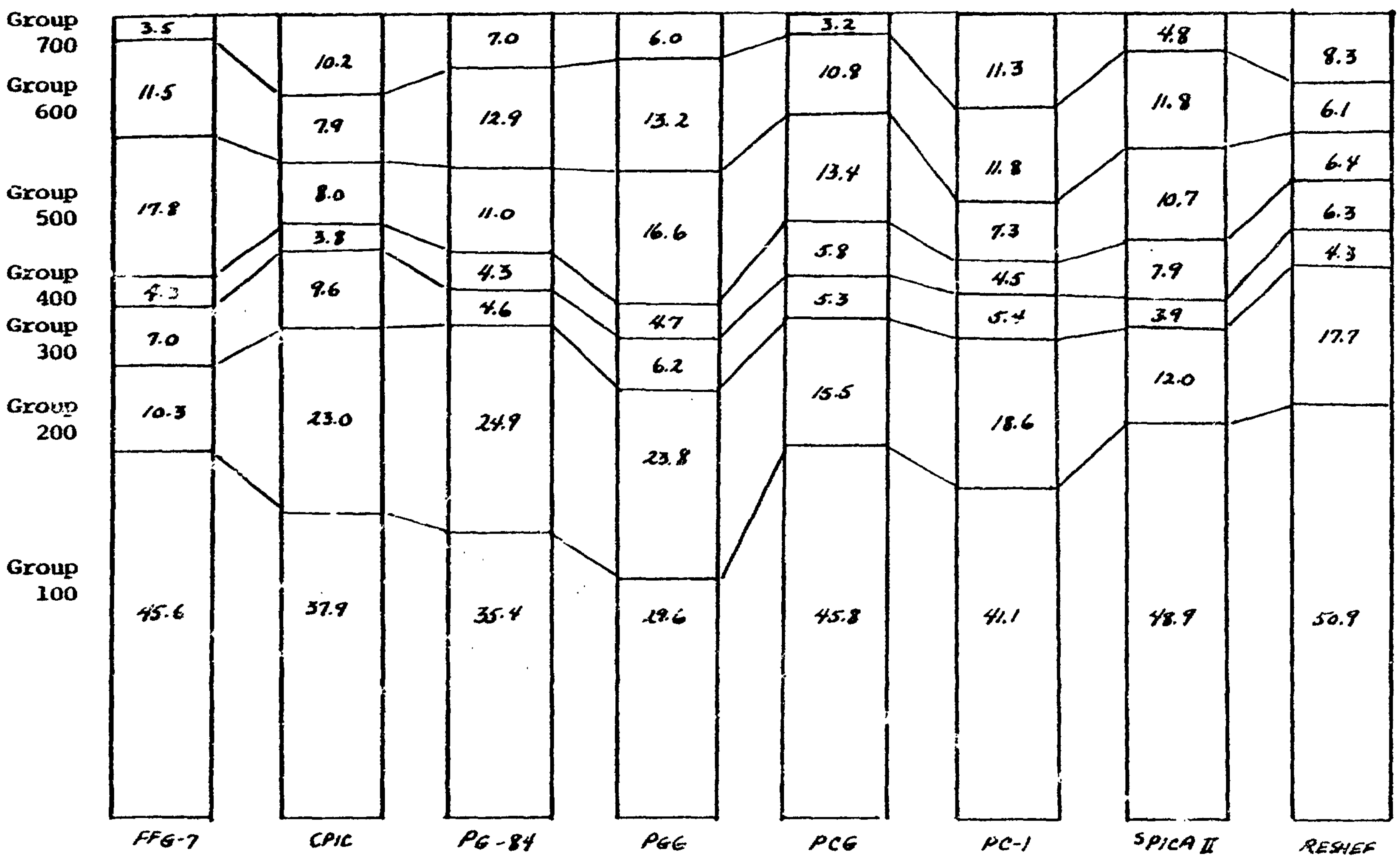
4.2.1 LIGHTSHIP WEIGHTS (FIGURE 4.2)

Group 100 (Structure) - The most evident feature of the lightship weights is the advantage of aluminum construction. The steel-hulled ships all have group 100 weight fractions (lightship) in excess of 45%. The aluminum ships (PG-84, PGG, PC-1, CPIC) have a distinct weight savings over the steel ships (FFG-7, PCG, SPICA II, RESHEF) which enables aluminum ships to dedicate more weight to other areas.

Group 200 weight fractions are lowest for the large, slow ships (FFG-7, PCG) and highest for the American small, fast ships (CPIC, PGG, PG-84). Deviations from the trend of increased W_2/Δ_{LS} are RESHEF and SPICA II. RESHEF is slow, but has a diesel plant which uses more weight per horsepower. SPICA II is very fast, but has a lightweight, all-gas turbine plant for group 200 savings.

Group 300 - The European ships tend to have lower group 300 weight fractions than their U.S. counterparts. CPIC has the highest, probably due to a minimum discrete generator size.

FIGURE 4.2 LIGHTSHIP WEIGHTS (Numbers represent percent of Δ_{LS})



Group 400 weight fractions are remarkably similar, but the European ships tend to emphasize command and surveillance more. They, therefore, have higher fractions for group 400.

Group 500 weight fraction is highest on the large ships. This is due to size, length of mission, and the requirement to support a larger crew. The RESHEF, on the other hand, has a very much lower W_5/Δ_{LS} indicating austerity in the area of habitability.

Group 600 - Outfit and furnishings are fairly constant, except for the lower-than-average figures for RESHEF (spartan) and CPIC (small, short-mission) for this group.

Group 700 - Armament weight fraction varies from 3% in FFG-7 and PCG to 11% for PC-1. This range is not a good indicator of combatability, since volume of weapon systems is more important in some of the ships.

4.2.2 ABSOLUTE SCALE, FULL-LOAD WEIGHTS

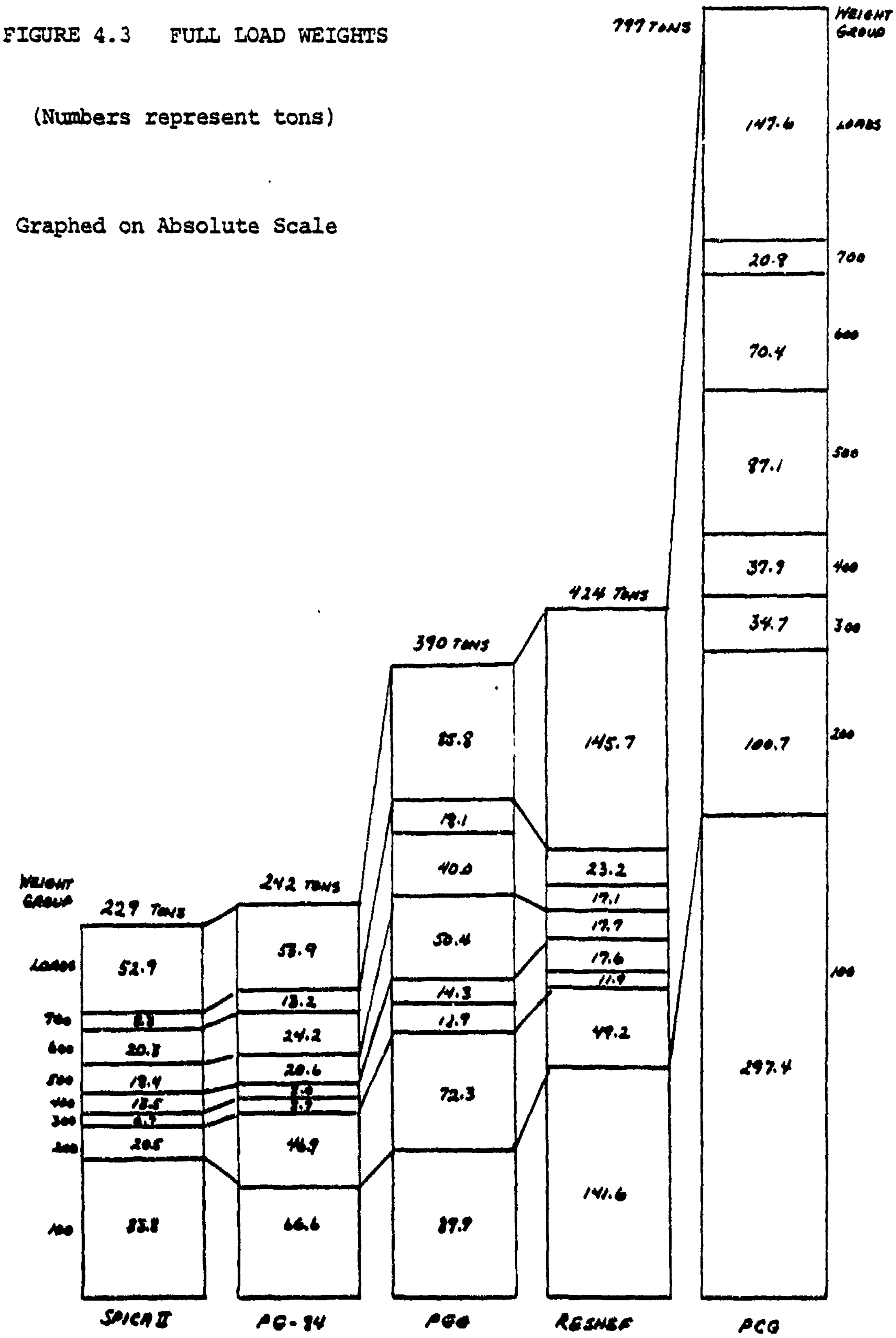
Figure 4.3 shows how differently ships of the same size can be built. SPICA II and PG-84 show a trade-off between groups 1 and 2, with SPICA having lightweight engines but steel construction. RESHEF and PGG have a similar trade-off. The outstanding points to be made from this graph are:

- PGG has a very high group 500 weight
- RESHEF and SPICA II have low group 300 and 500 weights
- RESHEF carries the same load as PCG, but is only half as big

FIGURE 4.3 FULL LOAD WEIGHTS

(Numbers represent tons)

Graphed on Absolute Scale



. PCG, using the same plant as PCG, has a much higher group 200 weight

The significance of these differences is explored in subsequent chapters.

4.3 Volume Comparison (Figure 4.4)

Allocation of internal volume (and weight) indicates where design emphasis has been placed. The bar graph in Figure 4.4 shows the three major volume groups (1 - mission, 2 - living, 3 - ship operation) and also main propulsion ($\nabla_{3.2}$) as part of group 300. The volume fractions are based on total usable internal volume of hull and superstructure as measured from drawings.

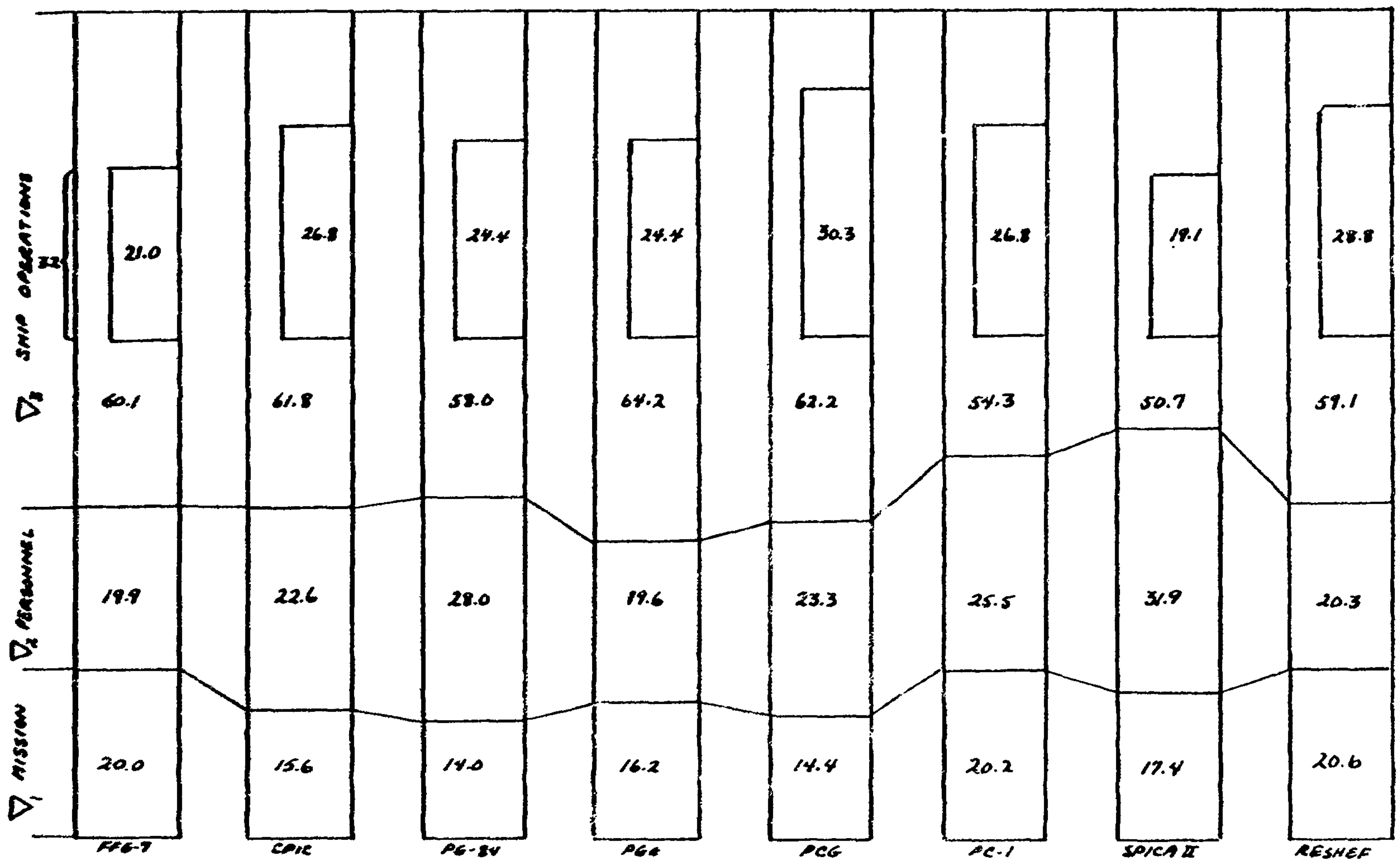
4.3.1 MISSION (∇_1)

Mission area received the smallest fraction of volume in all cases. Those with the most generous allocation to mission are FFG-7, RESHEF, and PC-1. Note that FFG-7 has a low payload weight fraction, but a high mission volume fraction. This indicates that its weapons systems are of low density. RESHEF gains extra volume for mission by sacrificing space for living. PC-1 does the same by reducing ship operations volume fraction.

4.3.2 PERSONNEL (∇_2)

Personnel volume fraction varies from 20% to 30%. The small ships do not appear to have any advantage in this area.

FIGURE 4.4 INTERNAL VOLUME ALLOCATION



Numbers represent percent of total enclosed volume

In fact, SPICA II uses the highest fraction here, but is the second from the smallest ship. The reasons behind the variation in this area are discussed in Chapter V.

4.3.3 SHIP OPERATION (∇_3)

Ship operation takes the largest portion of internal volume. It is relatively constant, at close to 60% of the total. There are three ships which deviate more than 2%. PGG is higher than average due to large auxiliary machinery rooms, and a large number of air conditioning spaces. PC-1 is lower than average, because of its technological advantage. SPICA II is very low, since its auxiliary plant and main propulsion plant are efficiently arranged.

Main propulsion ($\nabla_{3.2}$) volume fraction follows no particular pattern. SPICA II has a lower fraction than the others due to the compact engineroom mentioned above. RESHEF and PCG are higher than average. For RESHEF this is due to a large engineroom, which holds most of the auxiliaries. For PCG, it could be long uptake and exhaust for the gas turbine.

A word of caution is in order with respect to volume allocation. Only large differences in volume fractions should be taken as significant. The reason for this is twofold: first, volume measurements, no matter how carefully taken, are subject to error - especially for ships with such radical flare. Second, there is a matter of interpretation when assigning a space to any group. Therefore, two people making the same measurements might still come up with different volume fractions.

4.4 Weather Deck Space Comparison (Figure 4.5)

Utilization of weather deck space is critical for all combatant ships. Weapon launchers, sensors, deckhouses, and numerous other components compete for the available topside area. This is a major problem on small ships which rely heavily on deck-mounted, cannister launchers. The graph of space utilization (Figure 4.5) is produced by taking a "bird's-eye" view of the deck. Weapons and sensors are measured for their swing circles. Superstructure area includes all deckhouses and masts above the weather deck, minus any functions which have space on top of the house. Replenishment at sea space is included only it is is specified in drawings.

4.4.1 WEAPONS/SENSORS FRACTION

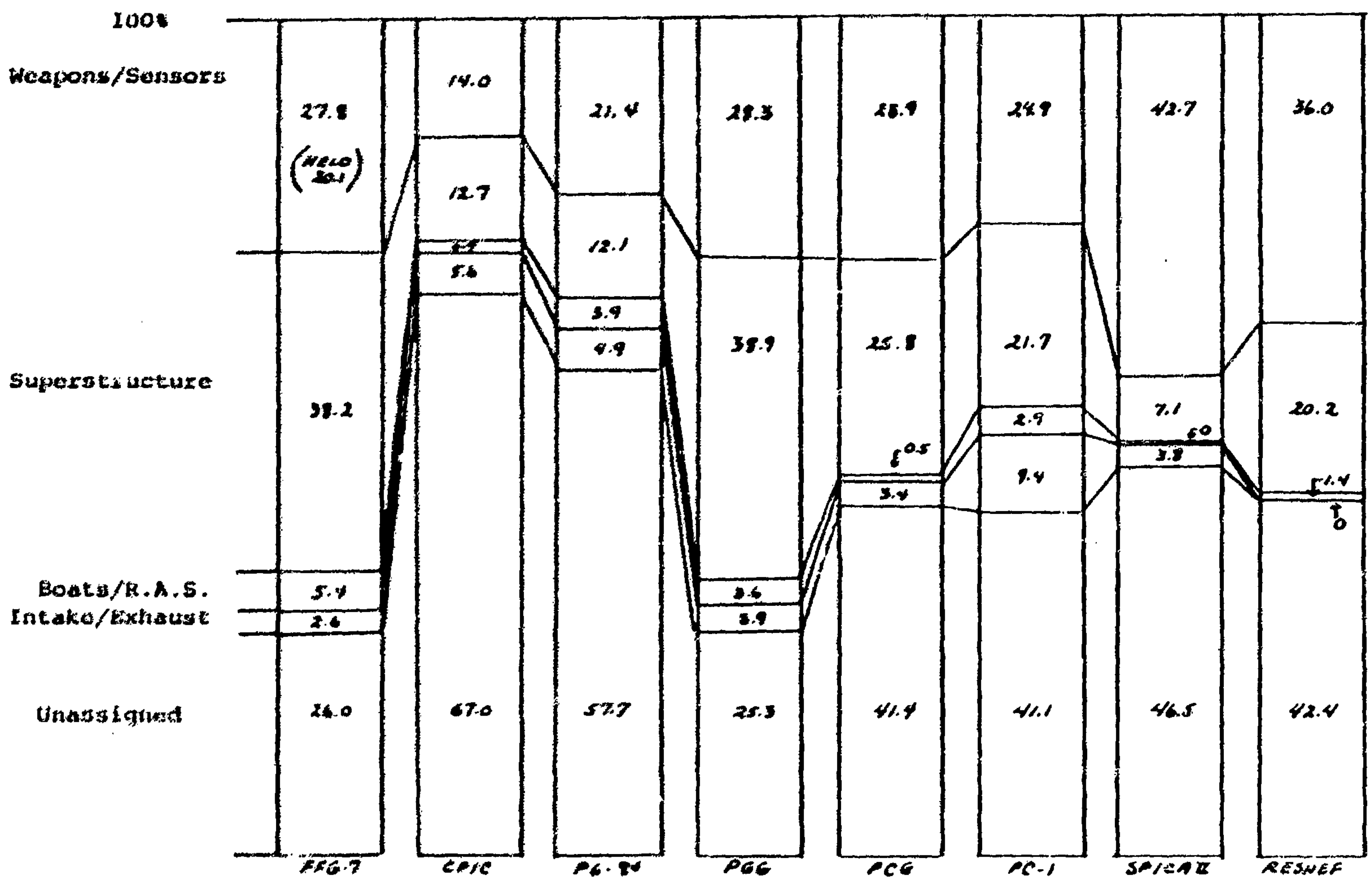
Weapons/sensors fraction varies considerably. CPIC is lowest at 14% due to small weapon systems. SPICA II is highest at 42.7%. This is chiefly due to mine rails and large torpedo tubes. The American ships use less space for weapons than Eurpoean designs in general. Note that most of FFG-7's weapons fraction is due to the helicopter deck.

4.4.2 SUPERSTRUCTURE FRACTION

Superstructure fraction is also considerably variable. It is generally lower in the small ships than for FFG-7. PGG

FIGURE 4.5 WEATHER DECK SPACE UTILIZATION

Numbers represent percent of total weather deck space



is a notable exception, as its profile drawing shows.

4.4.3 BOATS AND REPLENISHMENT-AT-SEA FRACTION

This fraction is extremely small on all the small ships. Their crew size and mission profiles necessitate little more than life-rafts and possibly one replenishment station.

4.4.4 INTAKE AND EXHAUST FRACTION

This generally follows the main propulsion ship-size ratio (SHP/Δ). That is, the higher horsepower per ton, the larger area fraction needed for intake and exhaust. RESHEF has no area for exhaust, since her exhaust is out the side of the hull, or underwater (at battle condition).

The same caveat mentioned in volume utilization applies to deck space fraction.

4.5 Chapter Summary

The fundamental aim of Chapter IV has been to identify each major design difference exhibited by any ship. Significant deviation from the design features of similar ships is cause for question and analysis. With these design features in mind, the next step is to try to determine why differences exist.

CHAPTER V

DESIGN INDICES BY FUNCTIONAL AREA

Significant differences in design elements have been identified in Chapter IV. In order to determine why these differences exist, it is necessary to undertake a second-level analysis. This analysis must probe each feature to a sufficient depth to determine the reason for any deviation from the norm. For organizational clarity, this chapter treats the investigation by functional areas as follows:

- mobility
- structure
- auxiliaries and outfit
- personnel
- electric power
- other functional areas

For each functional area, all pertinent design indices are listed. Then each index is reviewed in detail in order to identify the factors which determine its value. It is these factors which "drive" the design that are of interest, since they depict the requirements set down by the ship's mission. profile.

5.1 Mobility - Overview

Speed, endurance, seakeeping, maneuverability, and flexibility are all parts of the functional area called mobility. The large amounts of space and weight dedicated to propulsion and fuel (Chapter IV) dictate that this area be investigated rigorously. The object is to determine those features which must be emphasized in order to meet the mission specified needs of speed, fuel endurance, rough weather performance, etc.

With the above in mind, four major issues arise in the discussion of mobility. They are as follows: (1) speed; (2) range; (3) seakeeping; and (4) design integration standards. Each issue is addressed by first observing which design parameters are governing, and then by determining which parameters are stressed to obtain the desired performance traits.

5.1.1 SPEED

The value of speed is the subject of much debate (see references 1, 21, 24). Large combatants do not usually operate above maximum sonar speed (about 27 knots), and the difference between a top speed of 30 and 35 knots is negligible, such as aircraft and cruise missiles. Therefore, speed has been de-emphasized in destroyer design.

Small combatants are a different matter. They lack the sophisticated anti-aircraft systems found on destroyers, and must, therefore, complete their short missions in a maximum amount of time to avoid exposure to attack. This places a premium on speed. Thus, the small ships are all faster than FFG-7, as the table contained in Figure 5.2 shows. Of note are PC-1 and CPIC, both of which have high planing speeds. The remaining small ships have top speeds (listed in reference 28) of 30 knots or more. PCG is the slowest, because its mission emphasizes anti-submarine warfare.

In order to better understand the design features which affect speed, the following relationship is useful:

$$V = \frac{(W_2/\Delta)[(PC)(L/D)]}{(W_2/SHP_B)}$$

The factors on the righthand side of this equation can be restated as follows:

$$V = \frac{(\text{Design Budget})(\text{Hydrodynamic Efficiency})}{(\text{Design Standard})}$$

This means that speed is achievable either by a gross allocation of a larger propulsion plant, by a well-designed, hdyrodynamically efficient hull, or by an efficient design standard which requires a low ship impact for components. All of these factors are shown in Figure 6.1.

5.1.1.1 Hydrodynamic Efficiency

The hydrodynamic efficiency term consists of lift to drag ratio $\left(\frac{\Delta V}{EHP}\right)$ and propulsive coefficient (EHP/SHP). Both of these quantities are difficult to obtain. For FFG-7 and PG-84 reference 21 provides data. The other ships' figures are estimates from references 13, 18, 27, and 32. The influence of size is evident from the table. FFG-7 has a very high lift to drag ratio, due to the displacement term. It also has the highest propulsive coefficient, due to size and the use of a single screw. On the other hand, CPIC has the lowest propulsive coefficient and lift-drag ratio due to its small size. The remainder of the ships studies fall between these two in both size and hydrodynamic efficiency. Thus, overall, size can help to influence hydrodynamic efficiency.

If attention is restricted to the five ships of displacement between 200 and 500 tons, the observation is that the product of P.C. and L/D varies from 6 to 7.4. This is about 25% variation, and can thus be significant. The largest ship of this group (PCG) has the highest figure, as might be expected from the overall trend.

The conclusion to be reached is that hydrodynamic efficiency, in general, plays a role in production of speed. This conclusion is also valid within the narrow range of displacement of 200 to 500 tons, where it accounts for a 25% variation.

5.1.1.2 DESIGN STANDARDS

Design standards, manifested in main propulsion specific weight (W_2/SHP), vary considerably more than the hydrodynamic efficiency. There is a trend to lighter plants as speed goes up, as shown by Figure 5.1A. Thus, the requirement for speed has exacted a standard of design which demands lightweight, advanced technology propulsion plants in order to save weight.

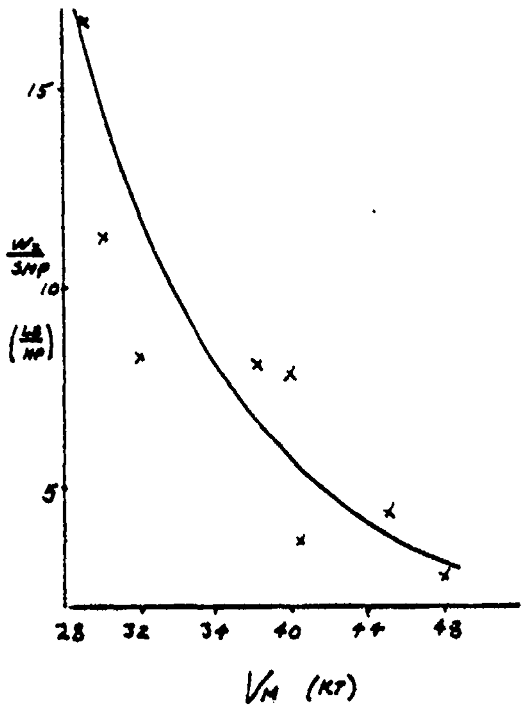
The fast ships can apply this technology due to their short missions, which do not require rugged machinery. Conversely, the larger, slower ships do not require the application of lightweight systems. In fact, their longer missions dictate a more flexible and rugged propulsion plant. Hence, they use a higher main propulsion specific weight than their fast counterparts.

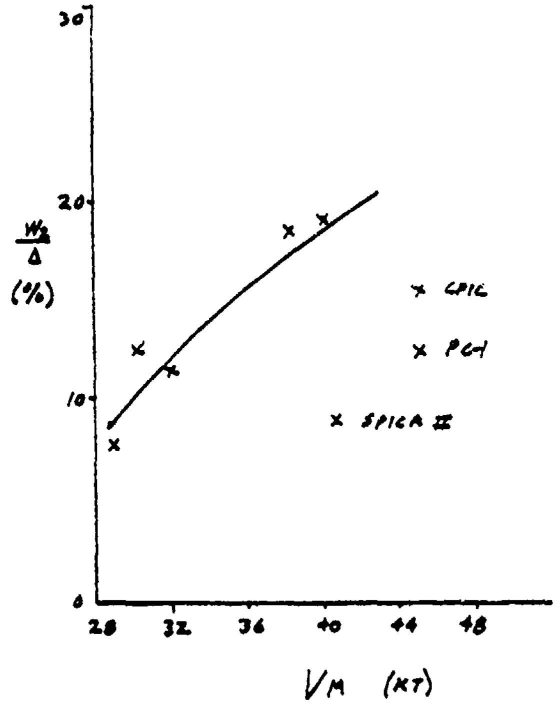
The conclusion to be drawn from the above discussion is that speed requirements dictate varying design standards, as does mission flexibility. The result of the design standard selected is a large variation of main propulsion specific weight. This variation is up to 70% in the nominal study range (200-800 tons).

5.1.1.3 Design Budget (Allocation Fraction)

The remaining term in the governing relation for speed is the main propulsion weight fraction (W_2/Δ). This is the amount of weight which has been dedicated to propulsion from Figure 5.2 . The variation in this factor is from 8% to 20% overall, and from 9% to 20% in the nominal displacement range. This represents a variation of 55% from the maximum figure. The allocation of weight is directly related to speed requirements, as shown by the curve in Figure 5.1 B. The ships which do not follow the curve all have extremely lightweight plants. Since main propulsion weight fraction is determined by the relationship,

$$W_2/\Delta = (W_2/SHP)(SHP/\Delta)$$





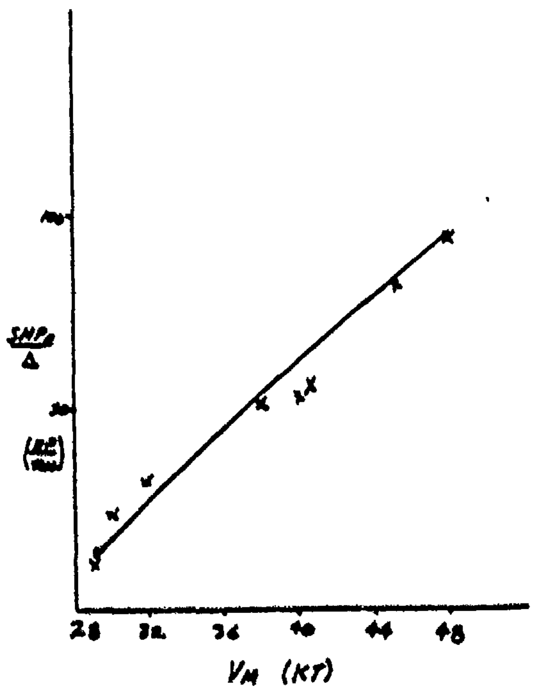


FIGURE 5.1

SPEED-RELATED QUANTITITES

A. Main Propulsion Specific Weight vs. Maximum Speed

B. Main Propulsion Weight Fraction vs. Maximum Speed

C. Main Propulsion Ship Size Ratio vs. Maximum Speed the two right-hand terms are included in Figure 5.1 . It is evident that the main propulsion ship-size ratio dominates as speed goes up. This shows that the gross allocation of horsepower to gain speed is very prevelant. This pushes up the group 200 weight fraction.

5.1.1.4 Conclusions

The figures and discussion from this section indicate that all three contributing terms to the relationship which determines speed vary enough numerically to be called significant. The two most important ones are design budget and design standard, both of which vary closely with speed. The third term, hydrodynamics efficiency, varies with ship size, and has less influence on speed, especially in the primary ships (of displacement between 200 and 800 tons).

5.1.2 FUEL AND STORES ENDURANCE

Fuel endurance is very important for large surface combatants, since their missions are of an extended nature. The emphasis on fuel range shifts, however, for smaller naval ships. Shorter missions, requiring less time and endurance, are typical. But it is desirable to complete the entire sortie at flank speed to minimize exposure to aircraft attack. Thus, high-speed range is important. Unfortunately, most range data is unavilable, or is classified. Therefore, the analysis must rely on unclassified figures and normalized estimates of range.

FIGURE 5.2

SPEED CHARACTERISTICS

Index	Units	FFG-7	CPIC	PG-84	PGG	PCG	PC-1	SPICA II	RESHEF
Displacement	Tons	3,782	72.5	242	390	797	1,109	229	424
Hull Type[1]	--	D	P	H/D	H/D	H/D	P	H	H
Plant	--	GT[2]	CODOG	CODOG	CODOG	CODOG	CODOG	GT	HSD[3]
Maximum Speed	KT	29	45	40+	38	30	45+	40.5	3.2
Lift/Drag[4]	--	~30	~7	~10	~10	~12	~10	~10	~12
Propulsive Coefficient[4]	--	.64	.45[5]	.60	.60[5]	.62[5]	.60[5]	.62[5]	.59[5]
(L/D)x(P.C.)	--	19	3	6	6	7	6	6	12
Main Propulsion Specific Weight	LB/HP	16.8	4.3	7.9	8.1	11.3	2.8	3.6	8.2
Main Propulsion Weight Fraction	%	8.0	15.9	19.4	18.6	12.6	11.7	9.0	11.6
Main Propulsion Ship Size Ratio	HP/Ton	10.6	82.8	54.3	51.2	25.1	94.7	56.3	31.8

[1] Hull Type: D-destroyer; P-planing; H-high speed displacement. [2] Gas Turbine

[3] High Speed Diesel. [4] At Maximum Speed [5] Estimate from References 7, 27.

Just as speed is affected by design standards, design budget and hydrodynamic efficience, range can also be thought of in these terms. The relationship by which they govern fuel endurance is:

$$R = \frac{(V)(PC)W_{FUEL}}{(SFC)(EHP)}$$

This expression can be rearranged to produce an equation which contains the three design-related quantities.

$$R = \frac{C_1(L/D)}{(SFC)}(WF/\Delta) \quad \text{(where } C_1 \text{ is a unit conversion)}$$

This is akin to the expression obtained for speed, in that it can be written as:

$$R = \frac{\text{(Design Budget)(Hydrodynamic Efficiency)}}{\text{(Design Efficiency)}}$$

With this relationship in mind, the table for this section has been constructed for a normalized range at 30 knots. This is done to see which ships can steam furthest on a high-speed mission. The CODOG ships would look better at a lower speed, where diesels could be used, but this is probably not a realistic scenario, unless the mission is offshore fisheries patrol. (However, such heavily-armed ships with a high speed would not normally be used for fishery patrol.)

The relative importance of the terms of the governing relationship can be found by an examination of Figure 5.3.

FIGURE 5.3

RANGE-RELATED PARAMETERS

	FFG-7	CPIC	PG-84	PGG	PCG	PC-1	SPICA II	RESHEF
Displacement (tons)	3,782	73	242	390	797	1,109	229	424
Plant	GT	CODOG	CODOG	CODOG	CODOG	CODOG	GT	DIESEL
L/D[1]	20+	~8	~10	~13	~9	~12	~9	~13
SFC[1] (LB/HP-HR)	.51	.6	.63	.63	.53	.63	.63	.40
WF/Δ[2]	16%	21%	15%	15%	14%	29%	14%	28%
Fuel End (NM)[1]	~2,000	~400	~500	~700	~900	~2,000	~800	1,500
Stores Eng (hr)	720[3]	60	336	336	336	216?	n.a.	240
Fuel End (hr)	67	13	17	23	30	67	27	50
Unrep ?	YES	NO	LIM	LIM	LIM	LIM	NO	LIM

[1] At 30 Knots (estimates)

[2] Estimate from tank drawings

[3] Chilled

5.1.2.1 Hydrodynamic Efficiency

As measured by lift to drag ratio at 30 knots, the hydrodynamic efficiency term varies up to 31% from the highest figure for the ships which fall in the displacement range of the study. The variation is even greater if the baseline ships (FFG-7, CPIC) are included. As mentioned in the previous section, displacement dominates this term, so large ships are aided by sheer size.

5.1.2.2 Design Efficiency

Fuel economy, measured by specific fuel consumption (SFC) has been calculated by using an approximation of both horsepower at 30 knots, and fuel weight. It is, therefore, a "soft" data point, but relative values are all that are needed for a comparison. The SFC figures in the table are high due to not taking into account the electric load.

Specific fuel consumption varies as much as 37% from the highest figure, so this term is slightly more significant than hydrodynamic efficiency. The diesel-powered ship (RESHEF) has a decided fuel efficiency advantage.

5.1.2.3 Design Budget

The gross allocation of resources (weight in this case) certainly applies to fuel endurance. If one desires to increase range, the simplest solution is to carry more fuel at the expense of other items. This method is apparently applied in several of the small combatants, since fuel weight fraction varies up to 50% from the highest figure. The most notable cases of this are RESHEF and PC-1, both of which have high ranges at 30 knots.

5.1.2.4 Stores Endurance

Stores endurance can limit the length of a ship's mission if much of that mission is inport. However, at sea, all of the ships run out of fuel well before the stores limit is reached. This is shown by the last few lines of the table in Figure 5.3. Some of the larger ships can replenish at sea and, thus, extend both fuel and stores endurance.

5.1.2.5 Conclusions

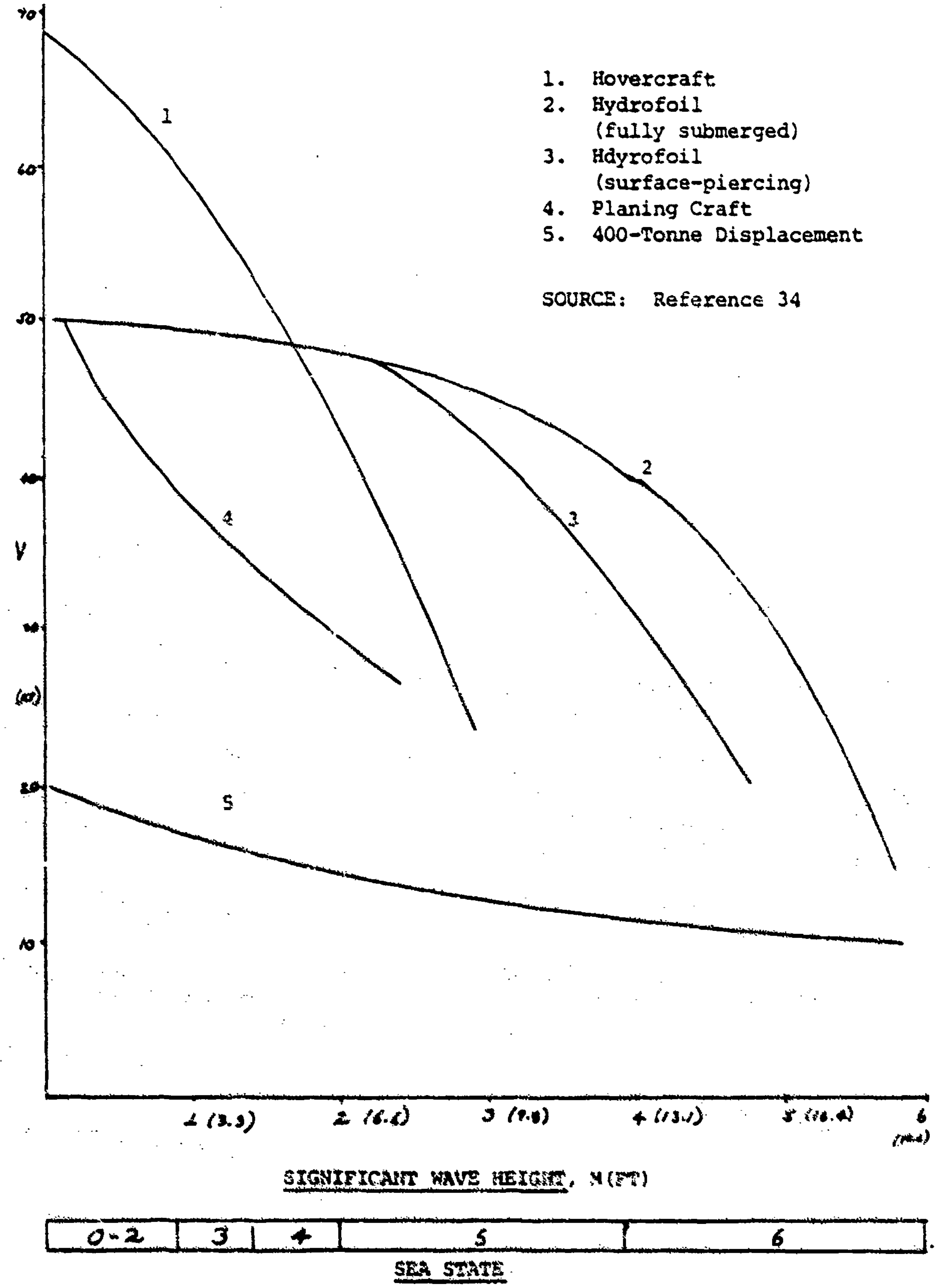
The results of this examination show that design budget of fuel weight is the most important method used to obtain longer range. Efficient design standards and hydrodynamic efficiency also play an important role, and are employed widely. Size has an inherent beneficial effect. Finally, it can be assumed that stores endurance does not normally limit ship operation, especially at high speed.

5.1.3 SEAKEEPING

Reduction of performance in heavy seas is a particularly distressing feature of conventional-hulled small combatant ships. As the curves in Figure 5.4, taken from reference 33, show, hydrofoils and surface-effect ships have a decided speed advantage over planing and displacement craft as sea state increases. This means that both weapon effectiveness

FIGURE 5.4

SPEED VS. WAVE HEIGHT



and ship speed suffer for conventional hulls.

Since performance is so swiftly curtailed for small ships as weather conditions worsen, a thorough investigation into this area is warranted. However, specific data is unavailable for all the ships. Therefore, one must proceed with a discussion of limiting factors in rough seas, and with a summary of desirable seakeeping traits.

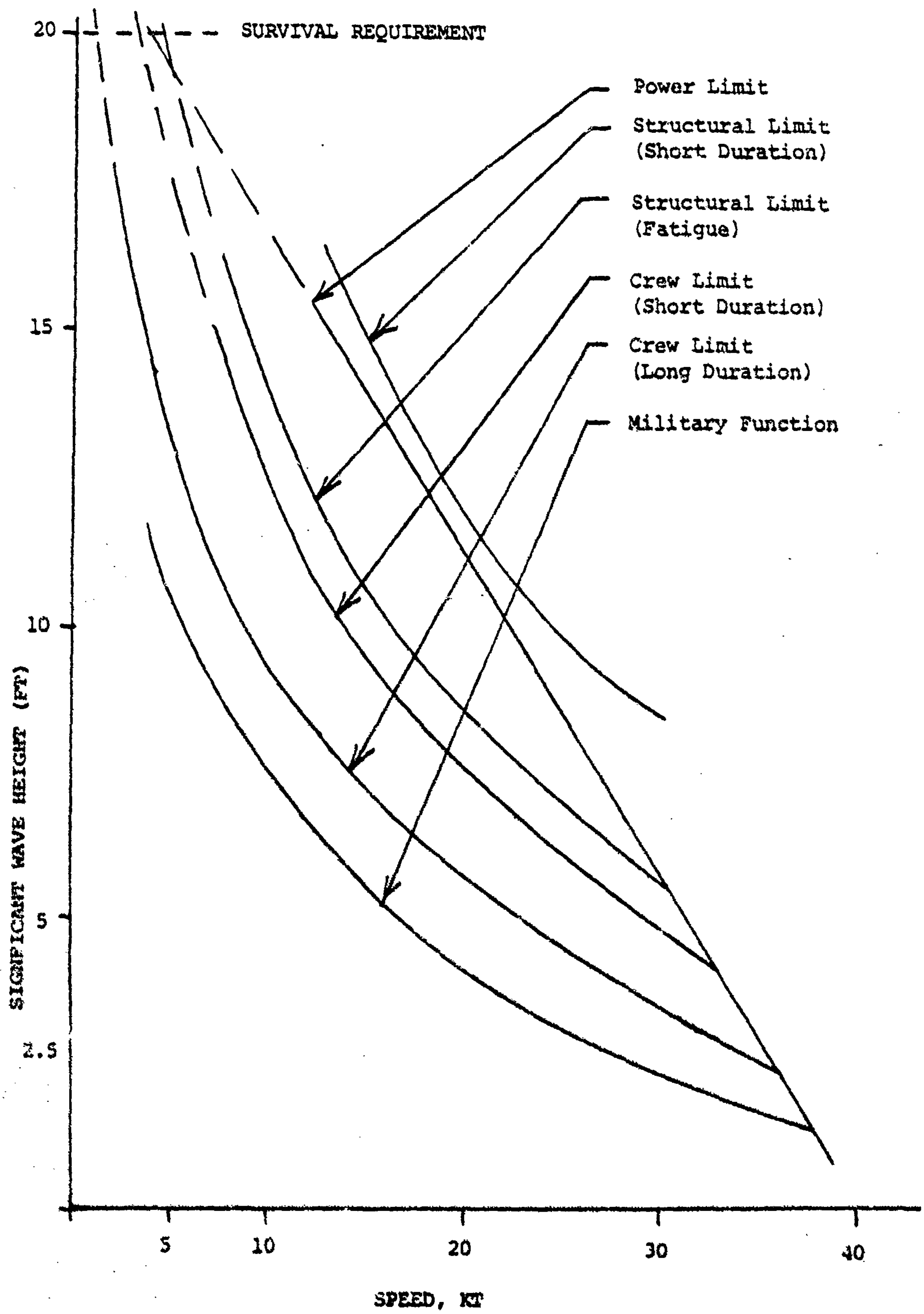
The limiting factors for rough weather are military performance, crew performance, structural load limit, and powering limit. A typical speed-wave height envelope (Figure 5.5) shows that military effectiveness is degraded first, then crew, then structural integrity. Therefore, in most cases, a ship will slow down before any platform-related problems occur. The problem is, then, to reduce acceleration (principally pitch and heave) in order to utilize the ship to its power or structural limit.

The desired characteristics for reducing motion in rough seas can be categorized by the phenomena which they are designed to counteract:

- deck wetness
- pitch and heave in head seas
- rolling
- broaching and directional instability in following seas

FIGURE 5.5

SPEED-WAVE HEIGHT ENVELOPE



5.1.3.1 Deck Wetness

Small ships have very wet decks. Efforts to combat this problem consist of increased freeboard and some method to throw spray outward rather than upward. Freeboard increase implies larger size, so it is not really explored, except possibly in PGG (see section 3.4). Instead, all of the non-planing ships use flare and spray chines. The planing hulls (PC-1, CPIC) use double hard chines, which reduce spray.

5.1.3.2 Pitch and Heave

These motions cause the greatest degradation of mission. Methods of countering them include: (1) slenderness ratio ($L/\sqrt[3]{\nabla}$) of 7 or more; (2) use of a deep vee forward to reduce slamming; and (3) carrying the vee aft to the transom to further reduce slamming and heave. The trade-off for high slenderness ratio is increased tendency to roll. The penalty for deep vee is a slight increase in resistance.

5.1.3.3 Rolling

Roll can often be corrected by changing course, but the design solutions are chines, vee, deep keels, and fin stabilization. The trade-off for any of these measures is increased resistance. For fin stabilizers, the payoff can be great, but it is at the cost of space, weight, resistance, and increased electrical load.

5.1.3.4 Broaching and Directional Instability

These are less serious motions than pitch and roll, in most cases. They can be improved upon with flare forward to stop diving, and through use of the same measures which counter roll.

5.1.3.5 Summary

The accompanying table (Figure 5.6) shows the design features of each ship which relate to seakeeping. All ships have an adequate slenderness ratio. The U.S. small non-planing ships use rounder hull forms and fin stabilization. The European ships use chines and deep vees with deep keel (RESHEF) instead. The large ships have the freeboard advantage. All the ships employ flare to reduce deck wetness. Ship size has an impact on seakeeping. The large ships can be considered to be better seagoing platforms. However, distinctions between ships in the nominal study range (200-800 tons) are difficult to make without detailed information.

5.1.4 PROPULSION SYSTEM DESIGN INTEGRATION

The efficient packaging and integration of the propulsion system is very important in small ship design. Any excess "budget" applied to propulsion severely impacts the weight, volume, and arrangement of the remainder of the ship. This is critical when space and weight are at such a premium.

The issues to be discussed under this topic are weight and volume impact, operability, and survivability. The purpose of the investigation is to discover the driving considerations, and to find out what can be considered good

FIGURE 5.6

SEAKEEPING PARAMETERS

SHIP	FFG-7	CPIC	PG-84	PGG	PCG	PC-1	SPICA II	RESHEF
$L/\sqrt[3]{\nabla}$	8.7	7.3	8.1	8.0	8.1	7.4	7.2	7.8
V Fwd	No	Yes	No	No	No	Yes	Yes	Yes
V Aft	No	Yes	No	No	No	Yes	No	No
Spray Chine	No	No	Partial	Partial	Partial	No	Yes	Yes
Flare	Small	Small	Yes	Yes	Yes	Small	Yes	Yes
Hard Chine	No	Yes	No	No	No	Yes	Semi	Semi
Deep Keel	No	No	No	No	No	No	Yes	No
Freeboard at Bow	30 FT	7 FT	13 FT	15 FT	18 FT	19 FT	11 FT	12 FT
Fin Stabilized	Yes[2]	Yes[2]	No	Yes	Yes	Yes[2]	No	No
Sea State[1]				4	4			

[1] Perform mission

[2] In design

practice in all four areas.

5.1.4.1 Volume Allocation

From Figure 5.7, it appears that SPICA II has the most compact arrangement, both in terms of main propulsion volume fraction and main propulsion specific volume, due to a very compact machinery arrangement. The other small ships use about 24% to 28% of volume for main propulsion. The small CODOG ships (PG-84, CPIC, PGG) obtain more power from this amount of space than does the diesel-powered RESHEF. Both PCG and FFG-7 have higher main propulsion specific volume than the other ships, due to requirements for uptakes, exhausts, and ease of maintenance in larger ships.

The principal conclusion to be reached with respect to volume usage is that most of the small combatants use about the same portion of total enclosed volume for the propulsion plant. However, those ships with gas turbines derive more power from the proportion of space.

Thus, they have lower main propulsion specific volume ratios than the diesel ship.

5.1.4.2 Weight Allocation

From the weight table (Figure 5.7), the dominating weight groups are prime mover (W_{230}), transmission (W_{240}), and support (W_{250}). This is no surprise, since little is left in group 200 after these "subgroups" are accounted for. It is interesting to note that the larger ships, and those with highly-rated gas turbines, use a very large portion of weight for the transmission system. This shows the need for reliability (FFG-7) or the need to handle high engine power (FFG-7, PGG, PCG, PC-1). These requirements generate heavier components to meet the increased load.

The main issue concerning weight is the degree of mobility which can be obtained for the weight allocation to main propulsion. Recalling the governing equation for group 200:

$$W_2/\Delta = (W_2/SHP)(SHP/\Delta)$$

group 200 weight fraction is driven by the capacity/ship size ratio and main propulsion specific weight ratio. Both of these quantities vary by as much as 100% so they each affect group 200 weight fraction. Recall, however, that in section 5.1.1, main propulsion weight fraction and propulsion ship-size ratio follow speed. That is, the fast ships require more HP/Ton. The efficiency with which this is done can be measured by the resultant W_2/Δ, through use of low W_2/SHP. The ships which obtain the most speed from the least weight are SPICA II and PC-1.

5.1.4.3 Operability

The ease of maintenance and operation can play a significant role in life-cycle cost, and is, therefore, worthy of examination. One basic measure of operability is to check the arrangements of the engineering spaces. The drawings

(Figure 5.8 through Figure 5.11) show that FFG-7 has a much greater space around basic components than all of the small ships. This accounts for FFG-7's high main propulsion specific volume. Among the smaller ships, PC-1, CPIC, and SPICA II are noticeably cramped, and would be hard ships to repair at sea. RESHEF and PCG have the most spacious enginerooms of the smaller ships.

The conflict between small, efficiently-arranged plants and operability represents an area where a trade-off must take place. Large, long-mission platforms require large machinery spaces for flexibility at sea; but the ships with high speed requirements must "pack" the engines into the smallest possible amount of space.

Arrangement of machinery is also a basic input to reliability. A compact arrangement and choice of prime movers may efficiently use space, but it may lack the redundancy to perform a mission under adverse conditions. Figure 5.7 shows that all of the plants have sufficient reliability for a 7-day mission at 16 knots, but that they vary at a high-speed mission. FFG-7 and PC-1 are most reliable at 30 knots. The differences in reliability for the remaining ships are due to arrangements, but also to choice of prime movers and configuration. For example, PG-84 suffers more reduction of reliability at 30 knots than PC-1, because it must use one reduction gear set. (The basis of these figures is the U.S. Navy RMA Handbook. The numbers are all artificially high because only major components are used: engine, clutch, reduction gear, shaft, bearings, and propellor. They are, therefore, not real world, and serve only as a comparison.)

5.1.4.4 Propulsion Plant Suvivability

The issue of suvivability can include many concepts. It can mean "take-home" ability, watertight integrity, or redundancy of machinery. A review of the machinery drawings shows that plants with the highest number of independent power trains (engine, gears, shaft) are most likely to survive a casualty. Thus, RESHEF, PC-1, CPIC, and SPICA II can be said to have the most "take-home" capability. FFG-7 with only one shaft, has poor redundancy of shafts, and actually has a small outboard engine installed to alleviate the deficiency.

FFG-7 has the best chance of surviving a hit, because of spread out arrangement and watertight bulkheads. The smaller ships all have poor survivability compared to FFG-7. Lack of safety features on these ships is de-emphasized, however, since one hit will sink any of them.

The benefits of redundancy on small ships, then, are derived from survival of material casualty or shipboard fire. Main engine redundancy is mentioned above, but generators are also an important consideration. Separation of generator sets is essential in order to carry on after an engineroom fire. Most of the ships do have generators in more than one space, and could survive a fire. CPIC does not, and would suffer accordingly. This might be expected of such a small platform.

5.1.4.5 Conclusions

To summarize design integration, it can be said that the requirement to put as much power into as small a space as possible runs counter to ease of maintenance, survivability, and ruggedness. FFG-7 is the best ship for operability, but it has no high speed requirement. The other ships reflect degraded operability due to requirement for horsepower. They show a de-emphasis in areas that imply long mission and reliability, in order to save space and weight.

5.2 Structure

Group 100 (hull structures) constitutes up to 37% of full load displacement. Since it is the largest single weight group, it is the logical target for weight-saving measures. If such measures must be undertaken, it should be without degrading the ability to withstand the loading conditions imposed by ship motion and seas.

In order to determine the major considerations for structure, the issues of loads, mission criteria, and construction practice must be addressed. The basic second-level breakdown of weight must also be discussed, to see which portions of structure take up the greatest amount of weight. Any possible economy of scale should be accounted for, and is identified for further treatment in section 6.1.

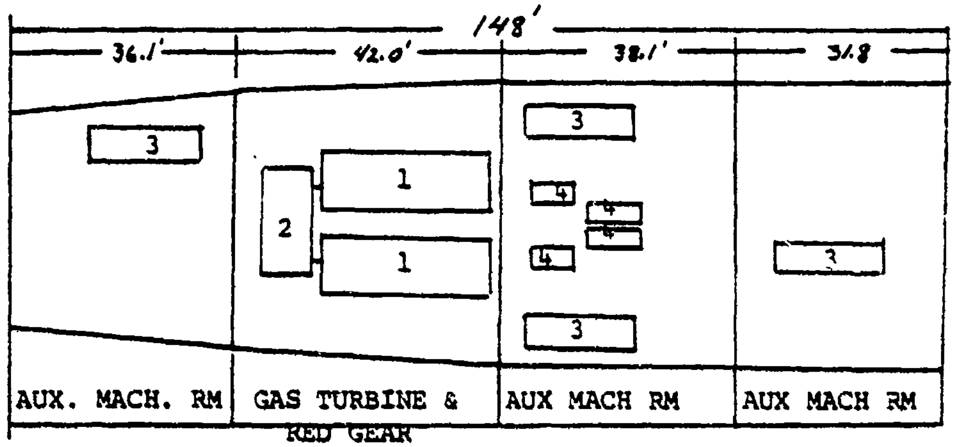
FIGURE 5.7

DESIGN INTEGRATION PARAMETERS

SHIP	FFG-7	CPIC	PG-84	PGG	PCG	PC-1	SPICA II	RESHEF
A. VOLUME								
$V_{3.2}/V$ (%)	20.3	26.8	24.4	24.4	30.3	25.7	19.1	28.8
$V_{3.2}/SHP_T$ (FT^3/HP)	2.7	.47	.7	.61	1.2	.50	.43	1.1
B. WEIGHT								
W_{230}/W_2 (%)	19.9	45.5	43.9	24.5	17.1	43.9	22.3	57.3
W_{240}/W_2 (%)	46.3	29.5	25.4	41.9	53.2	37.4	40.6	24.9
W_{250}/W_2 (%)	18.5	20.0	12.9	13.5	16.1	15.3	14.7	7.6
W_{OTHER}/W_2 (%)	15.3	5.0	17.8	20.1	13.6	3.4	22.4	10.2
W_2/Δ (%)	8.0	15.9	19.4	18.6	12.6	11.7	9.0	11.6
W_2/SHP_T (LB/HP)	16.8	4.1	7.1	7.2	10.0	2.7	3.6	8.2
SHP_T/Δ (HP/Ton)	10.6	87.9	61.0	78.4	28.7	97.9	56.3	31.8
C. RELIABILITY								
R(7) @ 16 KT	.9951	.9985	.9999	.9999	.9999	.9999	.9984	.9999
R(7) @ 30 KT	.0528	.6967	.8851	.8851	.8851	.9978	.6896	.8350

FIGURE 5.8

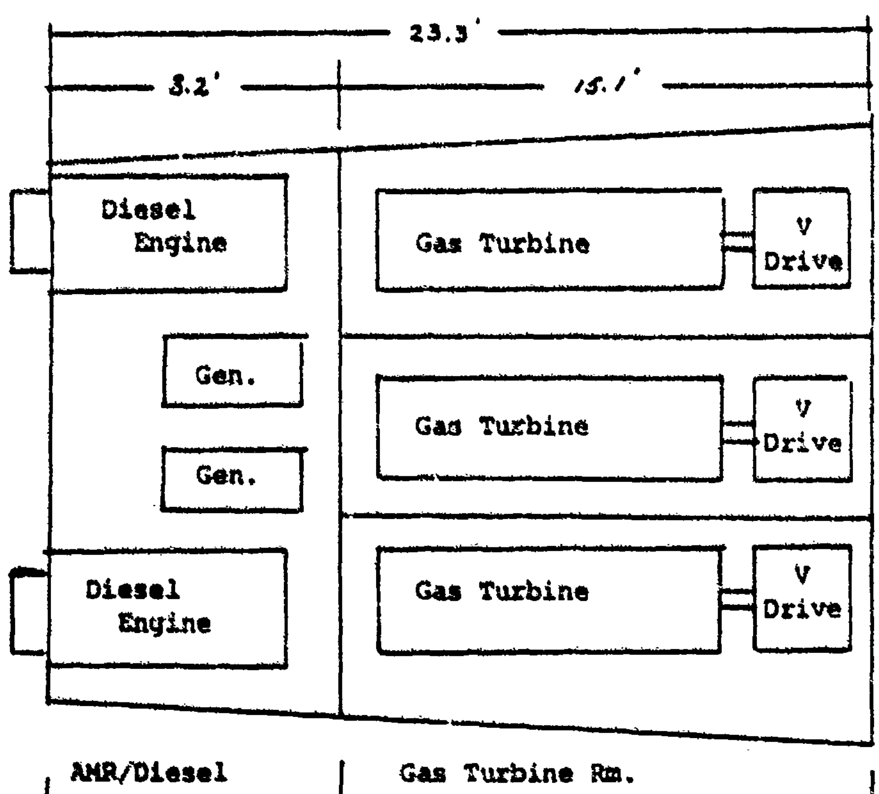
MACHINERY ARRANGEMENTS



1 - LM 2500; 2 - Reduction Gear; 3 - Diesel Gen. Set;

4 - A/C Plant

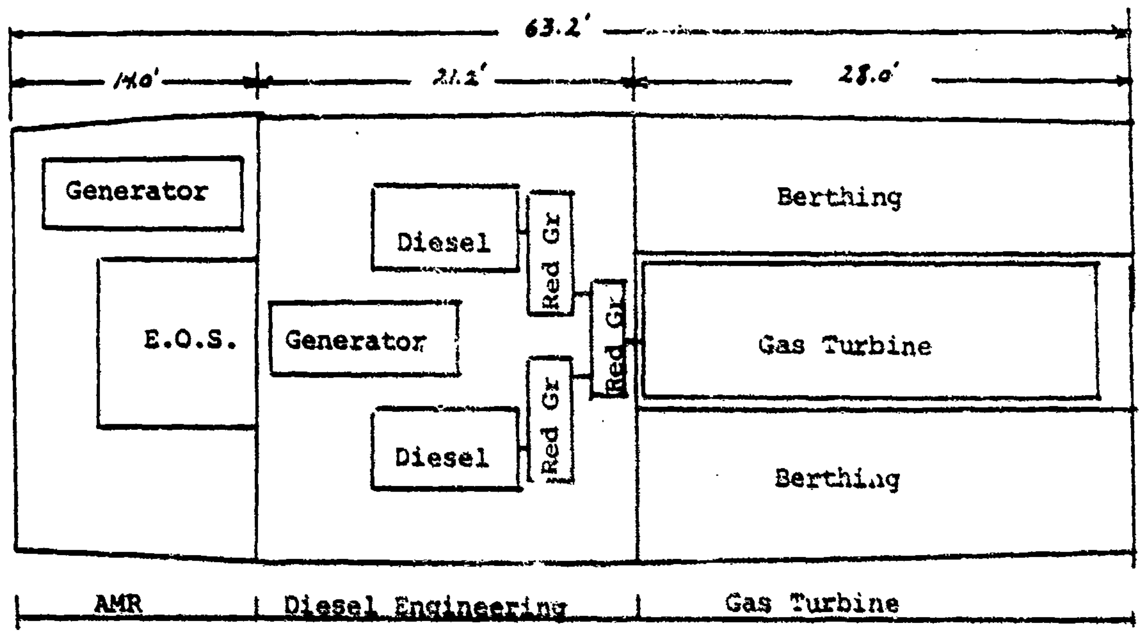
FFG-7



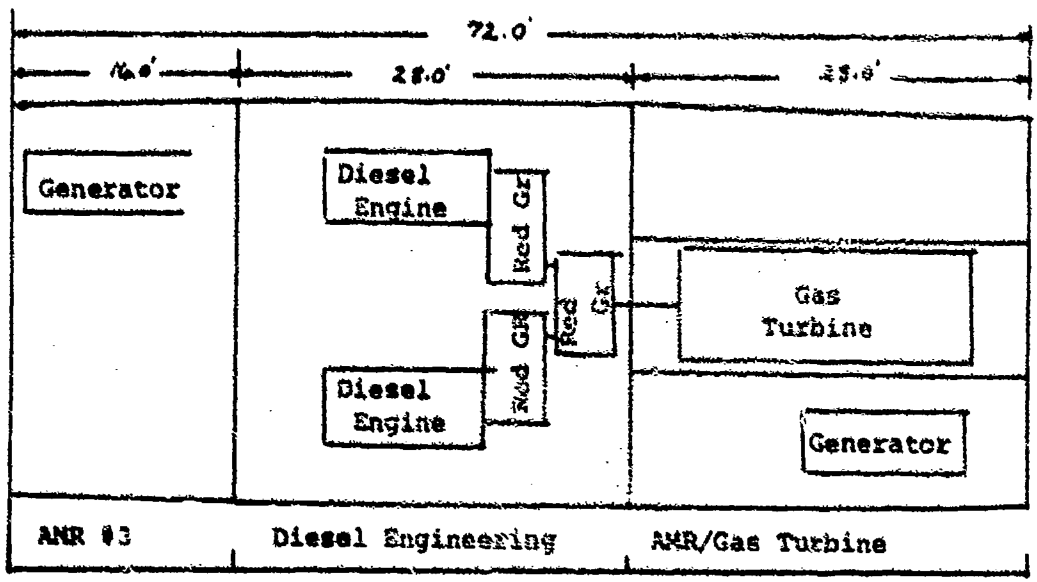
CPIC

FIGURE 5.9

MACHINERY ARRANGEMENTS



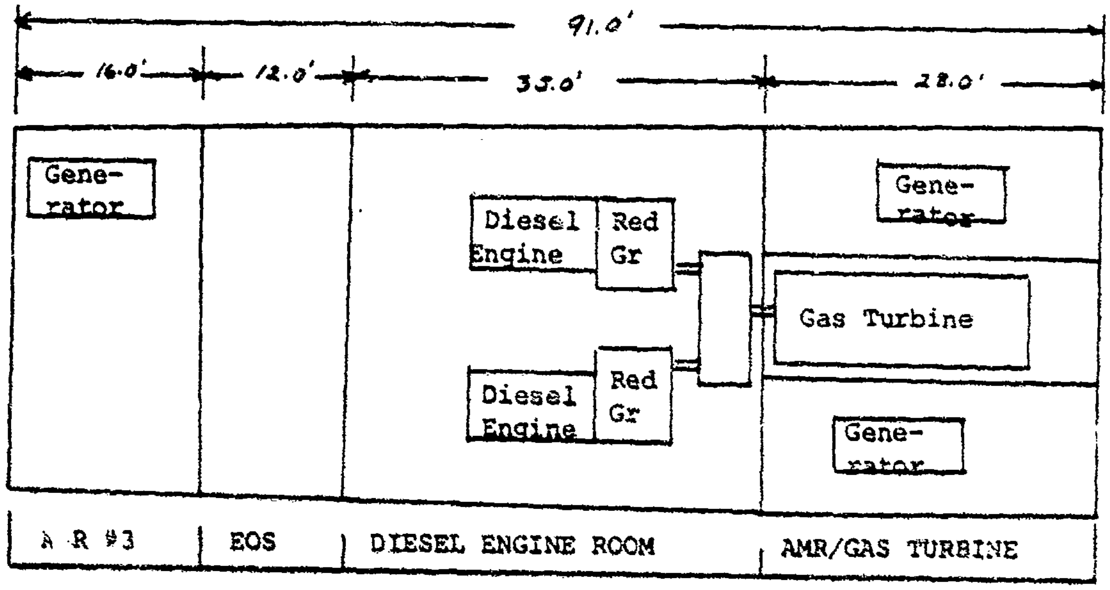
PG-84



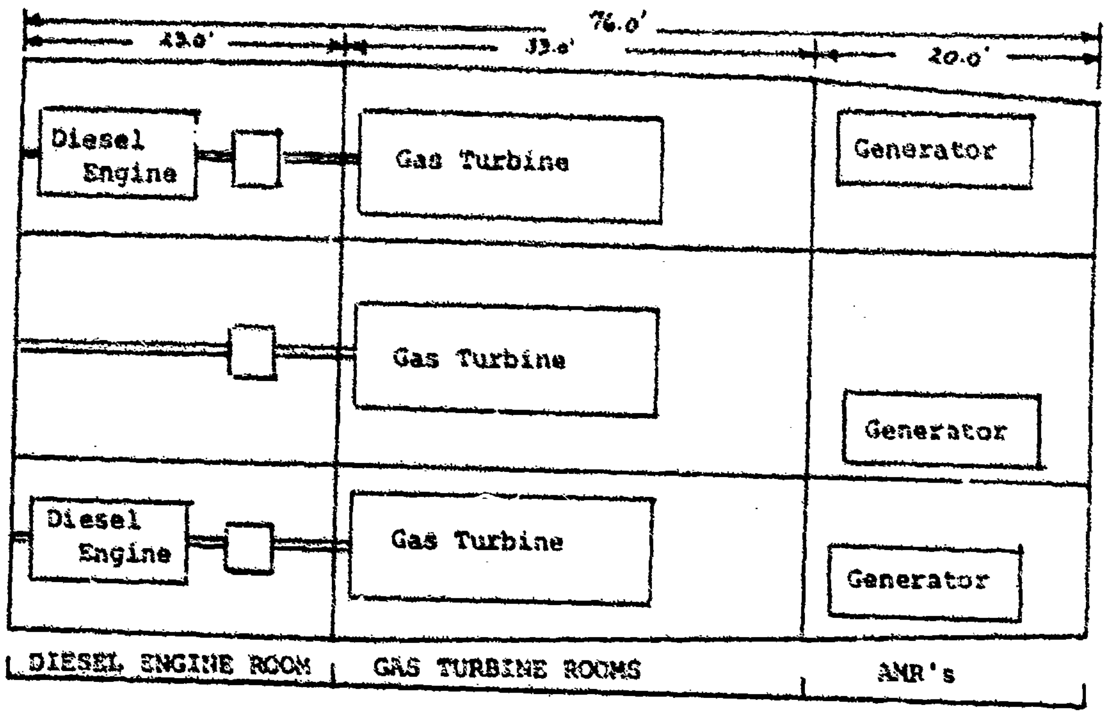
PGG

FIGURE 5.10

MACHINERY ARRANGEMENTS



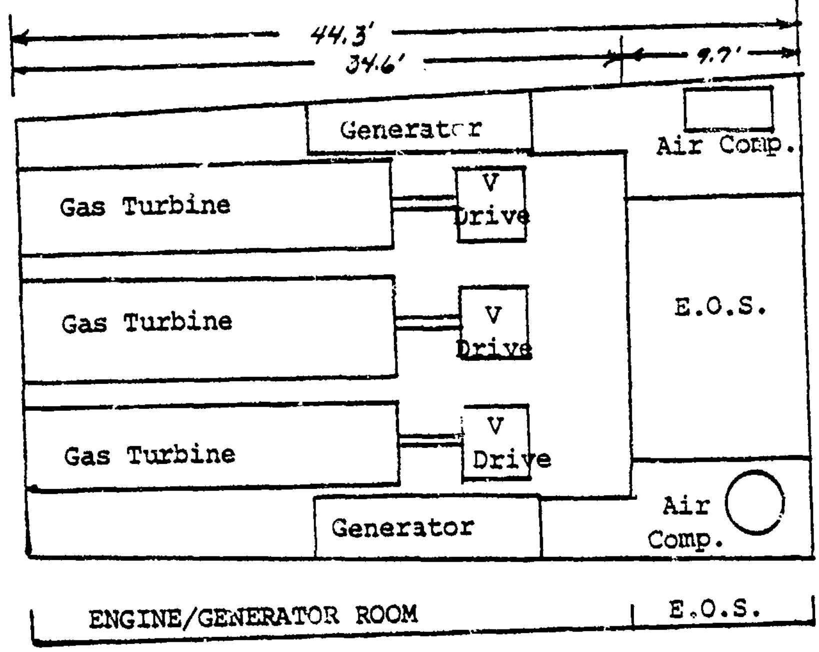
PC-2



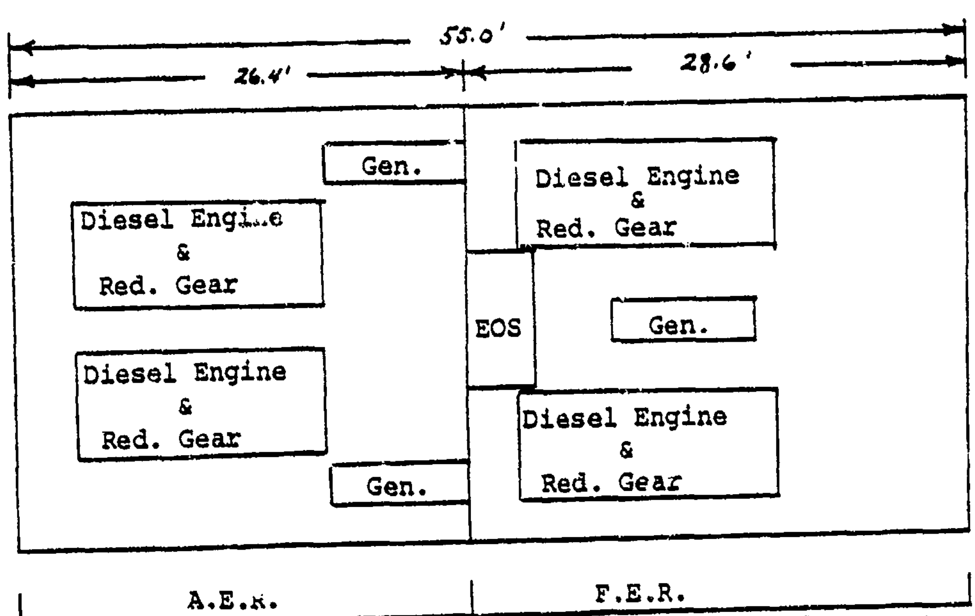
PC-1

FIGURE 5.11

MACHINERY ARRANGEMENTS



SPICA II



*Number of generators varies.

RESHEF

5.2.1 WEIGHT ANALYSIS

The governing relationship for group 100 weight fraction is $W_1/\Delta = (W_1/\nabla)(\Delta/\nabla)$. Thus, hull structure weight fraction is determined by structure specific weight and ship density. This relationship is not as meaningful as similar relationships for other weight fractions. The reason is that as ship density goes down, structure inherently becomes more efficient, so W_1/∇ also goes down. However, large differences in all three terms in the relationship exist, and, therefore, reflect a difference in design standards. As Figure 5.12 shows, the steel ships have the highest structure specific weight and the highest density, but structure specific weight is the more dominant term, therefore, it can be said that structure specific weight drives the relationship, as a result of material choice and design practice. The advantage of aluminum construction is evident, but the penalty paid for the weight savings is higher material and fabrication cost.

In addition to examination of the governing relationship, the components of group 100 should also be examined. The bar graph at the end of this section (Figure 5.13) shows that group 110, shell and frames, makes up the largest portion of group 100. When decks and bulkheads (groups 120 and 130) are added, most of group 100 is determined. This is important, because it shows that basic hull structure dominates weight, rather than deckhouses, foundations, etc. Thus, most of the effect of weight-saving measures to reduce W_1/∇ will be felt in groups 110, 120, and 130.

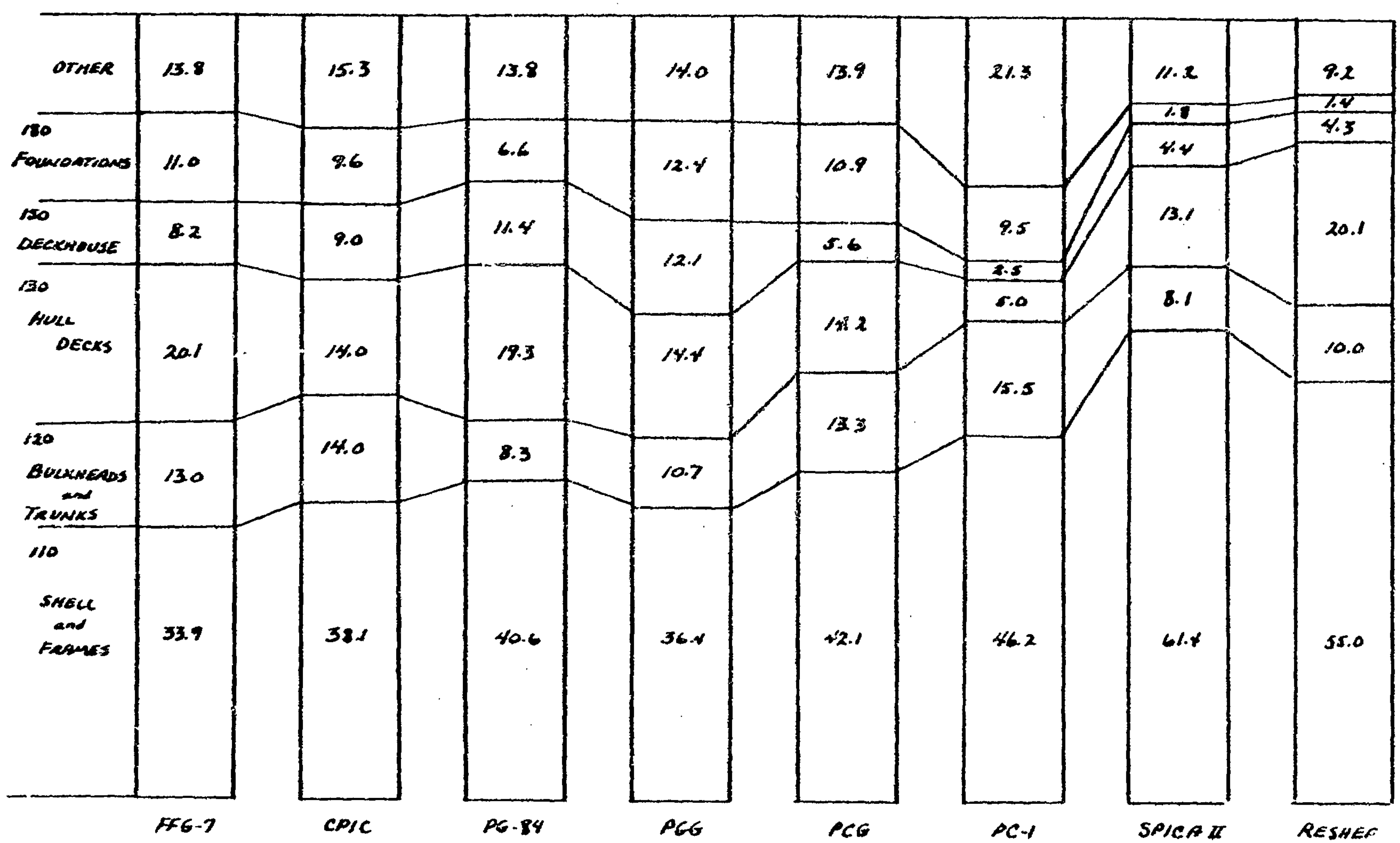
FIGURE 5.12

STRUCTURAL PARAMETERS

SHIP	FFG-7	CPIC	PG-84	PGG	PCG	PC-1	SPICA II	RESHEF
W_1/Δ_{FL} (%)	35.2	26.2	27.5	23.1	37.3	25.8	36.6	33.4
W_1/∇ (LB/FT^3)	5.6	3.6	3.4	2.7	5.7	2.9	6.4	6.1
Δ/∇ (LB/FT^3)	16.0	13.9	12.4	11.6	15.2	11.1	17.6	18.2
Hull	ST	AL	AL	AL	ST	AL	ST	ST

FIGURE 5.13 GROUP 100 WEIGHT

(Numbers Represent %)



The dominant portions of group 100 weight are now evident, but differences in weight allocated to these areas exist from ship to ship. These are now explored in further detail.

RESHEF and SPICA II have substantially higher shell and frame weight fractions than the other ships, including other steel-hulled ships. The probable cause is the use of more transverse frames, which increase the frame weight significantly. This is typical of European practice, and is a result of the hull form with deep V forward, which requires transverse frames for support. In addition, these two ships have deep floors in the aft part of the bottom; these further increase structural weight.

Group 120 (bulkheads and trunks) varies from 8% to 15% of group 100. There is a size trend, with the largest ships using the highest fraction for group 120. CPIC is also high, but this could be due to its very light shell.

Deckhouse weight fractions (W_{150}/W_1) vary with the size of the deckhouse. SPICA II and RESHEF have lower W_{150}/W_1 than the other ships because they have small deckhouses (section 3.4). PC-1 has similarly low W_{150}/W_1 from advances which should provide an ultra-light superstructure.

Foundation weight fraction (W_{150}/W_1) is very low on the European ships. This can be attributed to: (1) lower rated engines; (2) less ruggedness; (3) improper estimation; or (4) the deep floors on these ships taking much of the foundation load.

In summary, it has been established that groups 110 (shell and frames), 120 (bulkheads and trunks), and 130 (hull decks) appear to dominate group 100 weight. It is also apparent that structure specific weight (W_1/∇) is the most important design index governing the hull structure area.

5.2.2 DESIGN LOADS

Hull structure weight is heavily influenced by the design method. The loads for which structure must be designed vary with ship size and speed. A good representation of the design loads is given by Figure 5.14. This diagram shows that overall loads dominate for destroyer and frigate ships, but are less important for small ships. Instead, local pressures due to impact loading are dominant in small ship design. Several methods are used to design the structure of small ships. The general categories are listed below with short descriptions.

5.2.2.1 Destroyer Practice

The U.S. Navy has a standard system for structural design of destroyers. It is based on overall loads, with a provision for green seas on deck. The thrust of the method is to provide adequate section modulus to handle the hull girder load and bending moment. This moment is a hogging or sagging moment induced by a standard wave, usually $H=1.1\sqrt{L}$. The method also uses eight feet of sea on deck forward, decreasing to four feet aft. FFG-7, PG-84, PGG, and PCG are all designed to this method, or slight variations of it. They are

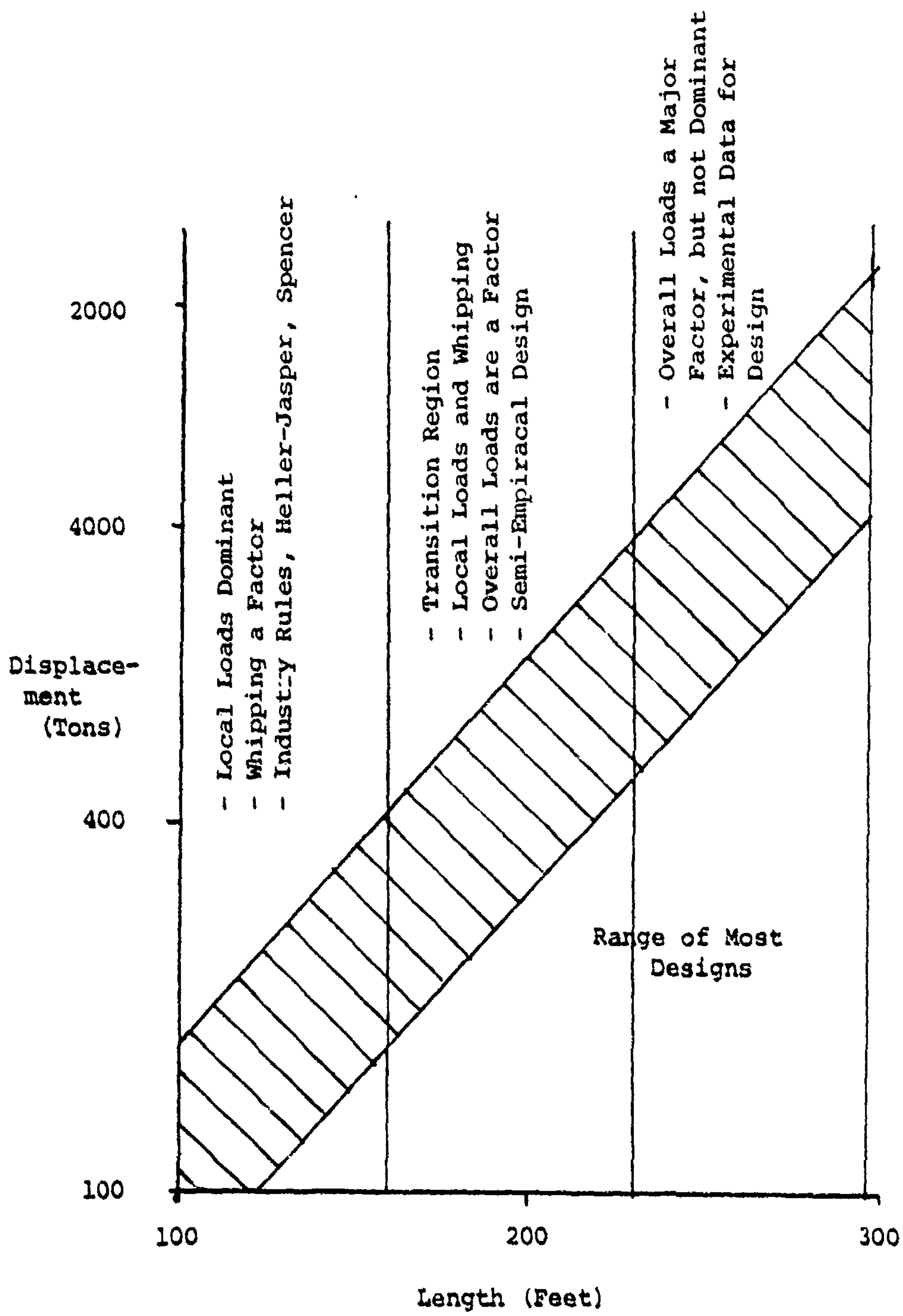


FIGURE 5.14

DOMINANT STRUCTURAL LOADS ACCORDING TO SHIP SIZE all longitudianlly-framed ships.

5.2.2.2 Semi-Empirical Methods

The increase in speed which makes local loads dominate renders the traditional method inadequate for structural design of small, fast warships. The semi-empirical methods come into play for higher-speed ships. The increased loads tend to increase structural weight, which is directly counter to the need to lighten the ship for high speed. Thus, the usual solution is to use aluminum to save weight while strength is increased. Fast ships which use steel are very heavily penalized in weight.

The most commonly used methods are Spencer, Heller-Jasper, and Jones-Allen. These methods all provide local pressures for which scantlings can be chosen. Basically, they allow a higher confidence factor, which enables the designer to safely reduce weight.

Many ships are designed by using a combination of traditional and semi-empirical methods. RESHEF and SPICA II probably fall into this category. PC-1 and CPIC are almost exclusively designed by semi-empirical formulas.

5.2.3 EFFECT OF SPEED

As implied in the previous section, the effect of increasing speed is twofold. It increases local loads, but also requires a large propulsion plant. Thus, there are conflicting requirements for increased structural strength and reduced structural weight. The U.S. designs resolve this conflict by use of aluminum. The European ships use a heavy steel hull structure, and suffer the penalty of increased weight.

Speed is a mission requirement which impacts areas beside structures. Extensive discussion of its effect can be found in section 6.3. Of particular interest is the trend to lower group 100 weight fraction with increased speed, and the apparent trade-off between groups 100 and 200 for speed.

5.2.4 CONSTRUCTION PRACTICE

Investigation of loads, component weights, and mission impact is valuable, but the most important discussion of structure is on the gross level. That is, concern must be directed toward how much structure weight must be used to enclose a unit volume.

Aside from group 100 weight fractions, the most practical measure of structural efficiency is structure specific weight (W_1/∇). This can be taken overall or with hull and deckhouse separately. The table on the following page (Figure 5.15) lists the important major parameters for structure.

The table shows that the steel ships suffer a large penalty in specific weights as well as weight fractions. This applies to overall structure specific weight as well as to basic hull structure specific weight. Superstructure specific weight is less clear, since all ships except SPICA II use aluminum for the deckhouse.

FIGURE 5.15

MAJOR STRUCTURAL QUANTITIES

SHIP	FFG-7	CPIC	PG-84	PGG	PCG	PC-1	SPICA II	RESHEF
W_1/Δ (%)	35.2	26.2	27.5	23.1	37.3	35.8	36.6	33.4
W_1/∇ (LB/FT^3)	5.62	3.63	3.42	2.67	5.67	2.86	6.45	6.07
W_{HULL}/∇_{HULL} (LB/FT^3)	5.6	3.0	2.9	2.6	5.6	3.2	6.5	6.5
W_{SUP}/∇_{SUP} (LB/FT^3)	3.1	1.9	1.8	1.0	1.3	0.3	2.1	2.0
W_{FOUND}/W_{2-7}	8.6	5.8	3.7	4.9	8.4	7.6	1.7	1.5
Hull	ST	AL	AL	AL	ST	AL	ST	ST
Deckhouse	AL	AL	AL/FRP	AL	AL	AL	ST	AL

The graphs at the end of this section show basic hull, superstructure, and overall structure specific weight. For basic hull and overall structure specific weight, the saving from aluminum is verified. There also appears to be economy of scale ot a slight degree. The superstructure specific weight shows an economy of scale with increasing volume for the small ships, but FFG-7 is way off the high side of the curve. This could be due to FFG-7's huge superstructure, or to a basic configuration change from small to large ship types. (Figure 5.16)

Foundation specific weight also increases with size. This can be expected, since the larger ships carry more equipment, and must be more rugged. The European designs have lower figures than the other ships probably due to the extra floors aft mentioned earlier in this chapter.

The basic conclusions to be reached from this analysis are:

1. Aluminum helps save weight considerably, at the cost of higher price.
2. Economy of scale is present with respect to increasing volume for W_1/∇, WH/∇_H, W_{SUP}/∇_{SUP}.
3. Foundation specific weight increases with displacement.

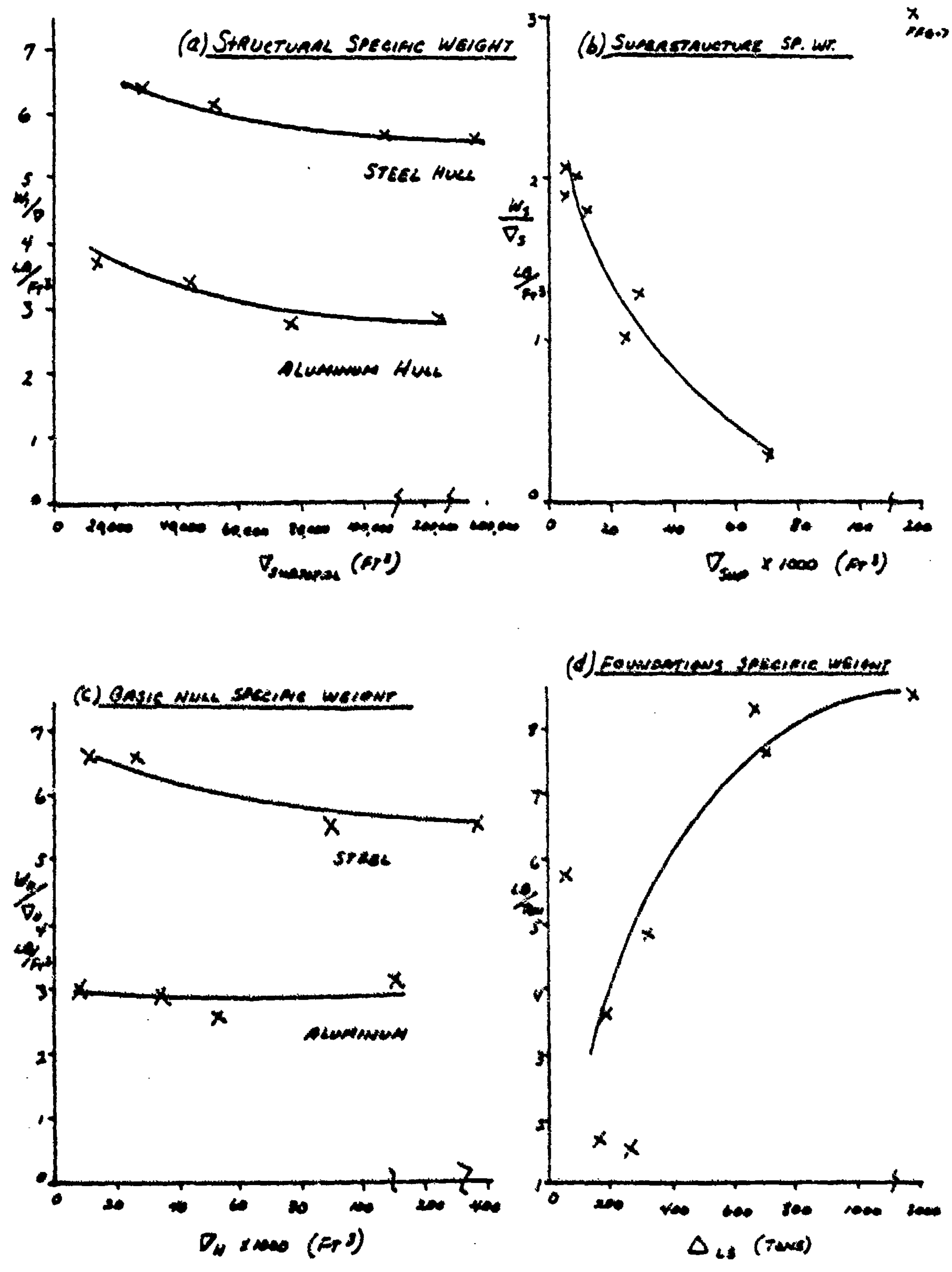


FIGURE 5.16 SIZE TRENDS FOR HULL STRUCTURE

5.3 Electric Power

Electric power weight fraction varies from 3% to 6% of full-load displacement. To find what influences this fraction, recall that $W_3/\Delta = (W_3/KW)(KW/\Delta)$. This shows that design standards (W_3/KW) or mission requirement for a performance standard (KW/Δ) impact the weight usage for power.

The table for electrical indices (Figure 5.17) shows that KW/Δ does not vary more than about 20%, except for PGG, which has an extraordinary amount of auxiliary loads plus a margin. Also evident is an age trend to this index (see section 6.4). That is, the new ships have increased electric loads from electronics and habitability items.

Electric power specific weight (W_3/KW) varies more than KW/Δ, and is thus the bigger driver. It is evident that FFG-7 and PCG have more rugged plants, as befit their longer missions. This is evidenced by their high W_3/KW (compared to the other ships). CPIC is similarly high, but this is probably due to the inefficiency of small generator set installations, rather than any ruggedness requirement. RESHEF and SPICA II both have efficient use of weight for electric power, but may lack reliability as a result. PG-84 has an above average W_3/KW for the small ships. This can be attributed to the lack of high-performance design standards in its electric plant.

From the above discussion, it can be inferred that both electric power specific weight (W_3/KW) and electric power ship

FIGURE 5.17

ELECTRIC POWER

SHIP	FPG-7	CPIC	PG-84	PGG	PCG	PC-1	SPICA II	RESHEF
Generators (KW)	4x100	2x30	2x100	2x350	3x300	3x500	2x120	4x110
Prime Mover[1]	D	D	D	D	D	D	G	D
W_3/Δ (%)	5.4	6.6	3.6	4.8	4.4	3.4	2.9	2.8
W_3/KW (LB/KW)	115.2	178.8	97.4	64.7	86.4	64.5	62.5	60.6
KW/Δ (KW/Ton)	1.06	.83	.827	2.41	1.13	1.35	1.05	1.04

[1] D - Diesel; G - Gas Turbine

size ratio (KW/Δ) vary enough to be influential in determination of electrical weight fraction. Electronics and habitability loads are steadily driving up KW/Δ, while high performance technology is helping to reduce W_3/KW.

5.4 Auxiliaries and Outfit

Weight groups 500 and 600 are not usually emphasized on small combatants due to the short nature of their mission. However, there is a large variance in W_5+W_6/Δ of 23% in PGG to 8% in RESHEF. This difference should be explained.

Auxiliaries and outfit functional areas encompass a vast array of systems, most of which grow with ship displacement or volume. Cassedy discusses size trends for group 500, but the differences observed among small combatants do not follow such trends. Instead almost each ship has unique reasons for allocation of weight and volume to these areas.

The table in Figure 5.18 shows that, although no components dominate group 500, the three largest are climate control, steering, and deck auxiliaries. Most of the remaining systems grow slowly with size. Reflecting the correlation mentioned by Cassedy. The table also includes other indicators of the degree of emphasis on auxiliaries. These are quantities such as electric power, ship density, and auxiliaries volume fraction.

No one factor dominates the auxiliaries area. It is best, therefore, to discuss the design problem on a ship-by-ship basis.

FIGURE 5.18

AUXILIARIES

SHIP	FFG-7	CPIC	PG-84	PGG	PCG	PC-1	SPICA II	RESHEF
W_5+W_6/Δ (%)	22.5	10.7	18.5	23.2	19.7	12.0	16.9	8.2
W_5+W_6/Δ (LB/FT^3)	3.5	1.5	2.3	2.7	3.0	1.3	2.5	1.5
$V_{3.3}/V$ (%)	5.9	10.6	9.2	19.9	8.0	8.8	12.0	5.7
Δ/V (LB/FT^3)	16.0	13.9	12.4	11.6	15.2	11.1	17.6	18.2
# AMR's	3	0	1	3	3	3	0	0
# GEN (KW)	4x1000	2x30	2x100	2x350	3x300	3x500	2x120	4x110
V_2/M (FT^3/Man)	571.3	228.9	504.4	462.5	472.5	715.3	290.6	241.3
$W_{Climate\ Control}/W_5$	11.6	6.2	12.6	11.1	8.5	2.9	13.0	19.1
$W_{Steering}/W_5$ *	14.4	30.6	5.2	16.6	18.1	6.2	21.7	14.2
$W_{Deck\ Aux}/W_5$	12.3	8.3	18.3	10.8	16.8	19.5	8.1	2.8
W_{Other}/W_5	52.1	53.0	53.2	53.2	48.9	67.0	46.0	50.6

* Not including roll fins

5.3.1 FFG-7

FFG-7 is large, and has a long mission; it needs the support functions which are included under groups 500 and 600. It has a high electrical load compared to the other ships and large air conditioning loads. It has a low auxiliaries volume fraction for two reasons: (1) its AMR's are much smaller in proportion to ship volume than those of the small ships; and (2) many of its systems are spread around the ship in spaces where volume cannot directly be assigned to group 3.3.

5.4.2 CPIC

CPIC is an austere ship with no extensive living support. It can sacrifice many auxiliary systems due to its short mission. Therefore, its generators are small, habitability low, and W_5+W_6/Δ is low. The auxiliaries volume fraction for this ship is average, but $\nabla_{3.3}/\nabla$ has already been shown above to be an unreliable index. Steering takes a large portion of weight due to use of outdrives for cruising.

5.4.3 PG-84

PG-84 has higher habitability standards than most of the ships. As demonstrated by its high personnel volume specific ratio. This, plus a lack of attention to reducing outfit weight gives the ship an above average W_5+W_6/Δ. Steering weight fraction is lower than the other ships, but this could be due to a difference in weight classification systems in raw data. PG-84 also has a high deck auxiliary weight fraction. This is due to older technology, and lack of need to reduce weight of winches, etc.

5.4.4 PGG

PGG, with updated design and habitability, uses high amounts of both weight and volume for auxiliaries. This ship has a great deal of climate control and support spaces, and also employs fin stabilization. The penalties in weight and space are thus understandable.

5.4.5 PCG

PCG is an expanded version of PGG, with the same habitability standards. Some economy of scale drives the weight and volume allocations down from those of the smaller ship.

5.4.6 PC-1

PC-1 shows technological advances in support areas, and thus uses small amounts of space and weight compared to the other ships.

5.4.7 SPICA II

SPICA II is about average for most quantities. No special attributes appear to drive this design.

5.4.8 RESHEF

RESHEF shows a trade-off of groups 500 and 600 for weight in other groups. The ship is spartan with regard to support functions. It does, however, have a high climate control weight fraction. This is for electronics, and also appears to be one of the few concessions to crew comfort.

5.5 Personnel

A ship's crew requires a certain basic level of support in order to perform. The level of that support depends on crew size, mission length, and the habitability standard of the country for which the ship is built.

As the table (Figure 5.19) shows, weight of systems dedicated to personnel is small compared to ship weight (low personnel weight fraction). However, the living spaces can take up to 32% of the available volume. A review of the table shows that a greater percentage of space and weight is allotted to living for ships with high Man/Δ (SPICA II). There is some economy of scale evident in volume use. This is related to the economy of scale for manning (see section 6.2). That is, as ship size increases, fewer men per ton of ship are needed to operate the ship. Therefore, M/Δ and ∇_2/∇ goes down.

The most important characteristic of the personnel area is the habitability standard. The measures of this standard are personnel volume specific ratio (∇_2/M) and the personnel weight specific ratios (living and support). Once crew size is chosen, the amount of space and weight allocated to each man impacts the design. There is a definite trend by nation for "spending" these commodities on personnel. The U.S. uses

FIGURE 5.19

PERSONNEL

SHIP	FFG-7	CPIC	PG-84	PGG	PCG	PC-1	SPICA II	RESHEF
Crew OFF/CPO/EN	17/15/153	1/2/8	4/20	4/28	5/53	7/5/63	8/6/18	5/39
Stores (D)	90/60/30[1]	2.5	14.0	14.0	14.0	NA	NA	10.0
Manning/Ship Size Ratio (M/Ton)	.049	.152	.099	.110	.073	.068	.140	.100
Personnel Weight Fraction (%)	0.6	1.8	1.2	0.9	0.8	0.8	1.9	1.1
Personnel Volume Fraction (%)	19.9	22.6	28.0	19.6	23.3	25.5	31.9	20.3
Personnel Living Space Weight (LB/M)	[illegible]5.5	515.4	708.0	728.7	700.2	667.8	525.6	221.5
Personnel Support Specific Weight (LB/M)	960.3	20.9	179.0	284.0	153.1	245.2	87.5	38.2
Personnel Volume Specific Ratio (FT^3/M)	571.3	228.9	504.4	462.5	472.5	715.3	290.6	241.3

NA = Not Available

[1] Dry/Frozen/Chilled

a high habitability standard and thus dedicates much higher portions of volume and weight per man. The result of this high habitability standard is a high volume usage. In direct contrast, the European ships trade off habitability to make room for mission-oriented items. RESHEF is the most austere ship (excepting CPIC which has a very short mission) of the study. SPICA II is similar to RESHEF. (SPICA II's large ∇_2/∇ is due to a high manning ship size ratio - habitability is still reduced in this ship.)

The conclusions to be reached are: (1) that habitability can be traded off for performance items; (2) economy of scale exists for manning and for items related to manning; and (3) national preference has a large impact on space and weight dedicated to the ship's crew.

5.6 Other Areas

With the major areas of mobility, structures, auxiliaries, electric power, and personnel covered, the residual design indices are now addressed. These are lumped into two categories: payload and ship operations.

5.6.1 PAYLOAD (FIGURE 5.20A)

Payload weight and volume fractions are significant, because they show how much of the ship is actually dedicated to mission area. The other launcher-related indices are subject to interpretation and are, therefore, less significant. The table shows that FFG-7 and PCG have lower than average payload weight fractions. This can be attributed partly to a reverse economy of scale, and partly due to use of less dense systems on larger ships, particularly on FFG-7. This ship uses a much more significant portion of volume than weight for its payload. Note that helicopter facilities heavily impact this ship.

The most "successful" of the small ships for getting payload onboard are RESHEF and SPICA II, which both have large proportions of weight and volume dedicated to weapons. CPIC and PC-1 also have this attribute, but both are really outside of the basic displacement range. They must, however, be considered to be successful since much of the effort in their design has been to enhance payload capability.

Although launcher-related indices are of questionable value, they do indicate a trend with size that is, as ship size increases, so does launcher size. Launcher numbers decrease with increasing ship size. These effects are discussed in section 6.2.

5.6.2 SHIP OPERATIONS (FIGURE 5.20 B)

Ship operations indices generally follow trends already mentioned in discussion of related areas. The two most significant indicators, ship operations weight and volume fractions, underscore the priority placed on support functions by the American designs. The U.S. ships all have higher proportions of weight and volume dedicated to these support-oriented functions.

FIGURE 5.20

OTHER INDICES

SHIP	FFG-7	CPIC	PC-84	PGG	PCG	PC-1	SPICA II	RESHEF
A. PAYLOAD								
Payload Weight Fraction (%)	9.6	16.2	12.2	10.8	8.9	13.4	14.4	12.4
V_1/V (%)	20.0	15.6	14.0	16.2	14.4	20.2	17.4	20.6
$\frac{W_4+W_7+W_{AMMO}}{V_1}$ (LB/FT^3)	7.6	15.2	10.8	7.7	9.3	7.7	9.7	10.9
W_7/NA (LB/Launcher)	14.2	.9	3.3	2.3	2.1	2.9	9.8	.8
NA/Δ (Launcher/Ton)	.002	.083	.017	.020	.013	.007	.048	.019
B. SHIP OPERATIONS								
Ship Operations Density (LB/FT^3)	8.87	7.49	8.22	7.86	8.33	5.39	9.07	6.59
Ship Operations Sp. Ratio (LB/FT^3)	3.62	1.49	2.30	2.69	3.00	1.33	2.98	1.49
Ship Operations WT Fraction (%)	44.3	31.7	38.5	43.5	34.1	24.8	26.1	21.4
Ship Operations Vol. Fraction (%)	26.4	19.6	24.0	27.2	19.8	15.5	20.1	10.5

5.7 Chapter V - Conclusions

This chapter has identified and explored the differences exhibited by various ships in each of the following areas: mobility, structure, electric power, auxiliaries and outfit, personnel, payload, and ship operation. The reasons for each major deviation from the norm have been outlined, so that one can understand what motivation the designer has for making his decision.

Several things in this chapter stand out for further discussion. The magnitude of the impact of speed and range requirements bears further discussion. Weight savings from aluminum, and structural design method also need to be evaluated for cost-effectiveness. Several of the areas exhibit trends which follow size or nationality.

Although each particular ship has been examined in this chapter, overall observations such as those above still need explanation. Thus, general trends or tendencies must be discussed. Chapter VI takes up these general issues by investigating those observations which appear time and again in the analysis of individual ships or design features.

CHAPTER VI

TRENDS AND ANALYSIS

Examination of the data presented in Chapters III, IV, and V suggests that major trends are present for many aspects of small combatant design. In this chapter, an attempt is made to present the data in a format which enables these trends to be identified and analyzed. When undertaking such a task, it is important to realize that the results will not be completely consistent. That is, conclusions must be drawn from graphs which have a good deal of scatter. The reason for this lack of completely definitive trends is that there are many factors which drive any one area of ship design. Mission-oriented performance requirements, nationality, economies of scale, etc., - each have an influence in design decisions. Emphasis on any one of these can lead to its dominating other aspects of the problem. Thus, much of the work in interpretation of the information is to distinguish a trend among data points which are influenced by many variables other than those which are plotted on a particular graph.

With the above problem in mind, Chapter VI proceeds with discussions of mission impact, size trends, design lanes, time-influenced design traits, and nationalistic preference.

6.1 Mission Impact

For small combatants, as for most ships, the ship mission and plan for use have extensive impact on design decisions. For small ships, however, there are some unique considerations. The mission of these ships is typically performed at high speed, over a short period of time. Since they carry no armor, and have scant ASW or AAW defense, minimum exposure time is a premier consideration. This forces speed to be the principal driving factor in most cases. Range at flank speed also receives high priority for similar reasons. This increases fuel weight. Finally, payload is the last driving factor. As cannister-type missile launchers become available, the topside deck arrangement has become a prime design requirement, since surface-to-surface missiles are a small combatant's primary weapon.

With speed, range at high speed, and payload being the three most important factors, sacrifices must be made elsewhere. The U.S. accomplishes weight reduction by use of aluminum to cut down structural weight. The solution for the Europeans is to reduce groups 300 (electrical), 500 (auxiliaries), and 600 (outfit), resulting in a mission-oriented platform with poor habitability.

The plan for use directly affects these trade-offs. The European countries, with restricted operating areas and a shore-supported maintenance philosophy, can afford to sacrifice those areas which enhance maintainability and mission endurance. They cannot afford aluminum construction as a solution due to its high cost and to lack of experience with aluminum fabrication. Thus, the habitability and operability items are sacrificed.

On the other hand, the U.S. has many aluminum boat builders. It maintains high habitability standards as a requirement, and can afford aluminum, so structural weight is where the sacrifice is made.

Advantages and disadvantages of the two approaches are hard to argue. They are scenario-dependent, and also are not completely separate. It should suffice to acknowledge that a sacrifice must be made somewhere, and to move on to the next point. That is, the relative importance of speed, range, and payload. It seems logical to assume that if any of these items is emphasized, the others must be reduced. In order to find out if this is true, the three are graphically compared as follows:

1. Range vs. V_{MAX} (Figure 6.1A)
2. Payload weight fraction vs. speed (Figure 6.1B)
3. Payload weight fraction vs. range (Figure 6.1C)

6.1.1 OVERALL RELATIONSHIPS

The absolute impact of speed, range, and payload is discussed (Chapter V), but is worth mentioning. A speed increase drives up group 2 weight and indirectly drives down group 1 weight. Range drives up fuel weight. Payload has little effect except on deck space, and increasing overall ship size to support new, larger launch systems.

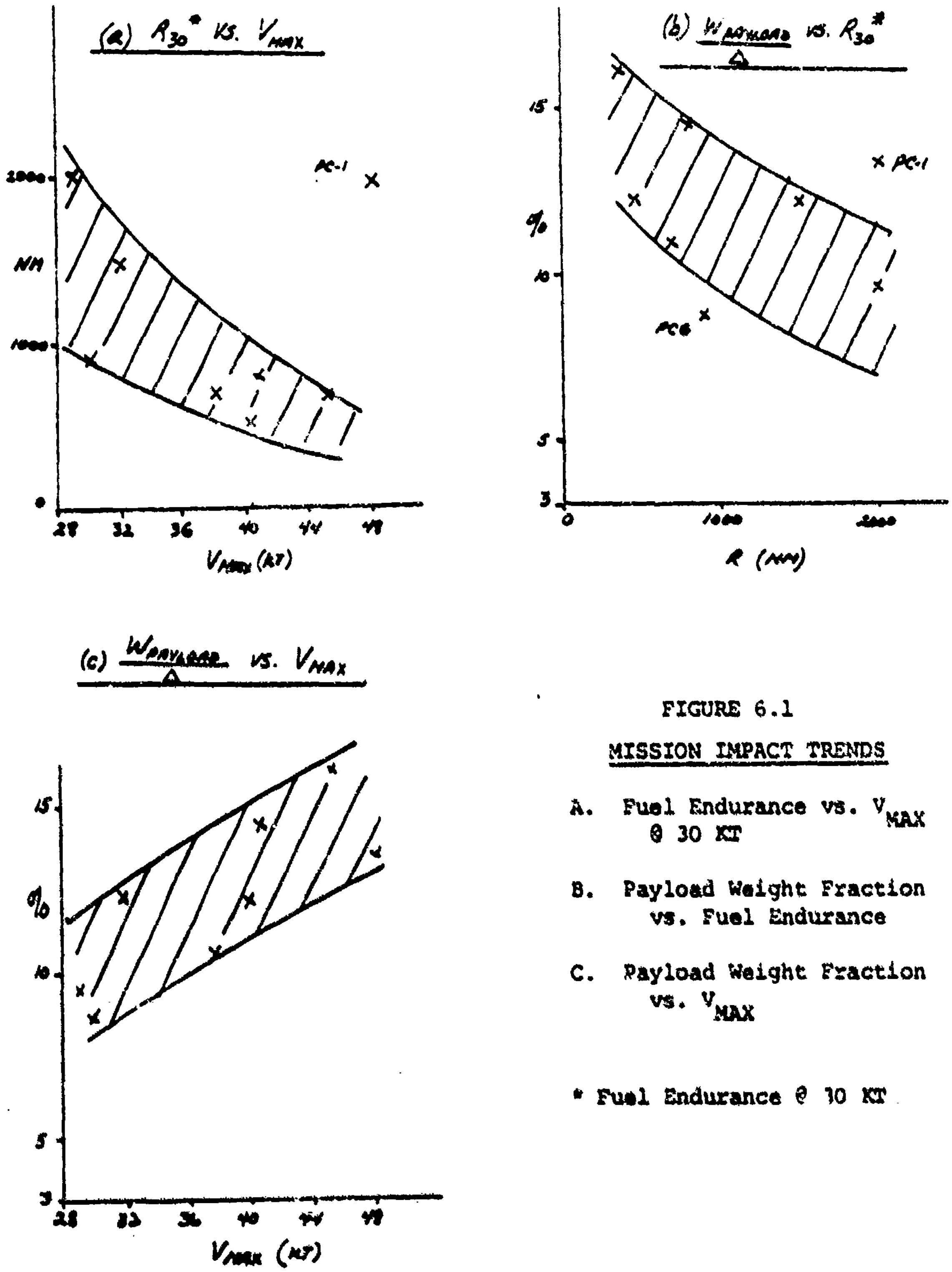


FIGURE 6.1

MISSION IMPACT TRENDS

A. Fuel Endurance vs. V_{MAX} @ 30 KT

B. Payload Weight Fraction vs. Fuel Endurance

C. Payload Weight Fraction vs. V_{MAX}

* Fuel Endurance @ 30 KT

6.1.2 RANGE VS. V_{MAX}

Curve (a) from Figure 6.1 demonstrates the basic trade-off of speed vs. range. There is a large amount of scatter, and the ranges are estimates, but the trend is valid even with these facts taken into account. If it is noted that the faster ships are also the smallest (Figure 6.2A) it can be inferred that long fuel endurance and mission length cannot be expected from them. Thus, the shortest missions are assigned to such ships, allowing range to be traded off for speed and payload (see section 6.1.4). The exception to the trend is PC-1 which, as a far-term platform, has been designed such that neither speed nor range suffers. Note that range at 30 knots is used, this being a more realistic measure for a fast, small platform than range at a lower speed.

6.1.3 PAYLOAD WEIGHT FRACTION VS. FUEL ENDURANCE

Figure 6.1B shows a downward trend of payload weight fraction ($W_4+W_7+W_{AMMO}/\Delta$) as range (at 30 knots) increases. This reflects the sacrifice of other loads in the interest of fuel. The ships with the longest range tend to be large, and thus have lower payload weight fractions, as demonstrated in section 6.2. Thus, there is a size trend partly driving this relationship. In addition, designers of ships which require a high fuel endurance are likely to employ the "gross allocation" method for increasing range (Chapter V). That is, they will add fuel at the expense of other loads. Thus,

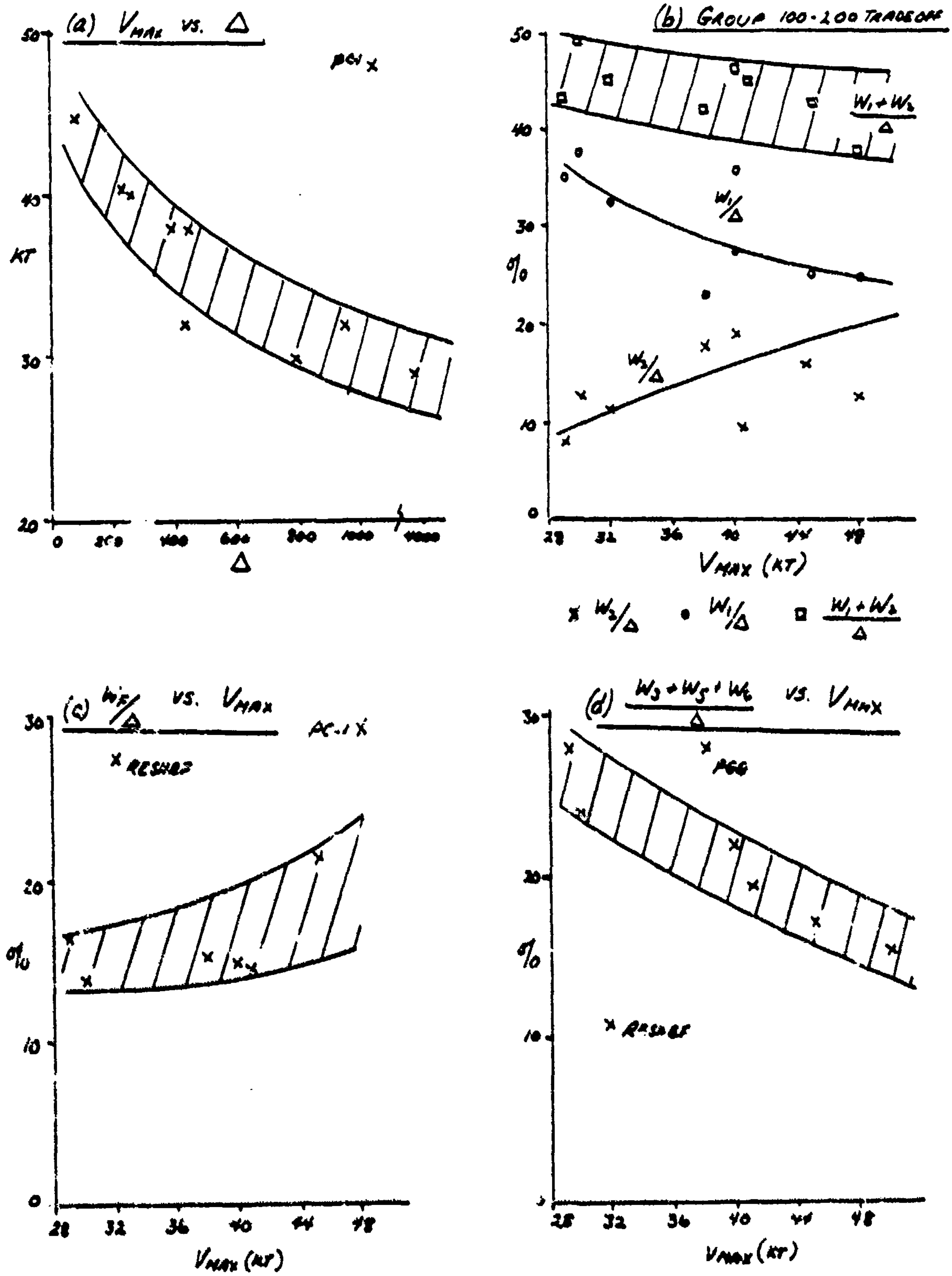


FIGURE 6.2 MISSION IMPACT - TRADE-OFFS WITH SPEED

military payload can be reduced.

The scatter in this graph is produced by national philosophy. The European designers allow habitability to suffer before payload. Therefore, their ships have higher payload weight fractions than U.S. ships with the same fuel endurance. In contrast, the American designs reduce military payload in order to maintain ship operation items (groups 300, 500, and 600). Hence, their payload weight fractions are low. PCG is low enough to be outside the "lane". PC-1 is excellent in this area, with both high fuel endurance and high WP/Δ, due to incorporation of high technology.

6.1.4 PAYLOAD WEIGHT FRACTION VS. MAXIMUM SPEED

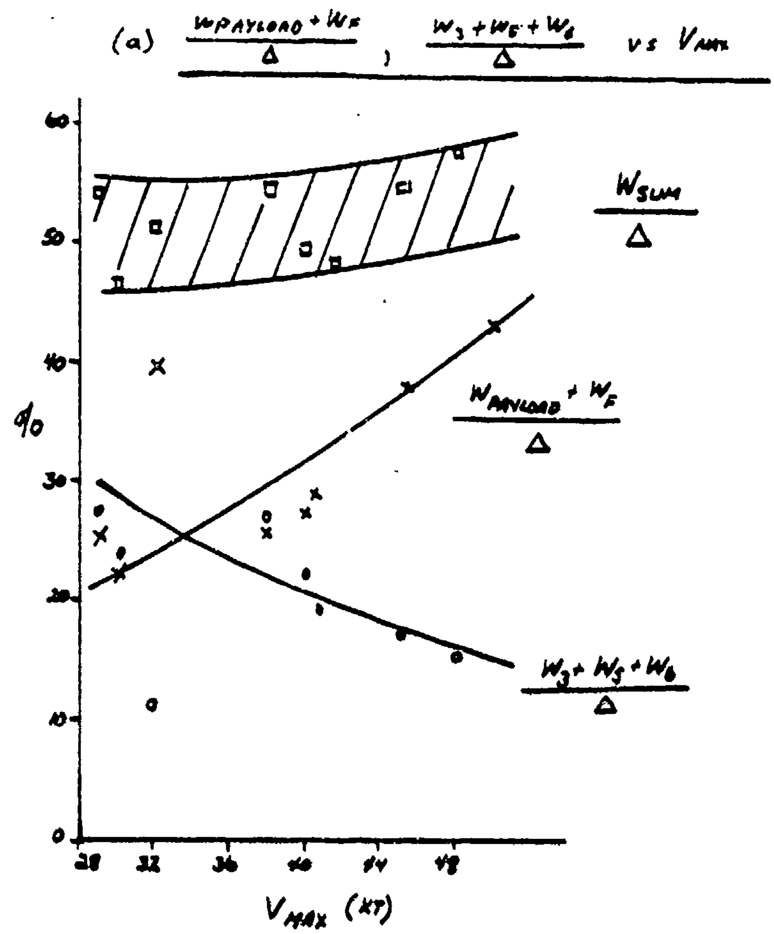
Counter to intuition, payload weight fraction increases with increasing speed, as shown in Figure 6.1C. This is a trend which must be explained. It has been established in Chapter V that group 200 weight increases with maximum speed. Thus, one would expect other areas to be traded off for this group. As Figure 6.2B shows, there is a trade-off between groups 100 and 200, so W_1+W_2/Δ is fairly constant. Thus, group 100 weight is reduced in an effort to reduce lightship weight for more speed. This still leaves the increase in payload weight fraction with speed unaccounted for. Therefore, the trade-off must be in other areas, notably fuel weight, or auxiliaries (groups 300, 500, and 600). Figure 6.2C shows that fuel weight fraction is not the compensating area, with a slight upward trend with speed. (RESHEF and PC-1 are excluded; RESHEF due to its previously mentioned fuel load, and PC-1 for its optimisitc design.) Thus, the trade-off for payload is clearly in auxiliaries (including electrical) and outfit, as Figure 6.2D demonstrates. If payload and fuel are taken together, the trade-off against auxiliaries can be graphically demonstrated, as in Figure 6.3A.

In actuality, it cannot be said if auxiliaries trade-off against payload, or against group 200 (propulsion). What can be said, is that as speed increases, both propulsion weight fraction and payload weight fraction increase. The trade-off areas are structure (group 200) and electrical, auxiliaries, and outfit (groups 300, 500, and 600).

6.1.5 SECTION CONCLUSIONS

This section has demonstrated the following:

- range decreases with increasing maximum speed
- payload weight is sacrificed for increased fuel endurance at high speed
- payload weight increases with increasing maximum speed due to:
  - (a) size effect
  - (b) a trade-off with auxiliaries, electrical, and outfit
- as maximum speed increases, payload weight fraction and main propulsion weight fraction increase. They are



TRADE-OFF - PAYLOAD VS. AUXILIARIES, ELECTRICAL, AND OUTFIT

FIGURE 6.3

compensated for with structure, electrical, auxiliaries, and outfit weight fraction reduction.

6.2 Size Trends

Many of the design features studied in Chapters IV and V exhibit trends which follow ship size. There are some very good reasons for this. Certain aspects are more efficient as size increases, demonstrating an economy of scale. Other factors, generally design standards, increase with size because the larger, long-range ships require more redundancy and ruggedness. Still other features remain constant regardless of ship size. The interplay between the various trends with size explains a substantial part of the decision-making on the part of the designers.

Since the primary thrust of study is to determine the "price" paid (in weight and space) for each function, a good way to examine the trends is to assemble those features which drive allocation fractions recalling the relationship from Chapter II:

(Allocation Fraction) = (Capacity/Ship Size Ratio)(Specific Ratio)

Each functional area can be described by its allocations and the factors which drive them. The approach here is to do just this, with an emphasis on the weight allocations. In addition, any other parameters which impact a functional area are also included. With these areas covered, the performance indices are plotted to show any size trends present here.

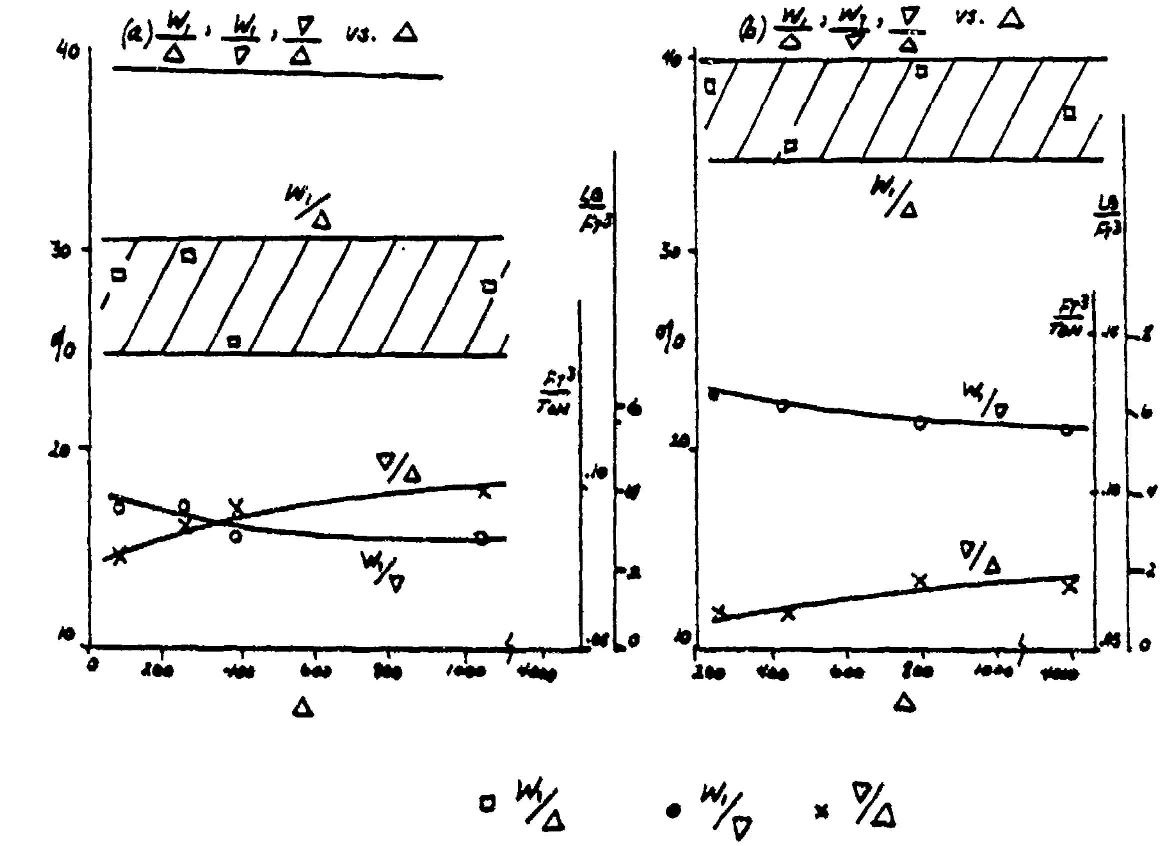
Many of the trends found in this study are present for all ship types. A good discussion of such trends (which is based on a larger data collection) is found in Cassedy.[8]

6.2.1 HULL STRUCTURE

Hull structure is the largest fraction of lightship weight. As such, it demands special attention. There is no volume group to examine, but a close look at the group 100 (hull structure) weight fraction is dictated. The governing relationship is $(W_1/\Delta) = (W_1/\nabla)(\nabla/\Delta)$, where the last term is the reciprocal of ship density. It is useful to plot all three quantities on the same graph, as in Figures 6.4A and 6.4B. These graphs show them for (A) aluminum ships and (B) steel ships. There is only slight variation with size, but the trends are there.

Structure specific weight decreases slowly with increasing displacement. This reflects an economy of scale. As ship size grows, structure becomes more efficient. This trend is more noticeable when plotted against enclosed volume, as in Figure 6.4C.

Specific volume (∇/Δ), the reciprocal of density, increases slightly with size increase (Figures 6.4A and 6.4B). This follows the physics of the problem. That is, as a volume enclosed by steel is enlarged, the density decreases. The added steel weight is proportionally lower than the volume increase, even if steel thickness is increased as volume grows, since thickness need not increase linearly with



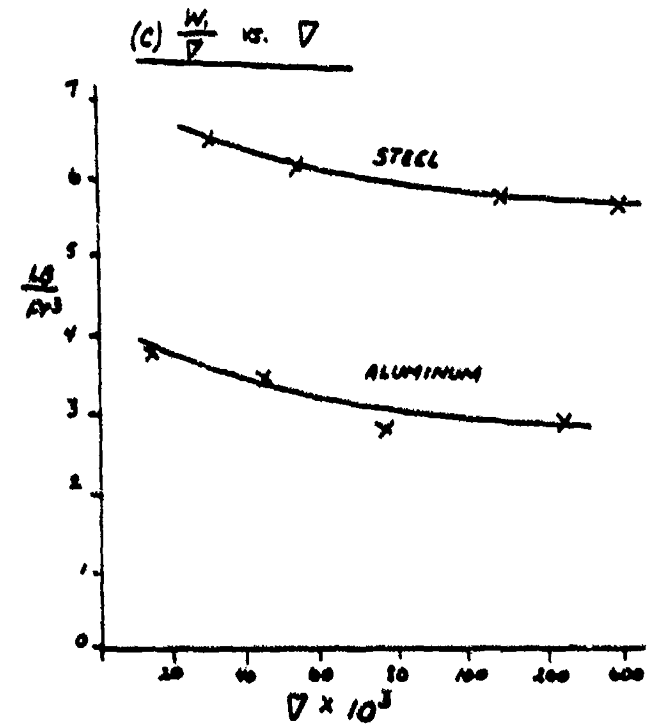


FIGURE 6.4

HULL STRUCTURE

A. Size Trends for Aluminum Hulls

B. Size Trends for Steel Hulls

C. Size Trend With Volume (From Chapter V) size to withstand structural loads.

The net result of the above two tendencies is to cancel each other out. This leads to a band of constant structure weight fraction on both graphs (B) and (C). This generally agrees with conclusions reached by Cassedy, who arrived at bands for both structure specific weight and structural weight fraction.

The related areas of superstructure specific weight, basic hull specific weight, and foundations specific weight are discussed in Chapter V, but bear repeating here. The first two quantities follow the economy of size shown for overall structure specific weight. Foundations specific weight, however, shows the opposite effect. That is, as ship size increases, so does foundation specific weight. The reason for this is the extended range and mission of the larger ships in the study. The mission requirements of these ships dictate a higher degree of shock mounting, ruggedness, and operability. Thus more weight is used for foundations in order to achieve the more demanding design standard for bigger platforms.

The most dramatic influence in hull structure is not size trend, but rather choice of material. This is discussed in Chapter V, and is graphically demonstrated here by the marked differences in the vertical position of all curves in Figure 6.4.

6.2.2 MAIN PROPULSION

Since small combatant design places emphasis on speed, the propulsion plant becomes an important consideration. It has already been demonstrated that speed drives main propulsion weight fraction. It remains to determine the other factors which impact group 200.

The first trend of interest is that of decreasing maximum speed with increasing displacement, shown in Figure 6.5A. This graph shows directly the increased emphasis on speed for the small ships. This extra speed must be "bought" at a high price (in weight and volume) because for a given speed, the smaller the ship, the higher the EHP/Δ required to attain that speed (Figure 6.5B). Thus, the small ships fight the physics of speed production twice; once to attain the high speed required and once to overcome the increased resistance inherent in the higher speed-length ratios at which they operate.

The two effects mentioned above dictate a higher main propulsion/ship size ratio (SHP/Δ) for the smaller ships, as shown by the curve of this index in Figure 6.5C. This downward trend in SHP/Ton is mentioned by Cassedy, and it occurs in other ship types as well as in small combatants.

Recalling that main propulsion weight fraction (W_2/Δ) is a product of main propulsion/ship size ratio and main propulsion weight specific ratio, or

$$(W_2/\Delta) = (W_2/SHP)(SHP/\Delta)$$

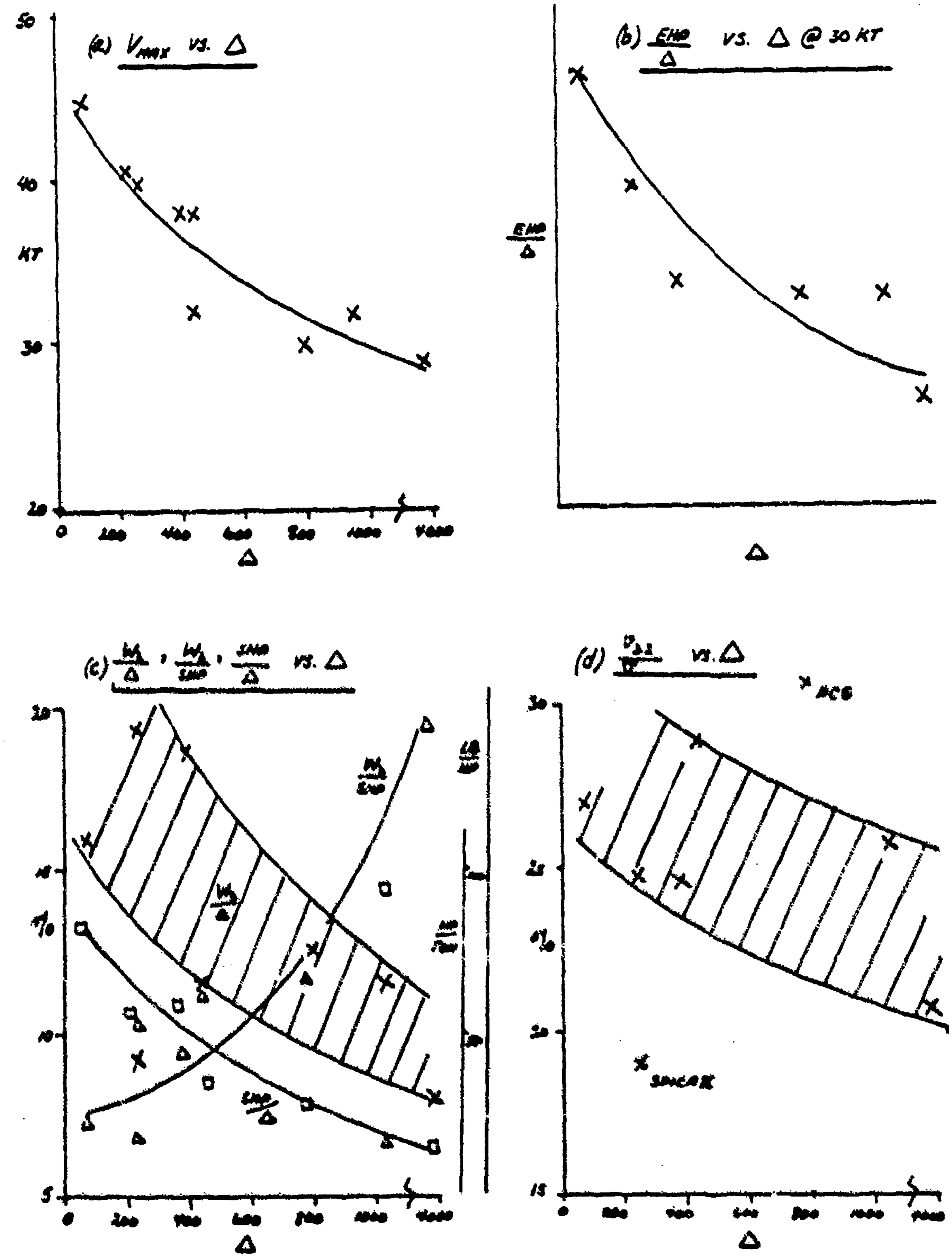


FIGURE 6.5 MAIN PROPULSION TRENDS WITH SIZE

it now is of interest to see how these terms affect the weight allocation. Figure 6.5C shows that main propulsion weight specific ratio grows with increasing displacement, thus tempering the effect of decreasing SHP/Δ already mentioned. This index increases with ship size due to the requirement for a more rugged propulsion plant. The larger ships must be more repairable, survivable, and generally more operable. This dictates an increased investment in weight per horsepower.

The net effect of the opposing trends in SHP/Δ and W_2/SHP is a decreasing main propulsion weight fraction as displacement increases. This is true for other ship types, as explained by Cassedy, and is also followed by a corresponding trend in main propulsion volume fraction (Figure 6.5D).

The conclusion to be drawn from Figure 6.5 and from section 6.1, is that resource allocation for main propulsion is impacted by mission requirements and by operability. For small combatants the emphasis on speed overwhelms the less stringent operability considerations at small displacement. Thus, the trend of increasing allocation fractions as size decreases.

It should be noted that the allocation fraction curves (W_2/Δ vs. Δ and $\nabla_{3.2}/\nabla$ vs. Δ) have a fair amount of scatter. This is due to national influence and different maximum speeds.

6.2.3 ELECTRICAL, AUXILIARIES, AND OUTFIT

Functional areas which support general ship operation do not take up large portions of weight when treated separately. However, if weight groups 300, 500, and 600 are considered together, they consume up to 28% of full-load displacement, and up to 40% of volume. The approach taken in this section considers electric power generation separately, due to its indication of combat systems and air conditioning loads. Then auxiliaries, outfit, and furnishings are lumped together as ship support functions.

Electric power generation does not follow the trend presented by Cassedy, who presents KW/Δ as decreasing with increasing displacement. The tendency shown by the ships of this study is opposite to this (Figure 6.6A). The reason for the reversal is that in small ships, electric loads are less important as operability decreases, with a concurrent reduction in supporting systems which contribute to the load. Also, the electronics are vastly simpler on the smaller ships; a factor which also decreases loads. It is submitted, therefore, that for small combatants these aspects override the inherent economy of scale suggested by Cassedy.

Electric power/ship size ratio, mentioned above, and electric power weight specific ratio, W_3/KW, drive group 300 (electrical) weight fraction through the relationship $(W_3/\Delta) = (W_3/KW)(KW/\Delta)$. Figure 6.6A shows that electric power weight specific ratio also grows with increasing ship

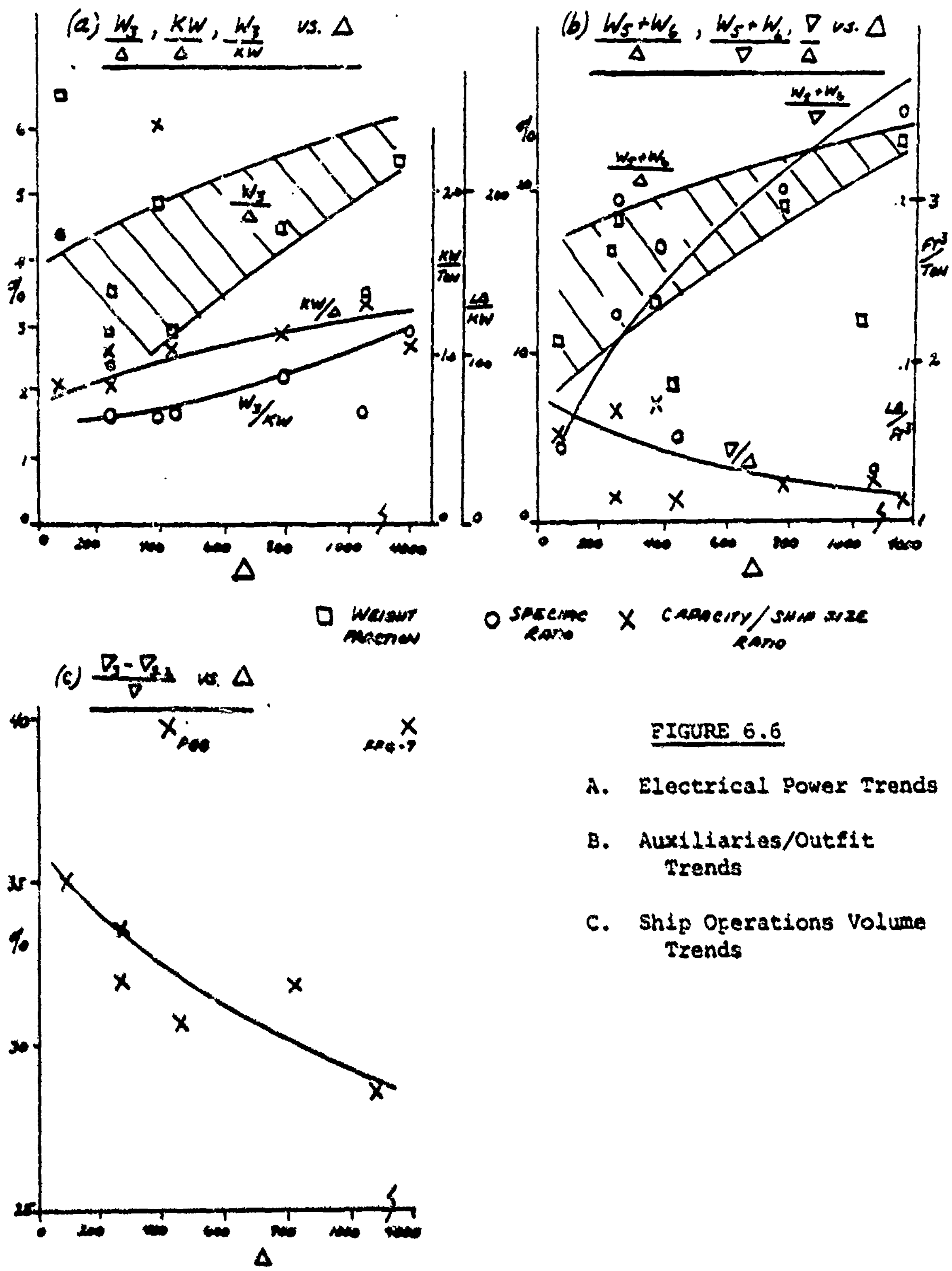


FIGURE 6.6

A. Electrical Power Trends

B. Auxiliaries/Outfit Trends

C. Ship Operations Volume Trends

size. The reason for this is the requirement (similar to the requirement for main propulsion) for extra ruggedness and serviceability.

With both right hand terms of the relationship having similar trends, the electric power weight fraction (W_3/Δ) must also increase with increasing ship size, as reflected by the shaded area of Figure 6.6A. (Note that scatter is still present, and that the upward trends may be represented as bands by another interpreter.)

Auxiliaries and outfit weight fraction $\left(\frac{W_5+W_6}{\Delta}\right)$ is determined by the relation

$$\frac{W_5+W_6}{\Delta} = \left(\frac{W_5+W_6}{\nabla}\right)\left(\frac{\nabla}{\Delta}\right)$$

where $\frac{W_5+W_6}{\nabla}$ is ship operations specific ratio, and ∇/Δ is the reciprocal of density (Figure 6.6B). The decreasing trend of ∇/Δ with size has already been discussed. $\frac{W_5+W_6}{\nabla}$, ship cperations specific ratio increases markedly as ship size grows. The reason for this is operability. As size increases, ruggedness, redundancy, and serviceability increase to meet mission demands. All ship's service related functions grow accordingly. The result is that this quantity drives the relationship, and, therefore, $\frac{W_5+W_6}{\Delta}$ grows with increasing displacement.

For completeness, Figure 6.6C shows ship operation volume fraction (less propulsion) vs. displacement. The scatter in this graph does not produce a clear trend. However, if FFG-7 and PGG are disregarded, there does appear to be some economy of scale. FFG-7 is a much more flexible rugged platform, and thus could have a larger fraction by virtue of a much enhanced operability compared to the small ships. PGG has been repeatedly cited for its high figures in all habitability, ship operation, and auxiliaries areas. It should be expected therefore, that this ship follows the same pattern for ship operation volume fraction.

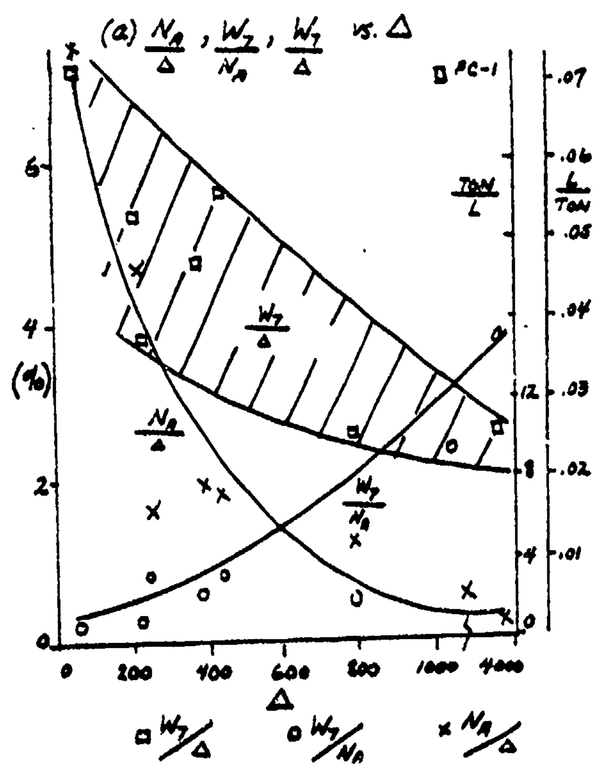
6.2.4 MILITARY PAYLOAD

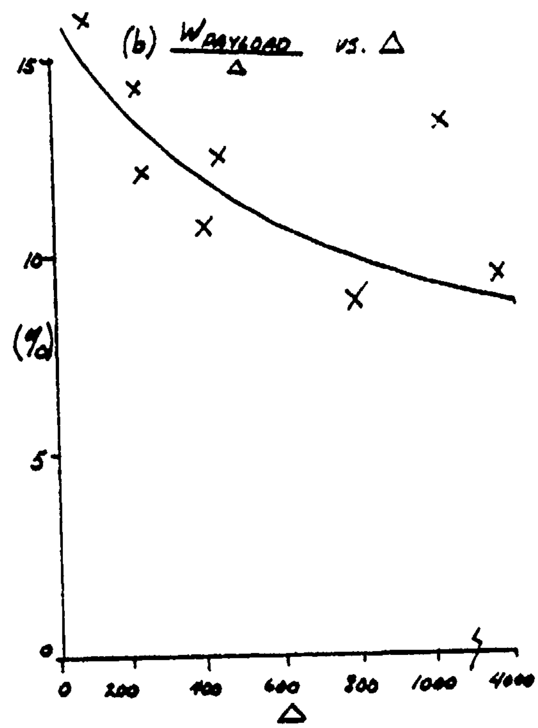
Military payload is important for any combatant ship. Thus, any size-correlated tendencies are of interest for group 700 (armament), a governing relationship exists:

$$W_7/\Delta = (W_7/N_A)(N_A/\Delta)$$

The three quantities in the equation are graphed in Figure 6.7A. The trend for armament specific ratio increases with increasing ship size. This is due to use of larger, more sophisticated launching systems in the larger ships. Conversely, armament/ship size ratio decreases with increasing displacement, due to the elimination of various small gun mounts in the larger ships. That is, the ship size goes up, the ships tend to fewer, but bigger and more powerful weapons delivery systems.

The result of the above effects is a decrease in armament weight fraction with growing displacement. This is





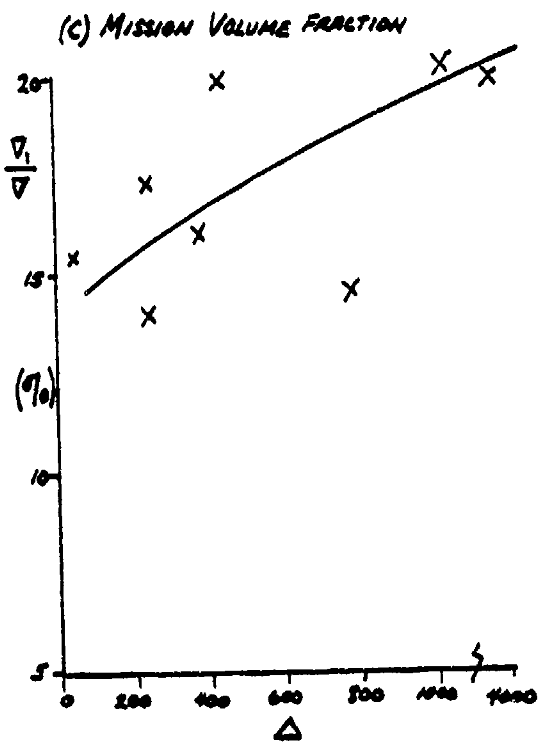


FIGURE 6.7

MILITARY PAYLOAD

A. Group 700 Trends

B. Payload Weight Fraction

C. Payload Volume Fraction

confirmed by Figure 6.7B, which depicts overall payload weight fraction. Figure 6.7C, however, shows an increase in payload volume fraction with increasing ship size. This indicates less dense systems on the larger ships.

For armament weight fraction, number of delivery systems dominates, and thus small ships use a higher proportion of weight. However, if internal volume is considered, then the complexity, redundancy, and flexibility of the launchers on the large ships dominate to cause increased use of space with increasing displacement. This is a good clue to the reason that frigates and destroyers are now "volume-driven" ships.

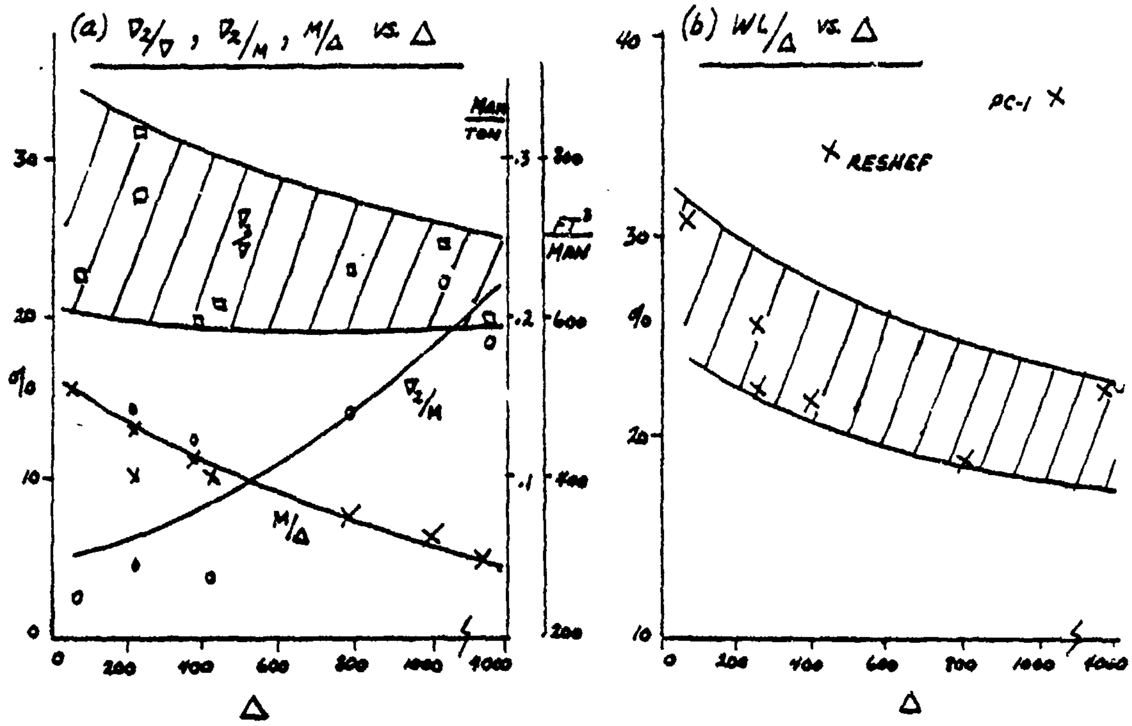
6.2.5 OTHER FUNCTIONAL AREAS

6.2.5.1 Personnel

Personnel considerations account for a large portion of life-cycle cost. Therefore, it is pertinent to examine size trends for personnel indices. Volume is the important quantity here, and ∇_2 takes up to 32% of total enclosed volume. Using the relationship

$$\nabla_2/\nabla = (\nabla_2/M)(M/\Delta)(\Delta/\nabla)$$

the graph in Figure 6.8A shows trends which relate to personnel volume fraction. Manning/ship size ratio (M/Δ) decreases with increasing displacement, showing the classical economy of scale mentioned by Cassedy. Conversely, the manning specific volume increases with increasing size. This reflects the need for more habitability on ships with longer



□ ∇_2/∇

○ ∇_2/M

× M/Δ

FIGURE 6.8

A. Personnel Trends with Size

B. Load Weight Fraction vs. Displacement missions. Density increases very slightly with size, so it has only slight effect.

The conclusion is that the economy of scale has the greatest influence, and it causes personnel volume fraction to decrease with increasing ship size.

6.2.5.2 Loads Weight Fraction

Figure 6.8B shows the trend for total loads to be decreasing with size. RESHEF and PC-1 are exceptions in which the design has been specifically oriented to carrying load/payload. Note that fuel dominates loads. Therefore, the graph tabulates fuel weight fraction indirectly. The decreasing trend shows the economy of size for fuel endurance. A smaller percentage of weight can be dedicated to fuel on the large ships, which have inherent size benefits.

6.2.6 PERFORMANCE INDICES

All of the performance indices in Figure 6.9 exhibit size trends. They reflect true scale effects or component factors which have already been discussed.

6.2.6.1 Maximum Speed (Figure 6.9A)

This trend has been mentioned in section 6.2.2. It reflects an emphasis on more speed for the smaller ships. Certainly, it is not impossible to increase speed at larger displacement, as demonstrated by PC-1. However, most larger ships do not require a high speed for their mission (see section 6.1).

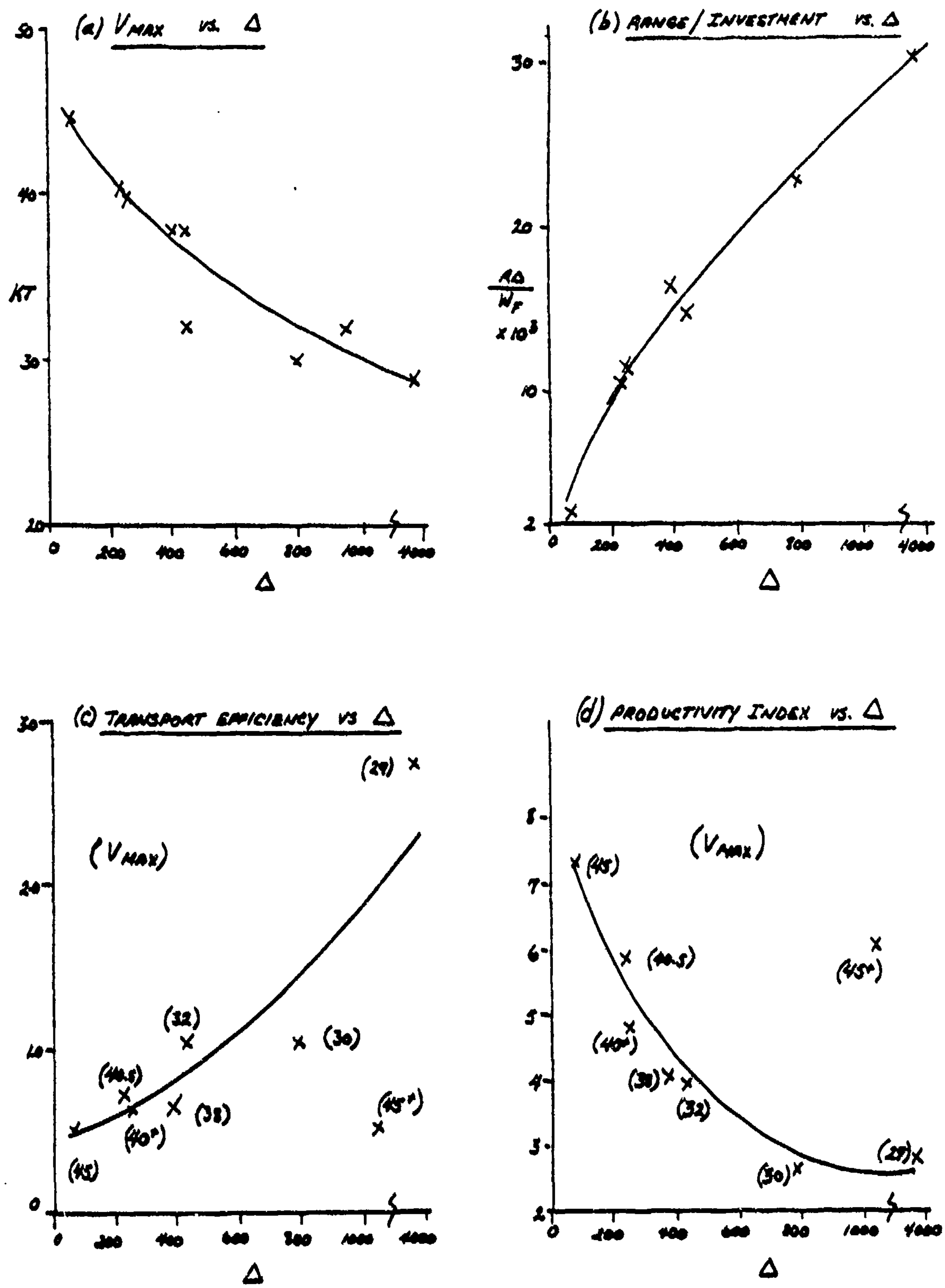


FIGURE 6.9 PERFORMANCE INDICES

6.2.6.2 Range per Investment (R/WF/Δ) (Figure 6.9B)

This figure is based on estimated or published range at 16 knots. The increase with increasing ship size shows the economy of size inherent in larger ships. The reason for this is the reduced EHP/Δ needed to drive a larger ship through the water at the same speed as a small ship (see section 6.1).

6.2.6.3 Transport Efficiency (Figure 6.9C)

Transport efficiency is the product of displacement times speed, divided by horsepower. The displacement term dominates, so increased size enhances (increases) this index. Also, as speed goes down, so does SHP. Since the trend with size is decreasing speed, the lower SHP drives $\frac{\Delta V_{MAX}}{SHP}$ even higher.

6.2.6.4 Productivity Index (Figure 6.9D)

As with transport efficiency, contributing terms drive productivity index. Since productivity index is payload weight fraction times speed, the variation of these parameters determines the value of the index. It has already been demonstrated that both payload weight fraction and speed decrease with increasing ship size. Therefore, productivity index goes down as displacement goes up.

6.2.6.5 Conclusion

The trends exhibited by performance indices are somewhat in conflict. Range and transport efficiency increase with increasing size, but speed and productivity index decrease as ship size grows. The decision to build a small or large ship can, however, still be made, based on all four indices. For the short, surprise mission, speed and payload matter most, while range and transport efficiency are secondary. Thus, small ships are the answer for this task. Conversely, durable long-mission ships will tend to be large, to benefit from increased range and efficiency.

6.2.7 SECTION CONCLUSIONS

The conclusion to be reached from this section is that operation and flexibility drives almost all size-related parameters. As the mission requirements become more demanding with regard to endurance and sophistication, ship size goes up. With increased displacement come more stringent design standards whose purpose it is to make the ship rugged and flexible enough to withstand the extra punishment of increasing mission scope. This means that auxiliaries, electrical outfit, and service oriented weight fractions increase. As weapons systems become larger and less dense, volume becomes critical. Fuel endurance is an issue which drives up ship size due to inherent economy of scale. Structure specific weight follows an economy of scale, also.

The features mentioned above are but a few of the many areas which size dominates. The attractiveness of size, however, directly conflicts with the inherent advantages of small ships (section 6.6). Thus, in summary, a basic statement can be made about ship size. That is, in order to stay small, the design trades of endurance, ruggedness, and mission options; to gain these desired features, ship size (and cost) must grow. The basic design decisions must be made with this in mind.

6.3 Design Lanes

With the collection of available data, ranges of various design parameters can be described for future use. The purpose in constructing a table of design lanes is to check existing designs, and to demonstrate the feasibility of new designs.

The table in Figure 6.10 shows major parameters used in the study. It should be considered as a basis for further work. Only the five ships in the displacement range specified by the introduction (200-800 tons) have been included. Therefore, much more data is needed to verify or correct the ranges listed here for each variable. Some of the ranges presented are wide, due to scatter. An increase in data points could be used to discard appropriate figures.

6.4 Trends by Age*

The history of small combatants over the past 20 years has exhibited certain time-related trends. Most of these

*PC-I has been left out of this section due to its far-term nature.

FIGURE 6.10

DESIGN LANES FOR SMALL COMBATANTS

	Low	High	Remarks
Powering			
W_2/Δ, (%)	9.0	19.0	CODOG above 12
SHP_B/Δ, (HP/TON)	29.0	59.0	Above 50 for V_s > 35 KT
$\nabla_{3.2}/\nabla$ (%)	19.0	30.0	
$V_3/\sqrt{L}$ KT/$\sqrt{L}$	1.9	3.3	80% Power (some est.)
W_2/SHP (LB/HP)	3.6	8.7	
KW/Δ (KW/TON)	.8	2.4	Most Around 1.0
Hull Form			
C_B	.40	.48	
C_P	.57	.72	
C_X	.60	.74	US > .720
$L/\sqrt{\nabla}$	7.2	8.1	
Deadrise θ	8°	15°	US Round-bilged
Deadrise AP	0°	1.8°	
LOA/B	6.1	7.8	
Personnel			
D (Day)	10.0	14.0	
M/Δ (Man/Ton)	.073	.14	
∇_2/M (Ft^3/Man)	240.0	500.0	US > 460, Eur < 300
∇_2/∇ (%)	20.0	32.0	
Weapons			
$\frac{W_4+W_7+W_{AMMO}}{\Delta}$ (%)	8.9	14.0	
∇_1/∇ (%)	14.0	32.0	
A_{WEAPS}/A_{TOT} (%)	21.0	43.0	
Structures			
W_1/Δ (%)	23.0	37.0	AL < 30
W_1/∇ (LB/FT^3)	2.7	6.4	AL < 4 ST > 78
Basic Hull SP.WT. (LB/FT^3)	2.6	6.3	AL < 3 ST > 75
Sup SP. WT. (LB/FT^3)	1.0	2.1	

reflect the changing role of the small ship from that of a large PT boat to that of a potently-armed, electronically-sophisticated platform. Ships of this group are now capable of more than overnight missions. They have compact but effective command and control systems and large combat operations centers. Automatic guns, missile launchers, and fire control radars have become standard on ships which have formerly carried torpedoes and machine guns.

In light of the expanded role of the "fast patrol craft", exploration of size and power trends is warranted, along with that of other areas.

6.4.1 PERFORMANCE INDICES (FIGURE 6.11)

The changing role of small naval ships is supported by the information in Figure 6.11. The graph of maximum speed (Figure 6.11A) shows a slight decrease with time. This is due to increased size of the ships, and an emphasis on rough-water speed instead of top speed. It also could show a decline in the need for speed, due to increased electronic sophistication counteracting speed loss. Note, however, that the change in speed is not great, so whatever effect the above influences have is small. The expanded emphasis on range is demonstrated by Figure 6.11B which shows an increase over time.

Transport efficiency (Figure 6.11C) has remained fairly constant over the years, as displacement increase and speed decrease counter-balance. Productivity index (Figure 6.11D)

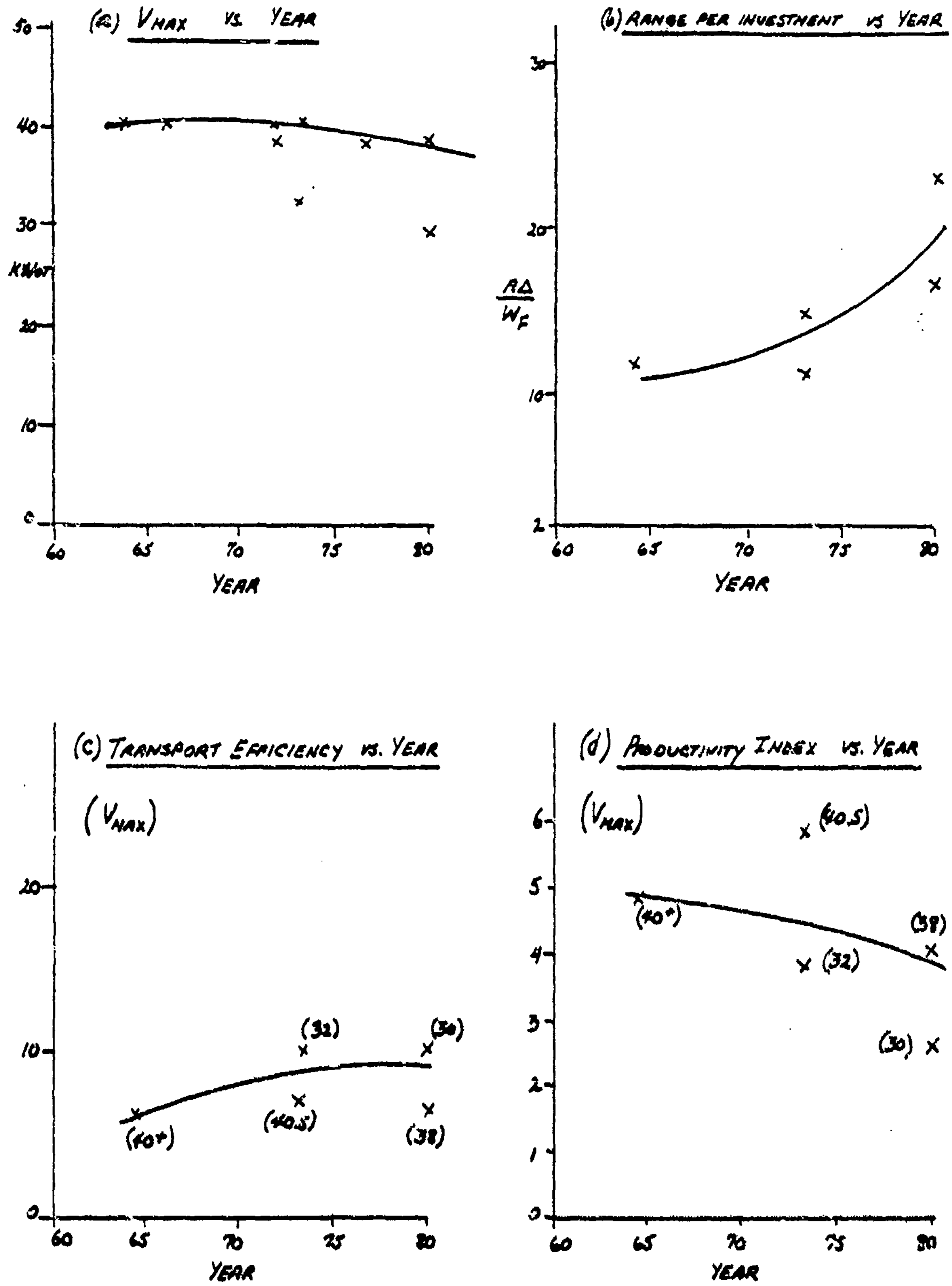


FIGURE 6.11 PERFORMANCE INDICES BY YEAR

shows a decrease with time, but is heavily influenced by the two U.S. designs delivered in 1980. Thus, the trend is suspect, and is driven by nationality more than time.

6.4.2 CAPACITY/SHIP SIZE RATIOS (FIGURE 6.12)

Electric Power/Ship Size Ratio (Figure 6.12A) shows an increase with time, reflecting: (1) increased electric load from electronics; (2) more air conditioning. This trend parallels that demonstrated in larger ships. Note that the U.S. high-performance ships (PHM, PGG) demonstrate a more dramatic increase than the others.

Main Propulsion/Ship Size Ratio (Figure 6.12B) shows a decrease with time, with CPIC expected due to size. This trend follows the decrease of speed with time.

Manning/Ship Size Ratio (Figure 6.12C) - there appears to be no identifiable trend in this area.

Specific Volume Ratio vs. Year (Figure 6.12A) - the reciprocal of density shows an increase over time. This reflects changing personnel support and electronics space demands as flexibility and operability increase. Note the disparity between aluminum and steel, as already discussed in section 6.2.

6.4.3 SPECIFIC RATIOS (FIGURE 6.13)

Electric Power Weight Specific Ratio (Figure 6.13A) - if the larger ships (PCG, FFG-7) and the very small ship (CPIC) are neglected, the trend is toward reduced weight of electri-

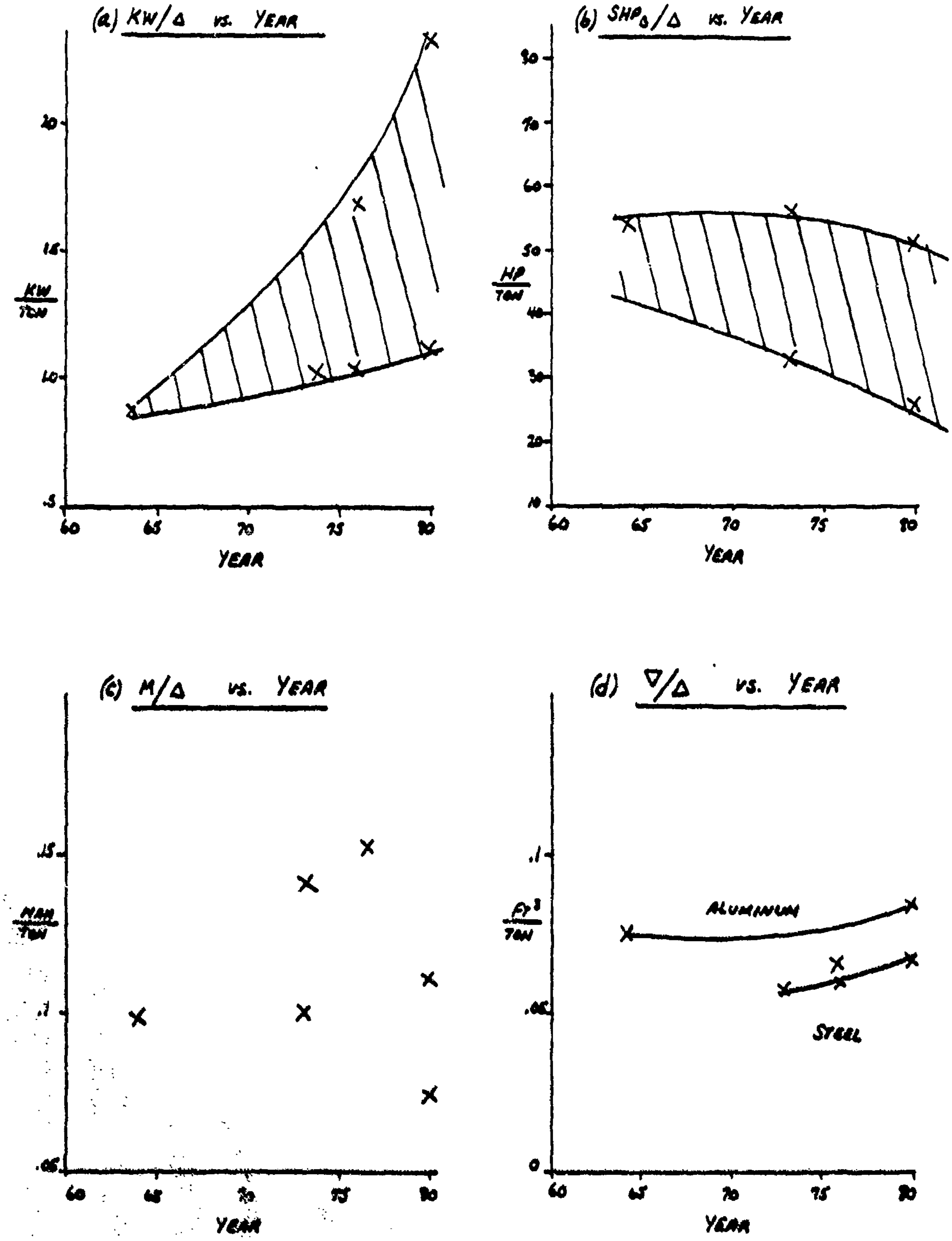


FIGURE 6.12 CAPACITY/SHIP SIZE RATIOS VS. YEAR

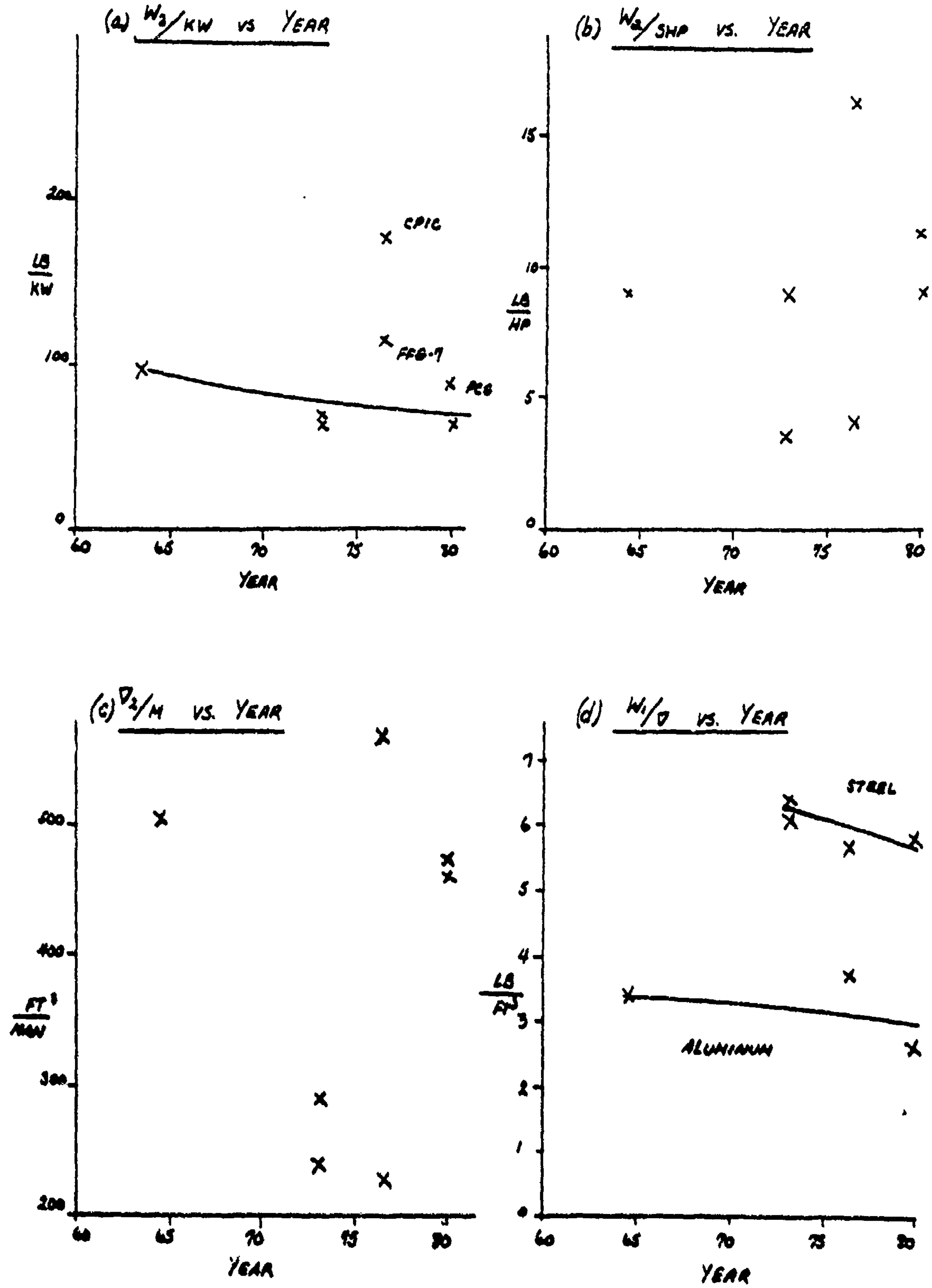


FIGURE 6.13 SPECIFIC RATIOS VS. YEAR

cal systems. This has been through application of higher technology to the electric plant, which allows lighter components.

Main Propulsion Weight Specific Ratio (Figure 6.13B) and Personnel Volume Specific Ratio (Figure 6.13C) - it appears as if no significant trends appear in these areas. (Plant type introduces much scatter in Figure 6.13B.)

Structural Weight Specific Ratio (Figure 6.13D) - if the ships are grouped by hull material. A slightly decreasing tendency over time is noted. This is probably due to improved design and construction practices, as more ships of this issue are built.

6.4.4 WEIGHT TRENDS (FIGURE 6.14)

Displacement has increased over time, as shown by Figure 6.14A. This can be traced to larger weapons and improving operability and flexibility in the newer ships. It is paralleled by a similar trend in larger combatant ships.

Structure Weight Fraction must be split into steel and aluminum ships, as in Figure 6.14B. There are not enough data points to show clear trends, but the aluminum ships appear to be slightly reducing this fraction over time.

Main Propulsion Weight Fraction (Figure 6.14C), Electrical Auxiliaries and Outfit Weight Fraction (Figure 6.14D), and Payload Weight Fraction (Figure 6.14E) - there appear to be no significant trends in these areas.

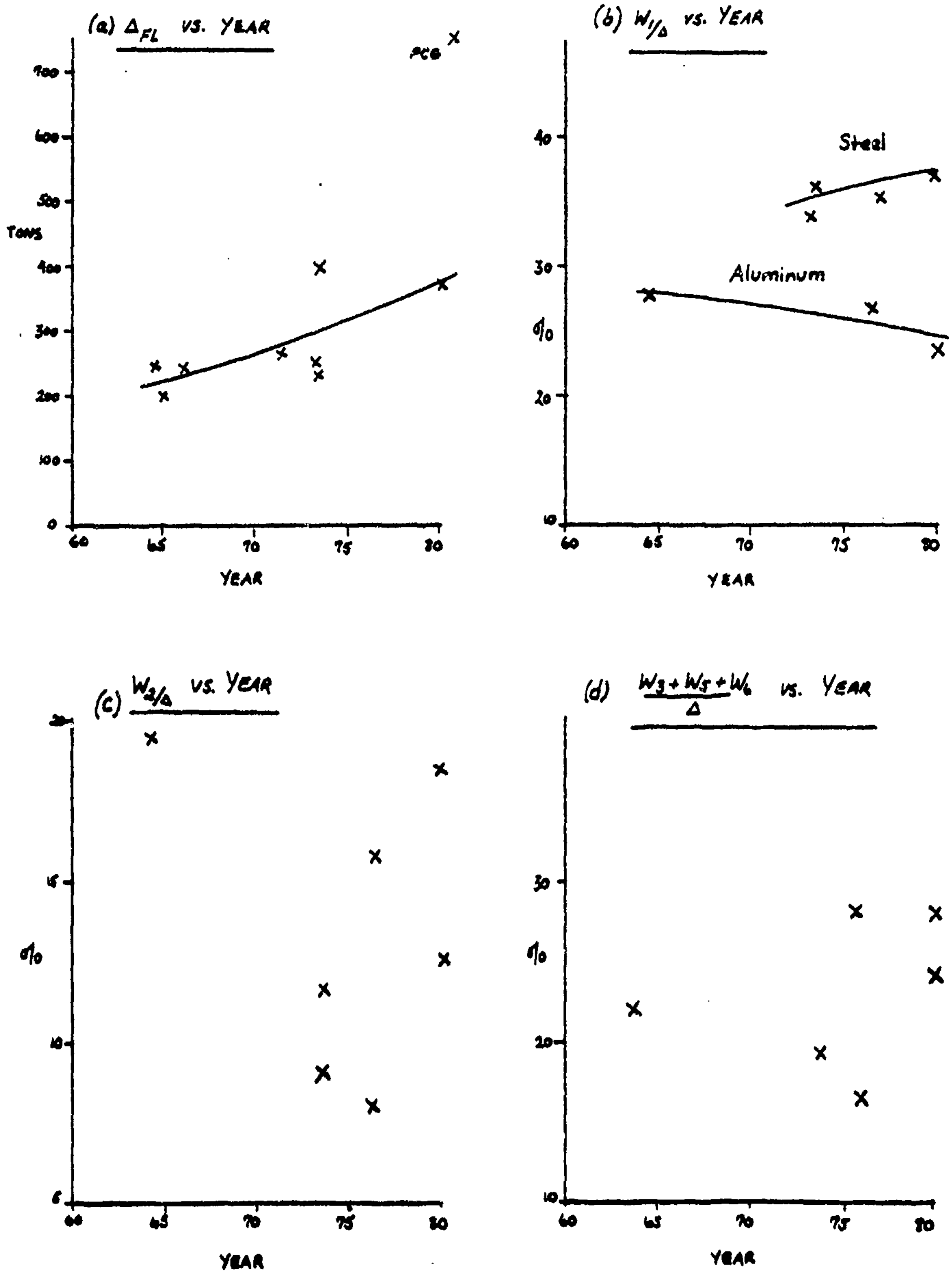


FIGURE 6.14 WEIGHT FRACTIONS BY YEAR

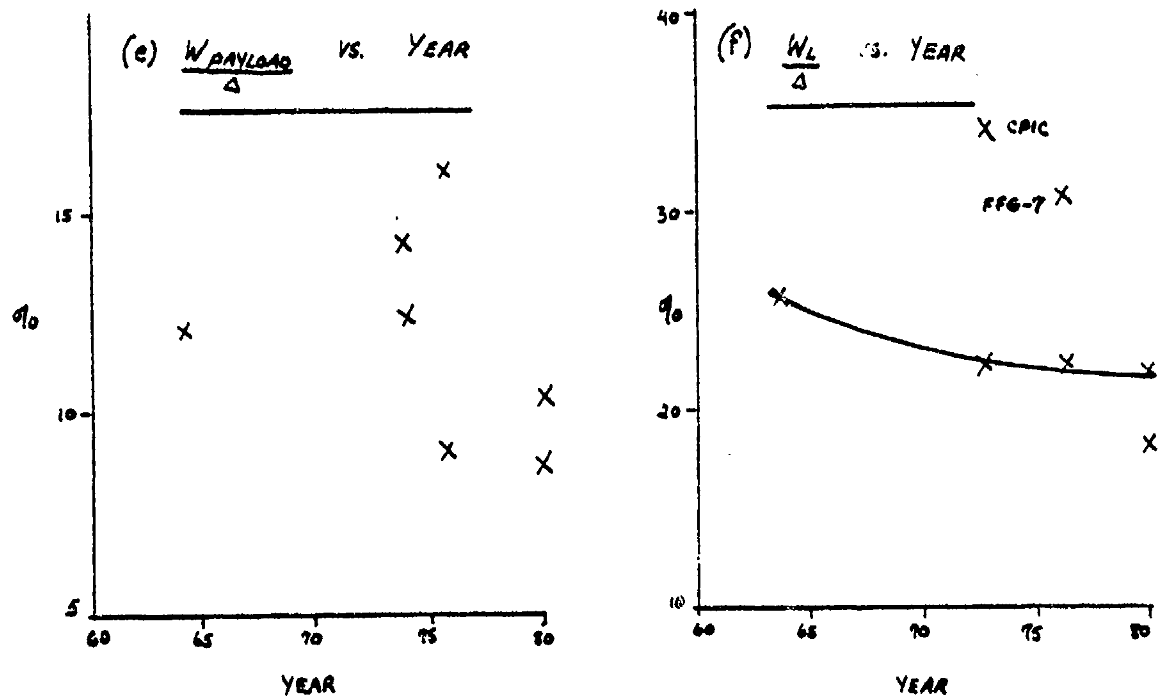


FIGURE 6.14 (Continued)

WEIGHT FRACTIONS BY YEAR

Loads (Overall) Weight Fraction - if the 5 ships of displacements from 200 to 800 tons are included, the trend is a downward one of about 4% with time. Since range is generally increasing, this reduction of fuel weight can be traced to improving specific fuel consumption.

6.4.5 SECTION CONCLUSIONS

The significant trends with time are caused by the tendency to upgrade performance, endurance, and platform flexibility. Thus, range, electric power, ship volume per ton (reciprocal of density) and displacement show increase over time. At the same time, maximum speed is sacrificed for better seakeeping range and operability, so the downward trend in V_{MAX} is not really inconsistent with enhanced capability.

Design standards have become higher and more stringent. This is shown by downward trends in the electric power and structure weight specific ratios.

It is cautioned that "trends" based on only five to seven points, over a span of 20 years, are not conclusive. Much more data is needed to validate the results obtained in this section.

6.5 Trends by Nationality

Many features of small ship design can be explained only by national priorities. It is difficult to try to canvass each country, or to try to produce absolute priorities from the limited data available. However, general conclusions can be made about U.S. vs. "European" practice. From these conclusions, a listing of national priority can be constructed.

6.5.1 U.S. PRACTICE

6.5.1.1 Mobility

The U.S.A. tends to use CODOG plants. This provides speed on turbines and range on diesels.

- gas turbines receive priority for boost power due to:
  - U.S. aircraft industry - engines are available
  - lack of a domestic high speed diesel
  - bad experience with foreign diesels in PTF's
- hull form is generally round bilged, like a small destroyer, with high L/B
- fin stabilizers are used to achieve seakeeping
- CRP propellers exclusively

6.5.1.2 Structures

- use of aluminum minimizes group 1 weight
- U.S. ships are longitudianlly framed exclusively, due to design standards and use of aluminum
- U.S. has high foundation specific weight, suggesting more shock hardening and silencing

6.5.1.3 Personnel

- U.S. designs reduce manning to fewer men per ton of ship

- U.S. has the highest habitability standards shown by high ∇_2/M, W_{PERS}/M (section 6.2)
- high auxiliaries and electrical weight fractions

6.5.1.4 Payload

- U.S. has followed foreign ships with automatic guns, cannister-launched surface-to-surface missiles
- low payload weight fraction (section 6.2)

6.5.1.5 Electronics

- U.S. installs a heavy electronics package, but no unified approach to CIC, fire control

6.5.1.6 Other

- high margins
- less deck space to weapons
- high FW/Δ
- maintenance by removal

6.5.2 EUROPEAN PRACTICE

6.5.2.1 Mobility

- primarily high-speed diesels with reversed reducting gears and multiple shafts are employed
- ships with gas turbines use multiple shafts also
- mostly fixed-pitch propellers
- hull form exclusively hard chine with deep V forward, flat run aft

- few ships with fin stabilization
- range at high speed is stressed

6.5.2.2 Structures

- steel almost exclusively used due to cost and availability
- transverse framing due to hull form
- deep floors aft provide some machinery foundation, so this may be reason foundation specific weight is low
- dense ships

6.5.2.3 Personnel

- higher M/Δ that U.S.
- lower habitability standard, reflected by lower KW/Δ, $W_3+W_5+W_6/\Delta$, ∇_2/M

6.5.2.4 Payload

- higher payload weight fraction than U.S.
- more deck space to payload than U.S.
- off-shelf systems are emphasized
- RBOC emphasized

6.5.2.5 Electronics

- stress integrated command and control system, which is oriented toward a specific scenario
- consolidation of functions into one large control center
- most ships have a mini-NTDS

6.5.3 EMPHASIS (Figure 6.15)

From the above observations, a general ranking of priorities is submitted.

U.S.A.	Europe
Personnel	Payload
Mobility	Electronics
Electronics	Mobility
Payload	Personnel
(U.S. - costly, optimal)	(Europe - good enough)

The American ships are sophisticated platforms with suboptimized systems. They have high priority given to some areas which are not mission-essential. In contrast, the European ships are "good enough" platforms with an emphasis on overall optimization. They are, in short, built to "go to war" tomorrow.

6.6 Assessment of Small vs. Large Combatant Ships

The merits and shortcomings of small combatants versus frigates and destroyers vary considerably depending on the scenario. The approach used here is to try to point out general benefits and detriments, and to demonstrate that these ships are best suited for certain missions.

MOBILITY

U.S.A.		Europe
CODOG	⟷	High Speed Diesel
CRP Propeller	⟷	Fixed Pitch Propeller
Destroyer-Like Hull	⟷	Deep V Forward Flat Run Aft
Fin Stabilized	⟷	Spray and Roll Chines

STRUCTURE

U.S.A.		Europe
Aluminum Hull	⟷	Steel Hull
Longitudinal Framing	⟷	Transverse Framing
Not Dense	⟷	Dense
Complex Details	⟷	Simple Details

FIGURE 6.15A

NATIONALITY TRENDS

PAYLOAD/ELECTRONICS

U.S.A.		Europe
Low Payload Weight Fraction	↔	Higher Payload Weight Fraction
Arc-of-Fire	↔	Deck Space Utilization
Many Systems	↔	Unified, Large CIC
Domestically Produced	↔	Foreign Off-Shelf Acceptable

PERSONNEL

U.S.A.		Europe
High Habitability Standard	↔	Minimal Habitability
High Aux. Load	↔	Low Aux. Load
Low M/Δ	↔	High M/Δ

FIGURE 6.15B

NATIONALITY TRENDS

6.6.1 ADVANTAGES

6.6.1.1 Speed

A considerable amount of weight, space, and money is invested in propulsion for these ships. The payoff comes in enhanced speed. They enjoy a 5 to 10 knot advantage over contemporary destroyer-type ships. This makes small combatants ideally suited for missions which require quick reaction time, such as surprise attacks, rapid insertion of special warfare teams, and fisheries patrol. The latter is especially important with the recent institution of the 200-mile limit.

6.6.1.2 Combat Capability

The installation of highly-capable missiles onboard small combatants makes even a 200 ton vessel a force to be reckoned with. This means that larger ships and task groups must reckon with large numbers of small targets. Thus, the small combatant can be used to "tie up" large amounts of a battle group's resources. This becomes more significant in restricted waters, where the surprise attack from a nearby harbor is possible. Small ships are ideally suited for such a mission.

The increasing range and electronic sophistication of small ships has served to increase the sphere of influence of the surprise mission. It also has enhanced AAW effectiveness. The small NTDS-like command and control systems now make it possible for a flotilla commander to be in complete control of several ships. This provides a capability for coordinated multiple attacks, all with small, cheap platforms.

6.6.1.3 <u>Inherent Size Benefits</u>

These include shallow draft, which enables the ship to operate in restricted waters for insertion, hideout, and for showing the flag in places where large ships cannot venture. Low radar cross-section aids these ships. Especially in high seas or areas with islands. (RESHEF has capitalized on this by careful design of the bow-on profile.) Maintenance costs are lower with ships which do not need large overhaul and drydocking facilities.

6.6.1.4 <u>Simplicity</u>

The simplicity of conventional small ships, relative to large ships and hydrofoils or surface effect ships provides versatility and cost savings. The same hull can be adapted to offshore fisheries patrol, AAW, or surface attack. Some success has been met with adaptation to ASW and troop insertion. Simple design means easy maintenance, short crew training periods, and easy replacement of combat systems or engineering components.

When compared to large ships or hydrofoils, displacement-hull and planing-hull small ships are at a disadvantage in seakeeping. But again, simplicity helps. The high-performance ships cost much more to acquire and to maintain, so fewer can be built.

6.6.1.5 Cost

Low cost is probably the most attractive feature of small combatants. The simplicity, mission, and size benefits already mentioned combine to make small ships a very good buy. Their disadvantages can more than be made up for by the increased numbers available. This is especially important for third-world countries with small defense budget, who must get the most capability per dollar. For large countries, a small outlay of money can buy these ships for coastal defense, allowing more costly ships to be freed up for more important missions.

To put this all in perspective, a cost table has been compiled from open literature. It can be seen that the smaller ships cost much less than FFG-7, as could be expected. This means that many small platforms can be bought for the price of one large ship. Of perhaps greater significance is the cost of the PHM. This shows that sophistication costs dearly. Thus, it may be more practical to go with a simpler ship, and again build more hulls.

Ship Type	FFG	Conventional Small Combatants	Hydrofoil
FY80 Cost Range	$180-250 M	$10-25 M	$45-60 M

6.6.2 DISADVANTAGES

Buying "cheap" and small is not without its drawbacks. The lower cost of small combatants is achieved by reducing features. Chief among the disadvantages are seakeeping, survivability, and the short end of economy of scale.

6.6.2.1 Seakeeping

The major disadvantage of conventional small ships is inability to perform missions in heavy seas. The accelerations from ship motion limit performance very quickly in these ships, as compared to destroyers. Thus, their use in unrestricted waters is somewhat limited. They can transit in heavy seas, but crew and weapon restrictions rule out any fast missions in high sea states.

It should be pointed out that location will dictate the success of such ships. For instance, a fisheries patrol vessel in the North Sea must be seaworthy. But a surprise attack craft in the Carribean need not be kept in port except during hurricanes. In view of the changing requirements of speed and weather, it has been proposed that a mix of hydrofoil, planing, and displacement craft can provide total coverage. This is suited to countries such as the United Kingdom.

6.6.2.2 Survivability

One missile, torpedo, or large-caliber gun direct hit will sink most small combatants. This fact must be faced in the evaluations carried out in any force-level or trade-off study. In addition, these ships have no armor. A strafing run by aircraft can disable the entire ship in a matter of seconds; hence, the need for speed and minimum exposure time.

Curiously, the overall vulnerability of small ships reduces the need for watertight integrity and separation of machinery for redundancy.

6.6.2.3 Economy of Scale

Small ships are at the undesirable (in terms of weight, space, and cost) end of economy of scale in some key areas. As mentioned in section 6.1, size pays off for speed and range. These items are then very costly in weight on a small ship. The lack of range and seakeeping rules out any extended mission for these platforms.

Weapons capability is reduced, due to lack of a sufficiently-sized platform to carry good fire control or AAW systems. Advances have been made, but the "bottom line" is that small craft still are very susceptible to attack. The premium on large offensive missiles leaves self-defense lacking.

The low end of economy also provides for increased crew cost due to more men per ton of ship. This is highly significant for life-cycle costing.

6.6.3 CONCLUSIONS

The basic conclusion to be derived from this section is that small ships trade off certain features in order to obtain cost savings, greater numbers, and mission-oriented features such as speed. The small combatants lose heavily in the general category of operability. They are not all-weather, multipurpose platforms. They cannot endure the rigors of extended missions, as can larger naval ships. Nor are they impressive enough to establish a naval presence. The conclusion is that small ships should not be expected to play more than a limited role in an overall naval strategy, if their cost and size is to remain small.

The expansion in the small combatant shipbuilding market suggests that many nations are willing to trade off the advantages of size for the reduced cost of small platforms. Indeed, most third world countries do not really have the luxury of choosing large or small ships. So, the evidence of the marketplace points to a growing interest in small ships. Most major countries are involved in the export of these ships, and the builders themselves are active in design work. From the level of activity, it can be inferred that the design and construction of small combatants for selected missions is a viable philosophy which must be maintained.

6.7 Net Assessment of the Five Midrange Size Surface Combatants

The danger of comparing relative merits of designs is that the evaluator does not precisely know which mission each ship is required to perform. Therefore, one must assume that all ships were designed for basically the same mission, and risk an unfair comparison. However, small combatants, being more restricted in mission (than larger warships) to begin with, are less likely to be unfairly rated. Their operational scenarios are, in fact, similar.

With the above in mind, the ships will not be evaluated in terms of a specific mission, but rather they will be rated for various facets of each major area (mobility, structures, performance, etc.). Each area will be rated for both effectiveness and "efficiency" (efficiency being economy of integration). The ratings are each assigned a weight factor, based on the relative importance of that design element. The ships are scored on the basis of one to five, there being five ships in the evaluation section. Only the midrange (200 to 800 tons) ships can be considered to have the same mission. FFG-7, CPIC, and PC-1 are thus eliminated.

This method is admittedly simplistic, and subject to the whims of the evaluator. However, the level of detail required to formulate a rigorous rating system is not within the scope of this study.

The results of the ratings appear in section 6.7.3.

6.7.1 CRITERIA FOR EVALUATION

			Factor
Mission Area Performance			
	Speed:	V_{MAX}	3
		W_2/Δ (economy)	2
	Range:	R @ 30KT (normalized)	3
		$R/(Wf/\Delta)$ (economy)	1
	Seakeeping:	Ranking	3
		Economy (fins, hull form, etc.)	2
	AAW:	Ranking	2
	ASW:	Ranking	1
	SUW:	Ranking	3
	Command and Control	Ranking	3
Cost	FY 80 Cost Estimate		10
Design Features			
	Propulsion:	Plant flexibility	2
	Personnel	Hab. Standard (∇_2/M)	1
		Economy (M/Δ)	2
	Structure:	Integration ($WH/\nabla H$)	2
		Economy (W_1/Δ)	2

Total Score Possible - 5x42 = 210 points

6.7.2 REVIEW OF RATINGS

The ships are rated, as discussed in the first section of this chapter. The final scoring is in section 6.7.3. This section points out the good and bad points of each design, hopefully explaining the ratings for the gross features. The ratings for the "economy"-type indices are straight from the appropriate section of Chapters IV and V, and are based strictly on relative numerical values.

6.7.2.1 PG-84

PG-84 is an outdated design. It has the attributes of high speed and low cost, but little else. Its capability is satisfactory for the time frame of the design, but has little to offer in the 1980's. The range is poor at 30 KT, and is undoubtedly worse at higher speed. This is due to the high specific fuel consumption of the vintage gas turbine and to low fuel load. Seakeeping of this ship has proven to be unsatisfactory for any serious offshore work. Neither hard chine nor a fin stabilizer is present to dampen rolling.

PG-84 is a structurally economical ship, with use of aluminum to reduce weight and longitudinal framing.

Habitability is good on this ship due to a low crew size. There is a low electrical load, however, which suggests that air conditioning and crew services do not necessarily follow the space allocated per man. In addition, higher numbers of men have eventually been assigned to this ship, with a resultant reduction in space and weight per man.

The area in which the PG-84 suffers most from obsolescence is in combat capability. It has an older main gun, machine guns, and no missiles. The fire control radar is also outdated. There is no missile system. An update has been built with an MK 87 fire control system and standard A.R.M., but even these missiles are out of date, and there is a stability loss. CIC is small and unsophisticated.

6.7.2.2 PGG

This ship is basically an updated, enlarged version of PG-84. Most of the speed has been retained, and the range has been improved, but it is still not as good as that of RESHEF and PCG. A hull form similar to PG-84 is used, but fin stabilization is employed for improved seakeeping. Reliability is as good as PG-84 or better.

Structurally, the ship is an improvement over PG-84, with the lightest group 100 weight fraction of the study.

Habitability on this design refelcts the high U.S. standards. The auxiliary load is high, with many support services. This is because the ship is built for a hot climate.

Combat capability on PGG is good, due to a good fire control system, modern gun, and long-range surface-to-surface missiles. There is space and weight reserved for a secondary AAW gun, presumably a close-in type system. PGG still lacks the fully integrated control center seen in European ships. No ASW capability is provided.

6.7.2.3 PCG

This ship enlarges the PG-84, PGG-type hull up to 750+ tons, for the purpose of gaining an ASW capability, and a good air-search radar. Most of the comments for PGG apply to PCG, and are not repeated. However, certain differences are notable. The most obvious is speed loss, which degrades the ship's missions, although this is not so serious for ASW. The use of a similar plant for both PGG and PCG may reduce maintenance cost, but it trades off top speed.

Structurally, the use of a steel hull dirves group 100 weight fraction very high. Habitability is almost identical to PGG.

The gain in combat capability from PGG makes PCG a truly three-dimensional combatant. Again the control center (CIC) is not as integrated as could be, but overall, this ship is quite capable. From the "fast attack craft" point of view, the cost in weight and money is too high. But from the corvette-frigate point of view, an impressive capability has been packed onto a small platform. The implication here is that PCG's mission is somewhat different from that of the norm.

6.7.2.4 RESHEF

This ship has placed well in the ratings. It is a good all-around platform with the most flexible and complete weapons suite. It represents a very large portion of the small combatants presently being constructed in Europe.

RESHEF's speed is low, due to deliberate use of small engines. However, it is a good rough weather ship, and has the best range at 30 knots of any ship rated. This makes up for the lack of calm water speed.

RESHEF is constructed of steel, and suffers a large group 100 weight fraction as a result. It compensates in habitability and outfit items, which make the ship an austere one for crew comfort. However, the ship has steamed across the Atlantic, and is thus capable of a long mission, if pressed.

The combat suite of the RESHEF class consists of two modern guns, and surface-to-surface missiles. Weapons launchers have priority for deck space, and several alternative configurations are possible by changeout of the after mount. The command center is large, well laid out, and completely integrated. The radar and infrared cross-sections are very reduced, through careful attention to design details. The ship employs two kinds of chaff launchers. To RESHER's credit, it has already been involved in combat with Soviet-built small combatants, and has proven itself to be a superior warship.

The cost figure used is for a similar craft ordered in 1980, and may be a little high. However, even with a cost penalty, this ship has the highest score, so a more realistic figure can only improve its position.

6.7.2.5 SPICA II

This ship scores very high in the table. It is not as capable, but it has many features which make it compare favorably to the U.S. designs.

The outstanding area for SPICA II is mobility. It gets a high top speed with a very small (in weight) gas turbine plant with fully-cavitating screws. Range at high speed is about in the middle of the group, while size is the smallest.

The steel structure uses up weight, but as in RESHEF, the SPICA II makes up for this by austerity in the habitability area.

The combat capability of SPICA II is about mid-range for the rated ships. It has no missiles, but later versions have had them installed. SPICA II has an impressive wire-guided torpedo capability, and an offensive mine-laying mission, which is unique to this ship. A mini-NTDS type command and control system is fully integrated into the combat system, making the ship easy to fight.

Perhaps most important is the small size of this ship. It is designed to operate in rough seas, to carry a large payload weight fraction with a modern electronics suite, all in 230 tons. This is an innovative, low-cost design, which can be built in numbers.

6.7.2.6 Conclusions

The results indicated in section 6.7.3 should not be interpreted as the last word on the relative merits of each design. Rather, they rate the ships by a set of features which are considered important by this researcher. They do point out that the U.S. tends to utilize high cost solutions to design problems, and to emphasize features which are not mission-critical. As mentioned in section 6.5, the European ships are spartan in non-military areas, and they emphasize mission performance with overall optimization vs. component optimization. The results would look worse for the U.S. if PHM were included due to its very high cost and technical emphasis, compared to the other ships.

Note that cost drives the ratings more than any other factor. If the weighting for cost were reduced, the results would be more competitive. However, cost is, in fact, a very important consideration, and it is felt that small, inexpensive ships ought to stay inexpensive. Thus, the emphasis on this feature has been left to stand.

6.7.3 Ship Ratings

	Attribute	Weight	PG-84 R	PG-84 S	PGG R	PGG S	PCG R	PCG S	SPICA R	SPICA S	RESHEF R	RESHEF S
Vehicle Performance	V_{MAX}	3	4	12	3	9	1	3	5	15	2	6
	W_2/Δ	2	1	2	2	4	3	6	5	10	4	8
	R	3	1	3	2	6	4	12	3	9	5	15
	$R/W_f/\Delta$	1	2	2	4	4	5	5	1	1	3	3
	Seakeeping	3	3	9	4	12	5	15	4	12	4	12
	Economy	2	1	2	2	4	3	6	4	8	5	10
Mission Perfor-mance	AAW	2	2	4	5	10	5	10	3	6	4	8
	ASW	1	2	2	2	2	5	5	3	3	4	4
	SUW	3	1	3	3	9	4	12	2	6	5	15
	CAC	3	1	3	2	6	3	9	4	12	5	15
Cost	Cost	10	5	50	3	30	2	20	4	40	3	30
Design Features	Flex	2	5	10	5	10	5	10	4	8	3	6
	HAB	1	5	5	3	3	4	4	2	2	1	1
	M/Δ	2	4	8	3	6	5	10	2	4	4	8
	W_H/∇_H	2	4	8	5	10	1	2	2	4	3	6
	W_1/Δ	2	4	8	5	10	3	6	2	4	2	4
TOTAL SCORE		42	131		135		135		144		151	

R = Rank S = Score

6.8 Chapter Summary

The conclusions reached in this chapter can be classified into three types. The first is the identification of features which have major influence on the design. The next group consists of observations about features which make small naval vessels attractive, or undesirable. Fianlly, overall evaluations of five ships have been executed based on an assessment of important design elements.

The results of this chapter point to mission criteria (notably speed) and benefits of size as being principal driving forces in design. Other factors which are less significant are nationality and age. The combination of these influences produces ships which are very desirable when looked at for cost, but not as attractive when their limitations (especially rough weather performance degradation) are considered. The ratings have introduced the idea that the European ships would be superiod in combat performance, but that the American ships are more habitable.

The conclusions drawn above, and those throughout the chapter, point to one underlying concept. That is, increased operability, flexibility, and ruggedness always push size upward. Increased endurance, addition of mission areas, and comfortable living are all features associated with large combatants. Thus, the demands of a long-range open-ocean mission call for certain design features which tend to increase ship size. This means that an effort to reduce the size of naval ships to the small combatant range necessarily results in a loss of flexibility, and in a reduction of performance in many mission areas. As a consequence, small combatants must be optimized for a limited specific mission. Those which follow this logic are successful. Those which try to cover a large mission portfolio do not fare as well.

CHAPTER VII

CONCLUSION

7.1 Summary of Conclusions

The purpose of this study has been the identification and analysis of those factors which have impact on small combatant design. To achieve this end, an investigation of the design features of several ships has produced a data base of design statistics. These, in turn, have been examined in order to highlight important aspects of design and to understand the philosophy which influences major design decisions. The results of this examination have been brought out in Chapter VI, and are summarized by major category below.

7.1.1 MISSION IMPACT

It is realistic to assume that the mission requirements which generate the need for a ship also have the most influence on its design. This is true for small combatants, as well as for any other ship type. The major observations of mission-impacted features have been stated in section 6.1. The most important of these is the requirement for speed, which pushes main propulsion weight higher, increases local loading due to pounding, and also generates an overall need to lighten the ship. This weight reduction is accomplished by lighter, more efficient structure, or by reduction of non-essential habitability and auxiliary systems.

The speed requirement is consistent with a short surprise offensive mission for small naval ships. Such a mission dictates, in addition to a large power plant, high range at flank speed, simple topside cannister-launched weapons, and a large, sophisticated control center belowdecks. The design impact of these features is fuel tankage increase, deck space arrangement, and concentration of weapons control and electronics into a large space. The surprise mission of short duration is also further justification to reduce habitability to a minimal level.

7.1.2 SIZE TRENDS

The chief areas for economy of scale are mobility and personnel. As pointed out by section 6.2, an increase in ship size results in increased range and speed for a lower weight penalty in machinery and fuel. Thus, increasing size to gain this benefit is very attractive for small combatants, which rely on speed to reduce their exposure to attack. More important, though, is the improvement in seakeeping which comes with increased size. As small, fast patrol ships expand their missions, this fact will be increasingly important.

In the personnel area, increased ship size allows a smaller investment of men for each ton of ship. Offsetting this trend is an increase in habitability. The net impact is a reduction of the volume fraction dedicated to living spaces as ship size increases.

The benefits of size also include enhanced weapons and electronics effectiveness. As ship size increases, more potent, sophisticated systems can be installed. Thus, the overall mission capability of a ship is dramatically enhanced by growth in size.

The basic concept underlying the three scale effects mentioned above is operability. With increased ship size comes longer mission, better crew comfort, and better combat effectiveness. Thus, many of the desirable attributes of a flexible combat system improve as ship size increases. The tendency, therefore, in small combatants, is to grow in size as the scope of their missions increases.

7.1.3 DESIGN LANES

Section 6.3 lists design lanes which appear to exist in small naval ships. They need verification with more data, but they do represent a rough approximation of design standards presently in use. It would be redundant to list the ranges of various parameters, but it is appropriate to note the following areas which differ from the more familiar frigate-destroyer design practice.

In general, investment in structural weight is lower in the ships studied than for most destroyers. Conversely, main propulsion weight fraction is higher than for destroyers. This follows a much higher main propulsion/ship size ratio (SHP/Δ) generated by high speed requirements. Payload weight fraction is higher on the small ships, but payload volume fraction is lower. This demonstrates the use of simple, topside-launched weapons. Because of the emphasis on short missions, non-essential items are eliminated in small combatants. Thus, auxiliaries (group 500) and outfit (group 600) weight fractions are reduced in deference to the groups mentioned previously.

Weight and volume usage are of primary interest, but performance indices are noteworthy. Speed has already been mentioned as being higher and more important to small combatants. Range is lower than that of larger ships, for reasons of scale. Transport efficiency is lower for smaller ships due to decreased displacement, while productivity index is higher because of improved speed and payload weight fraction.

7.1.4 INFLUENCE OF AGE

Expanding mission requirements, availability of increased horsepower, and the use of cruise missiles have heavily influenced small naval ship design over time. The net impact of these factors has been an enhancement of the ship system operability and flexibility. This trend generates all of the size effects mentioned in section 7.1.2. That is, displacement increases as range, seakeeping, and combat system performance requirements increase. The additional flexibility increases ship size further, through the design spiral, as auxiliaries, electric power generation, air conditioning, etc., loads increase.

From the above discussion, and section 6.4, it is evident that small combatants have undergone many of the same changes which are observed in frigates and destroyers. The trend to expanded mission appears to influence all naval combatant ships similarly.

7.1.5 NATIONALISTIC INFLUENCES

As section 6.5 points out, nationality can account for large differences in design practice. The major nationalistic tendencies found in that section include the following: (1) low habitability on European ships; (2) high structural weight fraction due to use of steel on European ships; (3) emphasis on CODOG propulsion in U.S. ships; (4) emphasis on high habitability in U.S. ships; (5) inexpensive solutions in European ships vs. expensive ones for U.S. ships; and (6) the tendency of European ships to be designed as if a state of war already exists.

It should be noted that the sample of European designs is too small to support an absolute conclusion. However, the national preferences mentioned above are on the gross level, and are not difficult to verify by an examination of Jane's Fighting Ships[28] or Combat Fleets of the World.[9]

7.2 Lessons Learned

A review of the results from Chapter VI leads to the resolution of the trends and conclusions into a few basic issues. These include cost, benefits of increased size, ship performance, and combat system performance. These areas are now summarized to illustrate what has been learned in a general sense about the fundamental issues of small combatant ship design.

Perhaps the most important feature to be discussed is cost. The small ship derives much of its desirability from being an inexpensive solution to the problem of maritime defense. As such, it is the only ship available to less-affluent countries. Even nations with abundant monetary resources cannot afford both coastal defense and global power projection unless the cost of the small combatant is reasonable. Therefore, any measures which increase cost without a very big payoff in fighting ability should not be employed. This is where the western European designers have learned to emphasize basic performance, and where the American ships tend to use expensive solutions for design problems, and to include "luxury" items. It is submitted that the money laid out for a small ship is best spent on electronics and weapons, where it will pay off in mission performance.

Since cost is related to ship size, the benefits to be gained from increased size must be weighed carefully for their value. Economy of scale says that "bigger is better" for the areas of personnel and main propulsion. However, the best reason for small naval ships to grow is for better seakeeping. The other factors increase operability and flexibility, but the designer of small ships must convince himself that he can indeed sacrifice these features in order to reduce ship size without severely degrading basic performance.

From the discussion of mission (section 6.1) it is evident that the speed of the ship is important. More specifically, speed in all weather, and range at high speed, matter much more for small combatants than for larger ships. Hence, installation of powerful plants (relative to ship size) is justified. Also evident from the mission discussion is the lack of a need for high habitability. The nominal missions for the ships is from 60 hours to 336 hours (excluding FFG-7), but only PCG is likely to see such a mission. The more typical one or two day sortie requires only the bare essentials. Again, the U.S. designs pay too high a price for habitability.

Combat systems should be versatile, able to be changed easily, and fully integrated. All of the ships show good flexibility of armament, and most have an emphasis on electronics. The ability of the Captain to have full control of every facet of ship operation in combat is paramount, since these small platforms must react quickly and effectively to a threat, and employ their scant defense measures in timely fashion.

To summarize the lessons learned in this study, the underlying concept in small combatant design is: keep inexpensive ships inexpensive, and use the money where the payoff is. This should be taken into consideration when weighing the various approaches to meeting mission requirements. Thus, economy of scale, the "brute force method", and clever or elaborate design practice must be combined with the philosophy of keeping cost down, or the attraction of a small platform is lost.

7.3 Recommendations for Further Study

At the conclusion of this project, there is much room for further research. This study has not been exhaustive in all areas, and the number of ships investigated has been limited. The major philosophies in small combatant ship design have been identified, the driving parameters have been explored, and the trends which are evident in this field have been examined. It remains for these to be verified utilizing a large data base.

The expansion of the data base may prove to be a difficult task. The availability of unclassified and non-proprietary material is poor, and has had a detrimental effect on the confidence of some of the conclusions. Hopefully, as designs proliferate, more information will be forthcoming.

After the findings of this study are verified and expanded, the next logical extension is a ship synthesis model for the ships from about 250 to 1,000 tons. This could be developed through a parametric study of the enlarged data base. This model could be used for new designs, or to check completed projects.

Some specific areas require intensive study. Chief among these is seakeeping. This weak point in the argument for small ships must be explored thoroughly for exploitation of any possible improvement. The CPIC and PC-1 projects go a long way toward meeting this end, and they should be included in any evaluation of seakeeping.

Another area for extensive research is combat capability assessment. The considerable variety of weapons and electronics systems available for use on small naval ships makes it very desirable to perform a comprehensive study of combat systems. The benefits of various trade-offs, and their impact on the total ship system, must be evaluated and made available to designers. A working base (which could be incorporated in the computer model) is a definite need, since the size and cost of small combatant projects do not justify extensive trade-off studies.

The projects outlined above should give a very good working knowledge of small naval ship design, and they would be well worth the effort.

7.4 The Future of Small Combatants in the U.S. Navy

The emphasis of the U.S. Navy has been almost exclusively on overseas power projection. Although possible roles for small combatants exist in the Mediterranean and Caribbean Seas, the United States has made no serious effort to procure small, fast warships since the early 1960's. This lack of attention is partially compensated by design and construction for foreign countries (PGG and PCG), but the U.S. still has a gap in the small-displacement range of ships.

It is not the purpose of this author to justify the use of small combatants by the Navy. However, possible missions for such ships clearly exist. If it is assumed that some need will present itself in the next twenty years, there should be a continuous policy toward design of small ships.

It is submitted that if the United States decides to build more small combatants, the first step would be to survey overseas, where the state of the art is constantly being pushed. Next, the Navy should make use of its own small combatant design talent to survey the lessons learned from foreign (and domestic) ships, and to apply them to any new design.

It is further submitted that the simplest, most inexpensive solution to basic platform design is the best approach. Thus, if the decision is made to build a ship which sinks after one hit, then a complex, expensive basic hull (e.g., hydrofoil) is not worth the extra cost of enhanced performance. Instead, the less capable ships should be procured in quantity, with perhaps a few high-technology ships to complement them. This approach would permit the emphasis to be placed on combat capability, systems integration, and on "improving the breed" of conventional small combatant ships.

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APPENDIX A

DESIGN INDEX LISTING

2.3.1 DESIGN INDICES BY TYPE

Symbol	Units	Explanation
2.3.1.1 Gross Characteristics		
L	FT	Length overall
Δ_{FL}, Δ	Long Tons	Full load displacement
Δ_{LS}	Long Tons	Lightship displacement
∇, ∇_T	FT^3	Total Internal Volume
V_{MAX}	KT	Maximum speed as listed in *Jane's Fighting Ships*
V_S	KT	Maximum sustained speed (80% power)
V_E	KT	Endurance Speed
R	NM	Range (fuel endurance)
M	--	Accomodations
N_A	--	Number of weapon launchers
D	Days	Stores Endurance

KW	KW	Electric capacity
SHP_C	HP	Cruise engine horsepower
SHP_B	HP	Boost engine horsepower
SHP_T	HP	Total installed horsepower
A	FT^2	Total weather deck space (top view)

2.1.3.2 Weight Fractions

W_1/Δ	%	Hull structure weight fraction
W_2/Δ	%	Main propulsion weight fraction
W_3/Δ	%	Electrical weight fraction
W_4/Δ	%	Command and surveillance weight fraction
W_5/Δ	%	Auxiliaries weight fraction
W_6/Δ	%	Outfit and furnishings weight fraction
W_7/Δ	%	Armament weight fraction

Δ_{LS}/Δ_{FL}	%	Lightship weight fraction
WF/Δ	%	Fuel weight fraction
W_{AMMO}/Δ	%	Ammunition weight fraction
W_{CREW}/Δ	%	Crew and effects weight fraction
W_{STORES}/Δ	%	Stores weight fraction
W_{WATER}/Δ	%	Potable water weight fraction
W_{LOADS}/Δ	%	Loads weight fraction
$\frac{W_4 + W_7 + W_{AMMO}}{\Delta}$	%	Payload weight fraction

2.3.1.3 Volume Fractions

$\nabla_{1.1}/\nabla$	%	Communication, detection, evaluation volume fraction
$\nabla_{1.2}/\nabla$	%	Weapons volume fraction
$\nabla_{1.3}/\nabla$	%	Aviation volume fraction
$\nabla_{1.4}/\nabla$	%	Special missions volume fraction

∇_1/∇	%	Payload volume fraction
$\nabla_{2.1}/\nabla$	%	Living spaces volume fraction
$\nabla_{2.2}/\nabla$	%	Living support volume fraction
$\nabla_{2.3}/\nabla$	%	Personnel stowage volume fraction
∇_2/∇	%	Personnel volume fraction
$\nabla_{3.1}/\nabla$	%	Ship control volume fraction
$\nabla_{3.2}/\nabla$	%	Main propulsion volume fraction
$\nabla_{3.3}/\nabla$	%	Auxiliaries volume fraction
$\nabla_{3.4}/\nabla$	%	Maintenance volume fraction
$\nabla_{3.5}/\nabla$	%	Storeroom volume fraction
$\nabla_{3.6}/\nabla$	%	Fuel and lub. oil tank volume fraction
$\nabla_{3.7}/\nabla$	%	Passageway volume fraction
$\nabla_{3.8}/\nabla$	%	Voids volume fraction
∇_3/∇	%	Ship operations volume fraction

2.3.1.4 Weather Deck Space Fraction
(Measured from a top view. Weapon area includes swing circles of mounts.)

$A_{Weapons/Sensors}/A$	%	Weapons sensors space fraction
$A_{Superstructure}/A$	%	Superstructure space fraction
$A_{Intake\ and\ Exhaust}/A$	%	Intake/Exhaust space fraction
$A_{Boats\ and\ R.A.S.}/A$	%	Boat/replenishment-at-sea space fraction
$A_{Main\ Deck}/A$	%	Main deck (unassigned) space fraction

2.3.1.5 Densities

Δ/∇	LB/FT^3	Ship density
$\dfrac{W_7 + W_4}{\nabla_1 - 1 + \nabla_{1.2}}$	LB/FT^3	Weapons/electronics density
$\dfrac{W_{PERS} + .3W_6 + W_{WATER} + W_{STORES}}{\nabla_2}$	LB/FT^3	Personnel density
$W_2/\nabla_{3.2}$	LB/FT^3	Main propulsion density
$\dfrac{W_{LUBE\ OIL} + W_{FUEL}}{\nabla_{3.6}}$	LB/FT^3	Fuel/lubricating oil density

$\frac{W_4+W_7+W_{AMMO}}{\nabla_1}$	LB/FT^3	Combat system density
$\frac{W_2+W_3+W_5+7W_6}{\nabla_3}$	LB/FT^3	Ship operation density

2.3.1.6 Specific Ratios

W_7/N_A	Ton/Launcher	Armament specific ratio
$\frac{W_{PERS}+.3W_6+W_{WATER}+W_{STORES}}{M}$	LB/Man	Personnel weight specific ratio
∇_2/M	FT^3/Man	Personnel volume specific ratio
W_1/∇	LB/FT^3	Structural weight specific ratio
W_2/SHP	LB/HP	Main propulsion weight specific ratio
$\nabla_{3.2}/SHP$	FT^3/HP	Main propulsion volume specific ratio
W_5/∇	LB/FT^3	Auxiliaries specific ratio

W_3/KW	LB/KW	Electrical weight specific ratio
$\frac{W_5+W_6}{\nabla}$	LB/FT^3	Ship operations specific ratio
$\frac{\nabla_{3.2}+\nabla_{3.3}}{SHP_T+(KW)1.34}$	FT^3/HP	Machinery specific volume

2.3.1.7 Capacity/Ship Size Ratios

N_A/Δ	Launchers/Ton	Armament ship size ratio
M/Δ	Men/Ton	Manning ship size ratio
SHP_B/Δ	HP/Ton	Boost horsepower ship size ratio
SHP_T/Δ	HP/Ton	Total horsepower ship size ratio
KW/Δ	KW/Ton	Electric power ship size ratio

2.3.1.8 Overall Performance

$\Delta V/SHP_T$	$\frac{(Ton)(KT)}{HP}$	Transport efficiency @ V

$\frac{(W_4+W_7+W_{AMMO})V_{MAX}}{\Delta}$	KT	Productivity index
L/D	--	Lift to drag ratio @ A Given V

2.3.2 DESIGN INDICES BY FUNCTION (Not already listed under type)

2.3.2.1 Main Propulsion

W_{230}/SHP	LB/HP	Prime mover specific weight
W_{240}/SHP	LB/HP	Transmission specific weight
W_{250}/SHP	LB/HP	Support and fluids specific weight
W_{241}/SHP	LB/HP	Reduction gear specific weight
SFC	LB/HP-HR	Specific fuel consumption
P.C.	--	Propulsive coefficient (EHP/SHP)

2.3.2.2 Electrical

W_{310}/KW	LB/KW	Generator specific weight

W_{324}/KW	LB/KW	Switch gear specific weight
W_{475}/KW	LB/KW	Degaussing specific weight
W_{340}/KW	LB/KW	Electrical support specific weight
W_{398}/KW	LB/KW	Electrical operating fluids specific weight

2.3.2.3 Auxiliary Systems

$\frac{(.5W_{512}+.5W_{514}+W_{516}+W_{517})}{W_5}$	%	Climate control weight fraction
$.4W_{521}/W_5$	%	Saltwater systems weight fraction
W_{531}/W_5	%	Distilling plant weight fraction
$\frac{(.8W_{551}+.8W_{536}+W_{553}+W_{554})}{W_5}$	%	Gas and fluids weight fraction
$\frac{(W_{571}+W_{572}+W_{581}+W_{582}+W_{583}+W_{584}+W_{585}+W_{589})}{W_5}$	%	Deck available weight fraction

W_{598}/W_5	%	Auxiliaries systems operating fluids weight fraction
$\dfrac{(.5W_{512}+.5W_{514}+W_{516}+W_{517})}{\nabla}$	LB/FT^3	Climate control specific weight
$.4W_{521}/\nabla$	LB/FT^3	Saltwater systems specific weight
W_{531}/M	LB/Man	Distilling plant specific weight
$\dfrac{(.8W_{551}+.8W_{556}+W_{553}+W_{554})}{\nabla}$	LB/FT^3	Auxiliaries gas and fluids specific weight
$\dfrac{(W_{561}+W_{562}+W_{566}+W_{568})}{\Delta}$	LB/Ton	Steering and maneuvering specific weight
$\dfrac{(W_{571}+W_{572}+W_{581}+W_{582}+W_{583}+W_{589}+W_{585}+W_{589})}{\Delta}$	LB/Ton	Deck auxiliaries specific weight
W_{598}/∇	LB/FT^3	Auxiliary systems operating fluids specific weight

2.3.2.4 Hull Structure

$\frac{W_{110}+W_{120}+W_{130}+W_{140}}{\Delta}$	%	Basic hull weight fraction
W_{150}/Δ	%	Superstructure weight fraction
$\frac{W_{160}+W_{170}}{\Delta}$	%	Special structure, mast, kingpost weight fraction
W_{180}/Δ	%	Foundations weight fraction
W_{198}/Δ	%	Free-flow liquid weight fraction
W_{150}/V_{SHP}	LB/FT^3	Superstructure specific weight
$\frac{(W_{110}+W_{120}+W_{130}+W_{140})}{V_{HULL}}$	LB/FT^3	Basic hull specific weight
$\frac{W_{180}}{W_2+W_3+W_4+W_5+W_6+W_7}$	LB/FT^3	Foundations specific weight

2.3.2.5 <u>Personnel</u>

$\frac{.2W_{521}+W_{528}+W_{641}+W_{642}+W_{643}+W_{644}+W_{CREW}}{M}$	LB/Man	Personnel living specific weight
$\frac{W_{434}+W_{439}+W_{528}+W_{591}+W_{695}+W_{650}+W_{661}}{M}$	LB/Man	Personnel support specific weight
$\frac{.5W_{533}+W_{638}+W_{672}+W_{STORES}+W_{WATER}}{M \cdot D}$	LB/Man-Day	Personnel storage specific weight
$V_{3.1}/M$	FT^3/Man	Personnel living specific volume
$V_{3.2}/M$	FT^3/Man	Personnel support specific volume
$V_{3.3}/M$	FT^3/Man	Personnel storage specific volume

2.3.2.6 <u>Hull Form</u>

L/B	--	Length to beam ratio
$L/\sqrt[3]{\Delta}$	--	Slenderness ratio
C_B	—	Block coefficient $\left(\frac{\Delta x35}{LxBxT}\right)$

C_P -- Prismatic coefficient $\left(\frac{\Delta x 35}{A_{MAX} x L}\right)$

C_X -- Maximum section coefficient $\left(\frac{A_{MAX}}{B x T}\right)$

CWP -- Waterplane coefficient $\left(\frac{A_{WP}}{B x L}\right)$