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"DESIGN TO COST"— A VIABLE CONCEPT IN NAVAL SHIP DESIGN

THE AUTHORS

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ABSTRACT

The "Design to Cost" concept is investigated from a practical viewpoint by analyzing the impact this design philosophy has had on recent Navy ships. The Guided Missile Frigate design is used as a case study to determine the differences between naval ships "Designed to Cost" and those conventionally designed. The case study includes an investigation of naval architectural features, performance, cost, and an analysis of the design "trade-off" decisions.

The analysis of the FFG-7 "Design to Cost" pointed out a number of significant differences compared to conventional ship design. A substantial weight and cost saving was realized due to the highly constrained design environment. It is estimated that the FFG-7 would have displaced about 1500 tons (40 percent) more if it had not been for the "Design to Cost" procedure. This saving was achieved primarily as a result of a reduction in performance requirements.

The future of "Design to Cost" as a viable design philosophy for naval ships is discussed. It is concluded that the Navy must follow this concept in order to hold down the cost of combatant ships but that a decrease in overall ship performance must be expected.

INTRODUCTION

THE NAVY'S APPROACH TO SHIP DESIGN and acquisition has experienced several dramatic changes in the past 15 years. In the early 1960's the Concept Formulation/Contract Definition (CF/CD)/Total Package Procurement (TPP) approach replaced conventional ship design and acquisition. CF/CD/TPP introduced a new method to accomplish the design (a rigorous systems approach emphasizing a design philosophy of cost effectiveness based on life-cycle cost) and a new approach to weapons system procurement (a single contract package for development and production of the entire ship class). This approach has been deemed unsuccessful for the acquisition of naval ships (and all military procurement for that matter), and it has been replaced by a new approach to weapons acquisition which the Authors will refer to as the "present" acquisition method. The present approach incorporates several of the strong points of each of the two previous approaches and introduces several new innovations. One of the most important of these innovations is the concept of "Design to Cost (DTC)."

There are many interesting aspects of the ship design and acquisition process which deserve discussion when comparing the three acquisition approaches. This paper will concentrate on only one — "Design to Cost." Although DTC is a relatively new concept, already there is a considerable body of literature available. Basic policy and guidance from higher authority are contained in Department of Defense Directives (References [1] through [4] and numerous papers address the implementation of "Design to Cost" in systems design ([5] through [10]). LEOPOLD, *et al* describe how DTC may be applied to the design of naval ships [11].

It is not the purpose of this paper to review this literature or dwell on material already covered. The objective of this paper is to answer the following fundamental questions which have not been adequately addressed:

—Is a naval ship designed under the DTC philosophy significantly different than ships designed by conventional means?
—If a DTC ship is different, what is the basic cause?
—Is the DTC product attractive?
—Should the NAVY continue to employ this concept in ship design?

Material was gathered to answer these questions primarily through a case study of the Guided Missile Frigate (FFG-7) design formerly designated as the Patrol Frigate (PF). The results from this study, combined with the Authors' observations in the general field of naval ship design, form the basis for the conclusions arrived at in this paper.

The paper will first provide a brief discussion of the background which led up to the establishment of the policy to "Design to Cost." The second Section will report the results of the analysis of the FFG-7 design. The final two Sections will discuss the future of DTC and present the conclusions of the study.

"DESIGN TO COST" BACKGROUND

Development of the DTC Policy

The concept of "Design to Cost" was first introduced as a formal policy in Department of Defense Directive 5000.1 in 1971 as follows:

> "Cost parameters shall be established which consider the cost of acquisition and ownership; discrete cost elements (e.g., unit production cost, operating and support cost) shall be translated into "design to" requirements."

The requirements for "designing to cost" were defined further in References [2] through [4], which explain that the intent of DTC is to make the unit cost of a weapon system conform to a value which has been established either prior to or very early in the design. Although DTC is certainly not a new concept for private enterprise, it does represent a change in the design philosophy for the NAVY.

A ship designer must have a design philosophy to guide him in making the numerous "trade-off" decisions and compromises which dominate the design process. Two issues which require guidance involve the relative importance of performance and cost and the selection of which cost is to be used in design "trade-offs." The guidance relative to these two points can be summarized as follows [2][3][4]:

1) Performance/Cost "Trade-off" —

> "There must be a willingness to trade-off desired performance to achieve the cost goals while assuring that a viable weapon system design is obtained."
>
> "A Design to Cost program should be implemented which prevents funds being spent beyond the point where costs rise rapidly for small increments of increased performance/reliability."
>
> "Although the Design to Cost concept does require cost, schedule, and performance trade-offs, minimum essential performance requirements must not be sacrificed."

2) Acquisition vs. Life-Cycle Cost —

> "Unit production cost must become a primary design parameter. But this emphasis should not be construed to imply that the unit cost is the sole driving consideration in systems acquisition. Acquisition cost reductions must not be achieved at the expense of increased ownership costs."
>
> "DTC is not a license to trade-off operating and support costs for reduced acquisition cost."

The guidance related to the performance/cost "trade-off" can be simplified further by saying that the Ship Acquisition Manager should be willing to pay for only what is absolutely needed. This guidance is provided to increase the cost consciousness of ship designers and acquisition managers and thus hold down the cost of ships. What remains to be determined is the fine distinction between minimum essential performance requirements and excessive performance capabilities. This distinction cannot be determined exactly but rather is subjective and strongly dependent on one's individual perception of naval requirements.

References [2] through [4] do not provide explicit direction to design to either acquisition or life-cycle cost. The guidance implies that the designer must achieve a balance between acquisition and life-cycle cost. Although it does not specify which should have priority, there is little doubt that the immediate visibility of specifying a constraint or unit production cost (i.e., acquisition cost) and the reality that initial budget requirements are established for acquisition cost will result in ship acquisition cost receiving the greatest attention.

Motivation for DTC

The objective of "Design to Cost" is to hold down the acquisition cost of weapon systems. With the extremely tight fiscal constraints facing the Department of Defense matched with the history of sharply escalating cost of weapon systems, it is not surprising that this policy is receiving high level attention in the weapon system acquisition business.

The situation in ship acquisition closely parallels that of any other weapon system. The unit acquisition cost of ships has increased dramatically, the purchasing power of the Shipbuilding and Conversion, Navy (SCN) budget has remained relatively constant, while the demand for new ships has increased. Quite simply the NAVY, as well as the entire Department of Defense (DOD), cannot afford to buy the weapons needed to maintain the desired strong defense posture. The resources made available to DOD to acquire weapons have just not kept pace with the rapidly spiraling costs of military hardware. Thus "Design to Cost" is an attempt to hold down the unit acquisition cost of ships so that the NAVY can afford to buy the number of ships needed to maintain the required Fleet levels.

Reducing the Cost of Naval Ships

Once the objective and motivation behind the "Design to Cost" concept are understood, one must determine how to go about the task of reducing cost. There are *three* ways one can attack the problem:

- Reduce performance (Since cost is directly proportional to performance, this is the most obvious but least desirable means of reducing ship cost).
- Take advantage of technology (Advances in technology have produced in some cases smaller, lighter weight, and simpler components which when incorporated into the ship design result in a reduction in ship cost).
- Improve management to produce a tight design (A rigorous design discipline is required to produce a design which is sized exactly to that required to fulfill the basic design requirements. An oversized ship will of course be more costly).

It is important to understand how much cost reduction can be associated with each of these methods. This issue will be addressed later in the paper. It should be pointed out that the customer (i.e., the NAVY's operating community) has the primary responsibility for specifying the ship's operational performance requirements and thereby controls cost reduction by the first method. On the other hand, the technical community is responsible for cost reductions which fall under the other two categories.

THE GUIDED MISSILE FRIGATE DEVELOPMENT—A CASE STUDY OF DTC

The discussion on "Design to Cost" provided in the previous Section and the analysis of this design approach which is available in the literature deal primarily with the *theory* of the "Design to Cost" philosophy. There now is a ship, the Guided Missile Frigate, which has been designed under this philosophy and thus it is possible to determine the actual impact of "Design to Cost." At the time of this investigation there were *three* combatant ships which had been designed under the "Design to Cost" philosophy: Guided Missile Frigate, Sea Control Ship, and DG Aegis. Only the Guided Missile Frigate has proceeded into production and for that reason was selected to form the basis of this case study. Figure 1 is an artist's rendition of the FFG-7.

The study of the FFG-7 was carried out to determine whether or not the DTC process produced a significantly different ship design. The Authors are well aware of the ever changing Washington environment with its continuous development of new initiatives and directives. A ship design reflects the design philosophy and methodology which governs during its development, and thus an examination of the design product

Figure 1. The Guided Missile Frigate FFG-7 — An Example of a "Design to Cost" Ship Design.

should permit a realistic assessment of whether or not DTC is a workable concept.

It should be noted that ship design analysis is by no means an exact science. The Authors formed their conclusions based on an examination of the documentation from the FFG-7 Project, interviews with key participants in the FFG-7 development, a comparative design analysis of the FFG-7 with recent frigate designs, and their previous experience in designing naval ships. Reference [12] reports in full the results of this investigation. The following Subsections of this paper will summarize the historical background related to the FFG-7 development, provide a brief comparative ship design analysis of the FFG-7, and analyze some of the more important design "trade-off" decisions made during the ship's development.

Overview of the FFG-7 Project

The FFG-7 serves as an interesting case study since its development spans the period when major changes in DOD acquisition policy were being made. Early in 1970 it was realized that there was a need for a large number of escort ships to replace the World War II destroyers. Studies indicated that a large number of ships in the 3,000- to 3,500-ton range represented the most cost effective solution. At this time, the "high-low" mix concept of naval forces was popular. It advocated a force structure composed of a few highly capable ships designed to perform the most demanding naval missions and a large number of ships with lesser capability (and cost) to carry out naval missions with less demanding performance requirements. In September 1970, ADMIRAL ZUMWALT, the Chief of Naval Operations, directed that development be initiated on the Guided Missile Frigate, a "low mix" ship in the 50 million dollar price range with a displacement of about 3,200 tons.

The early conceptual design phase of the FFG-7, characterized by an exceptionally large number of system level "trade-off" studies, resulted in the selection of characteristics for a single screw ship with primarily an Anti-Aircraft Warfare (AAW) capability. The technical community estimated that this ship would displace about 3,700 tons and cost approximately $50 million. In June 1971 as the ship proceeded into preliminary design, the CNO established a follow ship cost constraint of $45 million and a displacement constraint of 3,400 tons. Shortly thereafter an additional constraint on ship's manning was established at 185.

A number of observations can be made relative to the establishment of these "design to" constraints:

1) The timing of the FFG-7 design relative to the development of the official DOD "Design to Cost" policy made this ship design a pace setter of the DTC philosophy. As mentioned above, the FFG-7 design constraints were formally established in June 1971, although References [1] through [4] were yet to be issued in July 1971, SECNAVINST 5000.1 in March 1972, the Joint "Design to Cost" Guide in October 1973, and the "Design to Cost" Guide for Ship Acquisition in July 1975. It is apparent that the personnel directing the FFG-7 development anticipated and were well in tune with the changes in DOD and NAVY acquisition policy. In fact, the FFG-7 design became a standard which was followed by several "Design to Cost" ship designs which were pursued through 1974.

2) The "design to" constraints imposed by the CNO of $45 million and 3,400 tons were actually about 10% *below* the feasibility estimates developed by the NAVY's technical community. Thus the FFG-7 development became typical of an overly constrained design where one of the, if not the overriding, objectives was first to reduce the design to within the constraints and then to control the design to remain within the constraints. The "trade-off" decisions which were made to accomplish this goal are discussed in a later Section. The fundamental question which must be asked is whether this pressure imposed by this DTC philosophy resulted in a tighter and thus more efficient design which could still carry out the required mission, or whether the obsession with reducing ship size and cost resulted in a ship lacking in basic capability.

3) Several participants within the technical community felt that the "design to" constraints were dictated within the Offices of the CNO (OPNAV) without adequate dialogue with those responsible for the technical aspects of the ship design. The issue here relates to the communication and cooperation between the customer (CNO and OPNAV) and the producer (technical community). During the FFG-7 development the environment was such that the customer was the dominant party in the development of the FFG-7 performance requirements and design constraints. It is the Authors' opinion that *both* of these major participants must be on an equal level in ship design if a meaningful dialogue leading to balanced ship characteristics and DTC constraints is to take place.

4) There were *three* "design to" constraints which were to govern the design. The reason for specifying the acquisition cost is obvious and is consistent with the DTC directives. However, there was little basic motivation for designing a 3,400 ton

ship. That is, the customer did not particularly want a 3,400 ton ship. What the customer wanted was a $45 million ship with certain performance capabilities which happened to result in a ship design of 3,400 tons. The displacement constraint was specified primarily because it was easier to monitor weight than cost on a day to day basis. The manning constraint was established with the idea that reduced manning would hold down ship size and also decrease ship life-cycle cost.

There is a risk associated with specifying three such constraints early in the design development since there is insufficient design detail to insure that all three constraints are compatable and provide the desired guidance. Although in general ship cost is proportional to ship weight, there are certain design "trade-offs" which will reduce weight but increase cost. Likewise, reducing manning will normally make the ship smaller and less costly until the point is reached where the cost of automation and incorporating labor saving features dominates. It is the Authors' opinion that the three design constraints for the FFG-7 were established too early and without sufficient information as to their ultimate impact on the design.

5) The $45 million acquisition cost was based on the following assumptions:

—Constant Fiscal Year 73 unescalated dollars.
—Competitive shipbuilding environment (3 shipyards).
—Fixed procurement plan for 49 follow ships (7 ships in FY75, 11 ships in FY76, 10 ships in FY77, 10 ships in FY78 and 11 ships in FY79).
—All 49 follow ships identical.
—Full load displacement of 3,400 tons.
—95% cum average learning for labor.
—99% cum average learning for material.
—Continuous government furnished material procurement and production.
—Outfit and post delivery requirements excluded.

These assumptions are all significant and must be carefully analyzed when comparing the actual acquisition cost of these ships with the original constraint.

From the above discussion it is evident that the FFG-7 is representative of a ship developed under a "Design to Cost" philosophy. Although there are many interesting features of the FFG-7 ship acquisition which deserve attention, only those matters directly related to the design of the ship and in particular on the impact of DTC will be discussed in this paper. The readers are referred to a paper by Newcomb and DiTrapani [13] for a broader coverage of the FFG-7 project.

Comparative Design Analysis of the FFG-7

The FFG-7 was designed in a different environment and under a different design philosophy than previous escort ships. Just how different *is* the FFG-7 design from that of other escort ships? An elementary ship design analysis was conducted comparing the FFG-7 with seven post World War II designs, the FF-1037, FF-1040, FF-1052, FFG-1, DD-931, DDG-2, and DD-963 (Because of the lack of internal volume data on the FF-1040 and DD-963, these ships are used sparingly in the analysis). The objective of the analysis was to compare the naval architectural features, the cost, and the performance of these ships in order to identify whether or not the "Design to Cost" philosophy has really had an impact on naval ship design.

1) Naval Architectural Comparison

The naval architectural analysis consisted of a comparison of basic ship characteristics, weight and space allocation, and certain design indicies. In order to keep the study unclassified, the basic ship characteristics were catalogued from the open literature (References [14] through [17]). TABLE 1 provides a listing of the characteristics which were used throughout the investigation. It should be noted that although TABLE 1 and several of the TABLES and Figures which follow contain information on three twin screw ships (the DD-931, DDG-2 and DD-963), the primary focus of the study involved the comparison of the FFG-7 with the other single screw ships. Unless otherwise noted all comparative statements represent conclusions drawn in comparing the FFG-7 with the single screw ships, FF-1037, FF-1040, FF-1052, and FFG-1.

In comparing the basic characteristics, TABLE 1, a few preliminary observations can be made. The FFG-7 is the only gas turbine propelled single screw ship. The impact of the characteristic low weight of gas turbine plants will become quite apparent during the analysis to follow. The FFG-7 with its low manning level of 181, carries a significantly reduced complement as compared to the other ships. On the basis of number of crew per ton of ship displacement the FFG-7 has a 30% lower manning ratio. The most significant payload characteristic which sets the FFG-7 apart is its large helicopter facility capable of carrying and supporting two LAMPS helos. The significance of these

TABLE 1
COMPARISON OF SHIP CHARACTERISTICS

Ship Class	FF-1037	FF-1040	FF-1052	FFG-1	FFG-7	DDG-2	DD-931	DD-963
Year First Completed	1963	1964	1969	1966	1977	1960	1955	1975
Full Load Displacement (tons)	2650	3400	4100	3425	3540	4526	4034	7800
Maximum Sustained Speed	26	27	27+	27	28	33	33	31+
Type of Power Plant	600 psi steam	pressure fired steam	1200 psi steam	pressure fired steam	COGAG	1200 psi steam	1200 psi steam	COGAG
SHP	20,000	35,000	35,000	35,000	40,000	70,000	70,000	80,000
No. Shafts	1	1	1	1	1	2	2	2
ASW Systems	ASROC 6TT	ASROC 6TT	ASROC 4TT	ASROC 6TT	ASROC 6TT	ASROC 6TT	Hedgehogs 4TT	ASROC 4TT
Missile Systems	—	—	Note 2	Tartar	Standard	Tartar	—	BPDS
Guns	3 3"/50	2 5"/38	1 5"/54	1 5"/38	1 76 MM Clws	1 5"/54	3 5"/54 4 3"/50	2 5" LW
Helicopter	—	Note 3	Notes 2,3	Note 3	2 LAMPS	—	—	2 LAMPS
Complement	257	280	262	259	181	350	325	245

Notes:
1. All information taken from References [14] through [17].
2. None as built. Sea Sparrow missile system and 1 LAMPS helo were added during modernization. (Not included in analysis)
3. Originally designed with unmanned DASH helo. Ships have been upgraded to accommodate 1 LAMPS helo. (Not included in analysis)

differences in basic characteristics will be brought out later in the discussion.

An elementary weight and space allocation study was performed to develop an insight into design differences between the FFG-7 and "non-Design to Cost" ships. The allocation of weight and space to the various ship functions provides one indication of the relative importance the ship designers placed on these functions. Figure 2 shows the division of full load displacement into six functional categories describing the use of the weight as structure, engineering, payload, personnel, fuel and margin/ballast. Figure 3 shows a similar distribution of internal volume with passageway/access taking the place of structure. TABLE 2 relates this functional distribution to the familiar Ship Work Breakdown

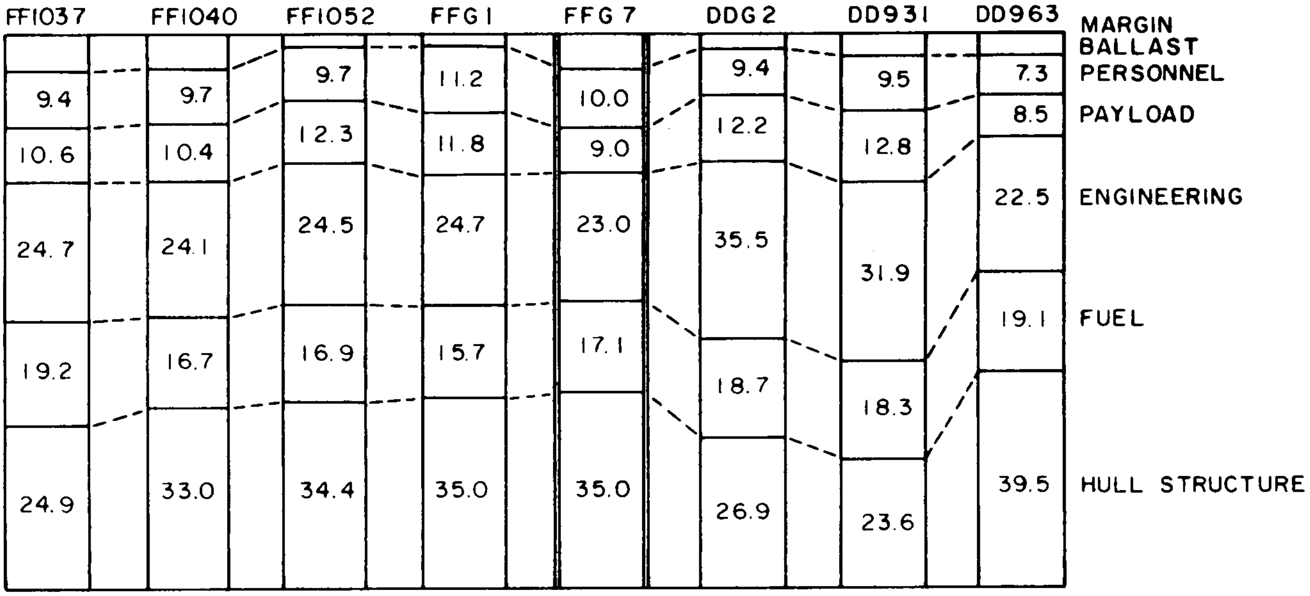

Figure 2. Allocation of Weight by Function in Destroyers and Frigates.

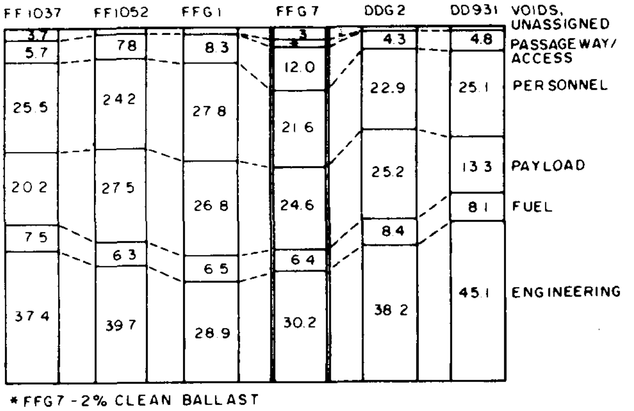

Figure 3. Allocation of Internal Volume in Destroyers and Frigates.

Structure [18] for categorizing weights and a proposed Space Classification System [19] for space categorization.

From a specific weight allocation standpoint (weight of function divided by full load displacement) the FFG-7 is quite similar to the other single screw ships with the exception that the payload weight fraction is about 20% less than the average of the remaining ships. As will be shown, this is primarily due to the low weight density of the FFG-7 payload. This low payload weight fraction should not be construed to mean that the FFG-7 carries significantly less payload than previous designs.

Since modern surface combatants are volume limited, the allocation of a ship's internal volume is a more meaningful measure of design priorities than weight allocation. Figure 3 shows that about 25% of the FFG-7's internal volume is devoted to military payload and that this is comparable to other designs. The FFG-7 has devoted about 15% less space to personnel but considerably more to passageways and access. The FFG-7 actually devotes considerably more space per man to human support functions, but because of its low manning level, allocates less overall space to the crew. This space savings due to manning reduction in part is offset by the large allocation of space to passageways and access required by the ship's maintenance by replacement concept. A new design feature which is incorporated into the FFG-7 is the clean ballast system necessitated by the present stringent environmental control standards. This new feature required 2% of the FFG-7's volume.

The relative importance of weight and space can be illustrated by investigating the weight density of the overall ship and the various functions. As previously mentioned, surface combatants are

TABLE 2

DIVISION OF SPACE AND WEIGHT INTO CATEGORIES FOR ANALYSIS

FUNCTIONAL AREA	WEIGHT GROUP (NOTE 1)	VOLUME GROUP (NOTE 2)
Hull (structural)	1 — Hull Structure	
Engineering	2 — Propulsion Plant 3 — Electrical Plant 5 — Auxiliary Systems Reserve Feed Water Lube Oil Fuel Oil	3.12 & 3.13 — Main Prop. & Damage Control 3.2 — Main Propulsion Machinery 3.3 — Auxiliary Systems Equipment 3.4 — Maintenance 3.51 — Liquids
Payload	4 — Command & Surveillance 7 — Armament Ammunition Aircraft JP-5 for Helo Aero/Ord Stores	1 — Military Mission Performance 3.11 — Ship Control 3.52 — Payload Stores
Personnel	6 — Outfit and Furnishing Officers, Crew & Effects Stores Potable Water	2 — Ship's Personnel
Passageway/Access		3.7 — Passageways & Access

NOTES:
1. Weight group categoriza.ion is from Reference [18].
2. Volume group categorization is from Reference [19].
3. Fuel oil weight and volume was separated from Engineering in Figures 2 and 3.

becoming increasingly volume limited. This is primarily due to the increased attention paid to habitability, the incorporation of payload requiring a great deal of internal volume, the use of light-weight gas turbine propulsion plants, and the requirement for increased accessibility. TABLE 3 defines and compares the overall ship density and the personnel, payload and engineering densities. The overall ship density (displacement/total internal volume) of the FFG-7 is nearly 25% less than the other ships. The FFG-7 actually has more internal volume, but a displacement of 500 tons less than the FF-1052. This implies that the FFG-7 is smaller below the waterline but has more volume above the waterline. The very low density payload and main propulsion systems along with the large passageways, high habitability standards, and the clean ballast system are all contributors to this exceptionally low ship density.

Another way of gaining an appreciation for differences in ship design practices is to compare certain specific ratios. Specific ratios may be defined in general as the "cost" (weight or space in this case) of a function divided by the capacity of the function. These specific ratios provide insight into the gross design standards associated with the function. TABLE 4 provides a comparison of specific ratios for the functional areas of personnel and propulsion. The specific personnel weight and volume ratios indicated that the FFG-7 was designed with the highest habitability standards. However, as was mentioned previously, the overall impact of the crew on the ship size was held constant by drastically reducing crew size. The advantages of gas turbine propulsion are evidenced by comparing both the specific weight and specific volume ratios for the propulsion plants.

From this elementary naval architectural analysis the following conclusions can be made:

—The FFG-7 design must have been characterized by intense weight consciousness resulting in a ship weight density 25% lower than previous designs. This low density was caused by incorporating light weight payload and propulsion subsystems and allocating a larger than usual amount of internal volume to passageways and a clean ballast system.

—The overall impact of personnel on the design is similar to previous designs. The very high habitability standards were made possible by the low manning level.

—A smaller percentage of total ship weight was allocated to payload, but an equivalent percentage of total ship volume was allocated to this function.

TABLE 3
COMPARISON OF SHIP AND FUNCTIONAL DENSITIES

Ship/ Density	Ship	Personnel	Payload	Main Propulsion Engineering w/o liquids	Total Engineering w/liquids
FFG-7	15.3	7.2	5.6	5.2	16.7
FF-1037	19.9	7.3	8.3	7.6	19.5
FF-1052	19.3	7.7	8.6	8.4	20.1
FFG-1	21.3	8.6	9.3	7.8	23.8
DD-931	21.8	8.2	17.1	15.5	20.6
DDG-2	19.6	7.3	10.4	14.3	21.1

NOTES: All densities in lbs/ft^3.
Ship Density equals displacement divided by total internal volume.
All functional densities computed by dividing functional weight by volume as defined in TABLE 2.

TABLE 4
COMPARISON OF SPECIFIC RATIOS

Ship	Specific Ratio Personnel[1] Weight		Propulsion[2] Weight	Volume
	Weight	Volume	Weight	Volume
FFG-7	1.92	604	14.4	1.5
FF-1037	1.16	354	33.0	3.9
FF-1040	1.32	—	22.5	—
FF-1052	1.63	475	28.0	2.8
FFG-1	1.61	419	22.5	1.9
DD-931	1.15	312	26.6	2.1
DDG-2	1.21	369	23.0	2.2

NOTES:
1. Specific Personnel Weight Ratio
$$= \frac{\text{Personnel Weight}}{\text{Complement}} \text{(tons/man)}.$$
Specific Personnel Volume Ratio
$$= \frac{\text{Personnel Volume}}{\text{Complement}} (\text{ft}^3/\text{man}).$$
2. Specific Propulsion Weight Ratio
$$= \frac{\text{Propulsion Weight}}{\text{SHP}} \text{(lbs/HP)}.$$
Specific Propulsion Volume Ratio
$$= \frac{\text{Propulsion Volume}}{\text{SHP}} (\text{ft}^3/\text{HP}).$$

2) COSTS

The "cost" of the FFG-7 was compared to that of the other Frigates by means of an analysis of their relative sizes and follow ship acquisition costs. Life-cycle costs were *not* compared due to a lack of accurate data on operating costs.

The usual parameter indicating overall ship size is the ship's full load displacement. Figure 4 displays the time trend of steadily increasing ship displacement for "pre-DTC" ships. The FFG-7 has unmistakenly reversed this trend. To lend additional credence to this observation, the displacement trend for twin screw destroyers is also provided in Figure 4. The DG Aegis, which was also a DTC ship, clearly reversed the escalation in displacement for this class of surface combatants. It can be concluded, therefore, that the DTC philosophy does produce a ship design with significantly reduced overall weight.

A second, but less used parameter which serves as an indicator of overall ship size is the ship's total internal volume. For volume limited ships this is a particularly significant parameter. As shown in Figure 5, the internal volume of Frigates has increased steadily with time. It is worthy of note that although the FFG-7 has checked the rate of increase of ship volume, this DTC ship is actually larger than any of its predecessors. The conclusion is that the FFG-7, a "Design to Cost" ship, is larger but lighter than ships designed under the previous design philosophies.

In light of the tight fiscal constraints on the unit production cost of naval ships, the time trend of follow ship acquisition cost has the greatest significance. Figure 6 presents this trend assuming all the ship classes will be purchased in FY76 dollars in a 50 ship production run. The cost figures for this plot were produced by first designing each of the ships using a ship synthesis model and then applying a cost model to each of these designs. The intent of the research was to determine the effect of DTC on the technical design features and the acquisition cost directly affected by these features. Put another way, the goal of the research was to determine the cost of the FFG-7 compared to the cost of "non-DTC" ships if purchased in the same year and it should be strongly emphasized that the absolute values for the acquisition costs plotted in Figure 6 may not be accurate. However, it is felt that the relative values for the six ships are consistent. From Figure 6 it can be concluded that the FFG-7 has reversed the trend in cost escalation for Frigates. *Cearly then, the "Design to Cost" philosophy does accomplish its principle objective of reducing the unit production costs of naval ships.* Figures 4, 5, and 6 all indicate that DTC has had a significant impact on the size and cost of naval ships.

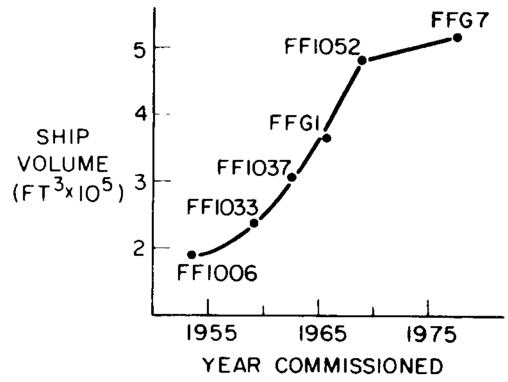

Figure 5. Ship Volume Trend for Frigates.

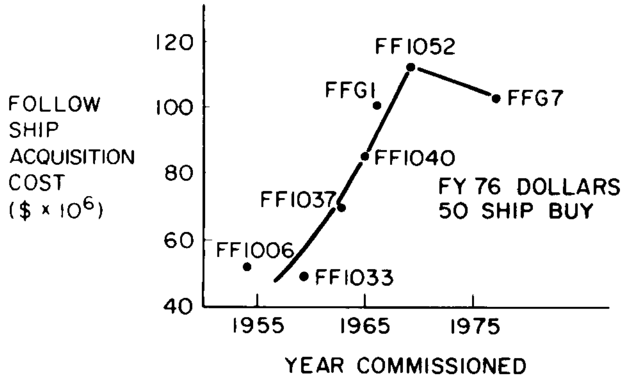

Figure 6. Acquisition Cost Trend for Frigates.

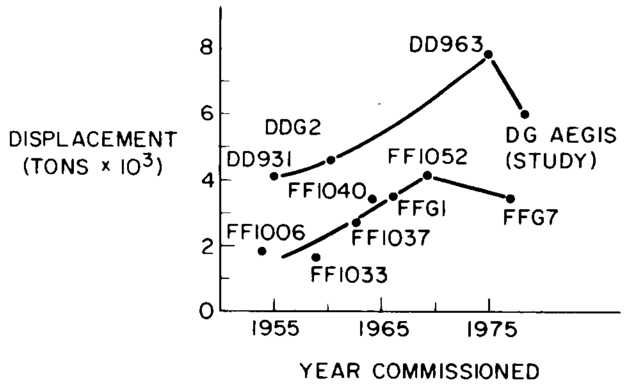

Figure 4. Displacement Trend for Surface Combatants.

3) PERFORMANCE

In the previous two Sections, the FFG-7's technical design features and costs were compared to those of "non-DTC" ships. Of course the most important area for comparison is military effectiveness. The overall performance of combatant ships is difficult to compare due to the wide range of capabilities required of a multi-mission warship. It is necessary to select suitable measures of effectiveness for each mission area and then evaluate each ship in various operational scenarios. Although such an evaluation was beyond the scope of this study, the Authors did make a cursory comparison of the ships' payload carrying capability, mobility, and support capability. The objectives of this analysis were to ascertain if the FFG-7 has performance capabilities adequate to perform its mission and if the FFG-7 represents a cost effective solution to this task compared to other escort ships.

The mission of the FFG-7 as stated in the Approved Characteristics of 24 October 1972 is:

> "To provide self-defense and effectively supplement planned and existing escorts in the protection of underway replenishment groups, amphibious forces, and military and mercantile shipping against sub-surface, air, and surface threats; and to conduct ASW operations in conjunction with other sea control forces tasked to insure our use of essential sea lines of communications."

Two elements of this mission statement are significant. First, the FFG-7 is intended to supplement the planned and existing fleet of escort ships. Second, the FFG-7 is intended primarily for operation with non-strike forces. The implication of the first element is that the FFG-7 is intended to operate with other escorts and that if these existing escorts possess an adequate capability in a certain area, the FFG-7 should not duplicate it. In other words, the FFG-7 was to be designed in a systems environment where the Fleet is the system. The objective then was the optimization of the Fleet system and the FFG-7 should be evaluated in this context. The second element implies that a 30+ knot speed capability is not required, that is, it is not intended as an escort for a Fast Attack Carrier Task Force. This mission statement is consistent with the spirit of the "Design to Cost" philosophy which advocates restraint in establishing performance requirements. As all designers painfully know, it is that last 5% to 10% of additional performance which causes the cost of systems to skyrocket. In establishing the ship's mission, it was realized that due to the limitations in funds the FFG-7 would not be a high performance, highly versatile, multi-mission destroyer.

In assessing the payload carrying capability of surface combatants, the three parameters commonly used as measures of design success are the number of weapon systems per ton of ship and the payload weight and volume fractions. The values for these parameters displayed in TABLE 5 for the five Frigates indicate that the FFG-7 possesses payload carrying capability similar to that of previous designs. Athough these indicators provide some insight into the "quantity" of payload, they by no means describe the effectiveness of the payload. To gain an appreciation for the effectiveness of the payload it is necessary to look at the effectiveness of each individual payload component and, more importantly, the degree of system integration.

The FFG-7, like all of the ships, possesses a capability to deal with air, surface and sub-surface threats. However, this ship is primarily an AAW ship with limited Anti-Submarine Warfare (ASW) and surface warfare capabilities. The other escorts are designed with varying degrees of emphasis in each of the three principle warfare areas. The FFG-7, with its more advanced weapons, sensors, and command and control suits, is the most capable AAW ship. With its limited sonar capability and installed ASW weapon system, the FFG-7 is inferior in the ASW area. However, the very capable helo facility adds a dimension not shared by the other ships. With its single 76mm gun, the FFG-7 is outgunned by the other ships in all but a close-in, self-defense encounter.

Looking at the mission capability of the FFG-7 and comparing it to the other escorts, it becomes evident that the FFG-7 does complement the existing escort fleet. Nearly all of the present escorts carry derivatives of the capable (but costly) SQS 26 sonar system and the ASROC weapon system. The FFG-7 complements the Fleet's ASW capability primarily with its helicopter facility. The majority of the existing escorts carry at least one 5-inch gun, and thus, the FFG-7 with its 76mm gun has not

TABLE 5

COMPARISON OF GROSS PAYLOAD CARRYING CAPACITY

	Number Weapon Systems per KTON of Ship	Payload Weight Fraction	Payload Volume Fraction
FFG-7	2.0	.09	.25
FF-1037	2.3	.11	.20
FF-1040	1.5	.10	.28
FF-1052	1.2	.12	.27
FFG-1	1.8	.12	.25

been called upon to add significantly to this warfare area. As an AAW ship the FFG-7 with its Standard Missile and Tactical Data System enhances the air coverage which could be provided by the large number of predominantly ASW ships of the FF-1052 and DD-963 Classes.

From a military mission standpoint the FFG-7 cannot be considered to be a highly versatile multi-mission warship. However, it appears to these Authors *that in conjunction with existing units, the FFG-7 will represent a significant increase in escort and sea control capability.* The FFG-7 certainly does not possess any excess military mission performance, but this is the fundamental cornerstone of the "Design to Cost" concept.

It is not possible to treat a comparison of the mobility characteristics of the ships in quantitative terms in this paper because of classification restrictions. The figures listed in Table 1 (which were available from unclassified sources) indicate that the FFG-7 possesses equal, if not greater speed and endurance capabilities as compared to the other single screw ships. The FFG-7 does not have the speed or endurance of the twin screw fleet escorts. Therefore, it would be only marginally effective as a carrier escort under the most demanding conditions. As in the military mission performance area, the FFG-7 was designed with adequate but no excessive mobility capability.

The third basic performance area involves the ship's ability to "support" its military mission and mobility capabilities. "Support" in this case is used in a broad sense and represents the collective features of crew size and composition; habitability level; the operability of the equipment as measured by its reliability, maintainability and availability; the maintenance capability provided by the platform; and the quality of the environment. To any Fleet operator, this performance area of "support" is very real and in many cases is what determines whether a ship is a good or poor overall performer. There is no reason to design into ships weapon and electronic systems with impressive capabilities and extended mobility capabilities if the systems cannot be operated and maintained by the crew in a shipboard environment. The "operability" of the ship is a vital performance characteristic of any ship, but one which is frequently neglected in a comparative analysis.

There are two features of the FFG-7 which cause some apprehension to the Authors in the area of "support": THE SHIP'S LOW MANNING LEVEL and LACK OF FUTURE GROWTH CAPABILITY. The FFG-7, a ship of greater size and with similar equipment complexity as the FF-1052, is designed to be manned with 70 fewer personnel. Although the FFG-7 is designed with manning reduction in mind and does possess numerous labor saving features and a low manning maintenance concept, the Authors believe this is a high risk area. Certainly the overall quality of the crew (rate structure, training and motivation level) will have to be superior to that existing in the Fleet today and the FFG-7 will have to be manned strictly in accordance with the Ship's Manning Document.

An interesting observation relative to manning trends is that the decrease in manning levels of recent ship designs has been accomplished primarily due to a reduction in watchstanding requirements. Figure 7 illustrates that the number of non-watchstanders on the FFG-7 is consistent with past practice but that the number of watchstanders has decreased by almost 50%. This observation indicates that at sea the FFG-7 will have an adequate preventive and corrective maintenance capability. However, when in port the FFG-7 will have a decreased maintenance capability, especially in the area of facilities maintenance (preservation, cleaning, etc.). From recent Fleet experience, the Authors realize that the most demanding manning situation is often not wartime Condition I or II at sea, but rather peacetime in port. While the incentive for reduced manning is certainly justified, it remains to be seen how well the FFG-7 will operate under this concept.

The second area of concern is the "tightness" of the FFG-7 design. One of the cost saving decisions made on this ship involved the reduction in future growth and service life margins. This means that the FFG-7 does not have as much flexibility as previous ships to accommodate new systems during modernization. In its "as delivered" condition the ship will be closer to many of its naval architectural limits than previous ship designs. The FFG-7

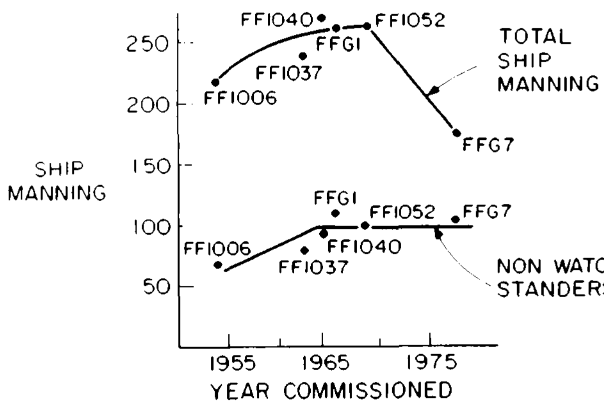

Figure 7. Ship Manning Trend for Frigates.

"tight" design concept is contrary to the modularity approach which some feel provides increased ship modernization flexibility, improved military effectiveness and reduced life-cycle costs [23]. This lack of future growth capability does represent an area of reduced ship's performance and does represent a tradeoff decision made expressly to hold down ship acquisition cost.

The principle conclusions reached by the Authors relating to ship performance follows. The FFG-7 is certainly not a performance optimized design possessing the ultimate in each and every performance feature. *The FFG-7 was designed to complement the capability of existing escorts and does appear to possess the payload and mobility features to do so.* The ship clearly has not been designed with any excesses in performance requirements which is consistent with the "Design to Cost" concept.

FFG-7 Design "Trade-off" Decisions

The comparative analysis of the FFG-7 indicated that it does differ from "non-Design to Cost" ships in a number of ways. The differences appeared to be significant enough to continue into a more detailed investigation of the numerous "trade-off" decisions made throughout the FFG-7 design. In an attempt to quantify the impact of the "Design to Cost" philosophy the Authors asked the question: "What would the displacement of the Guided Missile Frigate have been without the constrained ship design environment?" The numerous design "trade-off" decisions were analyzed and the "cost" impact of each was determined as measured by the change in full load displacement. The analysis of the "trade-off" decisions was developed from the records of the Naval Ship Engineering Center (NAVSEC) Configuration Control Board, a rough draft of the Technical History of the NAVSEC FFG-7 Design Project, and personal contact with personnel involved with the FFG-7 design. The Authors found that the resources were not always consistent in the evaluation of the effect of these "trade-off" decisions. Some of the effects were recorded as deck area, some as internal volume, some as weight, and some as a combination of the three effects. Secondary effects, such as electrical power, auxiliary services and endurance fuel were rarely documented.

In order to obtain an accurate assessment of the overall impact of a design feature on a ship, one must take all direct and indirect effects into account. Reference [20] discusses procedures for carrying out such an analysis. Because of lack of data, this study included only the impact of direct weight changes and space requirements documented in the records of the Configuration Control Board. The effect of space requirements on ship's displacement was computed using a factor of 0.0037 ton/ft^3. The direct weight change was then added to the weight change caused by the space requirements to yield the total weight impact. Since the impact on ship support systems and other secondary effects were ignored, the values for total weight impact represent a low estimate in most cases. (Reference [12] provides a more detailed description of the analytical procedures used in this assessment.)

The "trade-off" decisions, which at the time of the FFG-7 project were often referred to as austerity decisions, were placed into *six* categories:

1) Austerity decisions made during the conceptual design phase before the design constraints were established.
2) Austerity decisions impacting engineering features of the ship made during preliminary and contract design phase.
3) Austerity decisions impacting payload features of the ship made during preliminary and contract design phase.
4) Austerity decisions impacting hull structural features of the ship made during preliminary and contract design phase.
5) Austerity decisions impacting personnel features of ship made during preliminary and contract design phase.
6) Non-austerity decisions which tended to make the ship larger and more costly. These decisions are called "Inverse Design to Cost" decisions.

TABLE 6 provides a listing of these "trade-off" decisions and the Authors' estimate of the total weight impact of each. Because of lack of data, it was not possible to quantify the impact of several of the "trade-off" decisions. A summary of the weight impact of each of these six categories or "trade-off" decisions is presented in TABLE 7. In interpreting this data the Authors sought to draw conclusions relative to the overall weight impact of the "Design to Cost" philosophy and the method by which the weight savings were achieved.

As indicated in TABLE 7, the total impact of all of the austerity "trade-off" decisions was 1,303 tons. If the ship's displacement were to increase by this amount, an additional 166 tons of fuel would have to be included in order to maintain the endurance requirements. The total design impact on the FFG-7 design of the DTC philosophy is therefore 1,469 tons assuming the following:

TABLE 6

FFG-7 DESIGN "TRADE-OFF" DECISIONS

Tradeoff		Weight Impact (tons)	Category
I. CONCEPTUAL DESIGN			
1. Delete future change characteristics margin		—100.0	1
2. Reduce service life margin		— 95.0	1,3
3. Buy foreign weapon systems 76mm OTO MELARA vs. 5"/54 LW Gun		— 16.1	1,2
MK87 vs. MK86 GFCS		— 1.5	1,2
4. Reduce manning from 253 to 213		—131.2	1,3
5. Single vs. twin screw propulsion		—400.0	1
6. Reduce design and builders margins		NQ	3
	TOTAL	—743.8	
II. ENGINEERING			
1. Centralized workshops		— 17.0	3
2. One vs. two boats		— 13.0	1
3. One vs. two anchors		— 15.7	1
4. Decrease sized AFFF station		— 2.2	1,3
5. Smaller size air compressor		— 1.8	1,3
6. Two 325HP vice one 600HP on prop motors		— 21.9	3
7. Delete milling machine		— 1.8	1
8. Waste heat system vs. auxiliary boiler		— 21.8	2
9. Delete oil and water test lab		— 2.8	2
10. Delete main engine silencers and acoustic treatment		— 12.0	1
11. Remove one degaussing coil		— 3.3	3
12. Delete one decontamination station		— 0.6	1,3
13. Remove two fire pumps		— 2.1*	1,3
14. Delete cruise engine		— 1.2	1
15. Delete roll stabilization		— 35.0	1
16. Decrease electrical margins and delete one generator		— 50.0*	1,3
17. 12kW vice 250kW emergency generator		— 67.8	1,3
18. Reduced standard for shafting		— 9.0	3
19. Hard mounting of turbine modules		— 14.0	1,3
20. Simplified UNREP system		NQ	1,2
21. Inclusion of helo fuel as endurance fuel		NQ	1
22. Delete dial telephone system		NQ	1
23. Delete pneumatic tubes for interior communications		NQ	1
24. Reduced noise requirements		NQ	1
25. Delete STOPS treatment		NQ	1
26. Deletion of anti-roll tank		NQ	1
	TOTAL	—293.0	
III. PAYLOAD			
1. SQS 505 vs. SQS 23 PAIR Sonar; Addition of second helo		— 66.0	1
2. Delete TACTLASS		— 30.0	1
3. Delete signalman's shelter		— 2.0	1
4. Delete monorail hoist in hanger		— 15.0	1
5. Delete RPS custodian's office		— 2.0	1
6. Delete secondary conn		NQ	1
	TOTAL	—115.0	
IV. HULL STRUCTURE			
1. Delete ECM room on 0-2 level		— 1.0	1,3
2. Built in vs. circular chain lockers		— 2.3	3
3. Forward superstructure modifications		— 1.4	3
4. Tank rearrangement		— 4.0	3
5. Bulkhead removal between MK92 & CIC cooling rooms		— 0.2	3
6. Remove logitudinal bulkhead aft		— 6.6*	3
7. Reduce structural margins		— 15.5	1,3
8. Remove unnecessary watertight hatches		NQ	3
9. Reduce helo platform structural criteria		NQ	1,3
10. Vertical vs. inclined external ladders		NQ	1
	TOTAL	— 31.0	

(continued on next page)

TABLE 6 (Continued)

V.	PERSONNEL		
	1. Reduce in manning from 213 to 180	—108.2	1,3
	2. Reject increase in medical spaces	— 4.4	1
	3. Combined vs. separate crew and officers' galley	— 4.0	1,3
	4. Remove excess furniture in XO stateroom	— 0.2	1,3
	5. Doubling medical treatment room as forward battle dressing station	— 2.2	3
	6. Delete provision room	— 1.6	1,3
	TOTAL	—120.6	
VI.	INVERSE DTC		
	1. Enlarge office complex	+ 4.7	1
	2. Add athletic gear storeroom	+ 1.7	1
	3. Increase passageways for equipment removal	+ 19.1	1
	4. Add ability to ballast with fuel tanks	+ 5.5	1
	5. Add forward bulwark	+ 4.0	3
	6. Increase habitability standards above DE-1052	+ 87.0	1
	7. Add incinerator and sewage system	+ 9.9	1
	8. Add oily waste holding tank	+ 9.9	1
	9. Add clean ballast system	+ 39.3	1
	10. Add close in weapon system	+ 15.0	1
	11. Add helo hauldown and traversing system	+ 9.0	1
	TOTAL	+205.1	

NOTES:
NQ = not quantified. Data not available to determine weight impact.
• = decision reversed during detail design.
Category 1 — Customer decision
2 — Technical decision/technology
3 — Technical decision/tightness

—All of the quantified austerity "trade-off" decisions listed in TABLE 6 would have been made in the direction of increased performance and cost if it were not for the DTC philosophy.
—TABLE 6 represents a complete list of all "trade-off" decisions made throughout the FFG-7 design.
—The total weight impact of each design "trade-off" reflects the true impact on ship's displacement.
—The individual weight impacts are additive.

TABLE 7

SUMMARY OF IMPACT OF FFG-7 DESIGN "TRADE-OFF" DECISIONS

Conceptual Design	743 tons
Engineering	293 tons
Payload	115 tons
Hull Structure	31 tons
Personnel	120 tons
Total	1,303 tons
Fuel	166 tons
Total Design Impact	1,469 tons
FFG-7 Contract Design Displacement (12/72)	3,540 tons
FFG-8 Displacement without DTC	5,009 tons

Not all of the austerity decisions listed in TABLE 6 can be associated with the "Design to Cost" philosophy. A certain number of them might have been made based on "sound engineering judgement" even if it were not for the constrained design environment. However, in the environment of performance optimization which has characterized previous design philosophies it can be assumed that the majority of the decisions would have been made in the direction of increased performance and cost. One only has to compare the FFG-7's design features listed in TABLE 6 with those of the CGN-38 and DD-963 to verify this conclusion.

The list of quantified austerity decisions listed in TABLE 6 definitely does *not* represent a complete list of "trade-off" decisions made throughout the FFG-7 design. TABLE 6 itself lists a dozen decisions which were not quantified. During the early feasibility studies when the initial characteristics of the FFG-7 were established, hundreds of system "trade-off" studies were made utilizing a ship synthesis model to study the performance and cost impact of numerous payload mixes and platform features. Even though this was carried out before the constraints were established, the austerity environment prevailed and the majority of the decisions were made to reduce ship size and cost. In addition, the austerity decisions listed in TABLE 6 were only those which were formally documented by the FFG-7's Change Control Board. Once the results of these decisions were made known, an environment was created whereby the design participants could anticipate the inevitable decision based on weight and cost reduction and this simply did not propose performance enhancing ideas. Thus it is the Authors' conclusion that TABLE 6 contains only a partial listing of austerity decisions made during the FFG-7 design evolution.

The Authors have already pointed out that the documentation available to evaluate the weight impact of each decision lacked sufficient detail to perform a detailed analysis. The recent work which has been carried out using marginal cost factors [20][21][22] presents the type of study which should have been performed. In this investigation several secondary effects were ignored. It is felt that the total increase of 1,469 tons is an underestimation of the overall impact of the austerity decisions listed in TABLE 6. A detailed design study would be required to verify these numbers.

Taking all of the above discussion into account the Authors conclude that *the FFG-7 would have displaced close to 5,000 tons (40% more) if it were not for the "Design to Cost" philosophy.* This estimate is compared to that predicted from an extrapolation of the Displacement/Time Trend Curve out to the FFG-7's delivery date in Figure 8. As is shown, the 5,000 ton estimate lies midway between the actual FFG-7 displacement of 3,540 tons and the extrapolated prediction of 6,000 tons.

The second point of interest in interpreting the "trade-off" decision is to determine by which method the weight savings were achieved. An early Section of this paper stated that cost reduction could be achieved by the customer reducing performance, the designer taking advantage of technology to maintain performance but at a reduced cost, and the designer deleting the excesses thereby creating a tighter design. The last column in TABLE 6 attempts to place each "trade-off" decision in one or more of the above categories. Many of the readers will no doubt take issue with some of this categorization. The following subjective reasoning was utilized by the Authors in making these decisions. If the design feature modified an operational capability of the ship which is usually specified either directly or indirectly by the operational community, it was placed in Category 1, "Customer Decision." Those decisions which enabled the technical community to maintain or increase performance at a reduced cost by taking advantage of new technology were placed in Category 2, "Technical Decision/Technology." The third category consisted of those decisions which were made by the technical community aimed at reducing excesses and producing a tighter design. It can be argued that most excesses in weight, space, energy and manning provide a more flexible design and are later utilized in ship modernizations and thus enhance performance. However, decisions were placed in Category 3 if savings were realized without a change in specified ship performance. The Authors did *not* consider these categories to be mutually exclusive and as, indicated in TABLE 6, a number of decisions were placed in more than one cateory.

One can conclude from the numbers presented in TABLE 8 that the dominant method for reducing ship size and cost involves the reduction in ship performance. The total impact of those decisions made by the customer (Category 1) and by the customer in conjunction with the technical community (Categories 1, 2 and 1, 3) which affect ship performance represented about 90% of all the austerity decisions made on the FFG-7.

This is a significant observation and one which amplifies the importance of close cooperation and

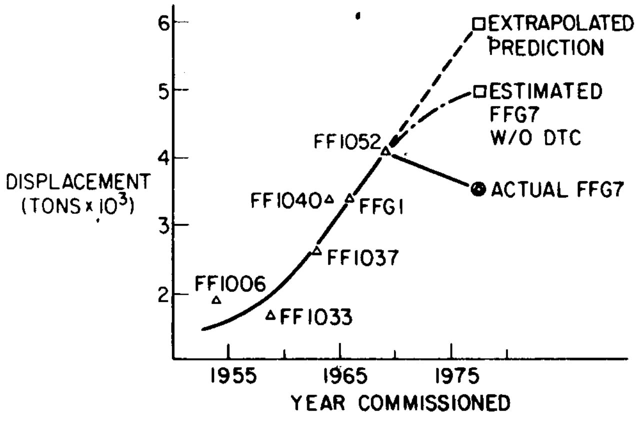

Figure 8. Impact of "Design to Cost" on Full Load Displacement.

TABLE 8

SUMMARY OF METHODS OF REDUCING COST

Category	Description	Number	Weight Reduction
1	Customer Decision	22	687
2	Technical Decision/Technology	2	24
3	Technical Decision/Tightness	12	91
1,2	Customer & Technical Decision/ Technology	3	17
1,3	Customer & Technical Decision/ Tightness	15	484
	Total	54	1303

understanding between the operational and technical communities. *The customer cannot expect more than perhaps a 10% reduction in ship cost through innovative and disciplined design procedures. The way to reduce cost is to reduce performance. This cost/performance "trade-off" must be made together by the customer and designer. This then is the essence of the "Design to Cost" philosophy — restraint in specifying performance requirements.*

The Authors want to emphasize the above observation, but at the same time also want to balance the final statement by stating that the execution of the design, once the performance requirements have been specified, *cannot* be neglected. From the previous Sections one gains an appreciation for the extreme weight and cost consciousness and tight design control which prevailed throughout the FFG-7 design. From the initial feasibility studies to the completion of the contract design, the FFG-7 was under closer weight and cost reduction scrutiny than any surface combatant designed in the last thirty years. Figure 9 portrays this weight "battle" by plotting the weight of the FFG-7 throughout its design development. The usual trend as a ship design evolves is one of increasing weight. The FFG-7 will be delivered at a full load displacement below the estimates made at the completion of conceptual design. This is a rare occurrence in ship design and it provides another indication that the "Design to Cost" philosophy, if properly implemented, produces results.

So far only the austerity decisions have been discussed. As indicated in Table 6 there were 12 documented "trade off" decisions which resulted in increase in ship size and cost and are thus referred to as "inverse Design to Cost" decisions. Ninety-three tons or 40% of the weight increase is associated with enhancing the habitability features of the ship. The new environment standards resulting in clean ballast and sewage systems resulted in an increase of 65 tons. Although the authors realize the importance of these features, it is significant that 158 of the 205 tons of "inverse Design to Cost" decisions are not directly related to military performance. *This does illustrate the point that it is difficult to design a WARSHIP in a peacetime environment.*

Conclusions Based on FFG-7 Analysis

Based on the case study of the FFG-7 the following principle conclusions can be made:

1) "Design to Cost" is a real and workable concept that does have a major impact on the characteristics of a ship design.
2) Significant weight and cost savings were realized in the FFG-7 design because of the "Design to Cost" philosophy. It is estimated that the FFG-7 would have been 40% heavier if it were not for "Design to Cost."

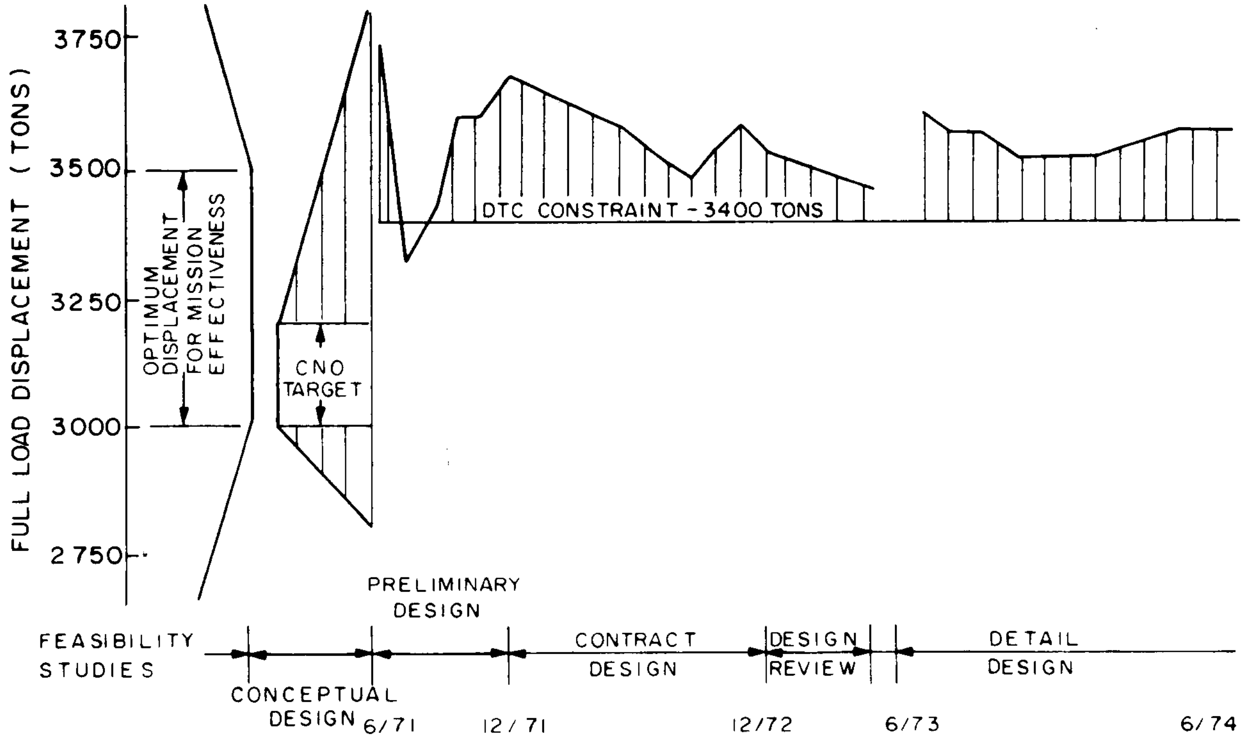

Figure 9. History of the Guided Mssile Frigate Estimated Displacement.

3) Over 90% of the weight savings was achieved through a reduction in some ship performance feature.
4) The payload and mobility performance features of the FFG-7 are adequate for it to carry out its mission. The restraint shown in specifying performance requirements and the discipline demonstrated in the execution of the design have produced a cost-effective design product.
5) From a naval architectural standpoint the most outstanding feature which sets the FFG-7 apart from previous designs is its low overall ship density. The primary cause for this low density is the light weight gas turbine propulsion plant, light weight payload system, high habitability standards, the large amount of space allocated to passageways, and the clean ballast system.

Past, Present, And Future Applications Of DTC To Naval Ship Design

In addition to the FFG-7, the Navy has designed four ships under the "Design to Cost" philosophy; the Sea Control Ship (SCS), the Anti-Aircraft Destroyer (DG-Aegis), a constrained aircraft carrier (CV), and the Fleet Oiler (AO-177). Only the FFG-7 and AO-177 have proceeded into production. The designs of the other ships have been discontinued and have been replaced by designs for more capable, "non-Design to Cost" ships. No other new DTC ship design projects have been initiated; thus at present there is *no* ongoing "Design to Cost" ship design.

From the previous Sections of this paper it can be concluded that the DTC philosophy does produce ships with reduced costs. Why then has "Design to Cost" lost its impetus in naval ship design? Two recent events have served to create this situation. In August 1974, Congress passed what is known as the "Title Eight Legislation" requiring the Navy to install nuclear propulsion in all new construction strike force ships. The size and weight of a nuclear reactor results in a large hull and large initial expenditure, and therefore creates a situation where it is not attractive to constrain severely other areas of the ship design. That is, once a decision has been made to invest in an "N Ship" it is not cost effective to limit other performance features of the ship. The second event is the change-over from Admiral Zumwalt to Admiral Holloway as Chief of Naval Operations. Admiral Holloway has stated on several occasions that the Navy needs surface ships with more offensive capability. These two features, unlimited endurance and more fire power, represent a substantial increase in ship performance. As has been discussed in this paper, performance drives a ship design, and these performance requirements are *not* compatible with the DTC concept.

The effect of these decisions can be dramatically illustrated by comparing the DG Aegis design with the Strike Cruiser (CSGN) design. The DG Aegis was a "Design to Cost" ship carrying the highly capable Aegis AAW weapon system on a relatively austere conventionally powered platform. At the end of preliminary design this ship was estimated to displace about 6,000 tons and have a follow ship acquisition cost of approximately $200 million. This design was scrapped and replaced with that for the nuclear powered Guided Missile Strike Cruiser, CSGN. This ship in addition to being nuclear powered also carries an offensive long range surface-to-surface missile and a more capable aviation facility. Conceptual studies indicated that the CSGN would displace over 16,000 tons and cost in excess of $850 million. Performance does cost, and this case dramatically illustrates the point.

The "Design to Cost" DG Aegis was discontinued because it lacked sufficient performance. On the other hand, the highly capable CSGN is so costly that the Navy cannot afford to procure this ship in sufficient numbers. A design concept is presently being investigated incorporating the DD-963 hull as a conventionally powered platform for the Aegis system. This design, designated DDG-47, represents somewhat of a compromise in cost and performance between the DG Aegis and CSGN.

From the above discussion it is apparent that the DTC concept has not been universally acclaimed as the answer to the Navy's Fleet replacement problem. In the design of naval ships, the "Design to Cost" philosophy has been pretty much synonymous with design austerity and the reduction in ship performance capabilities. As has been pointed out in this paper the primary means of holding down ship cost is by restraining performance requirements. But this constrained environment produces ships which to some decision makers do not possess the basic capabilities to perform the required missions.

Thus the Navy faces a serious dilemma. The fiscal climate which provided the impetus for "Design to Cost" has, if anything, worsened. The numerical strength of naval ships has declined below 500 active units while the Navy's global commitments require a Fleet of at least 600 ships. The "Design to Cost" ships which the Navy can just barely afford to acquire in numbers sufficient to build up Fleet numerical strength have been deemed to lack performance capabilities required of many of the NAVY's demanding missions. At present there has been a turning away from the "Design to Cost" philosophy. However, it is the Author's opinion that *fiscal realities will force a reevaluation of priorities and a return to some form of "Design to Cost" concept.*

How will the "Design to Cost" concept be implemented within the NAVY in the future? All of the basic directives and instructions are still in force specifying that the NAVY will "Design to Cost." Reference [4] provides an exception to "major national security programs in which performance, reliabilty and/or schedule take precedence over cost as a primary consideration." It appears to the Authors that this exception is being applied to the more recent ship designs.

It is the primary thesis of this paper that when performance dominates a design, the "Design to Cost" concept is meaningless. On the FFG-7 it was shown that less than 10% of the size reduction could be attributed to the other two methods of reducing size and cost. The NAVY is going to have to make that hard decision related to performance versus cost domination. *If cost is a parameter of at least equal importance with performance, the "Design to Cost" concept represents a viable concept. If performance dominates, there is no "Design to Cost."*

CONCLUSIONS

The principle conclusions from this study can be summarized as follows:

1) "Design to Cost" is a viable concept which produces naval ship designs with increased cost effectiveness.

2) Ships designed under the DTC philosophy are different than "non-DTC" ships. The FFG-7, a DTC ship, has reversed the trend of increasing ship weight and cost and checked the trend of increasing ship size. It is predicted that the FFG-7 would have had a 40% greater full load displacement is it had not been for the "Design to Cost" concept.

3) The primary means of reducing ship cost is to restrain performance. Over 90% of the weight reduction on the FFG-7 can be associated with a decrease in some performance feature.

4) The DTC concept can produce a ship with adequate performance capabilities for certain naval missions. The FFG-7 definitely complements and adds increased capabilities to the NAVY's current force of escorts.

5) In the light of today's constrained fiscal environment, ships designed under the DTC concept are attractive. The NAVY should continue to apply the DTC concept to all non-performance optimized ships.

6) The cornerstone of "Design to Cost" is in the willingness to pursue an aggressive cost and performance "trade-off." This "trade-off" must be made together by the Customer and Producer Communities. Where there is little restraint in specifying performance requirements there is no "Design to Cost."

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