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EVALUATION OF VARIOUS PROPULSION ARRANGEMENTS TO IMPROVE ENERGY CONSERVATION FOR NAVAL COMBATANTS - SUMMARY REPORT

Arthur M. Reed

and

William G. Day, Jr.

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Ship Performance Department

May 1984

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EVALUATION OF VARIOUS PROPULSION ARRANGEMENTS TO IMPROVE ENERGY CONSERVATION FOR NAVAL COMBATANTS - SUMMARY REPORT

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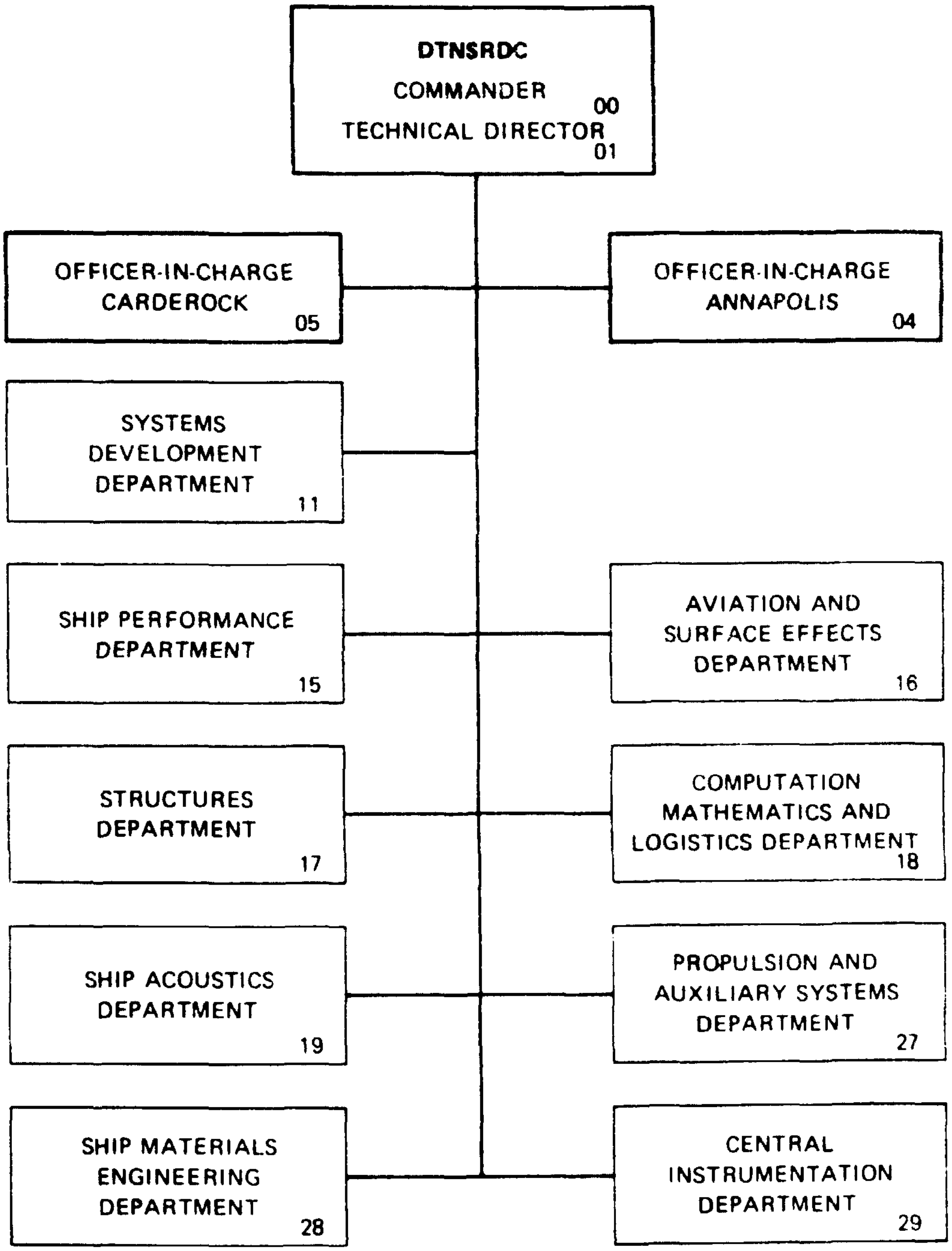

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Over the last six years, 13 propulsion configurations have been evaluated on models of a 7945 tonne (7820 ton) destroyer. This report presents a summary of how these 13 propulsion configurations and two other configurations, which have been assessed analytically, would perform with design propellers on a destroyer. In addition, analytical predictions have been made for nine propulsion configurations on a 3505 tonne (3450 ton) frigate and six propulsion configurations on a 12192 tonne (12000 ton) cruiser. The

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result of all these predictions is that substantial power reductions at a speed of 20 knots are possible on all three ship sizes, relative to controllable-pitch propeller baseline configurations. In particular, the delivered power of the destroyer could be reduced by as much as 20 percent, the power of the frigate could be reduced by as much as 12 percent, and the power of the cruiser could be reduced by as much as 15 percent.

The particular propulsion configurations which show the most substantial benefits are propulsion pods with contrarotating propellers, bearing-in-rudder post with controllable-pitch or fixed-pitch propellers, and contrarotating propellers with conventional shafts and struts.

Fixed-pitch propellers provide up to 10 percent power reduction relative to controllable-pitch propellers. Therefore, fixed-pitch propellers should be used under all circumstances where backing and stopping can be accomplished by reversing the rotation of the shafting.

In addition to the performance predictions discussed above, this report discusses the technical status of these various propulsion configurations. This report also has five appendices which contain: the details of the models built and tested; the powering predictions based on custom stock propeller experiments with 13 models; the projected powering performance for 15 propulsion configurations with design propellers; a brief summary of the research which has been performed on podded propulsion; and a history of the bearing-in-rudder post configuration.

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NOTATION

BRP	Bearing-in-Rudder Post
CP	Controllable-Pitch
CR	Contrarotation
FP	Fixed-Pitch
LD	Large Diameter
LDCP	Large Diameter Controllable-Pitch
LDFP	Large Diameter Fixed-Pitch
LDOL	Large Diameter Overlapping
S&S	Shafts and Struts

Other notations used in this document are consistent with the International Towing Tank Conference (ITTC) Standard Symbols.*

English - SI Equivalents

1 ft	= 0.3048 m (meters)
1 ft/sec	= 0.3048 m/s (meters per second)
1 in	= 25.40 mm (millimeters)
1 knot	= 0.5144 m/s (meters per second)
1 lb (force)	= 4.448 N (Newtons)
1 long ton (2240 lb)	= 1.016 tonne or 1016 kg
1 hp	= 0.7457 kW (kilowatts)

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* International Towing Tank Conference Standard Symbols 1976, The British Ship Research Association, BSRA Technical Memorandum No. 500 (May 1976)

ABSTRACT

Over the last six years, 13 propulsion configurations have been evaluated on models of a 7945 tonne (7820 ton) destroyer. This report presents a summary of how these 13 propulsion configurations and two other configurations, which have been assessed analytically, would perform with design propellers on a destroyer. In addition, analytical predictions have been made for nine propulsion configurations on a 3505 tonne (3450 ton) frigate and six propulsion configurations on a 12192 tonne (12000 ton) cruiser. The result of all of these predictions is that substantial power reductions at a speed of 20 knots are possible on all three ship sizes, relative to controllable-pitch propeller baseline configurations. In particular, the delivered power for the destroyer could be reduced by as much as 20 percent, the power of the frigate could be reduced by as much as 12 percent, and the power of the cruiser could be reduced by as much as 15 percent.

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ADMINISTRATIVE INFORMATION

The various projects summarized in this report have been sponsored by the Naval Material Command (NAVMAT 08E) under Program Element 63724N, the Navy Energy Program (Advanced). These projects have been administered by the David Taylor Naval Ship Research and Development Center, Energy Research and Development Office (DTNSRDC 2705), under various job order numbers extending from Fiscal Year 1977 through Fiscal Year 1983.

INTRODUCTION

In 1977 a program was initiated in the Ship Performance Department of the David Taylor Naval Ship R&D Center (DTNSRDC) to produce energy conservation in ship design through improved hydrodynamic performance. This program was sponsored by the Energy Research and Development Office of the Propulsion and Auxiliary Systems Department of DTNSRDC. The initial task performed under this program was the development of a number of position papers which were used to indicate the areas of research where the greatest benefit in terms of reduced propulsion power and the concomitant energy savings might lie.

Five position papers were prepared during the course of this study. These position papers covered novel and unusual hull forms, appendage design, propulsors, wake scaling, and potential improvements in the FFG-7 Class hull form. The specific report titles and their authors are as follows:

"Novel Stern Shapes for Improved Energy Conservation for Naval Surface Combatants" by R.F. Roddy (1980)*

"State-of-the-Art - Appendage Design - Its Potential for Energy Conservation" by H.Y.H. Yeh**

"Propulsors for Improved Energy Conservation on Naval Surface Combatants - A Hydrodynamic Assessment" by B. Cox and W. Haberman***

"Wake Scale Effects and Propeller Hull Interaction: State-of-the-Art" by C.A. Scragg (1980)

"Exploratory Frigate Design for Improved Energy Efficiency Based on FFG-7 Hull Form" by D.S. Jenkins (1980).

Of these five reports, the first three identified specific propulsion configurations for reduced delivered power and increased energy conservation.

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* References are listed in alphabetical order on page 275.

** Reported informally as Yeh, H.Y.H. (1980), "State-of-the-Art - Appendage Design - Its Potential for Energy Conservation," DTNSRDC Ship Performance Department Technical Memorandum TM 15-79-111.

*** Report of higher classification.

The hull form study, Roddy (1980), identified three configurations as having potential benefits: large diameter propellers with low tip clearance, large diameter overlapping propellers, and podded propulsion. The appendage study by Yeh identified the bearing-in-rudder post in conjunction with a straight rudder, contraguide rudder, and contraguide rudder with Costa bulb as having significant potential benefit. The propulsor report by Cox and Haberman identified both contrarotating and tandem propellers as being likely to improve propulsive efficiency. In addition, the propulsor report stated that single shaftline configurations would probably be superior to twin shaftline configurations due to the generally more favorable hull propulsor interaction coefficients found on single shaftline configurations. Finally, based on the significant reductions in power observed on the FF-1052 Class when going from controllable-pitch propellers, Wilson (1969), to fixed-pitch propellers, Hankley and West (1964), both fixed-pitch and controllable-pitch propellers were to be compared on those configurations where feasible.

Upon enumeration, 11 propulsion configurations were identified for evaluation on the DD-963 hull form, or variants thereof. Those configurations are listed in Table 1. Two other propulsion configurations, which employ controllable-pitch and fixed-pitch propellers on a single shaftline, were intentionally omitted from the list of configurations to be evaluated. They were omitted because it was felt that sufficient experimental data for single shaftline configurations existed to allow accurate performance predictions to be made.

Later in the program, two additional configurations were added to the experimental program. The first was a bearing-in-rudder post configuration employing fixed-pitch propellers and a straight rudder. This configuration was added because all previous bearing-in-rudder post concepts had employed controllable-pitch propellers, and it was considered desirable to assess the benefits of a bearing-in-rudder post in conjunction with the improved efficiency found with fixed-pitch propellers.

The second configuration added to the experimental program was revised fairwaters for the DD-963 with controllable-pitch propellers. This configuration was added when it was observed that the resistance differences between the baseline DD-963 with shafts and struts and the DD-963 with bearing-in-rudder post and controllable-pitch propellers were approximately twice the differences observed

TABLE 1 INITIAL PROPULSION CONFIGURATIONS CHOSEN FOR EXPERIMENTAL EVALUATION UNDER THE ENERGY CONSERVATION PROGRAM

1. Twin shaftline controllable-pitch propellers
2. Twin pods with contrarotating propellers
3. Twin shaftline contrarotating propellers
4. Twin shaftline fixed-pitch propellers

5a. Twin bearing-in-rudder post with straight rudder (controllable-pitch propellers)

b. Twin bearing-in-rudder post with contraguide rudder (controllable-pitch propellers)

c. Twin bearing-in-rudder post with contraguide rudder and Costa bulb (controllable-pitch propellers)

6. Twin shaftline large diameter low tip clearance fixed-pitch propellers
7. Twin shaftline tandem propellers
8. Twin shaftline large diameter overlapping propellers
9. Twin shaftline large diameter low tip clearance controllable-pitch propellers
10. Single shaftline contrarotating propellers
11. Single shaftline tandem propellers

in other comparisons of conventional shafts and struts with bearing-in-rudder post. After an analysis of the potential sources of this discrepancy, the blunt, button type fairwater on the DD-963 was identified as the most likely cause.

Thus in the end, 13 configurations were evaluated experimentally under this program. In addition, the two single shaftline configurations mentioned above were compared analytically under this program.

In conjunction with the Naval Sea Systems Command (NAVSEA), the Energy Office and the Ship Performance Department developed a plan for the evaluation of these configurations. This plan had the following two objectives:

- Provide an assessment of the propulsive performance of various propulsion configurations for use by NAVSEA in the preliminary and conceptual design of naval combatant ships.
- Provide assessment of the savings in power achievable by various propulsion alternatives, for use in the decision-making process for machinery development programs.

The plan was divided into three steps. The first step was to consist of stock propeller evaluations of all configurations. This was intended to provide a preliminary hydrodynamic assessment of the performance of the various configurations.

The second step was to consist of a series of ship impact studies. These studies were intended to provide: an estimate of design propulsor performance; an evaluation of hydrodynamic, structural, and machinery risks; and an assessment of the effect which a given concept would have on the fuel consumption of a ship fitted with a particular propulsor configuration. The fuel consumption studies were to take into account the impact of the propulsion configuration on ship displacement through changes in machinery and appendage suit weight.

The third and final step of the plan was to involve a thorough hydrodynamic evaluation of those configurations that seemed most promising based on the ship impact studies. These hydrodynamic assessments were to include an experimental evaluation of the chosen configurations using design propellers. Any high risk hydrodynamic questions involving areas such as maneuvering and vibration were to be answered through appropriate experiments and analyses.

The stock propeller propulsion experiments of Step One have now been completed. The estimates of design propulsor performance have also been completed along with a brief investigation of the hydrodynamic risk associated with the most promising configurations.

This report summarizes the findings of these studies and indicates the directions in which the program for propulsion configurations with reduced delivered power and increased energy conservation should proceed. The next chapter of this report, Rationale for the Selection of Propulsion Configurations, contains brief descriptions of the 11 configurations which were initially chosen for evaluation, along with a discussion of the initial performance estimates which were used to justify the selection of these configurations. This is followed by a chapter, Evaluation of Propulsion Configurations, which gives projections of the powering performance of the configurations based on stock propeller experiments and parametric propeller designs. This chapter also discusses the best configurations for application on the DD-963, the projected results from applying these propulsion concepts to frigate- and cruiser-size ships, and the potential risks in applying these configurations. The final chapter of the report is Recommendations. This chapter summarizes the most promising configurations and recommends the direction for follow-on work. This report also contains five appendices. The first, Appendix A, contains figures giving configuration details of the various models, appendage suits, and custom stock propellers which have been evaluated. Appendix B contains the propulsion data from the custom stock propeller experimental evaluations of the 13 propulsion configurations, along with a discussion of the various results. Appendix C contains the detailed projections of powering performance for all 15 configurations with design propellers, and a discussion of how these projections have been derived, both in general and on a case by case basis. Appendix D contains a summary of all analytical and experimental efforts which have been carried out relating to podded propulsion. Finally, Appendix E contains a brief history of the bearing-in-rudder post configuration, including identification of those cases where it has been employed full scale, and some unpublished experimental results.

RATIONALE FOR THE SELECTION OF PROPULSION CONFIGURATIONS

Once 10 configurations which promised to reduce delivered power (plus the parent DD-963 with controllable-pitch propellers) had been identified, estimates of the range of power reduction anticipated were developed for each configuration and presented to the DTNSRDC and NAVSEA Energy Offices. The anticipated power savings which were presented are given in Table 2. The order in which the configurations are presented has been rearranged from that of the original briefing to reflect the actual order of benefit which resulted from the study reported herein. The anticipated benefits presented in the table range from a low of 2 percent for the tandem propeller configurations to a high of 14 percent for two of the bearing-in-rudder post configurations.

When comparing the actual benefits of the configurations with the anticipated benefits in Table 2, it can be seen that significant errors occurred in predicting the anticipated benefits. These errors largely reflect an underestimation of the effect of changing appendage suits on the effective power of the various configurations. In fact, the trends indicated in Table 2 do reflect the changes in propulsion efficiency quite accurately.

As an example, pods were not projected to reduce resistance, so the 0 to 10 percent reduction in delivered power was assumed to result totally from an increase in propulsion efficiency. In fact, however, the resistance of the DD-963 hull form fitted with twin pods was reduced 10 percent, and a 10 percent propulsion efficiency gain was also achieved, resulting in a 20 percent reduction in delivered power.

The rest of this chapter contains a brief description of the individual configurations and a discussion of the anticipated gains which resulted in these configurations being chosen for evaluation. The reader is referred to Appendix A for a more detailed description of the individual configurations.

TWIN SHAFTLINE CONTROLLABLE-PITCH PROPELLERS

The twin shaftline controllable-pitch propeller as applied to the DD-963 Class was chosen as the parent for this propulsion study. This parent was chosen because it was one of the most modern naval combatant designs and seemed to be representative of modern destroyer and frigate designs, with a concentration on gas turbines as prime movers and controllable-pitch propellers for propulsors. This

TABLE 2 - ANTICIPATED DELIVERED POWER REDUCTION FOR ELEVEN INITIAL PROPULSION CONFIGURATIONS *

	Anticipated Power Reduction Relative to DD-963 with Twin Shaftline Controllable-Pitch Propellers (Percent)
1. Twin shaftline controllable-pitch propellers	0
2. Twin pods with contrarotating propellers	0 - 10
3. Twin shaftline contrarotating propellers	1 - 4
4. Twin shaftline fixed-pitch propellers	2 - 3
5a. Twin bearing-in-rudder post with straight rudder (controllable-pitch propellers)	5 - 10
b. Twin bearing-in-rudder post with contraguide rudder (controllable-pitch propellers)	8 - 14
c. Twin bearing-in-rudder post with contraguide rudder and Costa bulb (controllable-pitch propellers)	8 - 14
6. Twin shaftline large diameter low tip clearance fixed-pitch propellers	2 - 5
7. Twin shaftline tandem propellers	0 - 2
8. Twin shaftline large diameter overlapping propellers	3 - 6
9. Twin shaftline large diameter low tip clearance controllable-pitch propellers	2 - 5
10. Single shaftline contrarotating propellers	4 - 8
11. Single shaftline tandem propellers	0 - 2

* From Program Review for DTNSRDC (2705) and NAVSEA (05R13) Energy Offices, April 1979

trend was seen in the designs of the DD-963, FFG-7, CG-47, and DDG-51 Classes.

A further reason for the selection of the DD-963 as the parent for this study was the fact that, with a displacement of 7945 tonne (7820 ton), the DD-963 was in the middle range of displacements for conventionally powered surface combatants. It was felt that the results could be easily extrapolated upward to apply to cruisers, and downward to apply to frigates.

As can be seen in Appendix A, the parent DD-963 is a twin screw transom stern destroyer with the usual appendages found on such ships: skeg, bilge keels, and shafts and struts. The skeg in this case is a true appendage with no fairing between the hull and the skeg. The shafting is supported by intermediate and main strut barrels, each of which is in turn supported by a pair of V-struts. As is discussed several places throughout this report, the shafting diameter on the parent DD-963 is smaller than that which would be obtained if the current NAVSEA design practice for shafting were followed. Thus corrections have been made to the resistance of the parent hull to obtain the baseline for this report.

TWIN PODS WITH CONTRAROTATING PROPELLERS

Pods are a propulsion configuration in which the propellers are placed at the fore or aft ends of a nacelle which encloses an electric motor which powers the propellers. The nacelle is suspended below the hull on a strut, not unlike an out drive or outboard motor. This allows the elimination of the shafts and struts, and possibly the rudder, which under some circumstances can be included as a flap in the trailing edge of the strut. (The reader is referred to Appendix D for a more thorough discussion of pods and the research which has been conducted on pods.) Although little data was available at the start of this program which could be used to predict the performance of podded propulsion, it seemed reasonable to assume that if the size of the pod could be kept sufficiently small, the resistance of the pod would not exceed the resistance of the conventional shafts and struts. Under this assumption, the chief benefit of utilizing pods would be the 10 percent increase in propulsion efficiency which would be contributed by the contrarotating propellers. In addition to the hydrodynamic benefits which were assumed, the analysis by Levedahl (1978, 1980) predicted that significant displacement reductions could be attained through the increased flexibility in arrangements which were made possible by using an integrated electric plant in combination with the podded electric drive. All of this combined to indicate that pods were a potential energy saving concept which was worthy of investigation.

TWIN SHAFTLINE CONTRAROTATING PROPELLERS

This configuration utilizes two pairs of contrarotating propellers driven through open shafting supported by V-struts. In developing the powering benefit expected from this configuration, it was assumed that the shafting suit would be larger than that of the controllable-pitch propeller baseline, resulting in an increase in resistance which would offset, to some extent, the increase in propulsion efficiency, resulting in a reduction of delivered power by at most 4 percent. In retrospect, based on results such as those of Fisher (1981a), who reported on comparative powering characteristics of a single shaftline ship fitted with open shafts and struts and fixed-pitch and contrarotating propellers, power reductions of 10 to 14 percent should have been anticipated.

TWIN SHAFTLINE FIXED-PITCH PROPELLERS

This configuration again utilizes two open shafts supported by V-struts, with the parent controllable-pitch propellers replaced by fixed-pitch propellers. This configuration was assumed to have 2 to 3 percent lower delivered power than the controllable-pitch propeller parent. This was assumed to result from the 1 to 2 percent higher open water efficiency which fixed-pitch propellers show relative to controllable-pitch propellers, and from the 1 to 2 percent lower resistance caused by smaller appendages.

This low estimate of the delivered power reduction was developed in spite of results on a model of the FF-1052 Class, which showed power reductions of about 10 percent, Hankley and West (1964) and Wilson (1969). The reason the FF-1052 model results were given less credence than they should have been was the fact that the controllable-pitch propeller appendages fitted to this class were destined solely to demonstrate controllable-pitch propeller mechanical performance. Thus these controllable-pitch propellers and their appendages were not felt to reflect the best performance which could be obtained from controllable-pitch propellers.

TWIN BEARING-IN-RUDDER POST WITH CONTROLLABLE-PITCH PROPELLERS

In this propulsion configuration, the main V-struts and strut barrel are removed from a traditional shafts and struts configuration, and the spade rudder is removed and replaced by a horn rudder. The propeller and its shafting are then supported from behind by a bearing which is placed in the rudder post.

Two model-scale applications of this configuration, on models of the PG-84 and PCG Classes, were known at the initiation of the Energy Conservation Program. (For a full account of bearing-in-rudder post applications see Appendix E.) These two applications showed delivered power reductions of 14 and 8 percent, respectively. Therefore, it was assumed that the bearing-in-rudder post could provide power reductions in this range. The PCG model was evaluated with a straight rudder, while the PG-84 model had a contraguide* rudder, Saunders (1957), which was thought to increase the efficiency of the propeller-rudder combination through swirl recovery by the rudder.

The Costa bulb, Zeno (1953) and Greger (1961), was a feature which has been shown to provide an increase in propulsive efficiency when applied to the rudders of merchant ships. The Costa bulb has never been used in conjunction with a bearing-in-rudder post or a contraguide rudder, but it was reasonable to expect that the combination of all three concepts might lead to an improvement beyond that possible with any of the concepts individually.

TWIN SHAFTLINE LARGE DIAMETER LOW TIP CLEARANCE FIXED-PITCH PROPELLERS

Large diameter propellers with low tip clearance require a modification of the traditional destroyer hull form to include a deep skeg and a large fillet between the hull and the skeg. The radius of the fillet in way of the propeller is designed so as to provide a constant clearance between the hull and the propeller blade tips. The appendage suit employs the usual shafts and struts, although the propeller centerline is moved up closer to the hull. This serves to reduce the angle of inclination between the shafting and the flow, and to shorten the length of the struts, both of which would serve to reduce the appendage resistance.

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* A contraguide rudder has camber which reverses direction depending on whether it is above or below the propeller centerline.

There were three principles behind the anticipated delivered power reduction with the large diameter low tip clearance configuration. The first was the anticipated small reduction in appendage resistance. The second was an increase in hull efficiency due to boundary layer recovery made possible by the low tip clearance. The final factor was the contribution to improved propeller performance of reduced propeller thrust loading caused by the increase in propeller diameter.

TWIN SHAFTLINE TANDEM PROPELLERS

This configuration employs the DD-963 hull form with shafts and struts appendages and a simple compound propulsor in which two fixed-pitch propellers are placed one behind the other on each shaft.

The decision to include tandem propellers among the various propulsor configurations was made primarily for reasons of acoustics rather than direct energy savings. It was felt that for more stringent propeller acoustic performance requirements, tandem propellers were less likely to show propulsive performance degradation than other propulsion configurations of the same, more stringent, acoustic performance and same level of mechanical simplicity.

In order to increase the cavitation inception speed for surface ships, the propeller blade area must, in general, be increased. At the same time, the number of blades is often increased to reduce the unsteady blade forces and blade rate noise. This increase in number of blades is theoretically accompanied by an increase in the propeller efficiency. However, in practice, as the blade area increases along with the number of blades, the blades become so close to each other at the root that the flow between the blades becomes obstructed. Thus, the result of the increased blade area and number of blades is, in effect, an increase in hub diameter and some decrease in propeller efficiency. This is not the case for tandem propellers. Due to the longitudinal spacing between the two planes of propeller blades, the individual blades within the two separate planes achieve wide blade spacings and the propeller performance is maintained at higher levels than for a single propeller.

Experience with tandem propellers shows that they generally have about the same efficiency as a fixed-pitch propeller of the same diameter. The appendage drag was estimated to be slightly less than that of the parent configuration. Thus it was estimated that twin tandem propellers would demonstrate delivered power reductions of 2 percent relative to the parent DD-963.

TWIN SHAFTLINE LARGE DIAMETER OVERLAPPING PROPELLERS

Overlapping propellers are made by moving one of a pair of propellers aft and both propellers inboard so that, in end view, the two propeller discs overlap. In this particular application, a new hull form was developed such that the propellers would be behind a faired skeg to improve the inflow to the propellers. In addition, small tunnels were made in the hull to accommodate the propellers without their extending below the baseline.

In two previous cases involving twin screw merchant ships, 6 percent reductions in delivered power were obtained by overlapping the two propellers. Presumably in both of these cases, a large part of the gain was due to an increase in propulsive efficiency due to the partial recovery of the rotational losses of the forward propeller by the aft propeller. Neither the closed stern form, Pien and Strom-Tejsen (1968), nor the high speed container ship with an open stern, Strom-Tejsen and Roddy (1972), employed large diameter low tip clearance propellers. However, it was felt that by increasing the propeller diameter, which would decrease the propeller loading, the propeller efficiency could be increased. Additionally, by employing low tip clearances, the propeller would be operating to the maximum extent possible in the boundary layer of the hull, thus decreasing the wake fraction $(1-w_T)$ and increasing hull efficiency. It was felt that the increases in propeller efficiency and hull efficiency, combined with the increased recovery of propeller rotational losses, could lead to power reductions of up to 6 percent.

TWIN SHAFTLINE LARGE DIAMETER LOW TIP CLEARANCE CONTROLLABLE-PITCH PROPELLERS

This configuration employs the same hull form as the large diameter low tip clearance fixed-pitch propeller configuration discussed above. However, the appendages have been resized to account for the greater hub size and weight of the controllable-pitch propellers. The anticipated benefits from using the controllable-pitch propellers are the same as in the large diameter fixed-pitch propeller case. In retrospect, the effects of increased hub and appendage size for this configuration were greatly underestimated, and the anticipated power reduction should have been significantly lower than that of the large diameter low tip clearance fixed-pitch propeller configuration.

SINGLE SHAFTLINE CONTRAROTATING PROPELLERS

This configuration employs a new hull form developed by slightly modifying the parent DD-963 hull to decrease the depth of the hull at the centerline adjacent to the propeller. This modification was required in order to prevent the propeller from extending below the baseline while preserving the appropriate hull to propeller tip clearance. The shafting is of large diameter, and large bossings are required to enclose the flanges on the outer shaft.

In general, the propulsion efficiency of a single shaftline ship is higher than the efficiency of the same hull form fitted with twin screws. This is in spite of the increased propeller loading with its implied decrease in propeller efficiency, and results from the significant increase in hull efficiency which single screw ships have over twin screw ships. Thus a delivered power reduction of 4 to 8 percent was anticipated. As mentioned in the case of twin shaftline contrarotating propellers, this estimate was far too low based on the results of Fisher (1981a), and an estimate of about 15 percent would have been more appropriate.

SINGLE SHAFTLINE TANDEM PROPELLERS

This configuration was implemented on the same hull form that was used for the single shaftline contrarotating propeller experiments just discussed. As in the case of twin shaftline tandem propellers, this configuration was not included for explicit power reductions, but rather because of the fact that it could match existing fixed-pitch propellers in performance while providing improved acoustic performance. The single tandem configuration was assumed to provide a power reduction through its reduced appendage drag compared to twin shaftline configurations. Because of the uncertainty of the decrease in appendage drag, and because of the expectation that propeller performance would remain at present levels, the single tandem configuration was estimated to reduce the delivered power requirement by 2 percent.

ADDITIONAL PROPULSION CONFIGURATIONS

This completes the discussion of the propulsion configurations which were originally chosen for evaluation under the propulsor portion of the Energy Conservation Program. As was stated earlier, two configurations were evaluated by means of analytical calculations, and two more configurations were added to the experimental program. The configurations which were to be evaluated analytically were single shaftline fixed-pitch and controllable-pitch propellers.

These performance estimates were made using the resistance data for the single shaftline tandem hull form, with empirical adjustments for differences in appendage suit resistance. The hull-propulsor interaction coefficients for these two configurations were assumed from model-scale experiments on hull forms fitted with the appropriate propulsor configuration. The propeller characteristics were obtained from the results of parametric studies conducted using the assumed hull-propulsor interaction coefficients.

The two configurations added to the experimental program were two revised fairwater shapes for the DD-963 parent hull form with controllable-pitch propellers, and a bearing-in-rudder post configuration using fixed-pitch propellers.

The decision to add a fairwater series to the experimental program was motivated by the results of the bearing-in-rudder post experiments with controllable-pitch propellers. A comparison of the differences in effective power between the shafts and struts configuration and the bearing-in-rudder post configuration showed that in the case of the DD-963, the bearing-in-rudder post configuration reduced the effective power by 6 percent or more. On the models evaluated prior to this (see Appendix E), the bearing-in-rudder post appendage configuration reduced effective power by 3 percent or less relative to shafts and struts. An examination of the earlier configurations identified fairwater shape as a major difference between these earlier configurations and the DD-963 Class with its button shaped fairwater.

The base drag of the blunt DD-963 fairwater was identified as a likely candidate causing three differences. A very simple experiment on the large diameter low tip clearance controllable-pitch propeller configuration showed that fairwater shape could affect resistance by as much as 3 percent. Examination of published data identified one paper by Bau, et al (1981), which showed significant effects of fairwater shape on propulsion characteristics. Thus two fairwater shapes, a truncated cone and a short bullet-shaped fairwater were selected for evaluation in a series of resistance and propulsion experiments on the parent DD-963.

The bearing-in-rudder post experiments with fixed-pitch propellers were added because in all of the previous cases where comparable bearing-in-rudder post and shafts and struts data exist, controllable-pitch propellers were used. This restriction meant that there was no data available to allow assessment of what effect propeller hub size would have on bearing-in-rudder post performance. Thus the straight rudder configuration from the controllable-pitch propeller bearing-in-rudder post experiments was modified so as to have a smaller diameter fairing between the propeller hub and the rudder. This rudder was evaluated with two propellers: the original propeller used for the fixed-pitch shafts and struts experiments, and a second propeller designed especially for these bearing-in-rudder post experiments.

This concludes the discussion of how the propulsion configurations were chosen for evaluation. The actual performance predictions for these configurations now follow. As will be seen, many of the assumptions made in selecting the configurations were somewhat naive. However, the configurations which have been selected for evaluation cover a broad spectrum of configurations which are viable for the present and future, and there are very few useful configurations which have been excluded from this study.

EVALUATION OF PROPULSION CONFIGURATIONS

This chapter contains an assessment of the delivered power reductions which are possible with various propulsion configurations on three naval combatants of different sizes. The first combatant discussed is a 7945 tonne (7820 ton) destroyer based largely on the DD-963 hull form. The other two combatants are a frigate displacing 3505 tonne (3450 ton) and a cruiser displacing 12192 tonne (12000 ton). The summary of powering performance for each ship type is accompanied by a discussion of the relative merits of the various configurations for that ship type. The chapter concludes with a general discussion of the risks associated with applying these various propulsion configurations on naval combatants, including hydrodynamic, structural, and machinery issues.

PERFORMANCE ASSESSMENT

Detailed projections of the powering performance for a 7945 tonne destroyer have been developed for a speed range of 10 to 32 knots and are presented in Appendix C. With the exception of the predictons for single shaftline fixed-pitch and controllable-pitch propellers, all of these projections are based on model-scale evaluations of these configurations on variants of Model 5359 using custom stock (especially designed) propellers. Tables C-17 and C-18 summarize the effective and delivered powers and hull-propulsor interaction coefficients for each configuration at 20 and 32 knots, as well as the ratios of the effective and delivered powers for each configuration to the corresponding powers of the DD-963 baseline. Table 3 presents the ratios of delivered power, taken from Tables C-17 and C-18, for each of these configurations to that of the DD-963 twin shaftline controllable-pitch propeller baseline configuration, at speeds of 20 and 32 knots.

Table 3 presents the baseline configuration first and then the other propulsion configurations in order of increasing delivered power ratio at 20 knots. The twin shaftline configurations are followed by single shaftline configurations. Using conventional hull forms, in general the contrarotating propeller configurations, the bearing-in-rudder post configurations, and the fixed-pitch propeller with shafts and struts are superior. In particular, twin pods with contrarotating propellers is the best configuration, with a 20 percent delivered power

TABLE 3 - SUMMARY OF RELATIVE POWERING PERFORMANCE FOR FIFTEEN PROPULSION CONFIGURATIONS ON A 7945 TONNE DESTROYER AT 20 AND 32 KNOTS

	P_D/P_D DD-963 BASELINE	
Twin Shaftline Configurations	20 Knots	32 Knots
Controllable-Pitch Propellers (DD-963 Baseline)	1.00	1.00
Pods with Contrarotating Propellers	0.80	0.83
Bearing-in-Rudder Post with Fixed-Pitch Propellers	0.85	0.90
Contrarotating Propellers	0.87	0.87
Fixed-Pitch Propellers	0.88	0.93
Bearing-in-Rudder Post with Controllable-Pitch Propellers	0.88	0.92
Large Diameter Low Tip Clearance Fixed-Pitch Propellers	0.89	0.92
Tandem Propellers	0.92	0.93
Controllable-Pitch Propellers with Revised Fairwaters	0.99	0.99
Large Diameter Overlapping Propellers	1.01	0.98
Large Diameter Low Tip Clearance Controllable-Pitch Propellers	1.06	1.03
Single Shaftline Configurations		
Contrarotating Propellers	0.81	0.82
Fixed-Pitch Propeller	0.84	0.94
Tandem Propellers	0.91	0.97
Controllable-Pitch Propeller	0.91	0.98

reduction relative to the DD-963 baseline. This configuration is followed by single shaftline contrarotating propellers with a 19 percent power reduction; single shaftline fixed-pitch propeller with a 16 percent power reduction; twin bearing-in-rudder post with fixed-pitch propellers with a power reduction of 15 percent; and twin shaftline contrarotating propellers with a 13 percent power reduction. These configurations are followed by twin shaftline fixed-pitch propellers and twin shaftline bearing-in-rudder post with controllable-pitch propellers, each with a 12 percent reduction in delivered power.

At 32 knots, the delivered power saving, relative to the baseline configuration, in general decreased 3 to 4 percent from the corresponding savings at 20 knots. With three exceptions, the ranking of the configurations is the same, or within 1 percent of being the same, as at 20 knots. The three exceptions to this are twin bearing-in-rudder post with fixed-pitch propellers, which deteriorates 5 percent in performance; and single shaftline fixed-pitch and controllable-pitch propellers, which deteriorate 10 and 7 percent, respectively.

The source of the deterioration seen with bearing-in-rudder post with fixed-pitch propellers is not clear. However, it may relate to the fact that the performance of the first set of fixed-pitch propellers used in the experimental program, numbered 4274 and 4275, showed a much greater deterioration in performance than did the second set of fixed-pitch propellers, numbered 4864 and 4865. Because the performance of the first set of fixed-pitch propellers was mixed with that of the second set in projecting the performance of the fixed-pitch propeller bearing-in-rudder post configuration (see Appendix C), this deterioration in performance at 32 knots may be an artificial phenomenon. As such, it is a point to be investigated as part of any research on the bearing-in-rudder post configuration.

The deterioration of the performance of the single shaftline configurations is probably a result of the manner in which the hull-propulsor interaction coefficients for these configurations were derived. Although the hull-propulsor interaction coefficients for these two configurations were derived from those of the FF-1052 an FFG-7 Classes using Froude scaling to correct speeds between the two sizes of ships, this may not be adequate for the particular problem at hand. In particular, the ship self-propulsion point is not equal for the same model at two different scale ratios. This fact affects the propeller thrust loading, and may have a significant impact on propeller performance and hull-propulsor interaction coefficients, resulting in an artificial performance deterioration such as may be seen in this case. The only way in which this question will be resolved is through an experimental evaluation of these concepts at the appropriate scale ratio.

There are two issues which relate to the applicability and accuracy of these results. One relates to propulsion pods and the other relates to restrictions on the power on a single shaft. The issue with pods is not specific to ship size, i.e., 7945 tonne destroyer, but rather is related to the uncertainty of pod size for a given power level. The pods which were evaluated experimentally were the smallest, in both length and diameter, as was deemed possible with presently envisioned technology. As the pod length, and more importantly, the diameter increases, the drag of the pod will increase significantly, reducing the benefit of pods relative to other configurations that house the machinery within the hull. In order to illustrate this effect, resistance predictions for two alternative pod configurations, at 20 and 32 knots, have been carried out. The results of these predictions, which do not contain possible effects of increased wavemaking resistance, are included in Table 4. In particular these studies show that a 14 percent increase in pod diameter can increase the drag of the pod by 30 percent and the drag of the pod-ship system by almost 5 percent. On the other hand, an increase in pod length of almost 40 percent only increases pod resistance by 12 percent and the resistance of the pod-ship system by about 2 percent.

While the effects of changing pod size on total resistance are fairly straightforward, neglecting wave-making resistance, the effects of changing pod size on the hull-propulsor interaction coefficients and propulsive performance are not clear. It is certain that an increase in total resistance will have a slight deleterious effect on propeller efficiency. It is much less straightforward to predict the impact of increased pod size on the hull-propulsor interaction coefficients. Therefore, until further experimental data are obtained, the effect of pod size on the hull-propulsor interaction coefficients will remain an unknown.

The second issue associated with the projected results for the 7945 tonne destroyer relates to single shaftline configurations and the total power which

TABLE 4 - SENSITIVITY OF TWIN POD EFFECTIVE POWER TO INCREASED POD SIZE

Pod Size	Speed (Knots)	P_E for Two Pods (kW)	P_E-Two Pods / P_E-Two Pods as Tested	P_E-Ship with Two Pods (kW)	P_E-Ship with Two Pods / P_E-Ship with Two Pods as Tested
15.54m x 2.13m	20	1014	1.000	6345	1.000
(51 ft x 7 ft) [As Tested]	32	3087	1.000	34302	1.000
17.37m x 2.44m	20	1312	1.294	6644*	1.047
(57 ft x 8 ft)	32	3996	1.295	35212*	1.027
21.34m x 2.13m	20	1136	1.121	6468*	1.019
(70 ft x 7 ft)	32	3553	1.151	34768*	1.014

*Effects of increased pod size on wavemaking resistance not included can be transmitted on a single shaftline. For naval combatants such as frigates and destroyers, the usually accepted guideline is that the power allowed on one shaft should not exceed 30 mW (40000 hp). However, in our experiments, the following configurations violated this rule: the single shaftline fixed-pitch propeller configuration at 50.6 mW, the single shaftline tandem propeller configuration at 52.3 mW, and the single shaftline controllable-pitch propeller configuration at 52.9 mW. Whether or not the single shaftline contrarotating propeller configuration with its two concentric shafts, at 44.6 mW, falls under this restriction is not clear, but it is likely that some restriction would apply.

The powering performances for a frigate and a cruiser have been estimated for inclusion in this evaluation of various propulsion configurations. Because no actual model experiments have been performed, these estimates have been made using the available data for an existing frigate and cruiser model, and the propulsion results from the destroyer configurations just discussed. The estimates of performance for both the frigate and the cruiser have been made in a similar fashion. Therefore, the general method will be discussed, followed by some specifics on each of these ships.

The performance estimates for the frigate and cruiser have both been made in two steps. First, effective power estimates have been made, accounting for the differences in resistance between the appendage suits associated with the various configurations. Second, the propulsion efficiency for each concept was estimated, again taking into account the differences in performance of each propulsion configuration and the resistance of each ship type.

The resistance of the various configurations has been estimated by means of linear superposition, that is, by assuming that the total resistance of the ship is the sum of the resistances of the bare hull and the various appendages. The bare hull resistance is known from bare hull resistance experiments in all cases. The resistance of appendages such as bilge keels, rudders, keel mounted sonar domes, and skegs is estimated from appendage stripping experiments on other models. By this means, the resistance of each set of propulsion appendages on the destroyer hull form has been derived. The resistances of the propulsion appendages for the frigate and the cruiser have been estimated from that of the destroyer in the following manner. It is assumed that the ratio of the known resistance of the frigate or cruiser shafting to the known resistance of the same shafting configuration on the destroyer would be identical to the ratio of the unknown resistance of a particular shafting on the frigate or cruiser to the known resistance of this latter configuration on the destroyer.

For example, on the frigate, for which single shaftline controllable-pitch propeller configuration resistance data exists, it is assumed that the ratio of the resistance of the single shaftline controllable-pitch propeller shafting suit to that of the destroyer is the same as the ratio of the frigate twin shaftline fixed-pitch propeller shafting suit to that of the destroyer. Thus, by knowing the resistance of single shaftline controllable-pitch propeller shafting and twin shaftline fixed-pitch propeller shafting for the destroyer, it is possible to estimate the resistance of the twin shaftline fixed-pitch propeller appendages for a frigate.

The above assumption has not been followed in making resistance predictions with pods. In the case of pods, the resistance of the pod has been scaled, as diameter squared. This assumes that all pods will be geosims of the pods tested on the destroyer model, and that wave resistance of the pod-hull configuration does not vary significantly. This latter assumption may not necessarily be accurate based on what little model test data do exist (see Appendix D).

While this method is highly empirical, it should allow the determination of the resistance of all shafting configurations within 10 percent, and the resistance of the ship with that appendage configuration to within 2 percent. Because the purpose of these powering predictions is to estimate the relative powering performance of various propulsion configurations, this error should not be critical, and the relative accuracy of the effective powering predictions for these two ship sizes should be ±2 percent.

The estimates of propulsion efficiency have been made based on the results of the model tests on the 7945 tonne destroyer. The major adjustment to the destroyer propulsion efficiency was an adjustment of the propeller efficiency to reflect the changes in thrust loading based on propeller diameter and ship resistance. The adjustments in propeller efficiency were based on the parametric calculations presented in Nelka and Cox (1981).

The frigate resistance predictions are based on model test data for the FFG-7 Class, Woo, et al (1983). Based on the relative performance predictions for the destroyer, nine configurations were chosen for evaluation. These were made up of six single shaftline configurations with 5.03 meter (16.5 ft) diameter propellers, and three twin shaftline configurations with 4.14 meter (13.6 ft) diameter propellers. The single shaftline configurations were: controllable-pitch propeller, bearing-in-rudder post with fixed-pitch propeller, pod with contrarotating propellers, bearing-in-rudder post with controllable-pitch propeller, and contrarotating propellers. The single shaftline controllable-pitch propeller configuration was chosen as the baseline configuration for the 3505 tonne (3450 ton) frigate.

The twin shaftline configurations were: pods with contrarotating propellers, fixed-pitch propellers, and controllable-pitch propellers. This limited number of twin shaftline configurations was chosen because of the high resistance penalty which twin shaftline appendages display relative to single shaftline appendages.

Although no experimental data exists for single pods or single bearing-in-rudder post configurations, there is no fundamental reason why these configurations should not show good performance. Therefore, they have been chosen for inclusion in the sequence of data. The resistance of the single pod was derived by dividing the estimated drag for two pods on the destroyer in half and scaling this single pod resistance by square of the diameter. The resistance of a single bearing-in-rudder post was estimated by assuming that the ratio of the resistance of a single bearing-in-rudder post to that of a single controllable-pitch propeller would be the same as the ratio of a twin bearing-in-rudder post to that of a twin shaftline controllable-pitch propeller appendage suit.

The powering estimates for a 3505 tonne frigate are given in Tables 5 and 6 for 20 and 32 knots, respectively. These tables present the appendage drag factor (resistance of appended ship/resistance of bare-hull ship), the effective power, delivered power, propulsion efficiency, propeller open water efficiency, and the ratios of effective and delivered power to the respective power of the baseline for all nine configurations. The effective powers have been derived in the fashion discussed above, where the resistances of the appropriate destroyer shafting suit have been scaled to apply to a frigate. The appendage drag factors have been derived from these results. Due to similar propeller thrust loadings on the frigate and destroyer, the 20-knot propulsion efficiencies of the destroyer have been assumed to hold for the frigate at the same speed. Because of the significantly higher resistance increase for the frigate relative to the destroyer

TABLE 5 - POWERING ESTIMATES FOR A 3505 TONNE FRIGATE WITH NINE PROPULSION CONFIGURATIONS AT 20 KNOTS

Configuration	Appendage Drag Factor	P_E kW (Hp)	P_D kW (Hp)	η_D	η_O	$\frac{P_E}{P_E\text{-Baseline}}$	$\frac{P_D}{P_D\text{-Baseline}}$
Single CP (Baseline)	1.210	3945 (5290)	5635 (7557)	0.700	0.745	1.000	1.000
Single BRP-FP	1.138	3711 (4977)	4981 (6680)	0.745	0.760	0.941	0.884
Single Pod-CR	1.215	3966 (5319)	5052 (6775)	0.785	0.815	1.005	0.897
Single BRP-CP	1.146	3737 (5011)	5154 (6911)	0.725	0.745	0.947	0.915
Single CR	1.246	4064 (5450)	5244 (7032)	0.775	0.795	1.030	0.931
Single FP	1.153	3778 (5066)	5435 (7289)	0.695	0.740	0.958	0.965
Twin Pod-CR	1.290	4206 (5640)	5357 (7184)	0.785	0.820	1.066	0.951
Twin FP	1.268	4133 (5543)	5702 (7646)	0.725	0.765	1.048	1.012
Twin CP	1.386	4521 (6063)	6505 (8724)	0.695	0.750	1.146	1.154

Bare Hull Power (with keel dome and skeg) - 3261 kW (4130 Hp)
Bilge Keel Drag Factor - 0.04, Rudder Drag Factor - 0.04
Single Shaftline Configuration have 5.03m (16.5 ft) Diameter Propellers
Twin Shaftline Configurations have 4.14m (13.6 ft) Diameter Propellers
Notation: CP - Controllable-Pitch Propeller, BRP - Bearing-In-Rudder Post, FP - Fixed-Pitch Propeller, CR - Contrarotating Propeller

TABLE 6 - POWERING ESTIMATES FOR A 3505 TONNE FRIGATE WITH NINE PROPULSION CONFIGURATIONS AT 32 KNOTS

Configuration	Appendage Drag Factor	P_E kW (Hp)	P_D kW (Hp)	η_D	η_O	$\frac{P_E}{P_E\text{-Baseline}}$	$\frac{P_D}{P_D\text{-Baseline}}$
Single CP (Baseline)	1.129	24295 (32580)	37377 (50123)	0.650	0.695	1.000	1.000
Single BRP-FP	1.083	23305 (31252)	33532 (44967)	0.695	0.730	0.959	0.897
Single Pod-CR	1.103	23855 (31990)	32237 (43230)	0.740	0.795	0.982	0.862
Single BRP-CP	1.092	23513 (31532)	33832 (45370)	0.695	0.725	0.968	0.905
Single CR	1.141	24559 (32934)	31894 (42771)	~~0.645~~ 0.770	~~0.695~~ [illegible]	~~0.972~~ 1.011	~~0.979~~ 0.853
Single FP	1.097	23604 (31653)	36594 (49074)	0.645	0.695	0.972	0.979
Twin Pod-CR	1.141	24564 (32941)	33195 (44515)	0.740	0.795	1.011	0.888
Twin FP	1.141	24563 (32940)	35859 (48088)	0.685	0.730	1.011	0.959
Twin CP	1.201	25856 (34673)	38591 (51751)	0.670	0.730	1.064	1.032

Bare Hull Power (with keel dome and skeg) - 21524 kW (28864 Hp)
Bilge Keel Drag Factor - 0.025, Rudder Drag Factor - 0.025
Single Shaftline Configuration have 5.03m (16.5 ft) Diameter Propellers
Twin Shaftline Configurations have 4.14m (13.6 ft) Diameter Propellers
Notation: CP - Controllable-Pitch Propeller, BRP Bearing-In-Rudder Post, FP - Fixed-Pitch Propeller, CR - Contrarotating Propeller

at 32 knots, the propeller thrust loadings for the frigate are about 20 percent higher than for the destroyer at the same speed. Therefore, based on the parametric studies of Nelka and Cox (1981), the propeller efficiencies of the frigate have been lowered 0.02 relative to the values achieved in the destroyer predictions at 32 knots. This has, in turn, led to a corresponding decrease in propulsion efficiency for the frigate at 32 knots.

Examination of the relative effective power given in Tables 5 and 6 shows that the resistance of the various propulsion configurations on the frigate is about the same as on the destroyer. The one exception to this is the single pod, which is shown to increase the resistance by about one-half of one percent. This is due to the increase in pod size which was required to accommodate a motor of higher power than on the destroyer. Despite this increase in effective power, which does not in any way account for changes in wave resistance, a single pod could still be one of the best performing concepts when powering performance is taken into account.

The relative powering performance for nine propulsion configurations on a 3505 tonne frigate, at 20 and 32 knots, is summarized in Table 7. As in the previous similar table, this table lists the baseline configuration first, and the other configurations follow in order of decreasing performance. The order of the configurations is: the single bearing-in-rudder post with fixed-pitch propeller with a predicted 12 percent reduction in delivered power over the single shaftline controllable-pitch propeller baseline; a single pod with a 10 percent reduction; a single bearing-in-rudder post with controllable-pitch propeller with an 8 percent reduction; single shaftline contrarotating propellers with a 7 percent power reduction; and a single fixed-pitch propeller with a 4 percent delivered power reduction. The only twin shaftline configuration which showed a power reduction was twin pods with contrarotating propellers, which showed a 5 percent power reduction.

As can be seen from the list, the projected power reduction for all of these configurations is about one-half of that projected for the twin shaftline destroyer configurations. This is consistent with the results which would be expected if the single shaftline controllable-pitch propeller configuration had been used as a baseline for the destroyer calculations. The major reason for this reduced benefit is the lower appendage drag for all of these configurations, compared to

TABLE 7 - SUMMARY OF ESTIMATED RELATIVE POWERING PERFORMANCE FOR NINE PROPULSION CONFIGURATIONS ON A 3505 TONNE FRIGATE AT 20 AND 32 KNOTS

	P_D/P_D - Single Shaftline CP Propeller Baseline	
Single Shaftline Configurations	20 Knots	32 Knots
Controllable-Pitch Propeller (Baseline)	1.00	1.00
Bearing-in-Rudder Post with Fixed-Pitch Propeller	0.88	0.90
Pod with Contrarotating Propellers	0.90	0.86
Bearing-in-Rudder Post with Controllable-Pitch Propeller	0.92	0.90
Contrarotating Propellers	0.93	0.85
Fixed-Pitch Propeller	0.96	0.98
Twin Shaftline Configurations		
Pods with Contrarotating Propellers	0.95	0.89
Fixed-Pitch Propellers	1.01	0.96
Controllable-Pitch Propellers	1.15	1.03

the twin shaftline configuration on the destroyer. When the results for the frigate and destroyer were compared, the orders of the bearing-in-rudder post with fixed-pitch propeller and pod with contrarotating propellers were reversed. The only configuration which changed order significantly was the bearing-in-rudder post with controllable-pitch propeller, which moved up on the list.

The major uncertainty in the order shown on this list is the resistance of the single and twin pods, just as the resistance of the twin pods was the major uncertainty in the case of the 7945 tonne destroyer. As was the case with the destroyer, this uncertainty is a result of the indeterminancy of the pod size. A further unknown in the case of a single or twin pod on a frigate is the effect of this pod on the wave resistance of the ship-pod combination. In the case of the frigate, the pod is relatively larger than the ones on the destroyer. Therefore, the effect of the pod on the resistance of the total system is potentially much larger.

The resistance predictions for a twin screw 12192 tonne (12000 ton) cruiser have been made using model test data for a 17272 tonne (17000 ton) cruiser. This model was chosen as a basis because both bare hull and appended model resistance data existed, and because it had propulsion data with models of modern controllable-pitch propellers.

The methods used in deriving the resistance of the various configurations on the cruiser were the same employed earlier on the frigate. However, in the case of the cruiser, the appendage drag factor for the controllable-pitch propeller baseline was taken as the average of the values for the DD-963 Class and the 17272 tonne cruiser which was tested.

Due to the high power levels required to propel a 12192 tonne cruiser, all single shaftline configurations were eliminated from contention for this ship. This left the following six twin shaftline configurations for consideration: controllable-pitch propellers (the baseline); pods with contrarotating propellers; bearing-in-rudder post with fixed-pitch propellers; contrarotating propellers; fixed-pitch propellers; and bearing-in-rudder post with controllable-pitch propellers. All of these configurations were evaluated with 4.88 meter (16 ft) diameter propellers. This small propeller diameter (the DD-963 propeller diameter is 5.18 meter) is necessitated by the fact that the propellers on a cruiser cannot extend below the baseline of the ship. (For this reason, the propellers on the

17272 tonne cruiser were 5.47 meters in diameter.)

The powering predictions for these cruiser configurations were estimated based on the propulsion efficiencies for the same configurations on the destroyer. However, because of the smaller propeller diameters and higher resistance of this larger ship, these propellers have 15 percent higher thrust loadings than the propellers on the destroyer. Therefore, based on the parametric calculations of Nelka and Cox (1981), the propeller efficiencies for the cruiser at both 20 and 32 knots have been reduced 0.015. The propulsion efficiency has been reduced accordingly.

The powering performance estimates for a 12192 tonne cruiser are given in Tables 8 and 9 for speeds of 20 and 32 knots, respectively. These tables give the appendage drag factor, effective and delivered powers, propulsion efficiency, propeller open water efficiency, and the ratios of effective and delivered power to the respective powers for the baseline controllable-pitch propeller configuration. The effective power has been calculated using the drag estimated by the methods described at the beginning of this chapter. The appendage drag has been derived from these total resistance predictions and the measured bare hull resistance.

The relative effective powers in Tables 8 and 9 show reductions which are about one-half those for the same configurations on the destroyer. The smaller cruiser reductions are due to the fact that the appendage suits on the cruiser are relatively smaller than the equivalent appendage configurations on the destroyer, with one exception, the pod configuration, which shows about one-quarter of the power reduction. The smaller power reduction by pods is due to increased pod resistance caused by increased motor size. As in the earlier cases, this conclusion is very sensitive to pod size and no consideration of wave resistance has been taken.

The relative powering performance of six propulsion configurations on a 12192 tonne cruiser is summarized in Table 10, which presents results for 20 and 32 knots. In this table the baseline configuration is listed first followed by the other configurations in order of decreasing performance. The order of configurations in this case is: pods with contrarotating propellers with a 15 percent power reduction; bearing-in-rudder post with fixed-pitch propellers with an 11 percent reduction; contrarotating propellers with a 9 percent reduction; and fixed-pitch propellers and bearing-in-rudder post with controllable-pitch

TABLE 8 - POWERING ESTIMATES FOR A 12192 TONNE CRUISER WITH SIX PROPULSION CONFIGURATIONS AT 20 KNOTS

Configuration	Appendage Drag Factor	P_E kW (Hp)	P_D kW (Hp)	η_D	η_O	$\frac{P_E}{P_E\text{-Baseline}}$	$\frac{P_D}{P_D\text{-Baseline}}$
Twin CP (Baseline)	1.296	7805 (10467)	11312 (15170)	0.690	0.725	1.000	1.000
Twin Pod-CR	1.226	7383 (9901)	9588 (12858)	0.770	0.805	0.946	0.848
Twin BRP-FP	1.221	7354 (9862)	10074 (13510)	0.730	0.950	0.942	0.891
Twin CR	1.294	7790 (10447)	10318 (13837)	0.755	0.780	0.998	0.912
Twin FP	1.239	7462 (10007)	10510 (14094)	0.710	0.750	0.956	0.929
Twin BRP-CP	1.236	7445 (9984)	10486 (14062)	0.710	0.735	0.954	0.927

Bare Hull Power (with keel dome and skeg) - 6022 kW (8076 Hp)
Bilge Keel Drag Factor - 0.03, Rudder Drag Factor - 0.05
All Configurations have 4.88m (16 ft) Diameter Propellers
Notation: CP - Controllable-Pitch Propeller, BRP - Bearing-In-Rudder Post, FP - Fixed-Pitch Propeller, CR - Contrarotating Propeller

TABLE 9 - POWERING ESTIMATES FOR A 12192 TONNE CRUISER WITH SIX PROPULSION CONFIGURATIONS AT 32 KNOTS

Configuration	Appendage Drag Factor	P_E kW (Hp)	P_D kW (Hp)	η_D	η_O	$\frac{P_E}{P_E\text{-Baseline}}$	$\frac{P_D}{P_D\text{-Baseline}}$
Twin CP (Baseline)	1.190	44547 (59738)	65032 (87209)	0.685	0.725	1.000	1.000
Twin Pod-CR	1.135	42476 (56961)	57015 (76458)	0.745	0.800	0.954	0.877
Twin BRP-FP	1.134	42462 (56943)	60660 (81347)	0.700	0.735	0.953	0.933
Twin CR	1.177	44048 (59070)	58731 (78760)	0.750	0.785	0.989	0.903
Twin FP	1.154	43198 (57930)	62607 (83957)	0.690	0.735	0.970	0.963
Twin BRP-CP	1.151	43096 (57793)	61566 (82561)	0.700	0.730	0.967	0.947

Bare Hull Power (with keel dome and skeg) - 37434 kW (50200 Hp)
Bilge Keel Drag Factor - 0.03, Rudder Drag Factor - 0.035
All Configurations have 4.88m (16 ft) Diameter Propellers
Notation: CP - Controllable-Pitch Propeller, BRP - Bearing-In-Rudder Post, FP - Fixed-Pitch Propeller, CR - Contrarotating Propeller

TABLE 10 - SUMMARY OF ESTIMATED RELATIVE POWERING PERFORMANCE FOR SIX PROPULSOR CONFIGURATIONS ON A 12192 TONNE CRUISER AT 20 AND 32 KNOTS

	P_D/P_D - Twin Shaftline CP Propeller Baseline	
Twin Shaftline	20 Knots	32 Knots
Controllable-Pitch Propellers (Baseline)	1.00	1.00
Pods with Contrarotating Propellers	0.85	0.88
Bearing-in-Rudder Post with Fixed-Pitch Propellers	0.89	0.93
Contrarotating Propellers	0.91	0.90
Fixed-Pitch Propellers	0.93	0.96
Bearing-in-Rudder Post with Controllable-Pitch Propellers	0.93	0.95

propellers, both with a 7 percent power reduction.

As might be expected, the ordering of these cruiser configurations is the same as for the destroyer. The only difference is that the delivered power reduction is somewhat less, reflecting the smaller part appendage drag plays in the differences between these configurations. The only uncertainty in these predictions is, as seen previously, the effect of pod size on the performance of the twin pod configuration.

From the discussions of performance summarized in Tables 3, 7, and 10, it can be seen that three configurations show significant potential for reducing the delivered power and thus fuel consumption of naval combatants. These configurations are: pods with contrarotating propellers; bearing-in-rudder post with either fixed-pitch or controllable-pitch propellers; and contrarotating propellers with shafts and struts. In all cases, fixed-pitch propellers are superior to controllable-pitch propellers. This concludes the assessment of performance for the various propulsion configurations.

RISK ASSESSMENT

This risk assessment will concentrate on the potential problems with the applications of the various propulsion schemes discussed in this report, such as: vibration, shaft seals, or the lack of design tools. While this risk assessment is by no means complete or rigorous, it should provide a good starting point for planning future research and development efforts. This risk assessment will proceed in a configuration-by-configuration fashion and will follow the order of configurations given in Table 3.

Twin Shaftline Controllable-Pitch Propellers

Since this propulsion configuration is currently used in a number of high-speed naval combatants, there is a low risk for applications on future designs at current power levels. However, at higher power levels a major difficulty that must be overcome is the achievement of adequate structural and mechanical designs for the propeller hub. Significant research effort went into correcting the problems which occurred with the DD-963 controllable-pitch propeller hub, and future designs will require an even more rigorous design process prior to development. For further details on this process, the reader is referred to Reed, et al (1982).

Twin Pods with Contrarotating Propellers

There are four risks associated with using pods. The first risk relates to ship design. As discussed earlier, there are considerable uncertainties regarding: (1) appropriate pod size for a given installed power, and (2) the effect of the pod on resistance and propulsion characteristics of a given ship-pod configuration. This uncertainty is primarily manifested through the potentially large variation in wave resistance which can be caused by a pod (see Appendix D).

The second series of risks relates to the actual implementation of pods. The configuration of the machinery which must be placed in a pod varies greatly depending on the level of technology which is assumed. If the gearing or motor can absorb a side force, then a much shorter shafting run can be allowed to accommodate the overhanging moment from the propellers. Similarly, if the gears or motor can directly absorb the thrust from the propellers, a thrust bearing is no longer required, thereby allowing a reduction in pod length. The impact of simplifying the system is significant considering the complexity associated with a contrarotating thrust bearing. In addition to the problems associated with shafting supports, there is the question of enclosing the motor, either by incorporating the motor housing into the shell of the pod or by surrounding the motor by the pod. The necessity of providing access for maintenance and repair to the interior of the pod and of providing access to the exterior of the motor casing has a significant potential impact on the diameter of the pod.

Finally, there are two areas of hydrodynamic risk associated with the application of podded propulsion. These risks are associated with the related areas of cavitation and vibration. The presence of a well-faired body ahead of a pusher pod should lead to relatively uniform flow into the propeller circumferentially. This will lead to good cavitation and vibration performance of the pod configuration. However, the wake defect caused by the strut must be superimposed on the flow field. This wake defect will tend to cause the propeller blades to undergo a locally high angle of attack and may tend to induce cavitation. By skewing the propeller blades, the unsteady forces which lead to vibration can be lessened or eliminated. The extent to which the wake nonuniformity is a potential problem is at present unknown, and will remain so until a wake survey has been conducted and a series of detailed propeller design calculations have been performed.

In addition to the risks associated with the application of podded propulsion, there are two areas which remain substantially unexplored, tractor versus pusher propulsion pods, and maneuvering of a ship equipped with propulsion pods.

Twin Bearing-in-Rudder Post with Fixed-Pitch Propellers

The technical risks associated with the bearing-in-rudder post configuration are primarily associated with structural issues, vibration, and possible rudder cavitation and cavitation erosion. The structural and vibration issues have an aspect beyond the obvious ones relating to weight, noise, and habitability. This aspect is associated with bearing wear. The bearings currently used on naval combatants require extreme accuracy of alignment so that they do not wear excessively. Whether or not a rudder post with sufficient stiffness is attainable is a question which will have to be answered. Some bearing-in-rudder post applications have used a side strut attached to the rudder post to stiffen the system. While this has reduced the benefit of bearing-in-rudder post to some extent, it has not reduced the viability of bearing-in-rudder post.

As far as vibration is concerned, the Navy and Coast Guard have operational experience with the bearing-in-rudder post configuration on roughly 200 patrol craft with speeds up to 30 knots in some cases (see Appendix E). Because all of these vessels are under 61 m (200 ft) in length, and most achieved speeds of 20 knots or less, the powers in all of these systems were significantly less than that which would be considered for a major naval combatant. Although the experiences with these patrol craft are of very limited applicability to large combatants, the cases explored so far do not show any excessive vibration or cavitation.

A positive benefit from the application of the bearing-in-rudder post configuration is that the inflow to the propeller will be cleaner due to the absence of struts ahead of the propeller. This more uniform flow should lead to less cavitation on the propeller, a higher cavitation inception speed, and somewhat higher propeller efficiency.

From the ship-design point of view, the primary risk associated with bearing-in-rudder post, and in particular, those configurations with fixed-pitch propellers, is the lack of adequate design tools. This goes hand-in-hand with an inability to assess those situations where bearing-in-rudder post will have a positive benefit and those situations where it will not.

The conclusion for the bearing-in-rudder post configuration with fixed-pitch propellers is that it is a hydrodynamically viable configuration with the potential for reducing delivered power 3 percent relative to fixed-pitch propellers. Whether the trade-offs between the benefits and the risks make this an attractive configuration for use with fixed-pitch propellers should be determined by future research efforts.

Twin Shaftline Contrarotating Propellers

The hydrodynamic and mechanical risks associated with the application of contrarotating propellers in a shafts and struts configuration appear to be minimal. Contrarotating propellers may require larger shafting than is normally seen on ships, but this serves to reduce the structural risks. Bearings and seals for contrarotating shafting will still have to be dealt with. Since these issues have already been successfully resolved for submarines, there should be no reason why successful bearing and seal designs can not be developed for surface combatants.

One point, though not truly a risk, that should be thoroughly studied, is the method of coupling contrarotating shafting. The necessity of enclosing shaft flanges within strut barrels and bossings drives the size of these enclosures to extremes which are detrimental to the performance of shafts and struts configurations fitted with contrarotating propellers. A shafting configuration which does not require flanges on the outside shafting could result in a reduction in effective power of several percent, and could also lead to significant increases in propeller efficiency behind ship. The net result of these changes is that the delivered power of the contrarotating configuration with shafts and struts could be further reduced by 4 or 5 percent. This will be particularly true in the case of single shaftline configurations.

From the design point of view, the existing contrarotating propeller design programs are not adequate. These programs underpredict propeller efficiency and are not capable of producing designs which meet thrust and torque distribution requirements between forward and after propellers. While this is not critical (if an iterative procedure is followed, a successful set of propellers can be developed), it is imperative that reliable design tools be developed if high confidence levels are to be achieved for design purposes.

Twin Shaftline Fixed-Pitch Propellers

The hydrodynamic risks associated with the application of fixed-pitch propellers to the propulsion of naval combatants is extremely low. This is due to the large amount of experience with fixed-pitch propellers within both the design and operator communities. In fact the DD-963 is the first class of large combatants in the U.S. Navy to be fitted with controllable-pitch propellers.

The one risk area which can be identified is the difficulty of reversing the propeller rotation of fixed-pitch propellers on ships using gas turbines as prime movers. The task of reversing can be accomplished by the use of either reversing gears or a reversing turbine on ships with direct drive through reduction gears. Alternatively, in the case of electric drive, the task of reversing should be a straightforward switching problem. Although further discussion of these issues is beyond the scope of this report, some obvious areas have been identified where further research and development is required.

A possible hydrodynamic improvement (which is unrelated to efficiency) that can be achieved with fixed-pitch propellers relative to controllable-pitch propellers, is the reduced cavitation which can be achieved because of increased flexibility in the selection of blade shape. This increased flexibility is due to the fact that the blades do not have to be capable of passing themselves when the pitch of the propeller is reversed to allow backing and stopping of the ship.

Twin Bearing-in-Rudder Post with Controllable-Pitch Propellers

The technical risks associated with the application of the bearing-in-rudder post configuration with controllable-pitch propellers are the same as those enumerated in the discussion of the bearing-in-rudder post with fixed-pitch propellers, namely: structures, vibration, and cavitation and erosion of the rudder. An additional complexity which must be considered with the controllable-pitch propeller configuration is the control systems which pass down the shaft to change blade pitch. Although there are no obvious reasons why these control systems or their arrangements should have to change, or why the presence of these systems should render the bearing-in-rudder post with controllable-pitch propellers nonviable, consideration of these issues is mandatory. In addition, consideration will have to be given to the problem of attaching the propeller hub to the shafting.

In the case of bearing-in-rudder post with fixed-pitch propellers, the issue was raised as to whether the additional complications associated with using bearing-in-rudder post was worth the projected 3 percent reduction in delivered power relative to that of the same ship fitted with shafts and struts and fixed-pitch propellers. For bearing-in-rudder post configurations with controllable-pitch propellers, the answer to this question is much more straightforward. A significant increase in system complexity is easy to justify when a 12 percent reduction in delivered power results. Therefore, for ships with gas turbine prime movers where propellers provide reversing and backing, the bearing-in-rudder post configuration should be considered as a viable means of making controllable-pitch propeller performance competitive with that of fixed-pitch propellers.

Twin Shaftline Large Diameter Low Tip Clearance Fixed-Pitch Propellers

The primary technical risk associated with the large diameter low tip clearance configuration is vibration, in particular, propeller-induced hull vibration and noise, due to the close proximity of the propeller blade tips to the hull. The design of the large diameter hull form has attempted to take propeller-induced hull vibration into account through the geometry of the large fillet between the hull and the skeg. The fillet has been designed so that the blade tip clearance is constant over as large an arc as possible. It was intended that the included angle of this arc be large enough so that at least one propeller blade would be adjacent to the hull at all times.

While the above features are designed to intuitively minimize propeller-induced hull vibration, the issue will ultimately be decided by whether or not there is collapsing cavitation on the propeller blades adjacent to the hull. This issue cannot be addressed without performing a wake survey and conducting propulsion and cavitation experiments with design propellers. Therefore, if the propeller-induced hull vibration question is to be answered, a series of model experiments in conjunction with design propeller calculations will be required.

Twin Shaftline Tandem Propellers

The technical risks associated with the hull and propeller due to the application of twin tandem propellers are negligible. The machinery risks are the same ones found with the other fixed-pitch propeller configurations and relate to the problem of backing. As stated earlier, the advent of reversing gears or electric drive for gas turbine prime movers should eliminate reversing as an issue.

The major risk associated with tandem propellers is the design risk associated with the difficulty of obtaining a propeller which performs as desired. Despite this risk, a satisfactory tandem propeller design can be obtained through repeated design followed by experimental evaluation. Thus, the major risks are of time and cost.

Twin Shaftline Controllable-Pitch Propellers with Revised Fairwaters

The major technical risk associated with the use of revised fairwaters is a reduced inception speed for hub vortex cavitation. In the case of the truncated cone, it is, in fact, possible that the inception speed might well increase relative to that of the DD-963 propeller with its button-shaped fairwater. The only way to determine the effect of fairwater shape on hub vortex cavitation inception is through large-scale propeller experiments in a cavitation tunnel. These large-scale model experiments should be backed up by a thorough set of full-scale cavitation and acoustic trials on a prototype fairwater.

Twin Shaftline Large Diameter Overlapping Propellers

The major technical risks associated with the application of the large diameter overlapping propeller configuration are the same propeller-induced hull vibration and noise issues discussed in the section on the large diameter low tip clearance fixed-pitch propellers.

An additional risk not previously discussed is associated with the design of the aft propeller. Because the aft propeller operates partially in the slow wake of the ship and partially in the accelerated wake of the forward propeller, the design of this propeller presents a decided risk with regard to cavitation. If the aft propeller is designed to operate in the slow wake of the hull, there is a high probability of pressure-side cavitation in the wake of the forward propeller. If the aft propeller is designed to operate in the wake of the forward propeller, then there is a high likelihood of suction-side cavitation. Thus, in the selection of the after propeller's characteristics, it will be difficult to account for the flow downstream of the forward propeller.

Twin Shaftline Large Diameter Low Tip Clearance Controllable-Pitch Propellers

The major technical risks associated with this configuration are the same propeller-induced hull vibration and noise issues discussed for the large diameter low tip clearance fixed-pitch propeller configuration, and as such they will not be repeated here. It is, however, worth mentioning that the apparent blockage of the flow between the propeller hub and the hull will exacerbate any vibration problems which may exist. It is also worth mentioning that this configuration would necessitate the design of a new controllable-pitch propeller hub, a process which should not be taken lightly.

Single Shaftline Contrarotating Propellers

The most significant technical risk with this configuration is associated with the maximum delivered power level on a single shaftline. Currently, the maximum power on a single shaftline on destroyers and frigates is about 30 mW (40000 Hp). This is on the order of two-thirds of the power which is required by the single shaftline contrarotating propeller configuration, 45900 kW. However, on a per propeller basis, the single shaftline contrarotating propeller configuration is substantially below the 30 mW limit. Also, it should be noted that aircraft carriers regularly transmit powers of 48-52 mW on a single shaftline. Therefore, it may be concluded that although the single shaftline power levels for this contrarotating propeller configuration are higher than those normally seen on destroyers and frigates, both the per propeller and per shaftline power levels are well within the limits regularly seen on naval combatants.

The other risks associated with single shaftline contrarotating propellers are the same ones associated with twin shaftline contrarotating propellers discussed earlier, namely: machinery, shaft seals and bearings, shaft size, and design tool inadequacy.

Single Shaftline Fixed-Pitch Propeller, Single Shaftline Tandem Propellers, and Single Shaftline Controllable-Pitch Propeller

These three propulsion configurations require delivered powers which exceed the 30 mW limit for a single shaftline. This power limit was discussed under the section on single shaftline contrarotating propellers. The other risks associated with these configurations have been thoroughly discussed in the text concerning the twin shaftline version of the same type propulsor.

This concludes the chapter on the Evaluation of Propulsion Configurations. As was shown in the first section of this chapter, there are three propulsion configurations which show substantial delivered power reductions on frigates, destroyers, and cruisers: pods with contrarotating propellers, bearing-in-rudder post with fixed-pitch or controllable-pitch propellers, and contrarotating propellers with shafts and struts. The second half of this chapter showed that there are significant issues which still must be resolved if these configurations are to be applied in the design of naval combatants. This is particularly true in the case of pods and the bearing-in-rudder post configurations.

RECOMMENDATIONS

As described in the previous sections, 13 propulsion configurations have been evaluated experimentally on models of the DD-963 as part of the Energy Conservation Program. In addition, estimates of the performance of two other configurations, single shaftline fixed-pitch and controllable-pitch propellers, have been developed based on experimental data from other models. The results of all of these predictions are summarized in Tables 3, 7, and 10. These tables give the delivered power relative to the baseline configuration for all of the configurations at two speeds, 20 and 32 knots. Table 3 gives results for twin and single shaftline configurations on a 7945 tonne (7820 ton) destroyer, Table 7 gives similar results for a 3505 tonne (3450 ton) frigate, and Table 10 gives the results for a 12192 tonne (12000 ton) twin screw cruiser.

Examination of these three tables shows that three generic propulsor types have the greatest potential for power reduction (10 to 20 percent on a destroyer) and an ensuing reduction in energy consumption relative to current combatant configurations. These propulsor types are contrarotating propeller configurations, bearing-in-rudder post, and fixed-pitch propellers.

CONTRAROTATION

Of the contrarotating configurations, pods have the greatest potential for power reduction, up to 20 percent. Yet this is also the configuration with the greatest level of uncertainty. If machinery considerations require pod diameter to increase over diameters which have been evaluated to date, then the favorable position in which pods stand will quickly erode. Shaft and strut configurations or possibly nacelle configurations could become the most advantageous contrarotating configurations if pod diameter must increase significantly. Both the twin and single shaftline contrarotating configurations show similar gains of 13 to 19 percent at 20 knots over their respective controllable-pitch propeller configurations. With more favorable shafting designs and possibly development, these configurations could improve even more.

The following recommendations are made with regard to pods with contrarotating propellers. Because of the uncertainties with respect to the size of the mechanical system for pods, further research efforts on pods should follow two parallel courses. One effort should be aimed at resolving the mechanical design issues as quickly as possible. In particular, the minimal size for pods in the 30 mW power range should be established, through designs which could be implemented in the 5-to 10-year time frame without significant technical developments. Secondly, generic hydrodynamic efforts on pods should be aimed toward tractor propulsion. Also, parametric experiments relating to pod shaping, orientation, and placement should be carried out. Finally, when the mechanical design has narrowed in on feasible pod size, a design for either a pusher or tractor pod should be carried through analysis and evaluation relating to maneuvering, pod forces, vibrations, cavitation, structural design, and maintenance and repair considerations.

The drag penalties which are currently paid by the contrarotating configurations with shafts and struts would seem to indicate that mechanical design efforts should be undertaken to develop shafting configurations with smaller diameters. These efforts would primarily concentrate on the area of shaft couplings which seem to drive the size of current contrarotating shafting designs. If successful, these efforts would lead to lower effective powers and probably improved propulsion efficiencies, particularly for single shaftline configurations.

The first new ship design for which contrarotating propellers could be considered will probably be a single shaftline frigate. Therefore, it is recommended that an effort be carried forth to develop detailed performance data for single shaftline combatants with either shafts and struts, pods, or nacelles. The goal of this effort should be to have sufficient design information to show clearly the hydrodynamic advantages and mechanical feasibility of contrarotating configurations for a combatant ship design.

BEARING-IN-RUDDER POST

For a model equipped with controllable-pitch propellers, changing from a shafts and struts configuration to a bearing-in-rudder post configuration results in a 10 to 14 percent reduction in power. Similar or greater gains have been shown with models of the PG-84 and PCG Classes (see Appendix E), which are also fitted with controllable-pitch propellers. However, for a model of the DD-963 fitted with fixed-pitch propellers, changing from a shafts and struts configuration to bearing-in-rudder post configuration yields at best a 3 percent reduction in power. Based on our current understanding of the bearing-in-rudder post configuration, it would appear that bearing-in-rudder post has a significant benefit only when applied with controllable-pitch propellers. The benefit of bearing-in-rudder post relative to shafts and struts on ships with fixed-pitch propellers does not appear to be significant enough to justify the increased risks.

The dichotomy in performance of bearing-in-rudder post versus shafts and struts when going from controllable-pitch to fixed-pitch propellers illustrates our lack of understanding of the principles behind the effectiveness of the bearing-in-rudder post. More recent experimental efforts seem to indicate that the size of the propeller hub and the presence of a connection between the propeller hub and the rudder are important contributing factors to the effectiveness of the bearing-in-rudder post configuration. However, existing analytical tools for predicting propeller performance are not capable of explaining the success of the bearing-in-rudder post configuration. In addition to the lack of theoretical knowledge on the bearing-in-rudder post configuration, there is a lack of information concerning rudder effectiveness, which would allow the selection of the optimum rudder size. Measurements of the hydrodynamic forces on the rudder are needed for structural analysis and the subsequent structural design. Finally, the operational and maintenance questions associated with issues such as bearing design and shafting removal must be analyzed.

Therefore, it is recommended that a two-track approach be taken with the bearing-in-rudder post concept. Efforts should be undertaken to complete development of a fundamental understanding of the mechanisms behind the effectiveness of the bearing-in-rudder post configuration, and engineering design analysis tools should be developed. At the same time, an intensive engineering effort should be taken to implement a prototype bearing-in-rudder post configuration on a full-scale ship, such as the R/V ATHENA, as soon as is practical. This would involve a hydrodynamic design of the propeller and rudder, and model-scale evaluation of the configuration in resistance, powering, cavitation, maneuvering, and rudder forces. In addition, structural and mechanical designs would be required. The ensuing designs should be implemented full scale, and a thorough set of ship trials should be performed to completely evaluate the configuration hydrodynamically, structurally, and mechanically. Also, sufficient operational hours should be obtained on the system to determine the reliability of the components of the bearing-in-rudder post.

FIXED-PITCH PROPELLERS

Fixed-pitch propellers show a reduction in power of 10 to 12 percent over controllable-pitch propellers on a model of the DD-963. On other ship designs, the difference might be less. However, on ships where reversing can be accomplished without changing pitch, fixed-pitch propellers will clearly be superior to controllable-pitch propellers.

Therefore, it is recommended that fixed-pitch propellers, rather than controllable-pitch propellers, be employed on all ships where reversing can be accomplished by changing the direction of shaft rotation. It is recognized that this will require the development of reversing gears for those gas turbine-powered ships with geared propulsion. However, the effort involved in developing and certifying reversing gears may not be any greater than the effort associated with developing and certifying a controllable-pitch propeller for higher power levels. In fact, if a controllable-pitch propeller hub is required to carry greater power levels than the current 30 mW (40,000 hp), the hub will have to become larger to overcome hub materials limitations, resulting in yet poorer powering performance.

ADDITIONAL RESEARCH EFFORTS

Several additional experimental investigations seem to be justified based on the work summarized in this report. The performance predictions for the 3505 tonne frigate indicate that both a single bearing-in-rudder post and a single pod have significant potential for power reduction. Therefore, the series of experiments on Model 5359 should be extended to include both a single shaftline bearing-in-rudder post configuration and a single pod. The inclusion of these two configurations in the model test series would add much valuable information to the data base and provide the information necessary to answer design questions relating to future frigates.

In addition, the large diameter low tip clearance hull form with fixed-pitch propellers showed significant reductions in effective power. The available data do not provide enough details to determine whether this reduction was through reduced appendage drag or through reduced hull-form resistance. Depending on the source of these benefits, this hull form could have a significant impact on the design of future naval combatants.

The only way in which the source of the reduced resistance of the large diameter low tip clearance hull form and appendage suit can be identified is through a set of appendage stripping experiments. Depending on the results of these appendage stripping experiments, it may be worthwhile to consider additional propulsion experiments using the current DD-963 5.2 meter (17 ft) diameter design propellers on the same centerline as is used for the large diameter propellers. In the case of both the fixed-pitch and controllable-pitch propellers, this will result in smaller struts and strut barrels, and in the case of the fixed-pitch propeller, this will also result in smaller shafting. The result of this is that with 5.2 meter propellers, the large diameter hull form could have a resistance which is several percent lower than that obtained with the current appendages. Propulsion with this new configuration will probably show an increase in both hull efficiency and propeller efficiency behind. A controllable-pitch propeller configuration on this hull form may be as much as 11 percent better than the controllable-pitch propeller baseline configuration. A fixed-pitch propeller configuration may be as much as 13 or 14 percent better than the baseline configuration.

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APPENDIX A

DETAILED DESCRIPTION OF THIRTEEN PROPULSION CONFIGURATIONS FOR WHICH MODEL EXPERIMENTS WERE PERFORMED

CONTENTS - APPENDIX A

DETAILED DESCRIPTION OF THIRTEEN PROPULSION CONFIGURATIONS FOR WHICH MODEL EXPERIMENTS WERE PERFORMED

INTRODUCTION

This appendix contains descriptions and drawings of the hull forms, appendages and propellers which were used in the series of experiments reported herein. Although the rationale for each design is presented elsewhere in the report, the configuration details that follow are an important part of the technical data contained in this comprehensive summary report.

Two general statements of importance need to be made with regard to the design details of the entire range of configurations investigated:

- In all instances, attempts were made to keep complications of hull form changes out of the investigative process as much as possible. Discussion of specific examples of such action will be presented in the section of this appendix covering hull details.

- NAVSEA design practices were followed in all cases where practical. For those novel configurations where NAVSEA design practice did not apply, such as large diameter low tip clearance propellers and bearing-in-rudder post, the specific designs were developed in consultation with NAVSEA personnel.

In all cases the scale ratio (length ship/length model) is equal to 24.824. Drawings contain full-scale dimensions referenced to the forward perpendicular of the ship or local station numbers (station spacing equal to L/20).

The remaining sections in this appendix are concerned with Hull Form, Appendages, and Propellers, respectively. In each of these sections appropriate comments will be made with regard to design philosophy and pertinent design or arrangement specifics.

As the List of Figures for this appendix indicates, configuration description and pictorial details of the hull, appendages, propellers, and their arrangements are presented in groups of approximately four to seven figures. The ordering of such groups of figures is consistent with the order in which the material is presented throughout the entire report.

HULL FORM

Model 5359, representing the DD-963 as built, is used as the parent and baseline hull form for the experiments reported herein. It is a fiberglass replica of the first model of the DD-963 Class, Model 5265-1B. (This styrofoam model was replaced after difficulties were encountered with this model when changing configurations.) The terms "parent" and "baseline" are used throughout the text and appendices as follows: the "parent" is the DD-963 as built; the term "baseline" is the DD-963 hull form with appendages that meet current NAVSEA design practices. The hull form of both the parent and the baseline are the same, i.e., the hull of the DD-963 as built. Appendage differences will be discussed later in the appendix.

For the experimental program in this report, the same model forebody was used with different afterbodies. Every means possible was utilized to minimize complications of hull-form changes affecting the data. In this regard, the hull forward of Station 11 was held constant for all configurations. Furthermore, attempts were also made to hold constant the displacement and waterplane area, and the transom shape.

For purposes of clarity, the afterbodies were designated by a numeric or alphanumeric designator. The former refers to the afterbody change, and the latter to the afterbody plus an appendage suit change. An exception to this definition is the -1 stern, a second copy of the DD-963 stern, built to accommodate the many appendage changes detailed below. For example, Model 5359-1 represents the DD-963 hull form with fixed-pitch propulsion appendages and 5359-1A represents the hull form with appendages modified to incorporate a twin tandem propeller appendage suit.

In addition to the parent afterbody, four new afterbodies were constructed for this series of experiments:

o Model 5359-0 (the parent afterbody) was built for verifying resistance and propulsion performance with controllable-pitch propellers as well as for controllable-pitch propeller and fixed-pitch propeller bearing-in-rudder post experiments. This model was also used for experimental verification of the effect of fairwater shape on resistance as well as controllable-pitch propeller performance.

o Model 5359-1 was built for experiments with twin shaftline fixed-pitch propellers, contrarotating propellers, tandem propellers, and podded propulsion. The hull form and skeg of this afterbody represent the DD-963 as built.

o Model 5359-2 was constructed to accommodate the large diameter low tip clearance propeller configurations (both fixed-pitch and controllable-pitch). This configuration was chosen in an attempt to utilize wake velocity defect recovery close to the hull to improve overall propulsion performance. A 2.5 percent propeller diameter tip clearance was chosen (as compared to the usual 25 percent design criterion) for use with a 6.10 m (20 ft) diameter propellers.

As seen from an examination of Figure A-7.4, propeller tip-to-tip interactions were of concern. Therefore, the stern shape was modified by carrying the skeg more deeply than in the baseline configuration. Furthermore, to minimize propeller induced hull vibration, the fillet near the propellers was designed to keep a constant distance between the propeller tips and the hull over an arc, and to have one propeller blade adjacent to the hull on each side at all times.

o Model 5359-3 was constructed to accommodate the overlapping propulsor arrangement. This configuration was chosen in an attempt to derive some of the benefits of contrarotating propulsion with a twin screw configuration by having one propeller operating partly in the wake of the other propeller. As with the other large diameter propeller configuration, a propeller tip clearance criterion of 2.5 percent was selected for use with 6.10 m (20 ft) diameter propellers, and the skeg was carried more deeply than on the baseline (see Figure A-10.4). To locate one propeller slightly aft of the other and to achieve as much overlap of the propeller discs as possible necessitated a slight tunnel in the stern hull sections above each propeller. In addition, machinery (gearing) consideration influenced the transverse spacing of the shafts.

o Model 5359-5 was developed to accommodate single-shaftline propulsion for both tandem and contrarotating propulsion schemes. (Model 5359-4 had been developed for another unrelated project.) To maintain a 25 percent tip clearance criterion with large 6.10 meter (20 ft) diameter propellers, minor buttock and near-centerline hull changes were necessary, as seen in Figure A-12.4. These changes resulted in small variations in the sectional area curve, as compared to the baseline configuration.

APPENDAGES

Before proceeding to discussion of appendage details on various configurations, pertinent comments follow regarding appendage design philosophy and approach. Existing NAVSEA design practices and design data sheets were used in the design of specific appendages whenever possible. For example, in the design of appendage suits, shaft couplings were assumed to be no more than 24.38 m (80 ft) apart. Machinery arrangement practicalities were considered, such as reduction gear diameter effects on shafting-hull intersection locations and on shafting angle. In this regard, shaft pairs were designed parallel to the centerline for all twin shaft arrangements. A decision was made at the outset to locate all propellers at the same station as on the parent DD-963 controllable-pitch propeller configuration. If more than one propeller was used on a single shaftline, the forward propeller was located at this station.

With the exception of the parent DD-963, none of the model experiments were conducted with bilge keels. This approach was used to avoid conducting separate bilge keel flow visualization experiments and to eliminate the time and cost of building and installing on the models each set of bilge keels. The approach taken was to test the parent DD-963 model hull with and without bilge keels, and to apply the appropriate drag correction to the resistance results, and to include this drag in the D_f of the powering experiments of each of the other configurations.

The skeg was held constant on all configurations with the exception of large diameter low tip clearance propeller configurations (both fixed-pitch and controllable-pitch) and of the large diameter overlapping propeller configuration. The rudders were held constant in size and location for all configurations with the exception of the bearing-in-rudder post investigations; in these the movable portion retained the same area as on the parent DD-963. Propeller fairwater shapes were simple bullet shapes, except for the parent DD-963 configuration and the fairwater study which was performed on the parent model hull.

All model shafts, struts, and strut barrels, with the exception of those on the parent, were made to NAVSEA standards. The struts, however, were not twisted to align them with the flow, but were simply faired from flat bar stock. The parent DD-963 model appendages had two distinct differences as compared with other model appendages. First, the DD-963 parent shafting and strut barrels were smaller than those resulting from the application of current NAVSEA design standards. Second, the struts for the parent DD-963 model were twisted and shaped to align them with the flow. The aggregate effect of these differences on the results is due primarily to the shafting diameter disparity. To correct for this disparity a constant 1.5 percent increase in resistance has been applied to the results of the parent tests in arriving at the baseline results and to the controllable-pitch propeller bearing-in-rudder post and fairwater shape results.

Delineated below are additional important specifics concerned with appendages on tested configurations:

o The twin-shaftline contrarotating propulsion arrangement (see Figure A-4.4) used non-standard shafting design for the internal shaft, therefore resulting in a smaller diameter outer shaft than standard Navy design practice would have used. Shaft-length restrictions also affected the intermediate strut and hull bossing lengths, in that they are longer and larger than in normal practice (see Figure A-4.4).

o The bearing-in-rudder post appendages were created to accommodate the design controllable-pitch propellers. Three shapes were designed: one without camber to the rudder but with continuous fairing of the propeller hub (5359-0A); a second with camber (contraguide) features incorporated in the rudder (5359-0B); and a third with camber and with a large bossing about the propeller hub-rudder intersection called a Costa bulb (5359-0C) (Figures A-6.4). The amount and location of camber on the rudder sections were determined from Saunders (1957) because little other information was available to provide guidance. For the fixed-pitch propeller bearing-in-rudder post arrangement, the diameter of the propeller hub bossing of the straight uncambered rudder (5359-0A) was reduced from that of the controllable-pitch propellers to that of the fixed-pitch propeller hubs, forming configuration 5359-0A1. The contraguide and contraguide with Costa bulb bearing-in-rudder post configurations were not used with fixed-pitch propellers.

o The model size of the propulsion pods was developed by incorporating information from estimates of machinery size and other requirements. The pod diameter was determined by the propulsion motor size and thrust bearing location and size. Initially, a 2.13 m (7 ft) diameter pod with a length-diameter ratio of five was estimated to be adequate to house a contrarotating propulsion motor. Therefore, the models of the propulsion pods were initially sized to represent 2.13 m (7 ft) diameter and 10.67 m (35 ft) long pusher pods with contrarotating propellers. Subsequently, the decision was made that an increase in length would be required because the thrust bearing in the pod could not be integral to the propulsion motor. The final models for the propulsion pods represent pods 15.54 m (51 ft) in length and 2.13 m (7 ft) in diameter. The pod shapes were based on Series 58, Gertler (1960). The strut size was based on structural-strength studies, and designed with a low resistance chord shape properly proportioned to the pod. Although the strut-hull intersection had no filleting, the strut-pod intersection had a small fillet. The orientation of the pod center-lines was parallel to the baseline and the centerline of the ship. The pod centerline was located vertically so as to allow a 25 percent hull-propeller tip clearance for the forward or larger propeller of each contrarotating pair.

o The large diameter low tip clearance configuration had shafting shorter than the baseline by approximately one-half station. There is also a much smaller angle between the buttock and the shaft lines. Generally, the large diameter low tip clearance propeller shafting diameters are larger than in the DD-963 baseline, with the fixed-pitch shafting being smaller in diameter than the controllable-pitch shafting. (Note that the diameter of the hub in the controllable-pitch propeller arrangement is sufficiently large to result in flow blockage between the aft part of the shaft and struts and the hull).

o The large diameter overlapping configuration also has a smaller angle between the shaft and buttock line than on the baseline hull form. This configuration also has a shorter shaft length than the DD-963 baseline.

o The single shaft contrarotating configuration necessitated either hull bossings or extremely long shaft strut barrels, due to the 24.38 m (80 ft) shaft section length criterion, either of which, necessarily, affects resistance and propulsion performance. A decision was made to increase the length of the shaft strut barrel (see Figure A-12.5). The previously itemized general constraints that provided for a hull form to be held close to that of the baseline DD-963 are the source of this unusual strut barrel configuration, which probably results in slightly higher resistance and slightly lower propulsion efficiency for this configuration than might be necessary. A hull form designed for this configuration under less artificial design constraints probably could avoid these appendage anomolies and their resulting penalties.

PROPELLERS

Three general statements may be made with regard to the design of the propellers that were used throughout the experiments. First, to minimize complications, a decision was made to use only two propeller diameters on the various propulsion configurations. Consistent with the DD-963 propeller diameter of 5.18 m (17 ft) all twin shaftline configurations, with the exception of the three large diameter arrangements, were designed to 5.18 meter (17 ft) diameters. In the case of the twin shaftline contrarotating and tandem propeller investigations, the average diameter between the forward and aft propellers was maintained at 5.18 m (17 ft). A diameter of 6.10 m (20 ft) was selected for the single shaftline configurations based upon propeller tip clearance design criteria and propeller draft limitations; compound propulsor arrangements maintained an average diameter of 6.10 m (20 ft). This diameter was also used for the twin shaftline large diameter configurations.

Second, all propellers were designed and selected to satisfy DD-963 cavitation and propulsion performance criteria. This primarily affected propeller pitch and blade area ratio.

Third, all propellers were new, custom-designed stock propellers, with constant pitch and no skew, and their design included consideration of appropriate hull-propulsor interaction coefficient estimates. In the case of the compound propulsors, the axial spacing selected was one quarter of the mean diameter. With the exception of the large diameter propellers, all of these propellers were custom built to reduce tolerances. The large diameter propellers closely matched propellers available from Michigan Wheel. These off-the-shelf propellers were turned to a constant diameter, and the leading and trailing edges were faired. During open water testing the performance of all propellers was found to be satisfactory, with the exception of the compound propulsors.

Following are some important comments regarding the propellers used in the experiments:

o Models of the design controllable-pitch propellers of the DD-963, numbers 4660 and 4661, were used with the shafts and struts and bearing-in-rudder post configurations. These propellers represent five-bladed, 5.18 m (17 ft) diameter screws with a design pitch-diameter ratio of 1.54. During the course of the experimental program, the performance of these propellers deteriorated. Another set of open water data was obtained and used in the analysis of data from later experiments using these propellers. Subsequently, a new set of propellers, numbers 4868 and 4869, were built to the same design as the original pair of model propellers. These propellers were used for the study of improved fairwater shapes for the DD-963. Their open water characteristics matched those of the original models of the design propellers.

o Results indicated that the first sets of twin shaftline contrarotating propellers, numbers 4768 & 4769 and 4770 & 4771, designed for torque ratio of one, operated with a large thrust and torque imbalance at equal rpm. Therefore, new aft propellers were designed and built, resulting in stock contrarotating propellers, numbered 4768 & 4839 and 4770 & 4828. These new propellers were used with the twin shaftline as well as with the twin pod contrarotating propulsion arrangements. A significant increase in performance was achieved with this second set of stock contrarotating propellers, relative to the first set.

o Similar problems to those of the twin shaftline contrarotating propellers were encountered with the first set of single shaftline contrarotating propellers, numbered 4783 and 4784. These problems were resolved by designing and building a new forward propeller resulting in a propeller set numbered 4859 and 4784.

TWIN SHAFTLINE CONTROLLABLE-PITCH PROPELLERS (PARENT DD-963)

Afterbody - DD-963, unmodified (see Figure A-1.5) - Models 5265-1B and 5359

Rudders - Twin; same dimensions and location as on DD-963 - Wetted surface of two rudders is 648 ft^2

Propeller Shafts	
Number	2
O.D./I.D. Shafts in way of main strut bearing (inches)	26.25/–
O.D./I.D. of exposed shafts, forward of main strut (inches)	21.50/–
Main Strut Arms	
Chord (inches)	38.0
Thickness (inches)	7.6
Webbed surface of four struts	330.0 ft^2
Intermediate Strut Arms	
Chord (inches)	25.5
Thickness (inches)	5.1
Propellers	
Type	C.P.
Number of blades	5
Dp (ft)	17.0
$P/D_{.7R}$	1.54
E.A.R.	0.73
Weight (pounds each, approximate)	48,000
RPM (approximately) at 20 knots	96.6
RPM (approximately) (design full power)	168
Propeller model	4660; 4661 4868; 4869

Figure A-1.1 - Appendage, Afterbody, and Propulsor Characteristics of the Parent DD-963 Configuration - Twin Shafts and Struts with Controllable-Pitch Propellers, from Tomassoni and Slager (1980)

SHIP AND MODEL DATA
FOR

TWIN SHAFTLINE CONTROLLABLE-PITCH PROPELLERS (PARENT DD-963)

MODEL 5265-1B and MODEL 5359

APPENDAGES: Bow Sonar Dome and Centerline Skeg

DIMENSIONS	UNITS	SHIP	MODEL	LWL COEFFICIENTS			
LENGTH (LWL)	ft(m)	530.2 (161.60)	21.359(6.5651)	C_B	0.482	C_{WP}	0.736
LENGTH (LPP)	ft(m)	530.2 (161.60)	21.539(6.5651)	C_P	0.576	C_{WPA}	0.917
BEAM (B_X)	ft(m)	55.0 (16.76)	2.216(0.6754)	C_X	0.836	C_{WPF}	0.562
DRAFT (T)	ft(m)	19.5 (5.94)	0.786(0.2396)	C_{PF}	0.545	L_E/L	0.550
DISPLACEMENT (Δ)	tons(t)	7835 (7960)	0.498 (0.506)	C_{PA}	0.630	L_P/L	0.000
WETTED SURFACE	ft^2(m^2)	33660 (3127.1)	54.623(5.0747)	C_{PE}	0.576	L_R/L	0.450
DESIGN VELOCITY	knots	30.0	6.021	C_{PR}	0.577	L/B	9.640
$\overline{FB}$/LWL 0.512	$\overline{FB}$/LPP 0.512	λ 24.824		C_{VP}	0.655	B_X/T	2.821
WATERLINE ENTRANCE HALF ANGLE 7.0°				C_{VPA}	0.566	$S/\sqrt{\Delta L}$	16.520
WETTED SURFACE OF TWO BILGE KEELS - 1497 ft^2				C_{VPF}	0.799	C_∇	0.00184
						f	0.289

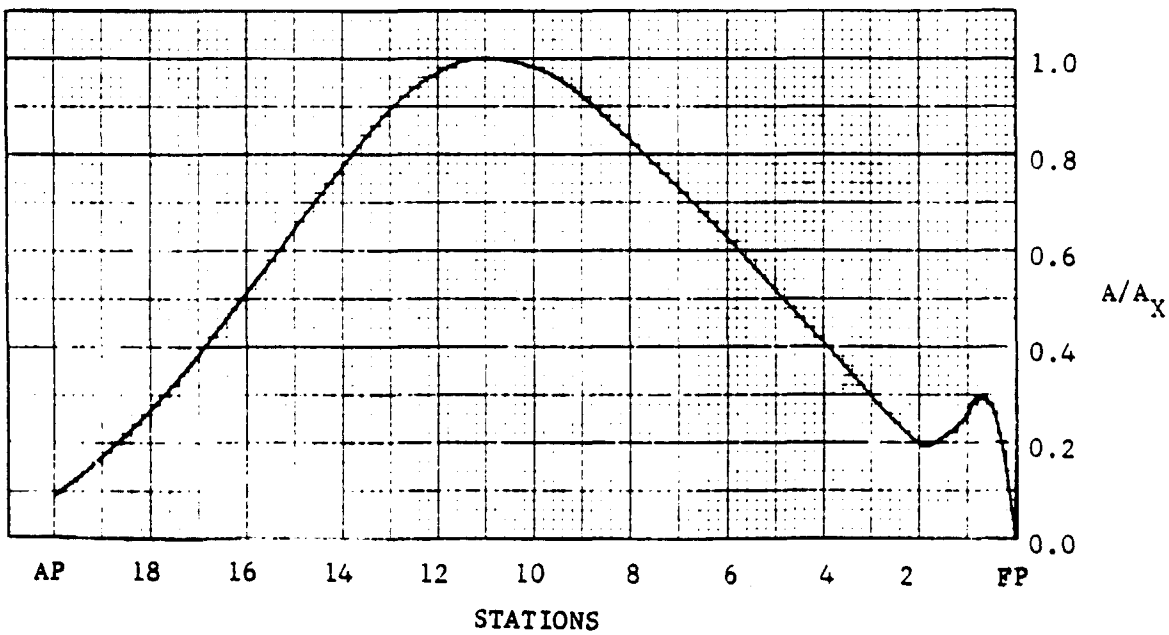


Figure A-1.2 - Ship and Model Data for DD-963, Model 5265-1B Representing the Parent Configuration - Twin Shafts and Struts with Controllable-Pitch Propellers

TWIN SHAFTLINE CONTROLLABLE-PITCH PROPELLERS (PARENT DD-963)

PROP. NO.	LINEAR RATIO	DIA. MODEL IN.	DIA. SHIP IN.	PITCH MODEL IN. @70%	PITCH SHIP IN. @70%	PITCH RATIO @70%	NUMBER OF BLADES	EXP. BLADE AREA	E.A./D.A.	M.W.R.	PROJ. AREA	P.A./D.A.	B.T.F.	RAKE ANGLE @ TIP	ROTATION	SHIP MODEL	SECTION LENGTH MODEL IN. @70%
4660	24.824	8.218	204.000	12.654	314.130	1.540	5	38.733	.730	.328	31.327	.591	.054	-6.649°	R.H.	5265-1A	3.226
4661															L.H.		

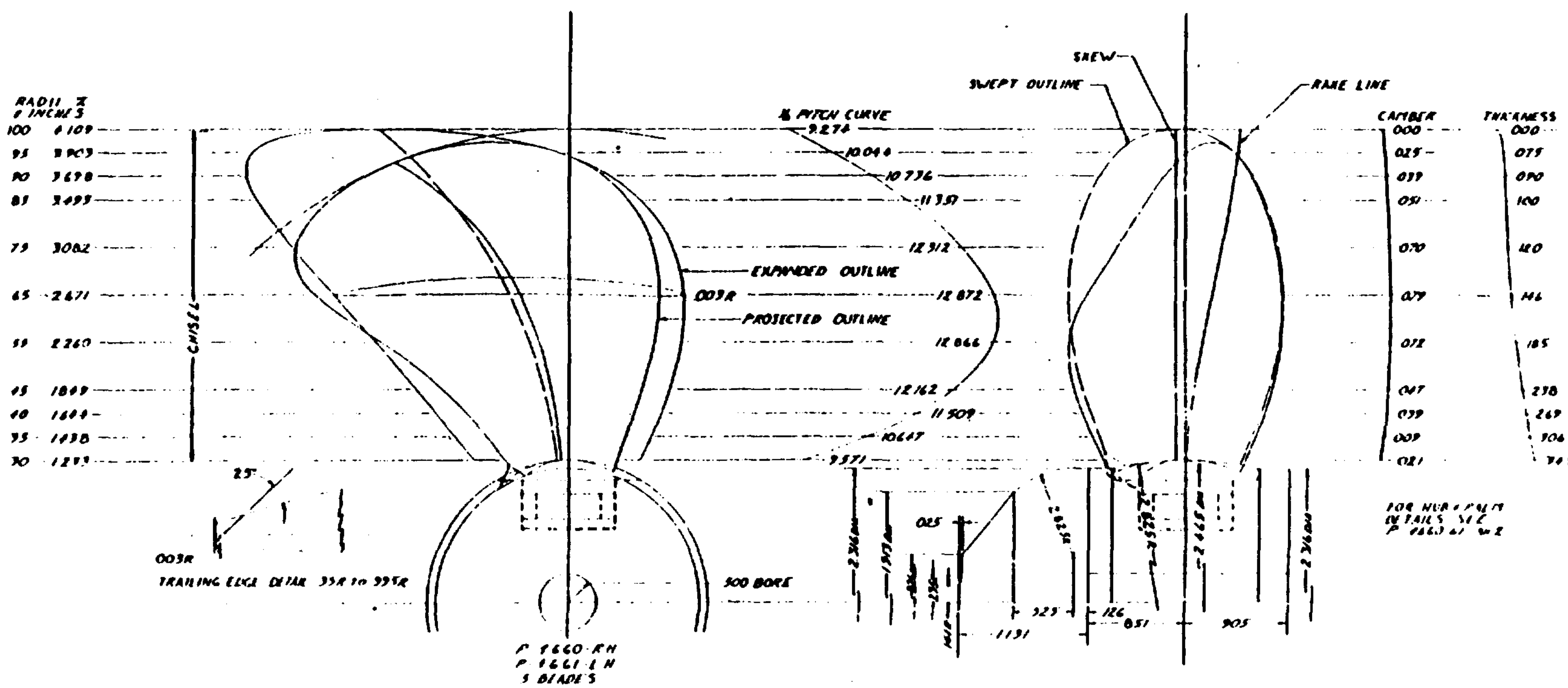


Figure A-1.3 - Drawing of Propellers 4660 and 4661 - DD-963 Design Controllable-Pitch Propellers

TWIN SHAFTLINE CONTROLLABLE-PITCH PROPELLERS (PARENT DD-963)

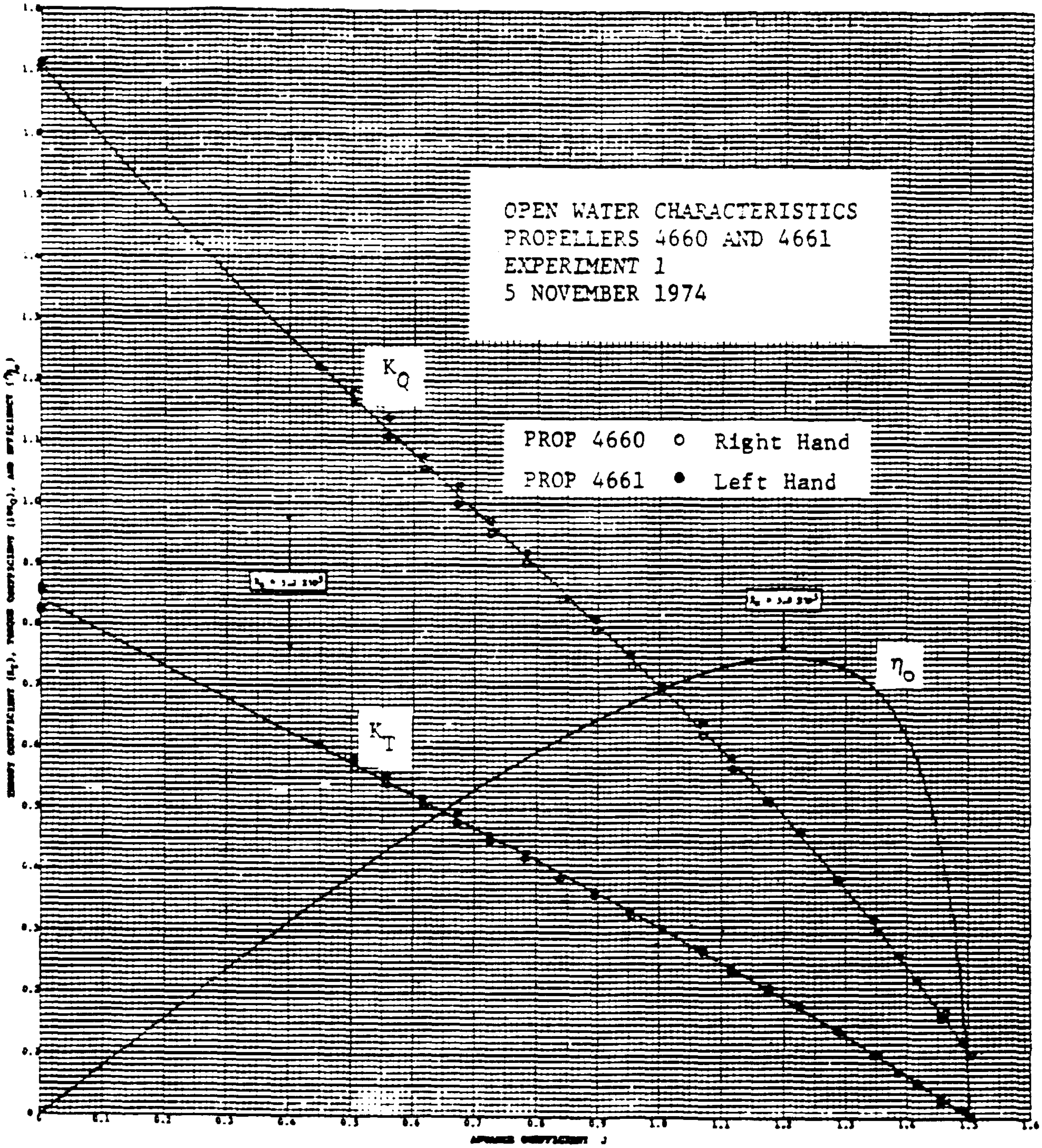


Figure A-1.4 - Open Water Curves for Propellers 4660 and 4661 - DD-963 Design Controllable-Pitch Propellers

TWIN SHAFTLINE CONTROLLABLE-PITCH PROPELLERS (PARENT DD-963)

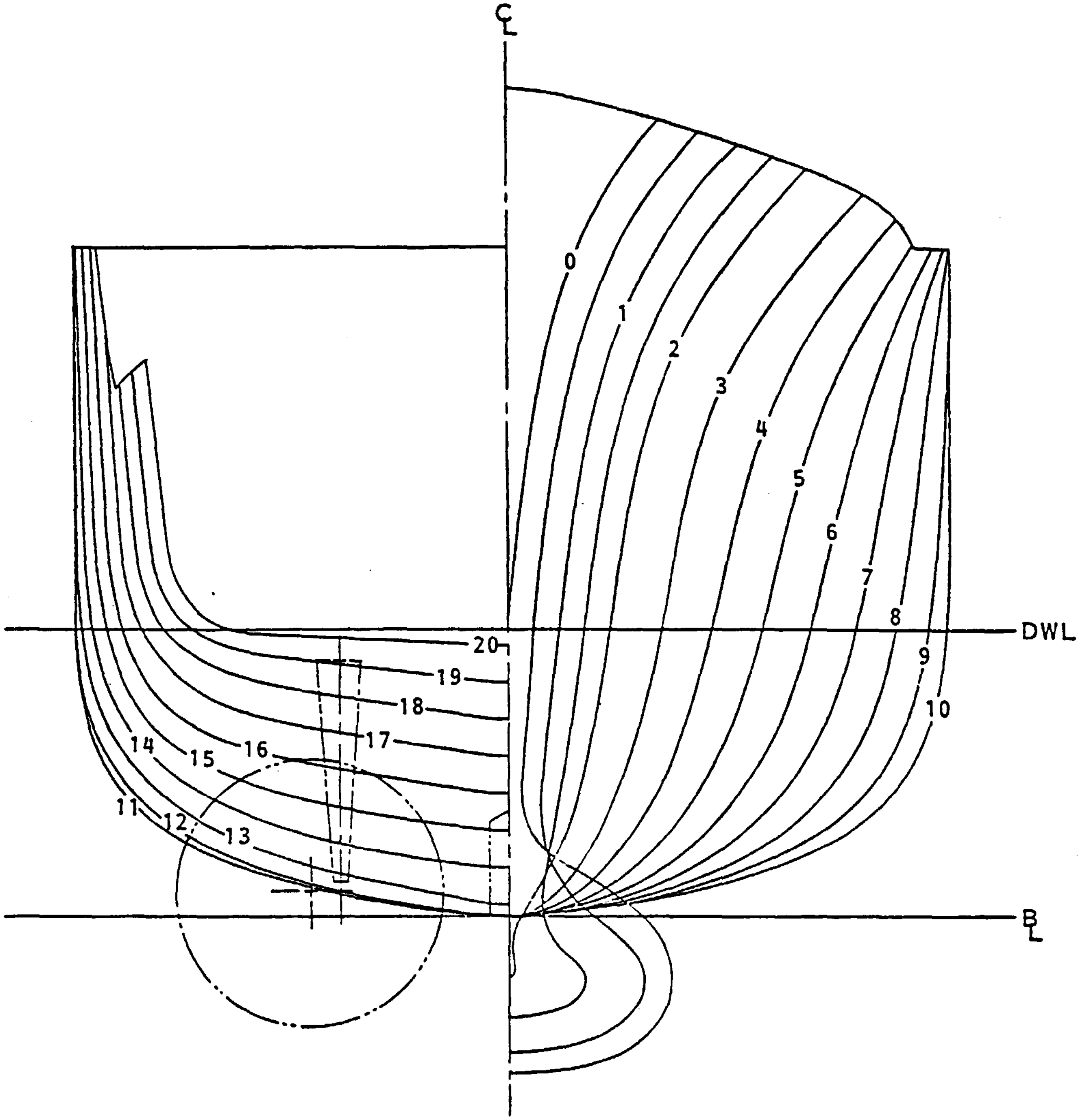


Figure A-1.5 - Body Plan of DD-963 Hull Form (Model 5359)

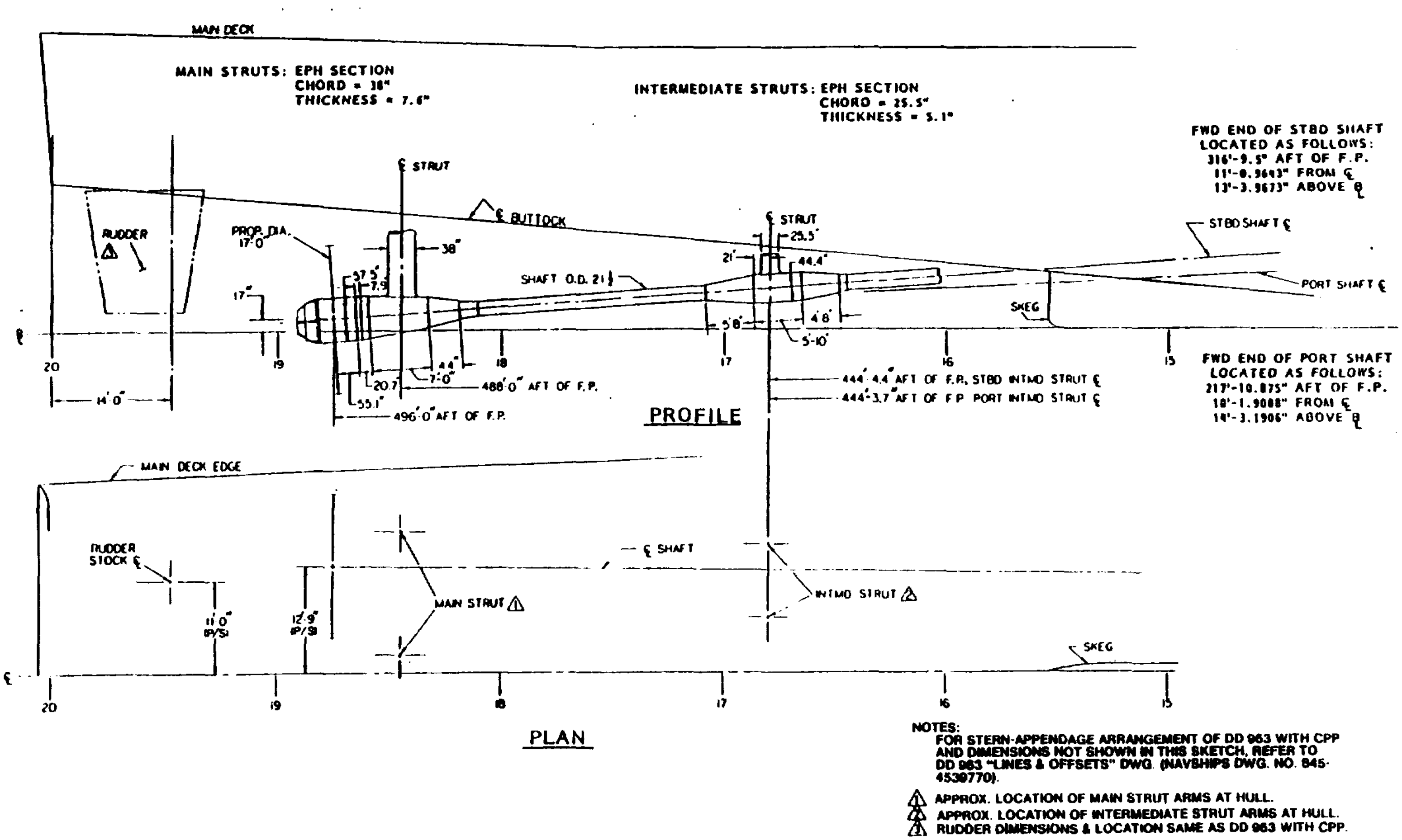


Figure A-1.6 - Stern Appendages of Parent Configuration, Twin Shafts and Struts with Controllable-Pitch Propellers - Profile and Plan Views, from Tomassoni and Slager (1980)

TWIN SHAFTLINE CONTROLLABLE-PITCH PROPELLERS (PARENT DD-963)

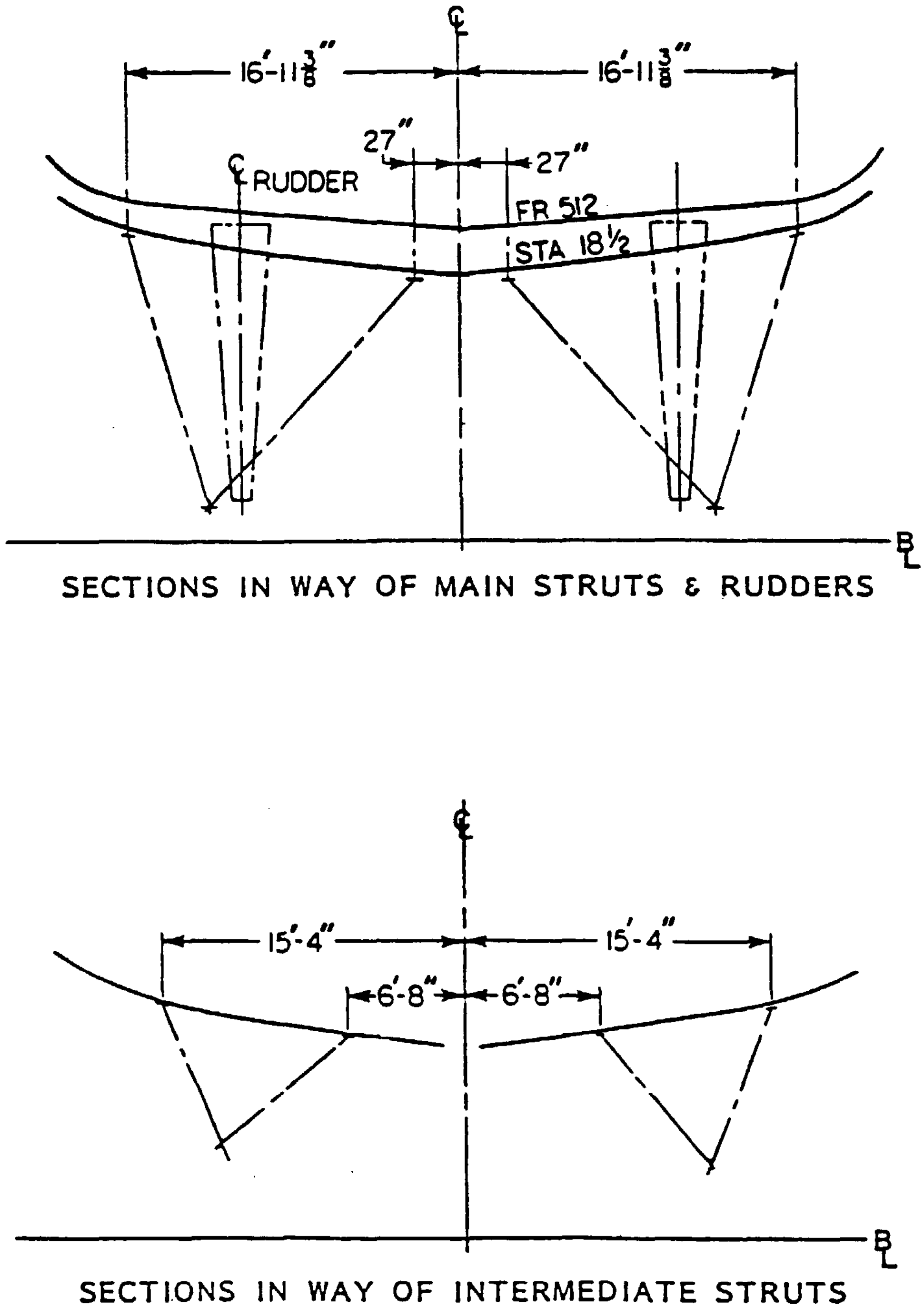


Figure A-1.7 - Stern Appendages of Parent Configuration, Twin Shafts and Struts with Controllable-Pitch Propellers - Sectional Views - Model 5359, from Tomassoni and Slager (1980)

TWIN SHAFTLINE CONTROLLABLE-PITCH PROPELLERS (PARENT DD-963)

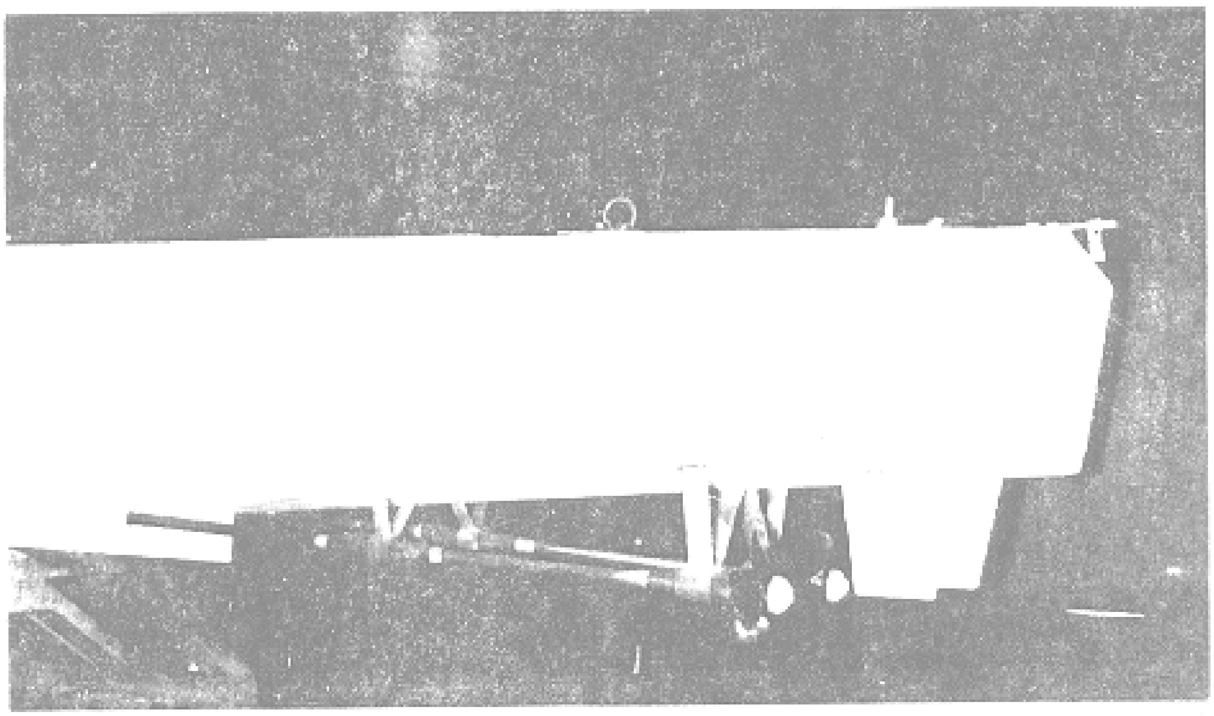


Figure A-1.8 - Photograph of Stern of Model 5359 Representing the DD-963 Parent Configuration with Twin Shafts and Struts and Controllable-Pitch Propellers

TWIN PODS WITH CONTRAROTATING PROPELLERS

Afterbody - DD-963, unmodified (see Figure A-1.5) - Model 5359-1C

Rudders - Twin; same dimensions and location as on DD-963 - Wetted surface of two rudders is 648 ft^2

Pods (port & stbd.)

Length		51.0 ft
Diameter		7.0 ft

Struts

Chord		18.0 ft
Thickness		3.0 ft

Propellers

Type		Contrarotating
Diameter	fwd/aft	17.38/17.05
Number of blades	fwd/aft	5/4
$P/D_{.7R}$	fwd/aft	1.65/1.89
E.A.R.	fwd/aft	0.365/0.365
Model propeller numbers	fwd/ aft	4768; 4770 4838; 4839
Distance between fwd and aft propellers		4.25 ft

Figure A-2.1 - Appendage, Afterbody, and Propulsor Characteristics of the DD-963 Hull Fitted with Twin Pods and Contrarotating Propellers

TWIN PODS WITH CONTRAROTATING PROPELLERS

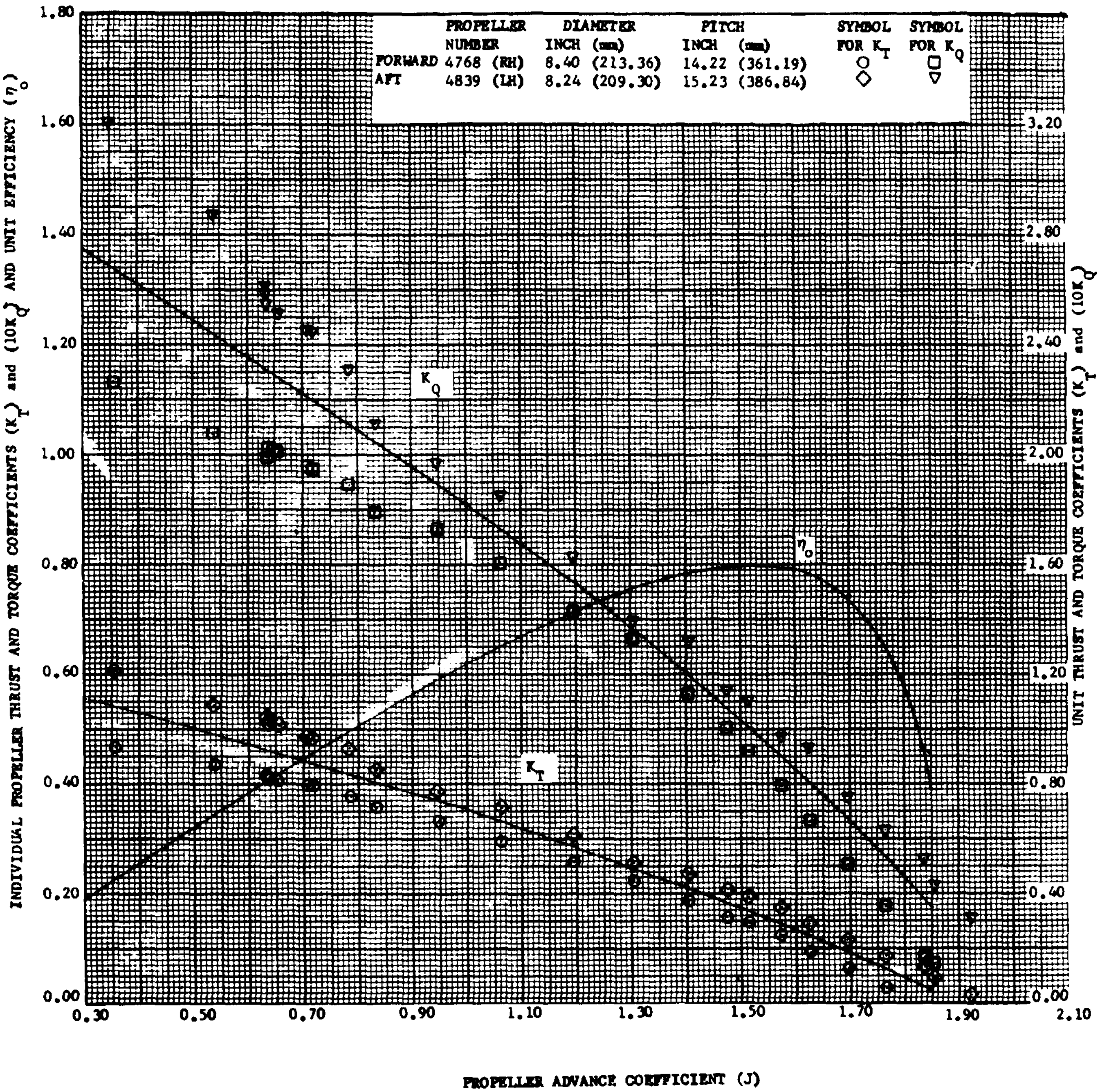


Figure A-2.2 - Open Water Curves for Contrarotating Propellers 4768 and 4839

TWIN PODS WITH CONTRAROTATING PROPELLERS

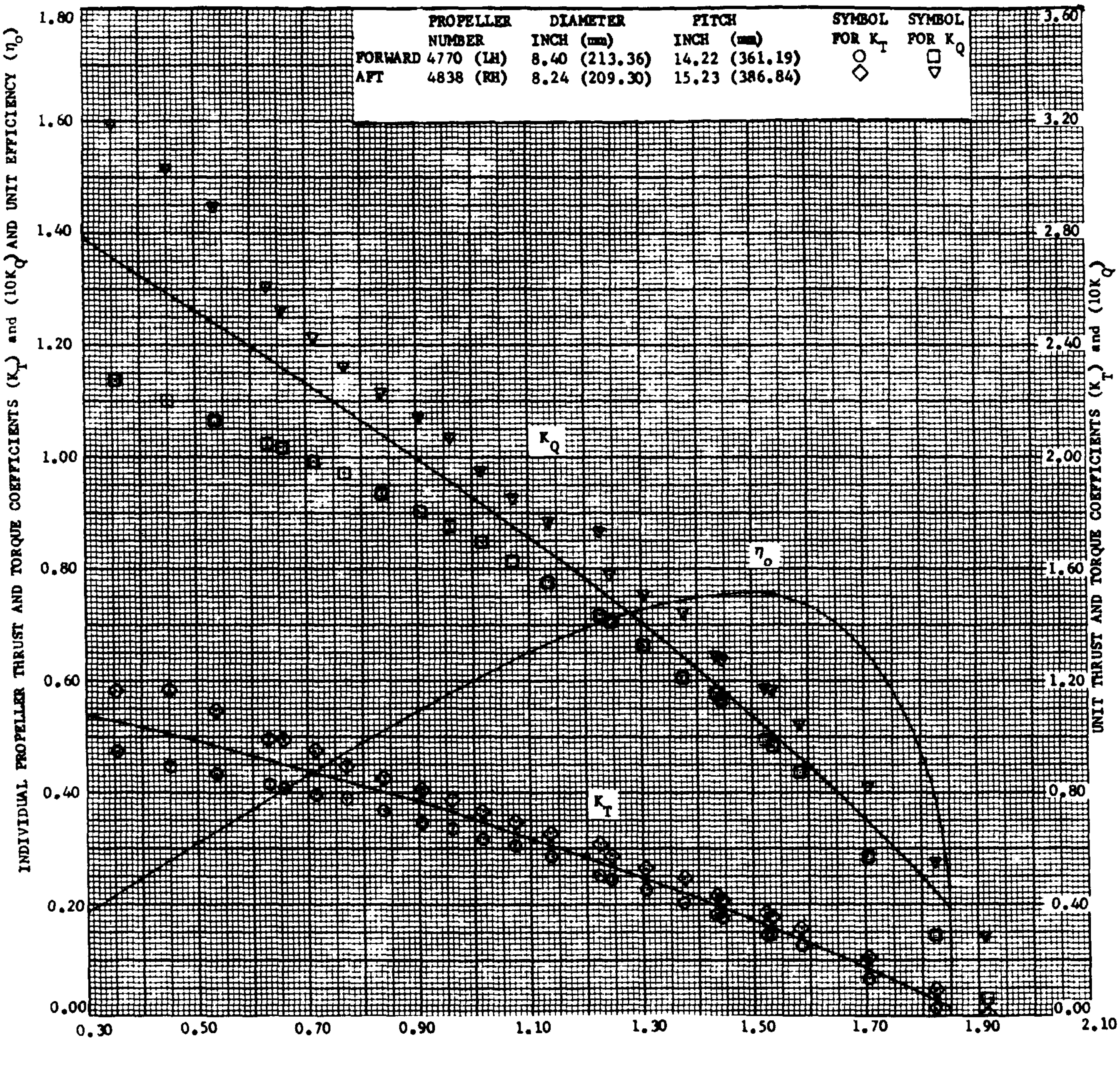


Figure A-2.3 - Open Water Curves for Contrarotating Propellers 4770 and 4838

TWIN PODS WITH CONTRAROTATING PROPELLERS

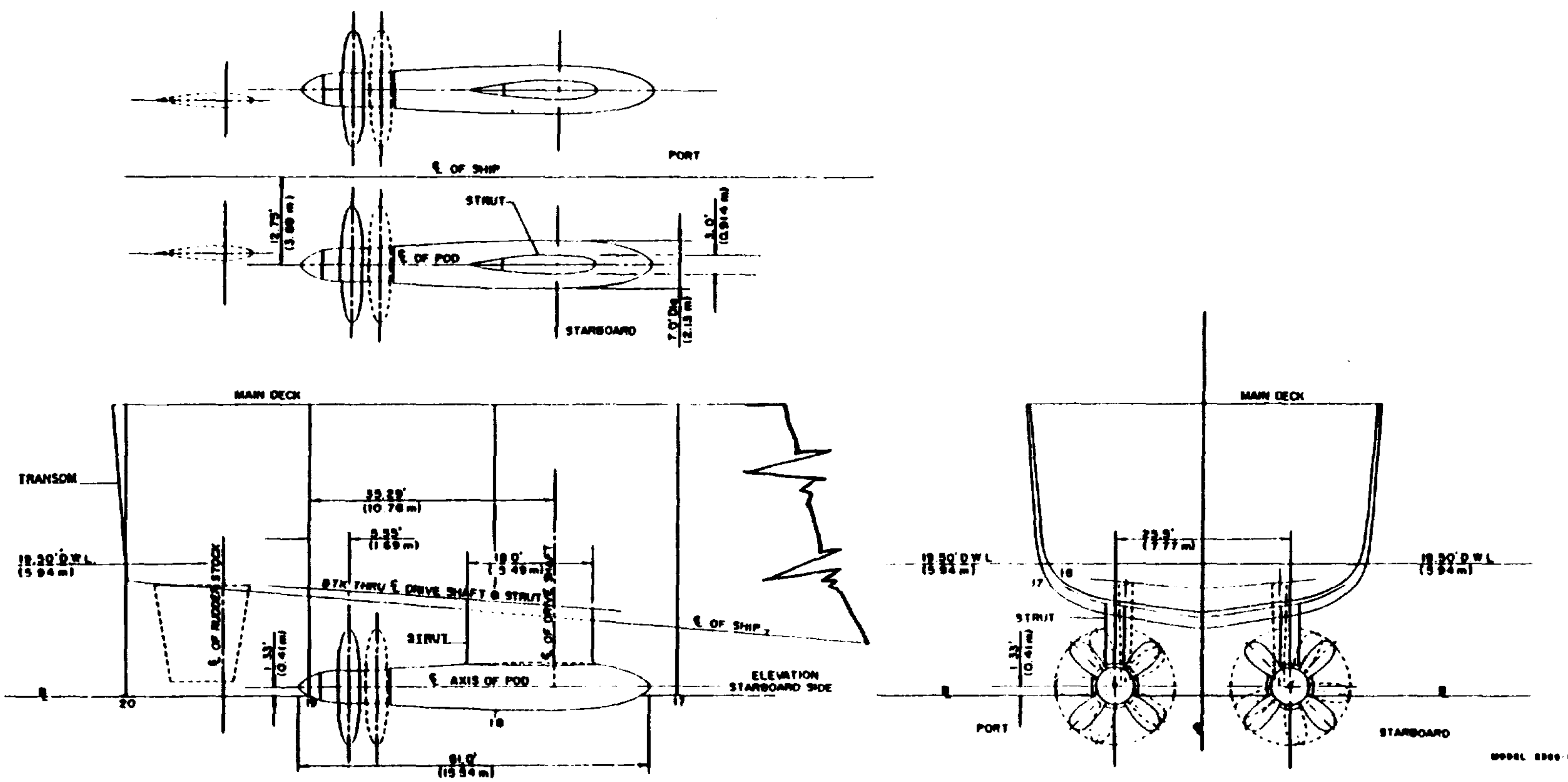
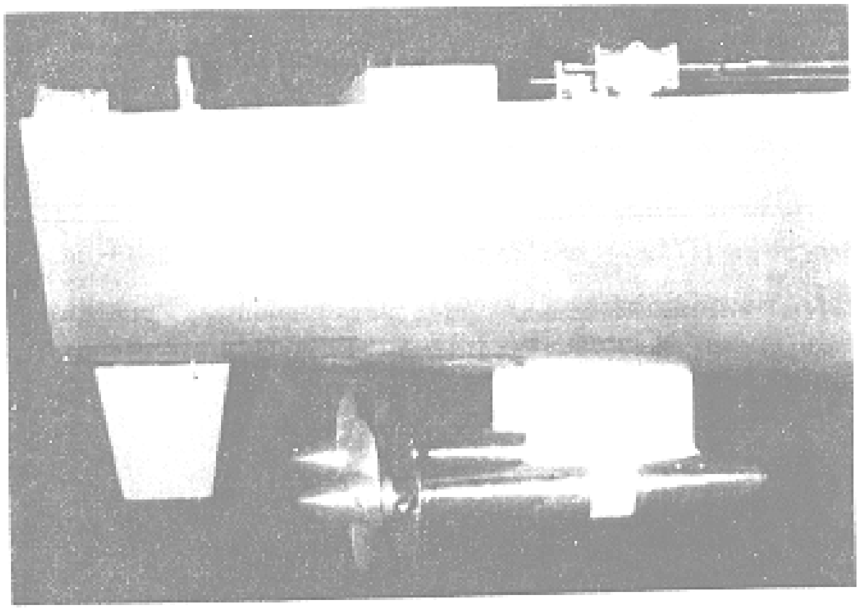


Figure A-2.4 - Form and Dimensions of Twin Pods with Contrarotating Propellers Fitted on DD-963 Hull Form, Represented by Model 5359-1C

TWIN PODS WITH CONTRAROTATING PROPELLERS



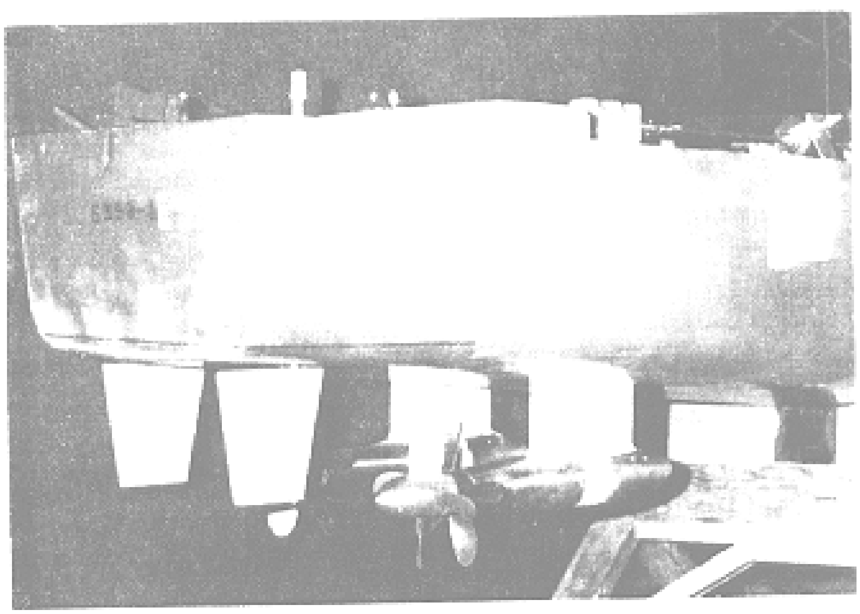


Figure A-2.5 - Photographs of Model 5359-lC with Twin Pods and Stock Contrarotating Propellers - Stern Profile and Quarter Views

TWIN BEARING-IN-RUDDER POST WITH FIXED-PITCH PROPELLERS

Afterbody - DD-963, unmodified (see Figure A-1.5) - Model 5359-0A1

Rudders - Twin; with bearing-in-rudder post arrangement. Straight rudders with no spanwise twist. Total rudder wetted area is 1518 ft^2

Propeller Shafts	
Outside diameter	20.25 Inches
Intermediate Strut Arms	
Chord	22.5 Inches
Thickness	4.5 Inches
Propellers	
Type	Fixed Pitch
Number of blades	4
Diameter D_p (ft)	17.0 ft
P/D at $_{.7R}$	1.53
E.A.R.	0.736
Propeller model number	4864; 4865

Propeller location - same as fixed-pitch shafts and struts configuration

Figure A-3.1 - Appendage, Afterbody and Propulsor Characteristics of the Bearing-in-Rudder Post Configuration with Fixed-Pitch Propellers

TWIN BEARING-IN-RUDDER POST WITH FIXED-PITCH PROPELLERS

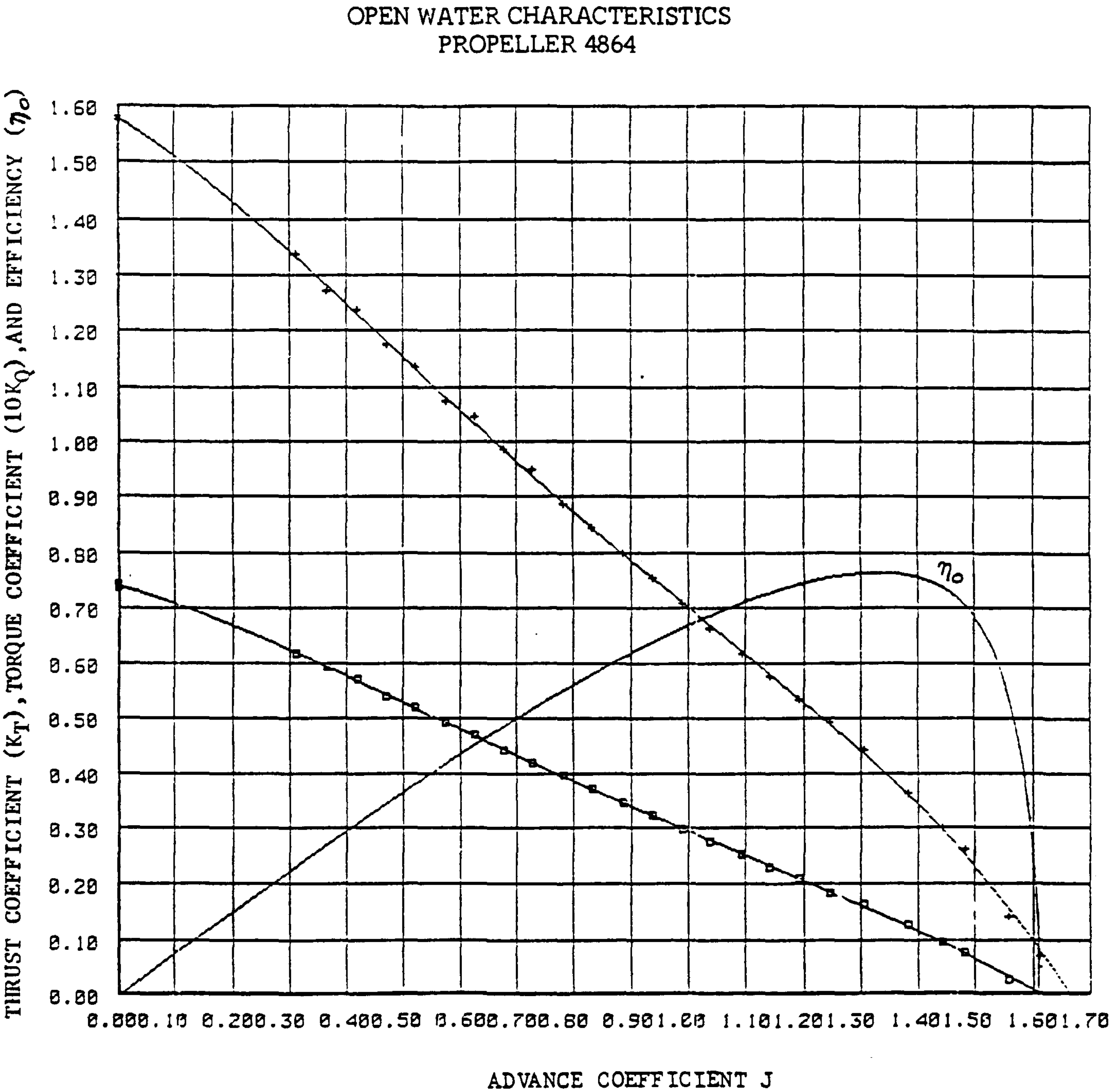


Figure A-3.2 - Open Water Curves for Propeller 4864

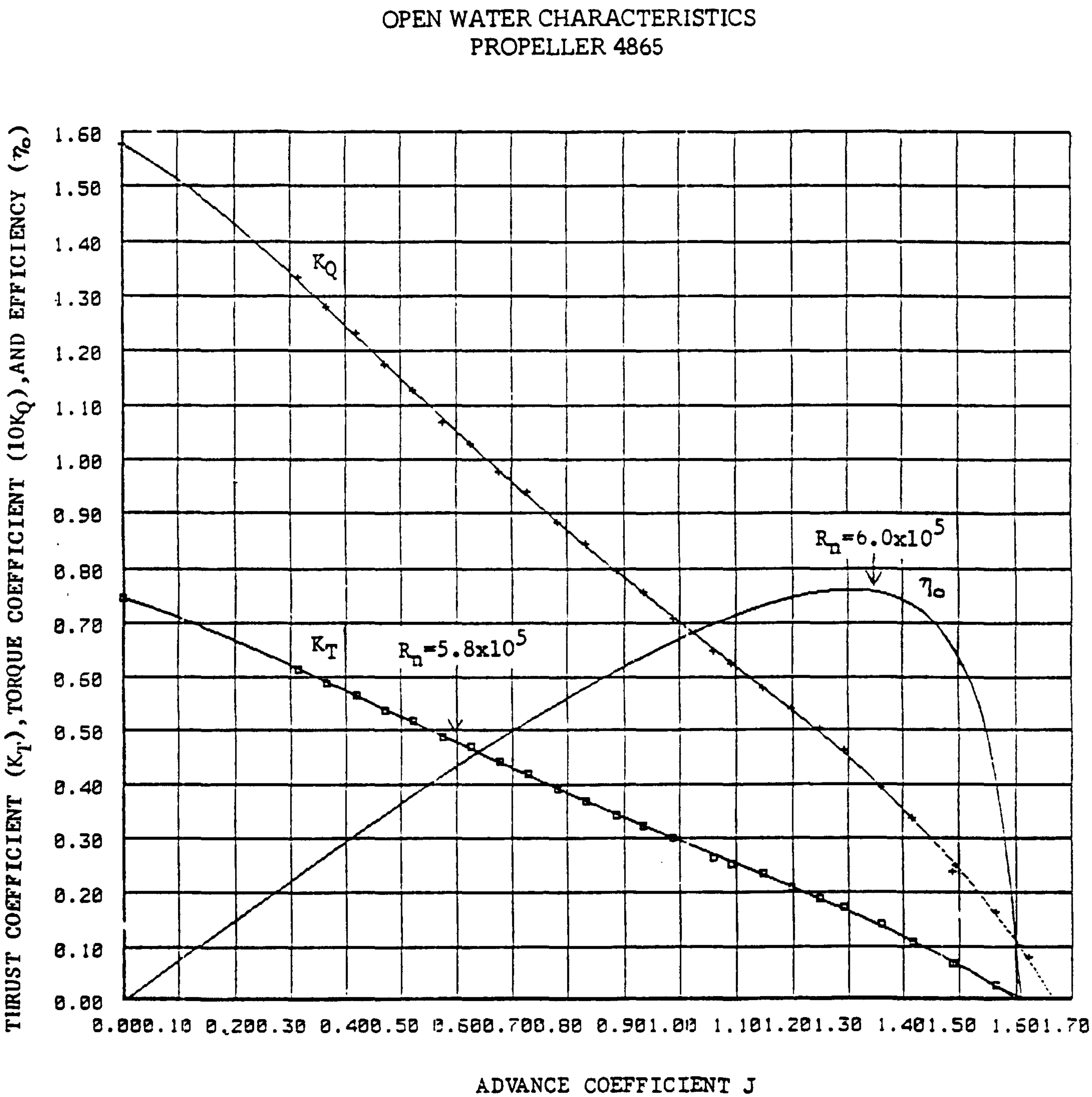


Figure A-3.3 - Open Water Curves for Propeller 4865

TWIN BEARING-IN-RUDDER POST WITH FIXED-PITCH PROPELLERS

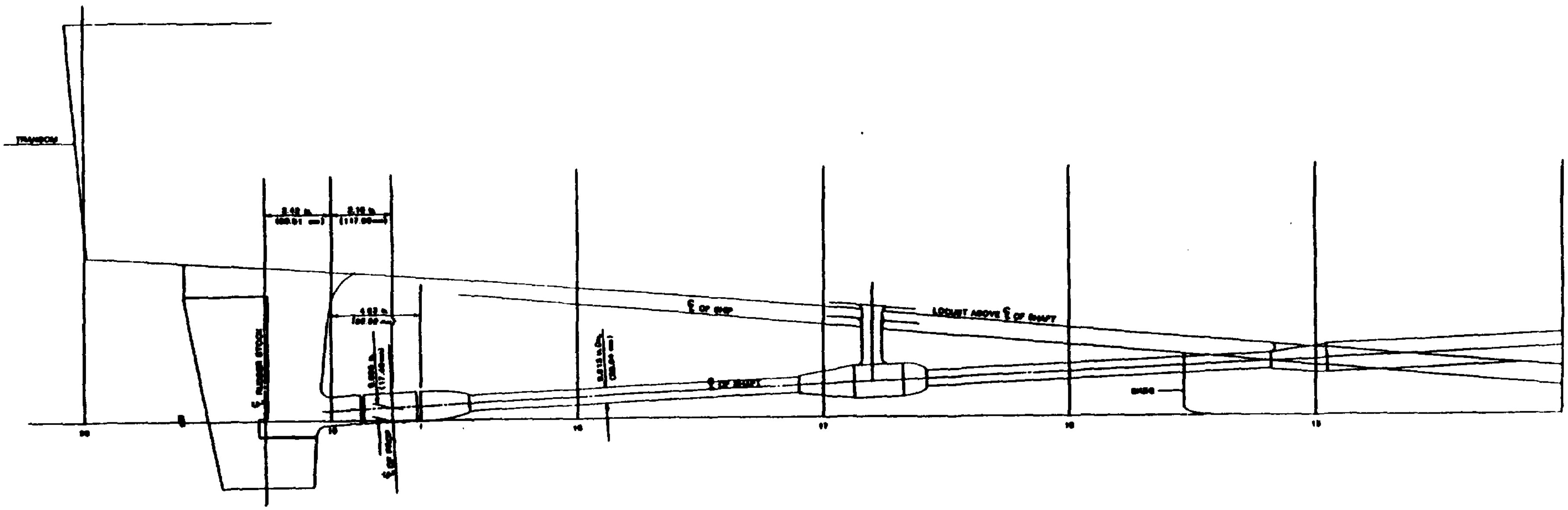


Figure A-3.4 - Stern Appendages of the Bearing-in-Rudder Post Configuration with Fixed-Pitch Propellers - Profile View

TWIN BEARING-IN-RUDDER POST WITH FIXED-PITCH PROPELLERS

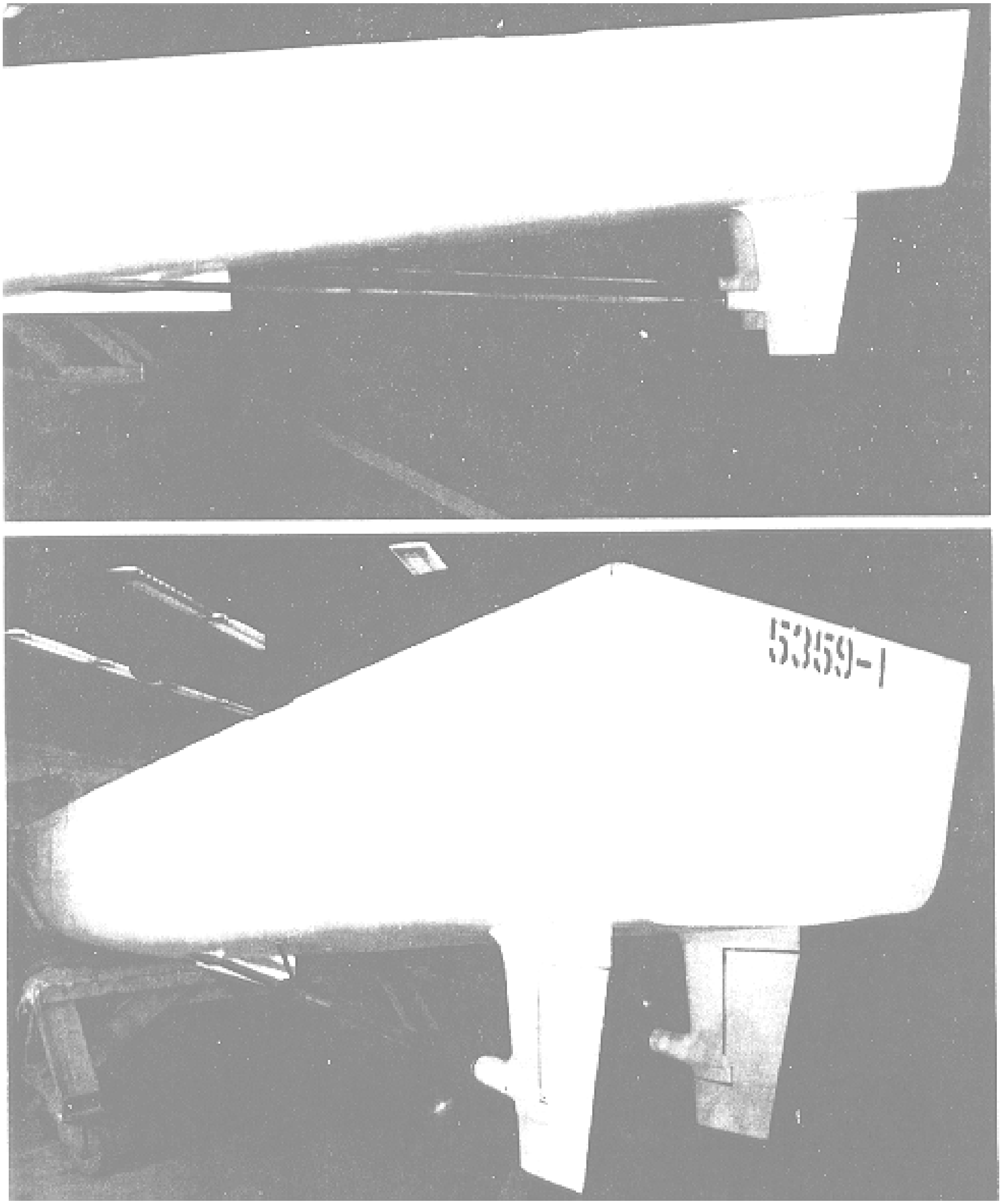


Figure A-3.5 - Photographs of Stern of Model 5359-OAL - Bearing - in -Rudder Post Configuration with Fixed-Pitch Propeller - Profile and Stern Quartering Views

Afterbody - DD-963, unmodified (see Figure A-1.5) - Model 5359-1B

Rudders - Twin; same dimensions and location as on DD-963 - Wetted surface of two rudders is 648 ft^2

Propeller Shafts	
Number of shaftlines	2
O.D./I.D. of outer shafts (inches)	27.625/20.875
O.D./I.D. of inner shafts (inches)	16.875/11.250
(Shaft diameters not reduced, fwd of main strut bearing)	
Main Strut Arms	
Chord (inches)	39.0
Thickness (inches)	7.75
Intermediate Strut Arms	
Chord (inches)	24.0
Thickness (inches)	4.8
Propellers	
Type	F.P., Contrarotaing (2 sets)
Number of blades, fwd/aft	5/4
D_p fwd/D_p aft (ft)	17.38/17.05
P/D $_{.7R}$ fwd/P/D $_{.7R}$ aft	1.65/1.89
E.A.R. fwd/E.A.R. aft	0.365/0.365
Weight, fwd/Weight, aft (lbs, approx.)*	24000/20900
RPM (approximately) at 20 knots	79.1
RPM (approximately) (design full power)	138
Propeller number fwd	4768; 4770
aft	4838; 4839

* Weight per propeller; there are a total of four propellers.

Figure A-4.1 - Afterbody, Appendage, and Propulsor Characteristics of the Twin Shafts and Struts Contrarotating Propeller Configuration

TWIN SHAFTLINE CONTRAROTATING PROPELLERS

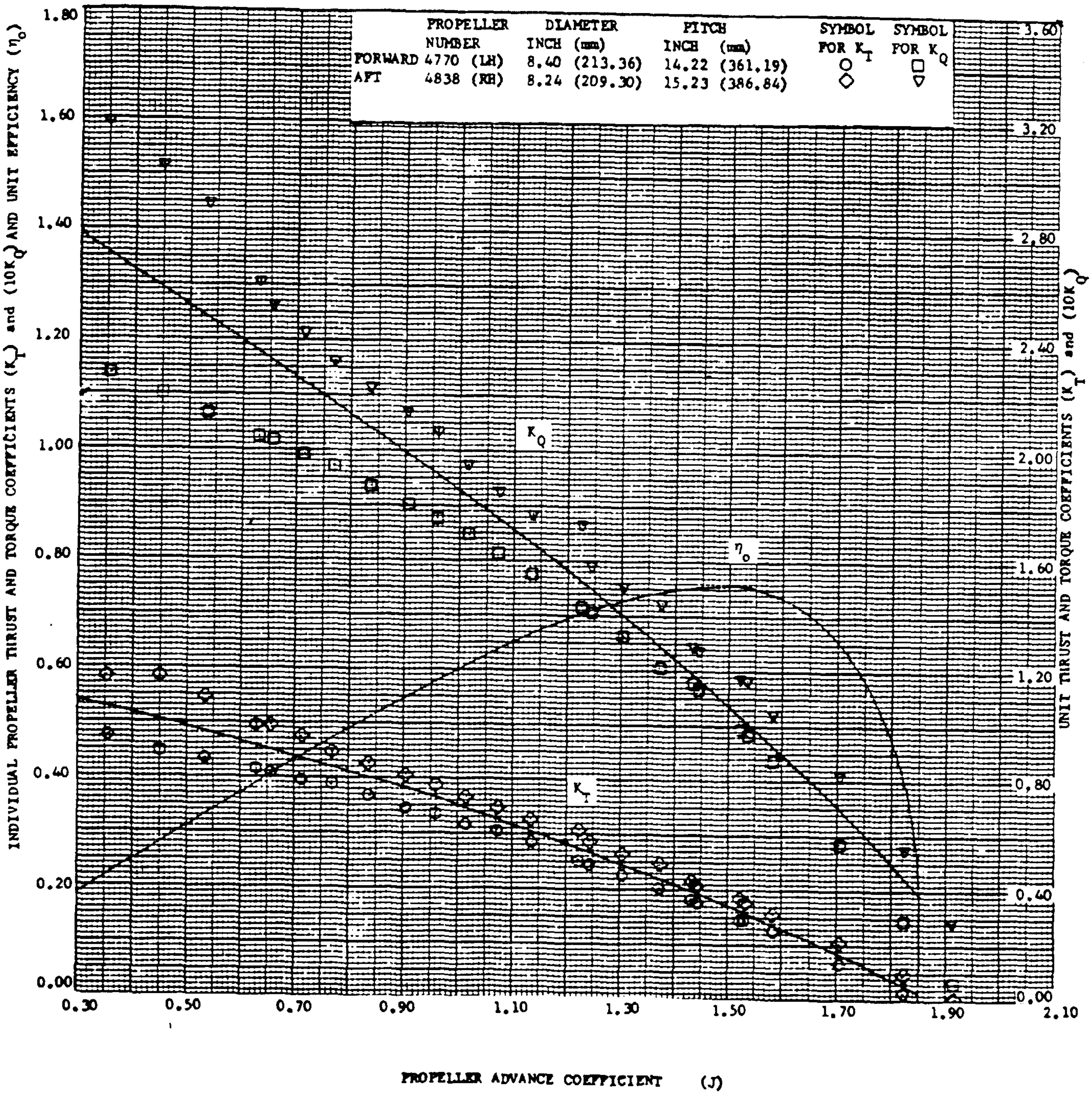


Figure A-4.2 - Open Water Curves for Contrarotating Propellers 4770 and 4838

TWIN SHAFTLINE CONTRAROTATING PROPELLERS

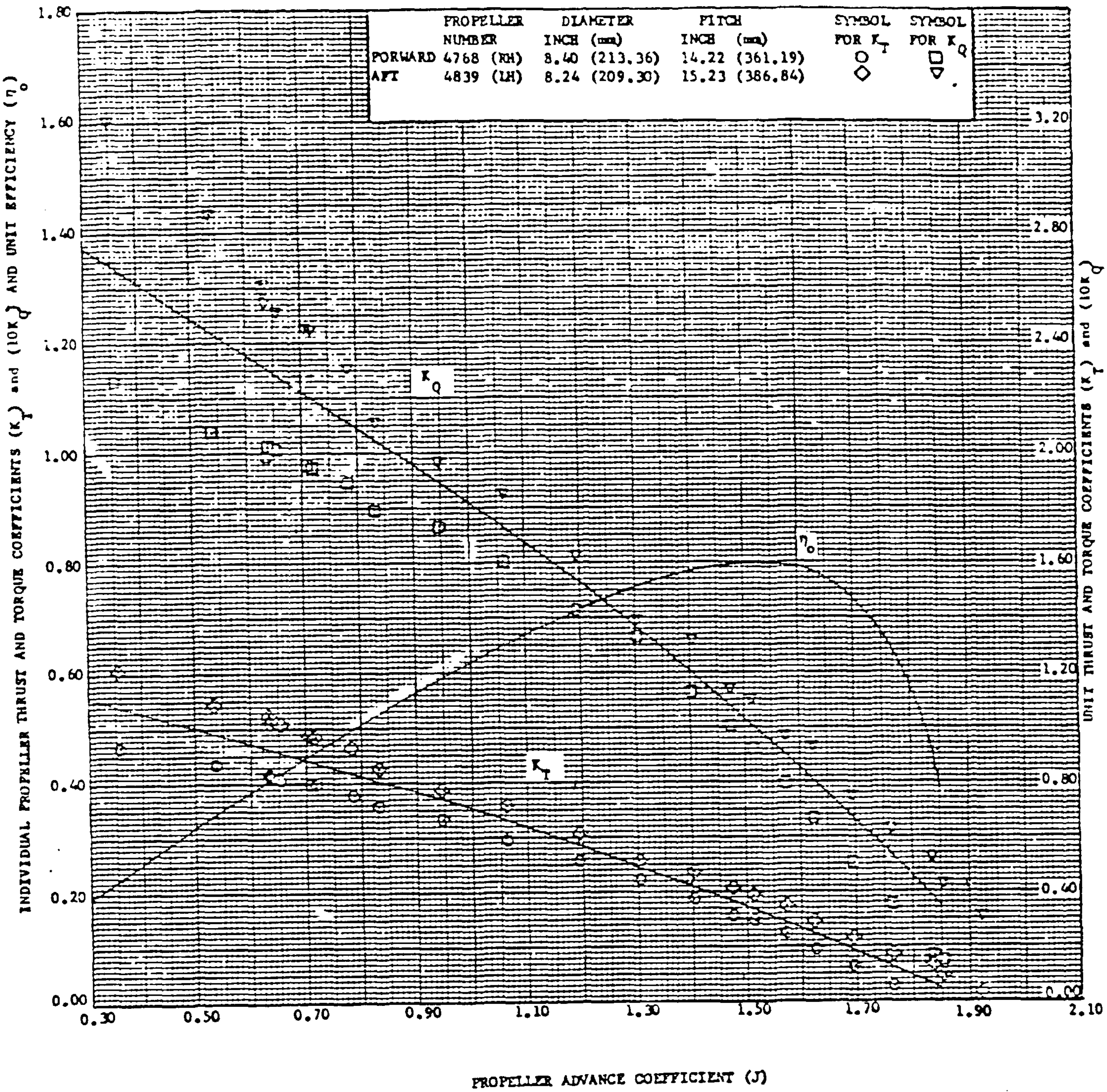


Figure A-4.3 - Open Water Curves for Contrarotating Propellers 4768 and 4839

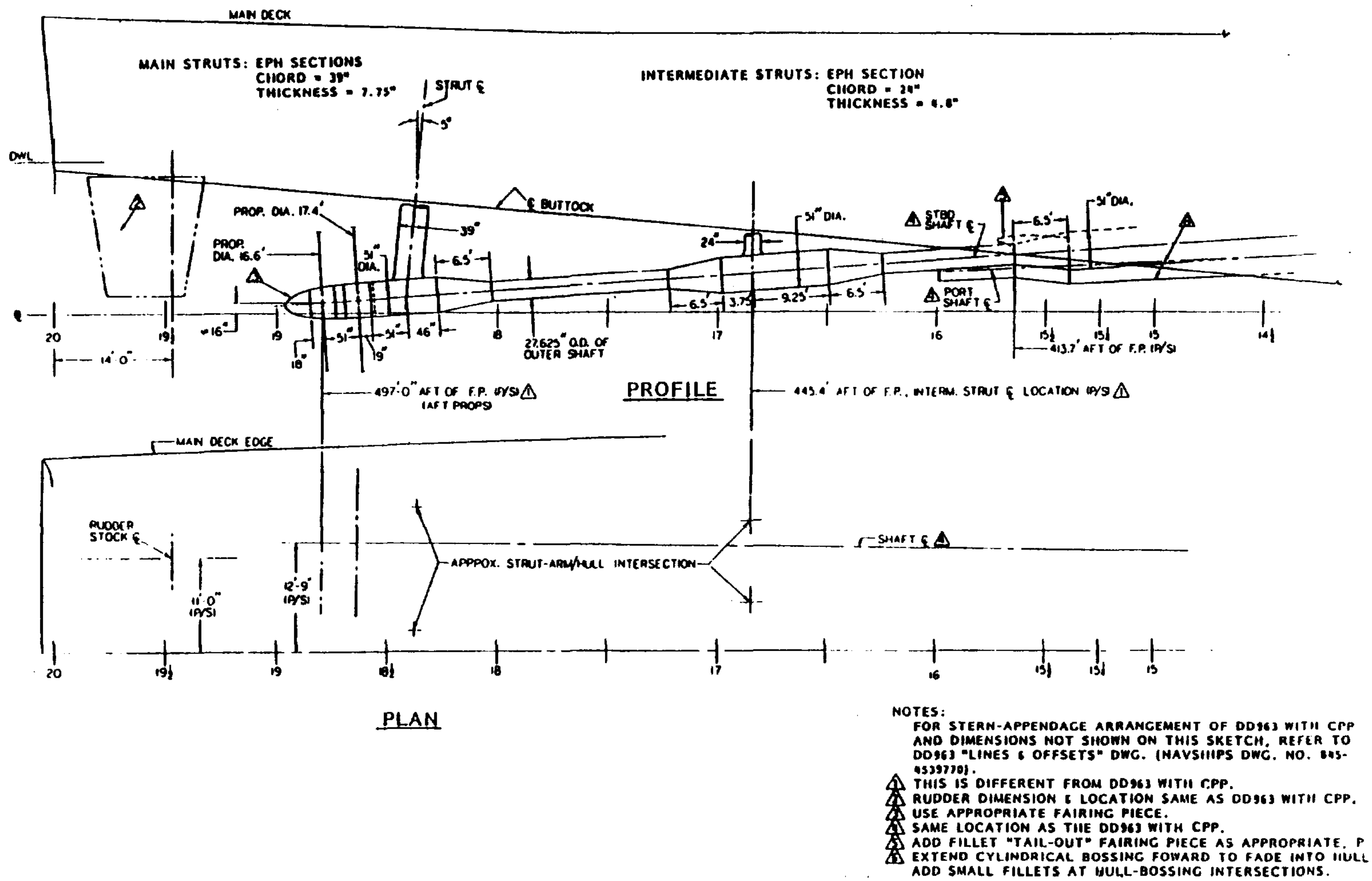


Figure A-4.4 - Stern Appendages of the Twin Shafts and Struts Contrarotating Propeller Configuration - Profile and Plan Views, from Tomassoni and Slager (1980)

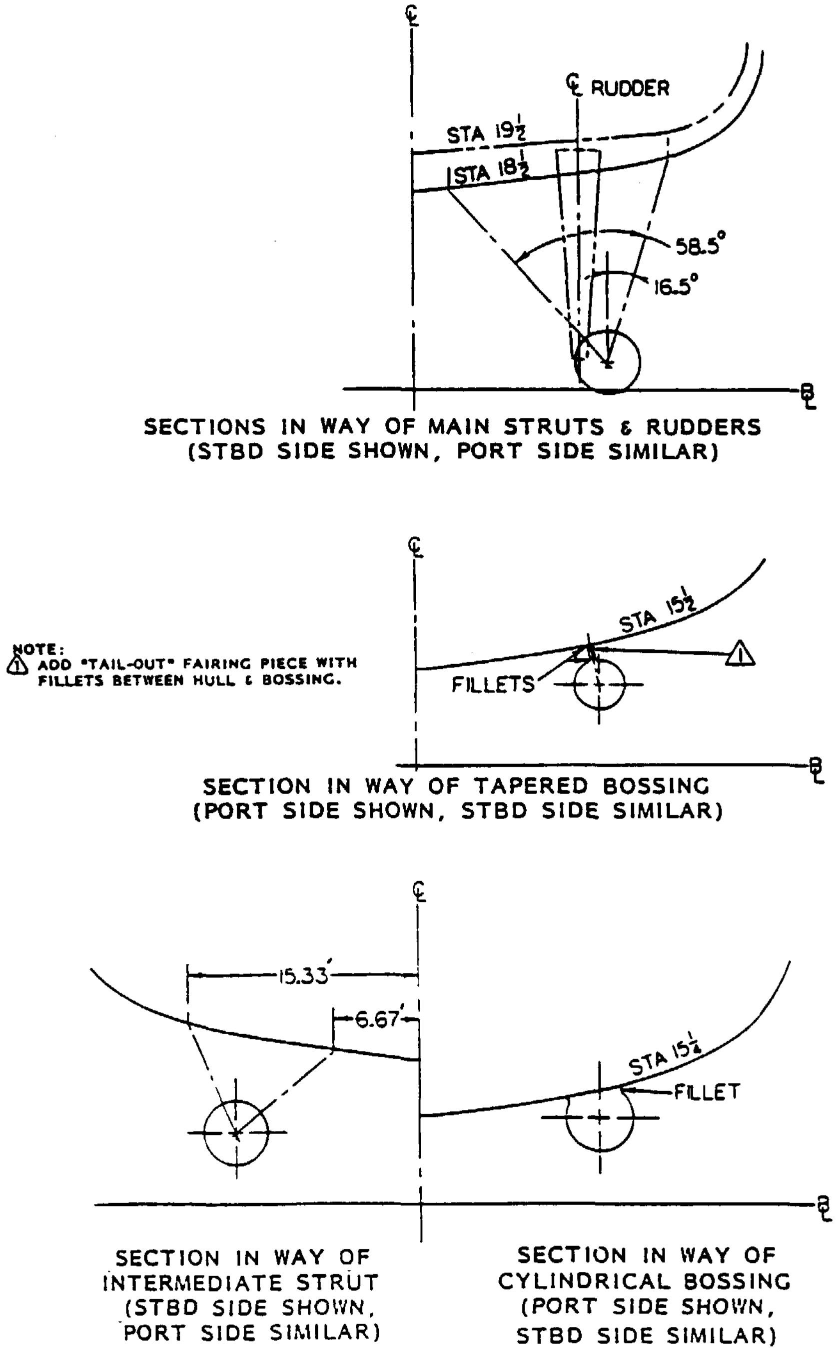
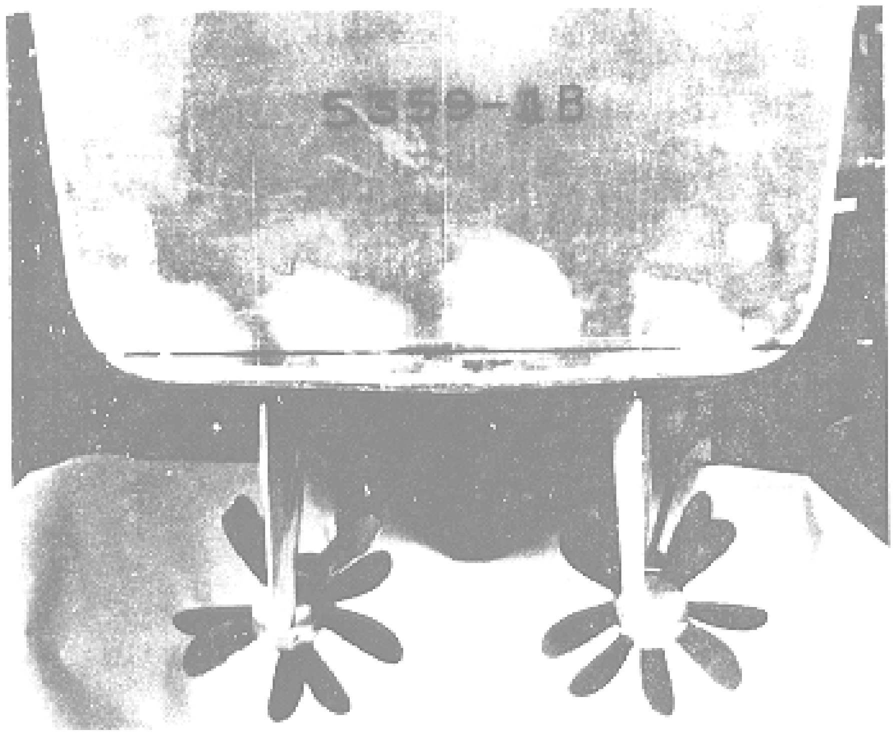


Figure A-4.5 - Stern Appendages of the Twin Shafts and Struts Contra-rotating Propeller Configuration - Sectional Views, from Tomassoni and Slager (1980)

TWIN SHAFTLINE CONTRAROTATING PROPELLERS



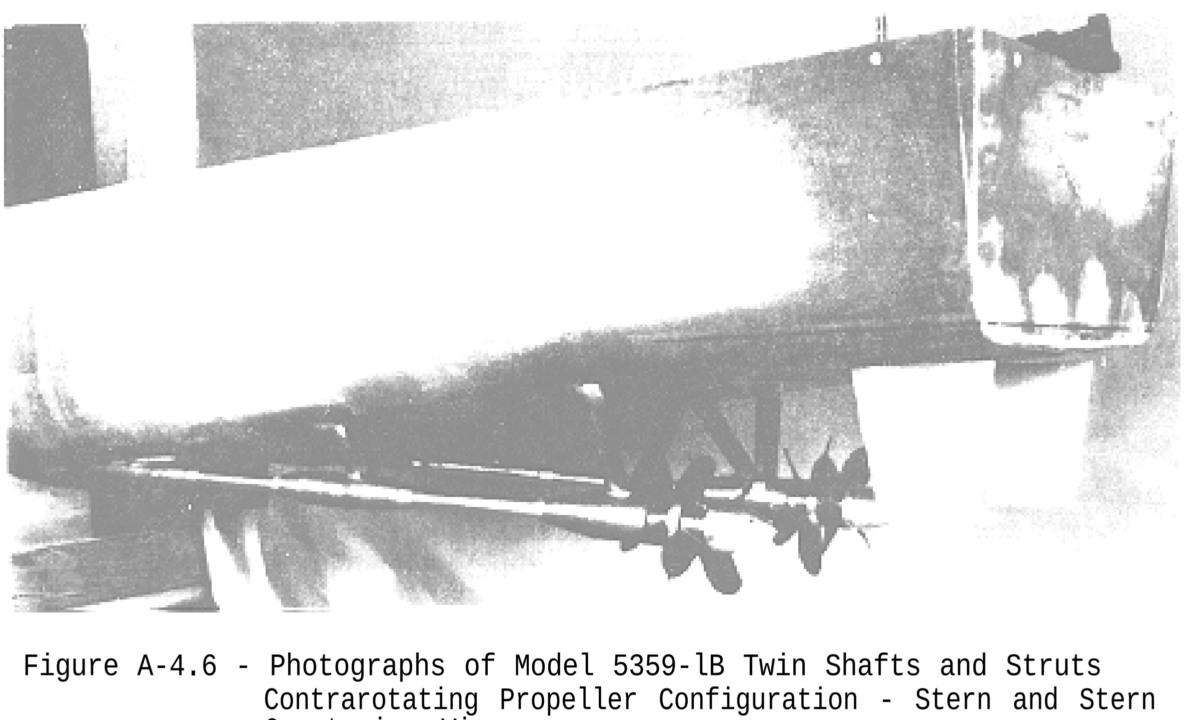


Figure A-4.6 - Photographs of Model 5359-lB Twin Shafts and Struts Contrarotating Propeller Configuration - Stern and Stern Quartering Views

TWIN SHAFTLINE FIXED-PITCH PROPELLERS

Afterbody - DD-963, unmodified (see Figure A-1.5) - Model 5359-1

Rudders - Twin; same dimensions and locations as on DD-963
Wetted surface for two rudders is 648 ft^2

Propeller Shafts

Number	2
O.D./I.D. Shafts in way of main strut bearing (inches)	20.25/13.5
O.D./I.D. of exposed shafts, forward of main strut (inches)	20.25/13.5

Main Strut Arms

Chord (inches)	35.0
Thickness (inches)	7.0
Webbed surface for four struts	317.0 ft^2

Intermediate Strut Arms

Chord (inches)	22.5
Thickness (inches)	4.5

Propellers

Type	F.P.
Number of blades	4
D_p (ft)	17.0
$P/D_{.7R}$	1.54
E.A.R.	0.72
Weight (pounds each, approximate)	36900
RPM (approximately) at 20 knots	96.6
RPM (approximately) (design full power)	168
Propeller model numbers	4864; 4865

Figure A-5.1 - Afterbody, Appendage, and Propulsor Characteristics of the Twin Shafts and Struts Configuration with Fixed-Pitch Propellers, from Tomassoni and Slager (1980).

TWIN SHAFTLINE FIXED-PITCH PROPELLERS

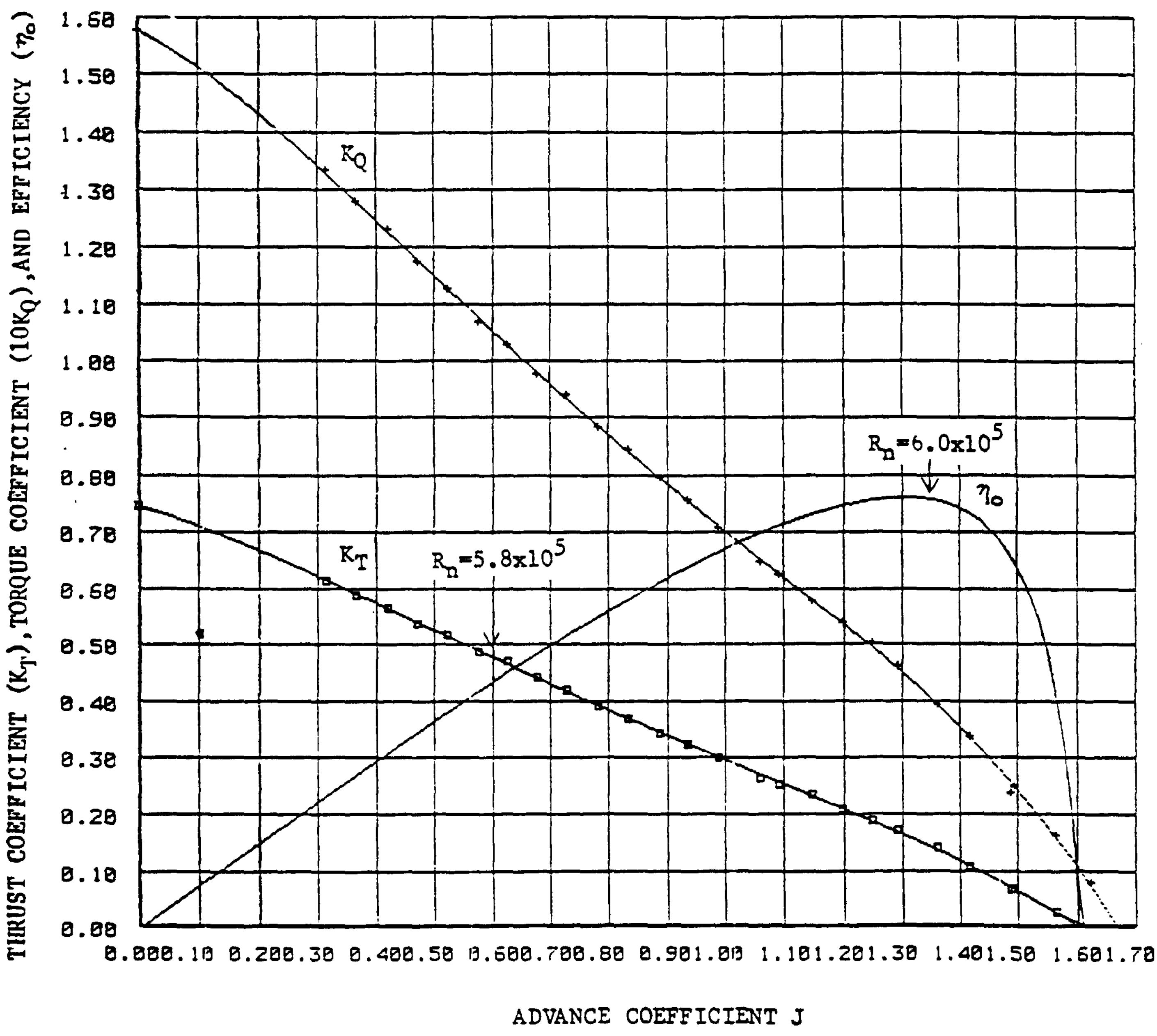


Figure A-5.2 - Open Water Curves for Propeller 4865

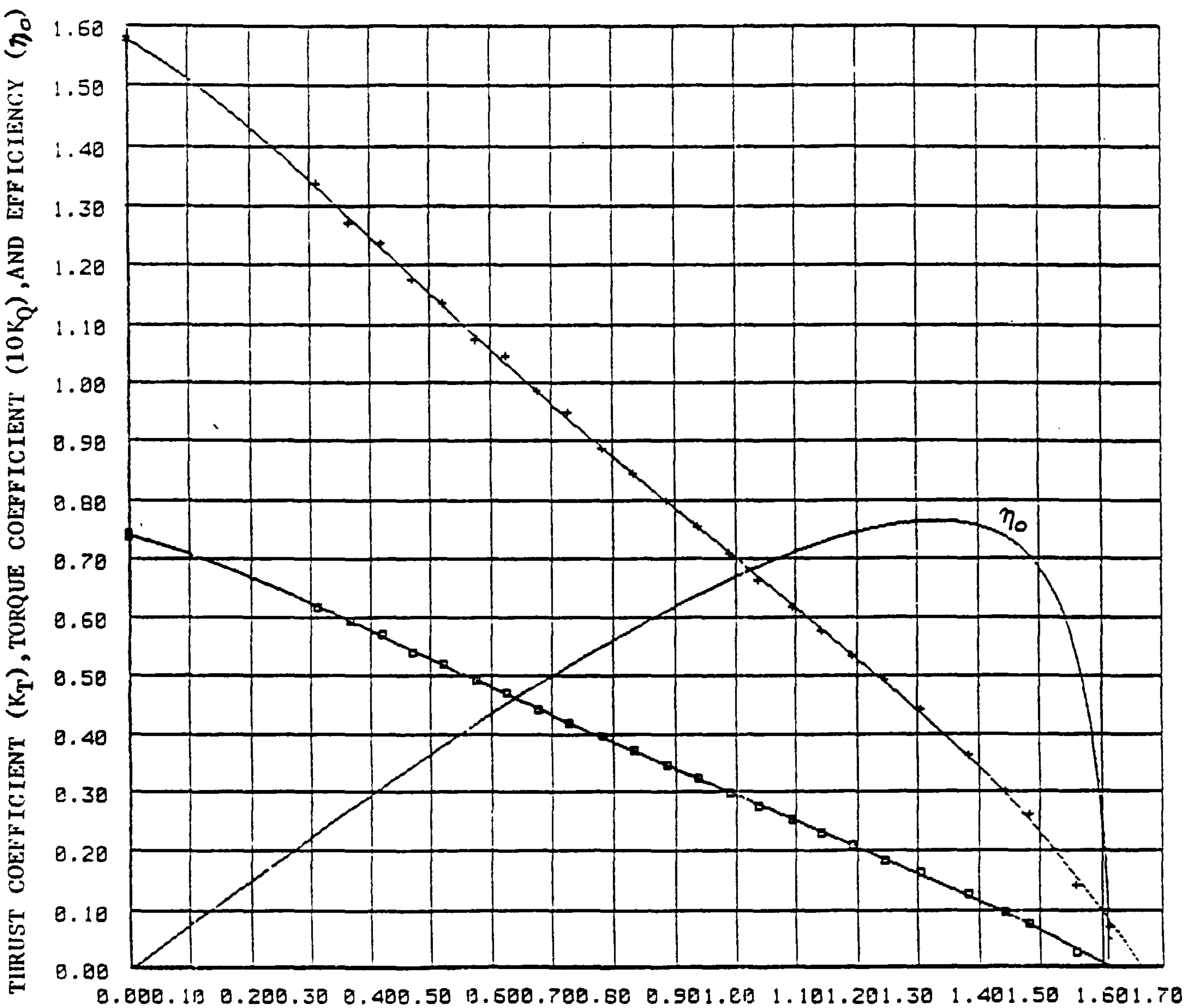


Figure A-5.3 - Open Water Curves for Propeller 4864

TWIN SHAFTLINE FIXED-PITCH PROPELLERS

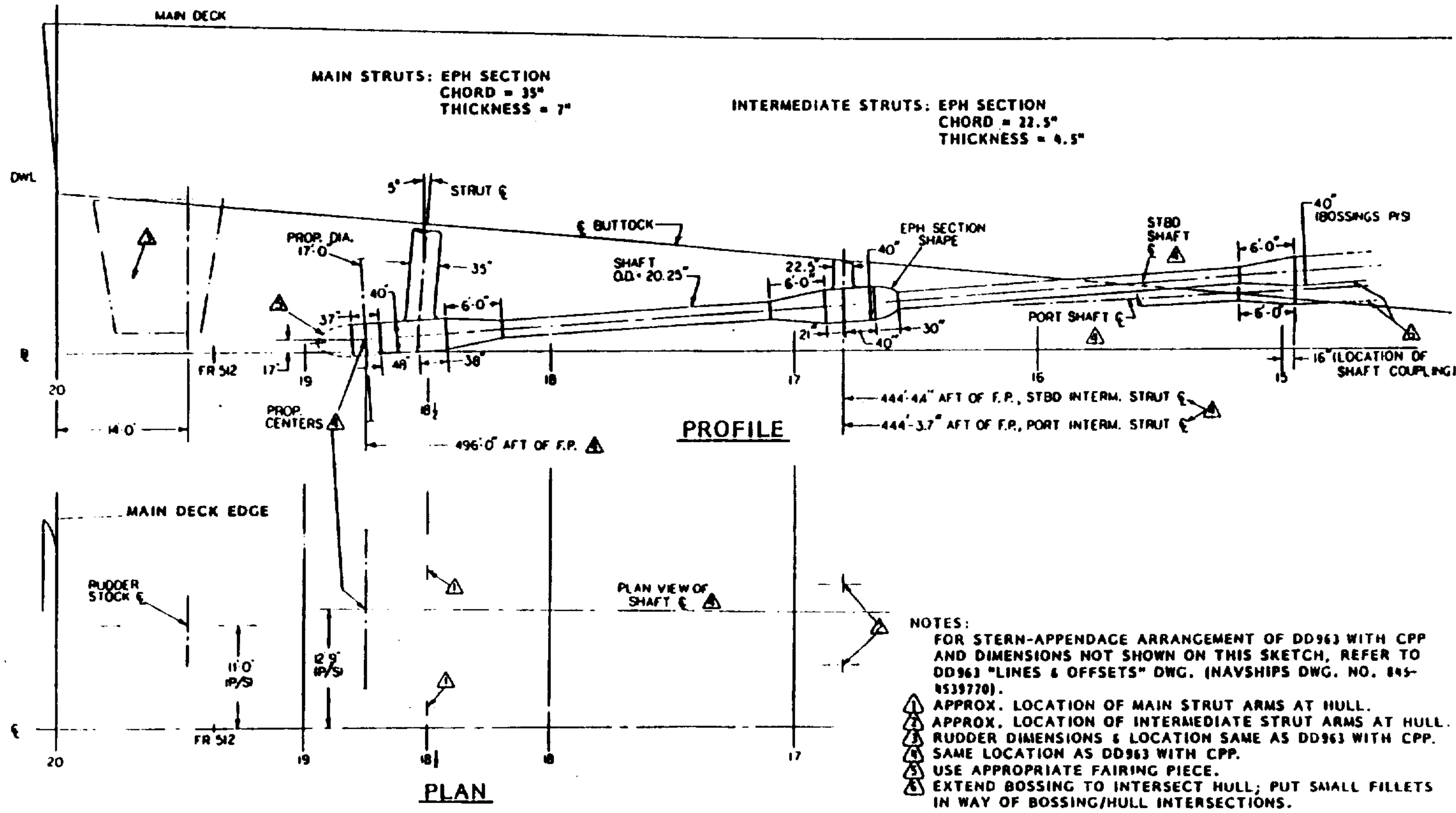
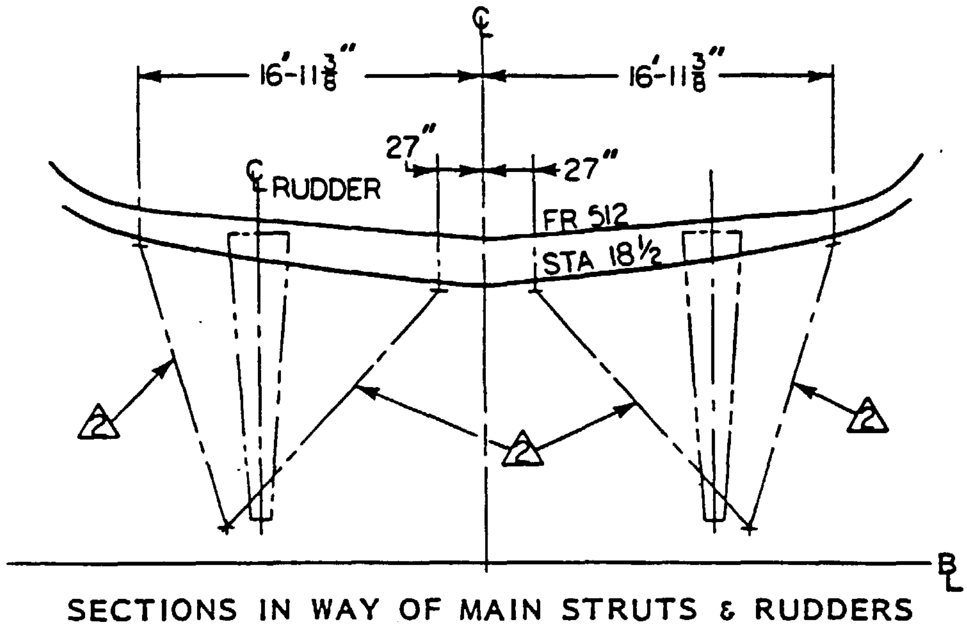


Figure A-5.4 - Stern Appendages of Twin Shafts and Struts Configuration with Fixed-Pitch Propellers - Profile and Plan Views, from Tomassoni and Slager (1980)

TWIN SHAFTLINE FIXED-PITCH PROPELLERS



NOTES:
1. INTERMEDIATE STRUT LOCATIONS TO BE THE SAME AS THE DD963 WITH CPP
2. MAIN STRUT-ARMS INTERSECT THE HULL AT THE SAME DISTANCE OFF CENTERLINE AS THE STRUT-ARMS OF THE DD963 WITH CPP.

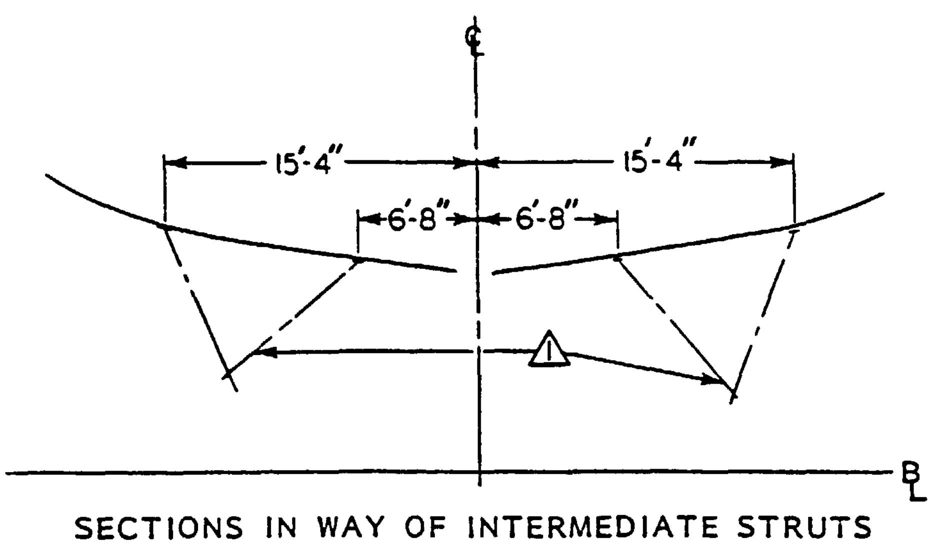


Figure A-5.5 - Stern Appendages for the Twin Shafts and Struts Configuration with Fixed-Pitch Propellers - Sectional Views, from Tomassoni and Slager (1980)

TWIN SHAFTLINE FIXED-PITCH PROPELLERS

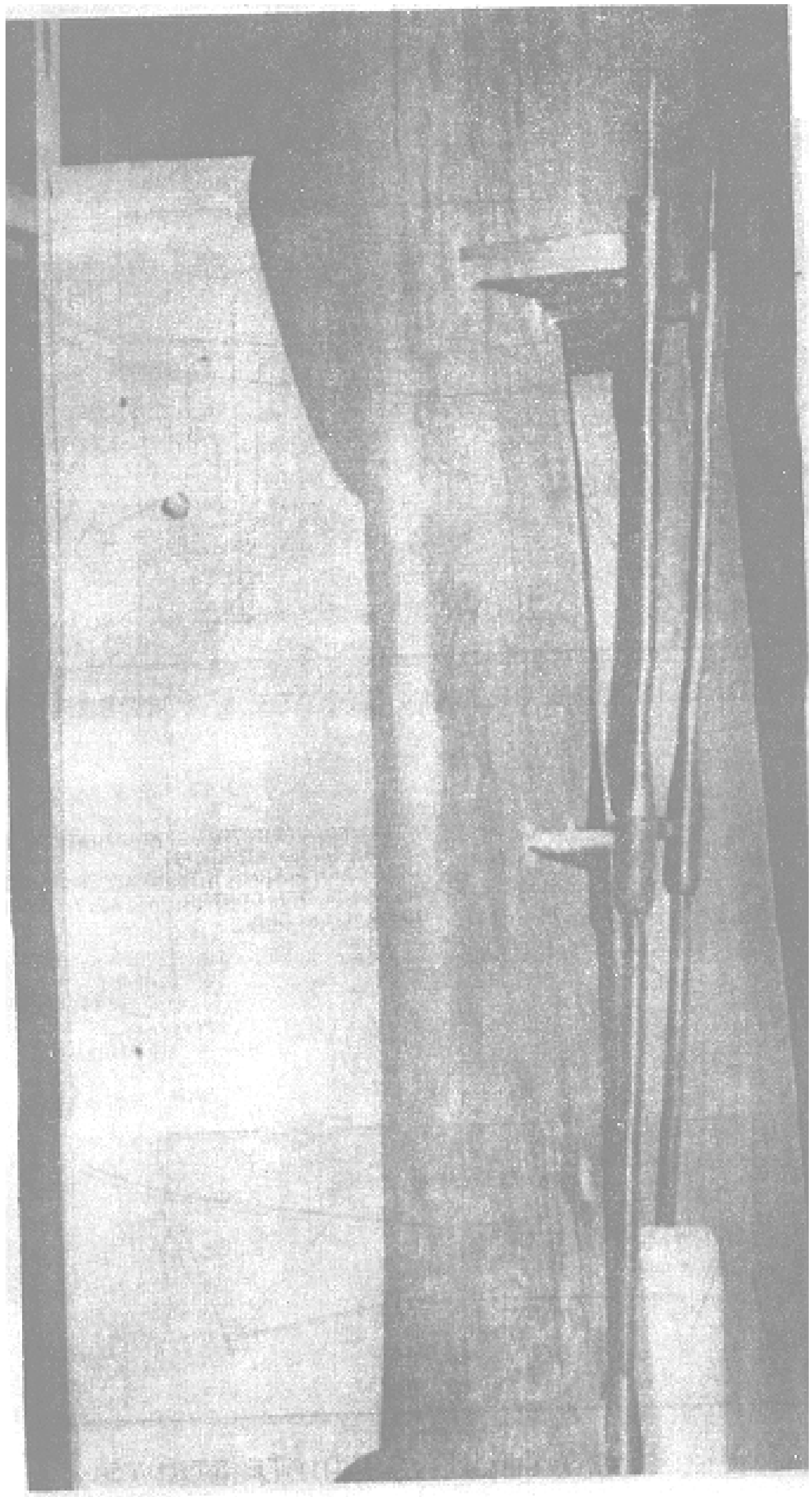


Figure A-5.6 - Photograph of Stern of Model 5359-1 - Twin Shafts and Struts Configuration with Fixed-Pitch Propellers

TWIN BEARING-IN-RUDDER POST WITH CONTROLLABLE-PITCH PROPELLERS

Afterbody - DD-963, unmodified (see Figure A-1.5) - Model 5359-0A

Rudders - Twin; with bearing-in-rudder post arrangement. Total rudder wetted area is 1536 ft^2

Propeller Shafts	
Outside diameter	21.5 inches
Intermediate Strut Arms	
Chord length	25.5 inches
Thickness	5.1 inches
Propellers	
Type	F.P.
Number of blades	5
D_p (ft)	17.0
$P/D_{.7R}$	1.54
E.A.R.	0.73
Propeller model number	4660A;4661A

Figure A-6.1 - Appendage, Afterbody and Propulsor Characteristics of the Bearing-in-Rudder Post Configuration with Controllable-Pitch Propellers

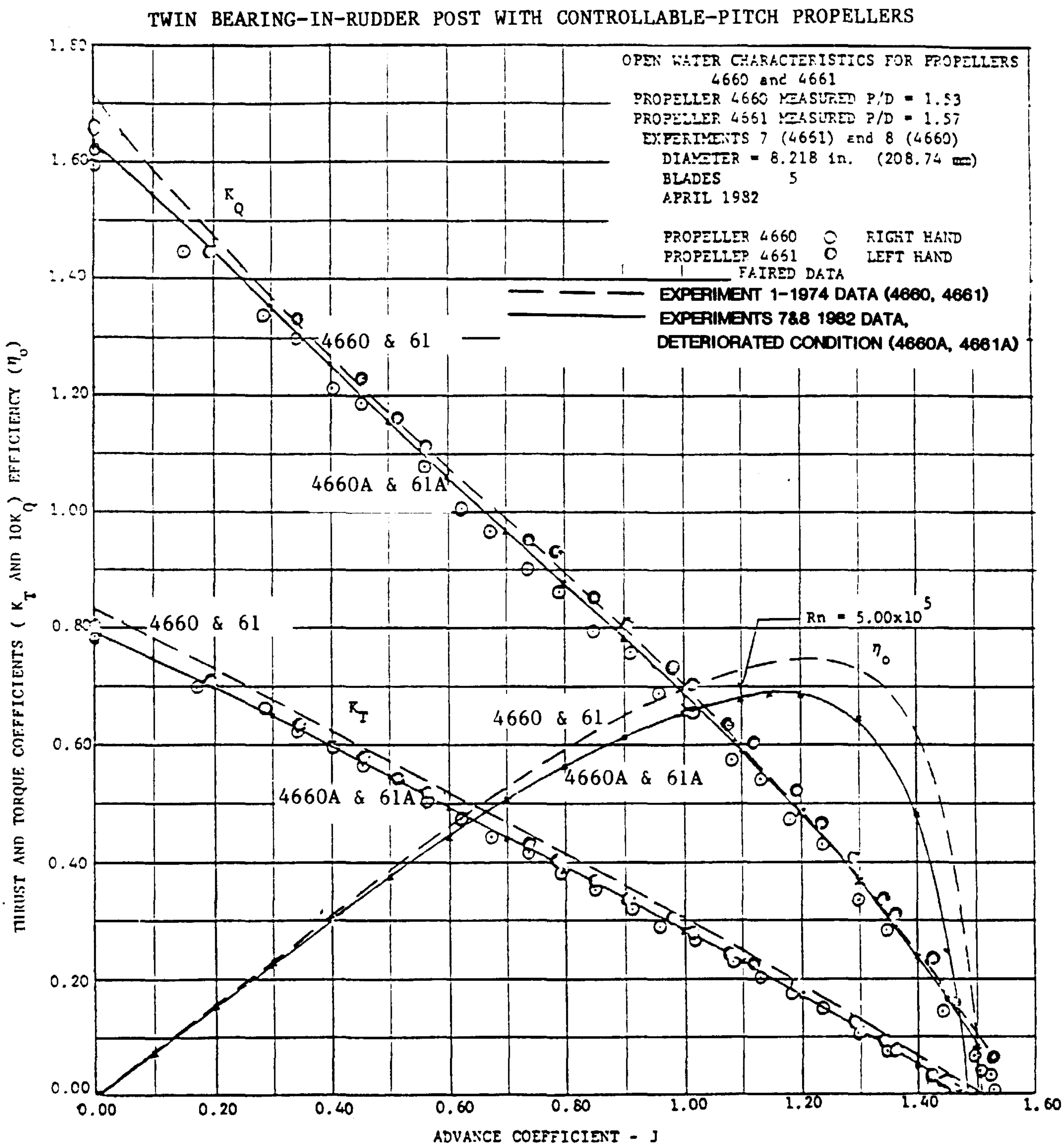


Figure A-6.2 - Open Water Curves for Propellers 4660A and 4661A in a Deteriorated Condition

TWIN BEARING-IN-RUDDER POST WITH CONTROLLABLE-PITCH PROPELLERS

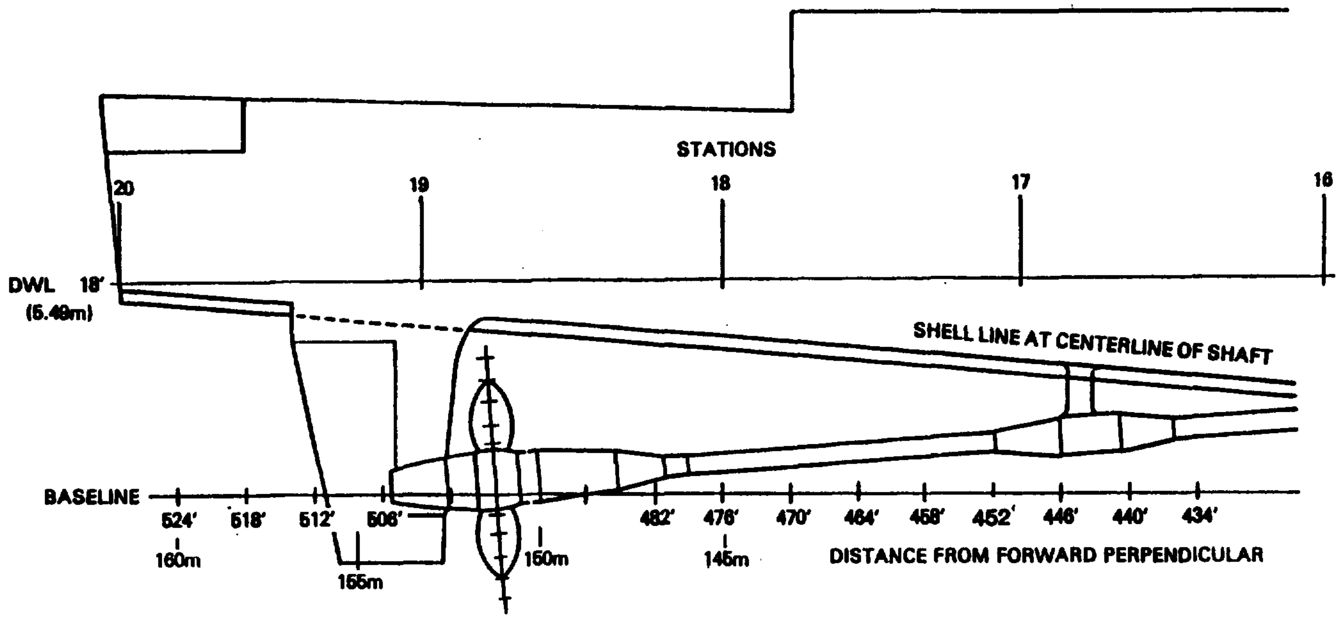


Figure A-6.3 - Stern Appendages of the Bearing-in-Rudder Post Configuration with Controllable-Pitch Propellers - Profile View

TWIN BEARING - IN - RUDDER POST WITH CONTROLLABLE-PITCH PROPELLERS

STRAIGHT RUDDER | CONTRAGUIDE RUDDER | CONTRAGUIDE RUDDER WITH COSTA BULB

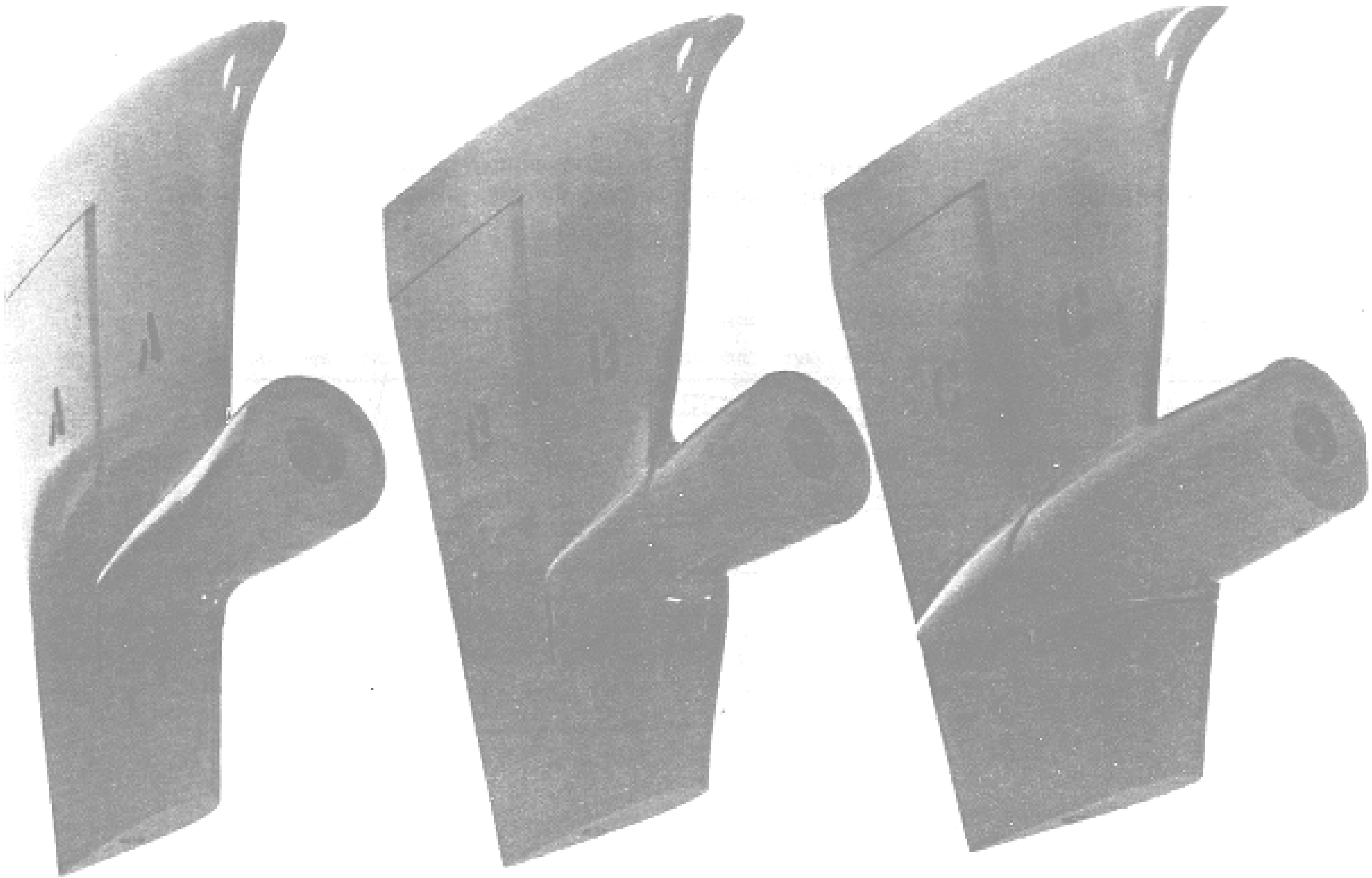


Figure A-6.4 - Photographs of Three Experimental Horn Rudders for the Bearing-in-Rudder Post Configuration with Controllable-Pitch Propellers

TWIN SHAFTLINE LARGE DIAMETER LOW TIP CLEARANCE FIXED-PITCH PROPELLERS

Afterbody - Deep skeg form with large fillet (see Figure A-7.4) - Model 5359-2

Rudders - Twin; same dimensions as on DD-963 athwartships and vertical locations different from DD-963, to suit modified lines and propeller centers. See Figure A-7.5

Propeller Shafts	
Number	2
O.D./I.D. Shafts in way of main strut bearing (inches)	22.75/15.125
O.D./I.D. of exposed shafts, forward of main strut (inches)	22.75/15.125
Main Strut Arms	
Chord (inches)	37.0
Thickness (inches)	7.4
Intermediate Strut Arms	
Chord (inches)	22.5
Thickness (inches)	4.5
Propellers	
Type	F.P.
Number of blades	5
D_p (ft)	20.0
$P/D_{.7R}$	1.345
E.A.R.	approximately 0.6
Model propeller number	4751; 4752
HUB diameter	3.75 ft

Figure A-7.1 - Afterbody, Appendage, and Propulsor Characteristics for the Large Diameter Low Tip Clearance Fixed-Pitch Propeller Configuration, from Tomassoni and Slager (1980)

TWIN SHAFTLINE LARGE DIAMETER LOW TIP CLEARANCE FIXED-PITCH PROPELLERS

SHIP AND MODEL DATA
FOR

MODEL
5359-2

APPENDAGES: Bow Sonar Dome and Centerline Skeg

DIMENSIONS	UNITS	SHIP		MODEL	LWL COEFFICIENTS			
LENGTH (LWL)	ft (m)	530.2	(161.6)	21.359 (6.510)	C_B	0.480	C_{WP}	0.736
LENGTH (LPP)	ft (m)	530.2	(161.6)	21.359 (6.510)	C_P	0.576	C_{WPA}	0.917
BEAM (B_X)	ft (m)	55.0	(16.8)	2.216 (0.675)	C_X	0.836	C_{WPF}	0.562
DRAFT (T)	ft (m)	19.5	(5.9)	0.786 (0.239)	C_{PF}	0.545	L_E/L	0.550
DISPLACEMENT (Δ)	tons (t)	7799	(7925)	0.496 (0.504)	C_{PA}	0.625	L_P/L	0.000
WETTED SURFACE	ft^2 (m^2)	34073	(3165.5)	55.292 (5.137)	C_{PE}	0.577	L_R/L	0.450
DESIGN VELOCITY	knots	30.0		6.021	C_{PR}	0.571	L/B	9.640
$\overline{FB}$/LWL 0.512		$\overline{FB}$/LPP 0.512	λ	24.824	C_{VP}	0.652	B_X/T	2.821
WATERLINE ENTRANCE HALF ANGLE 7.0°					C_{VPA}	0.583	$S/\sqrt{\Delta L}$	16.756
WETTED SURFACE OF TWO BILGE KEELS - 1497 ft^2					C_{VPF}	0.799	C_∇	0.00183
							f	0.289

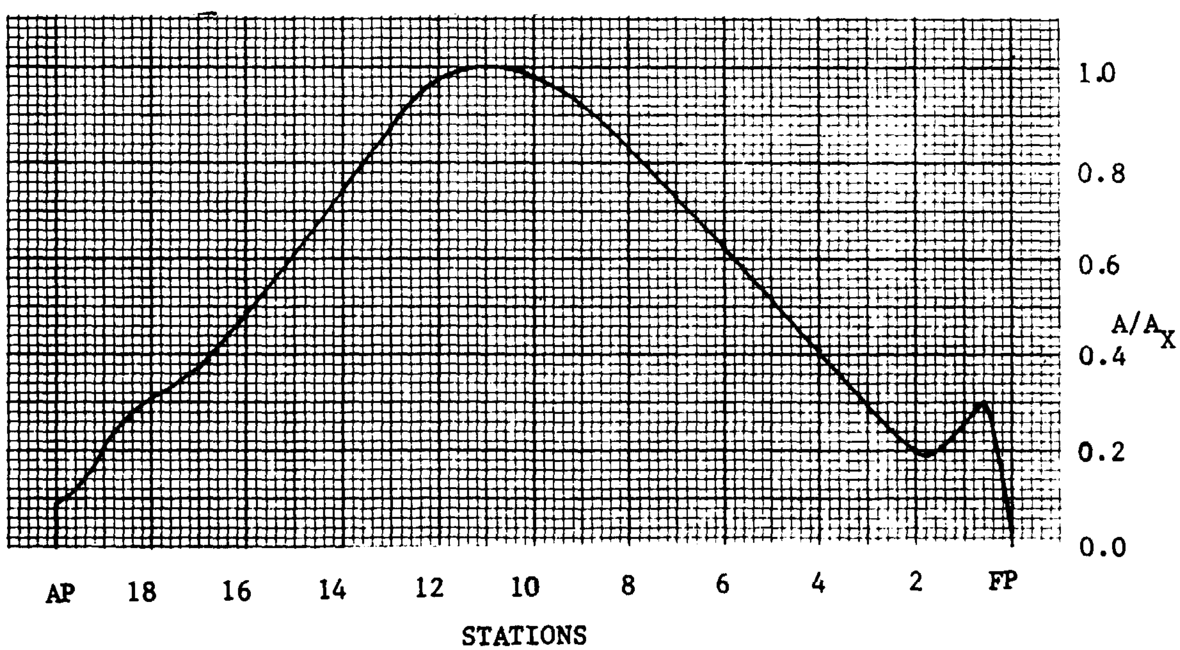


Figure A-7.2 - Ship and Model Data for the Large Diameter Low Tip Clearance Fixed-Pitch Propeller Configuration Represented by Model 5359-2

TWIN SHAFTLINE LARGE DIAMETER LOW TIP CLEARANCE FIXED-PITCH PROPELLERS

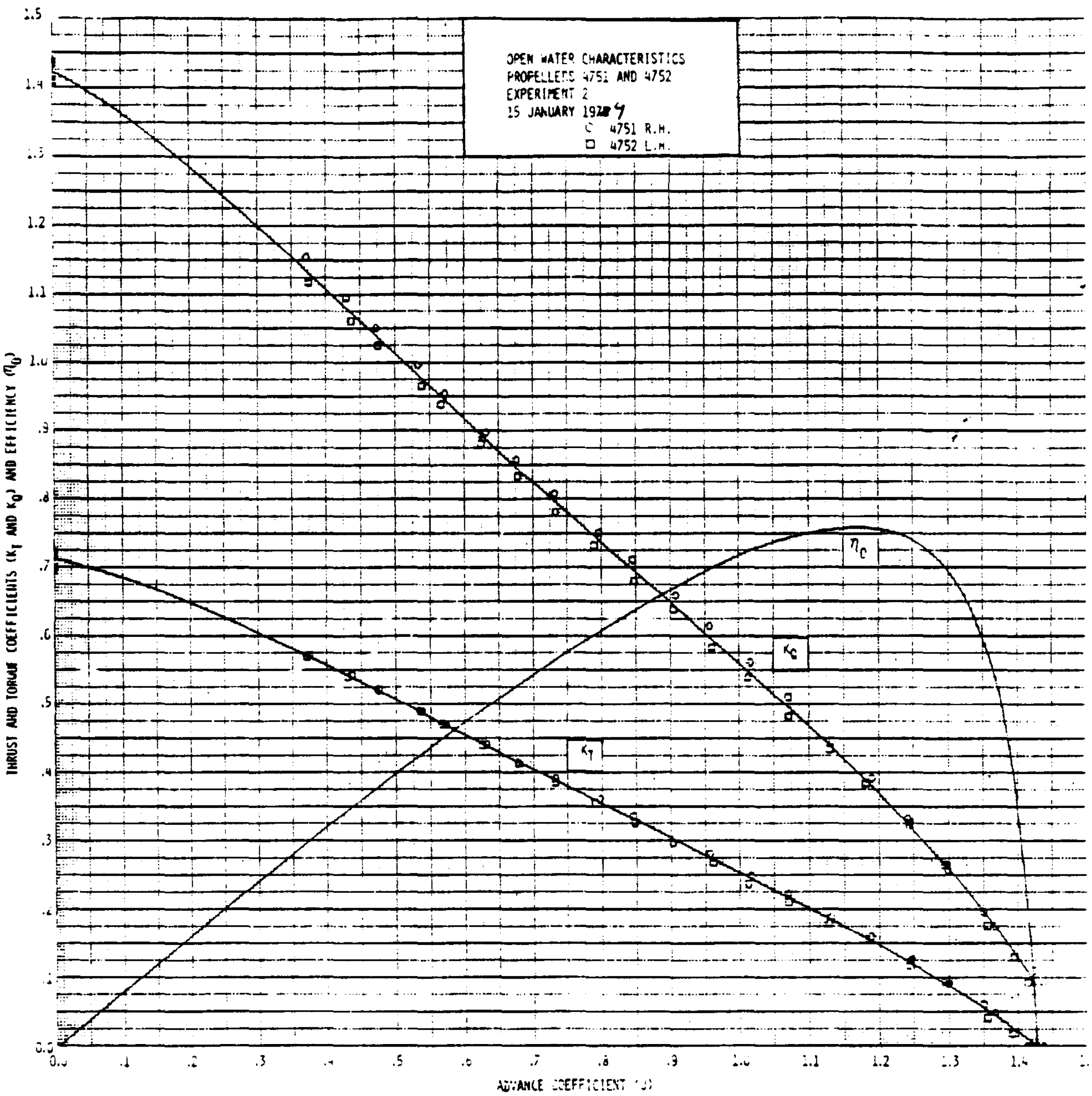


Figure A-7.3 - Open Water Curves for Propellers 4751 and 4752

TWIN SHAFTLINE LARGE DIAMETER LOW TIP CLEARANCE FIXED-PITCH PROPELLERS

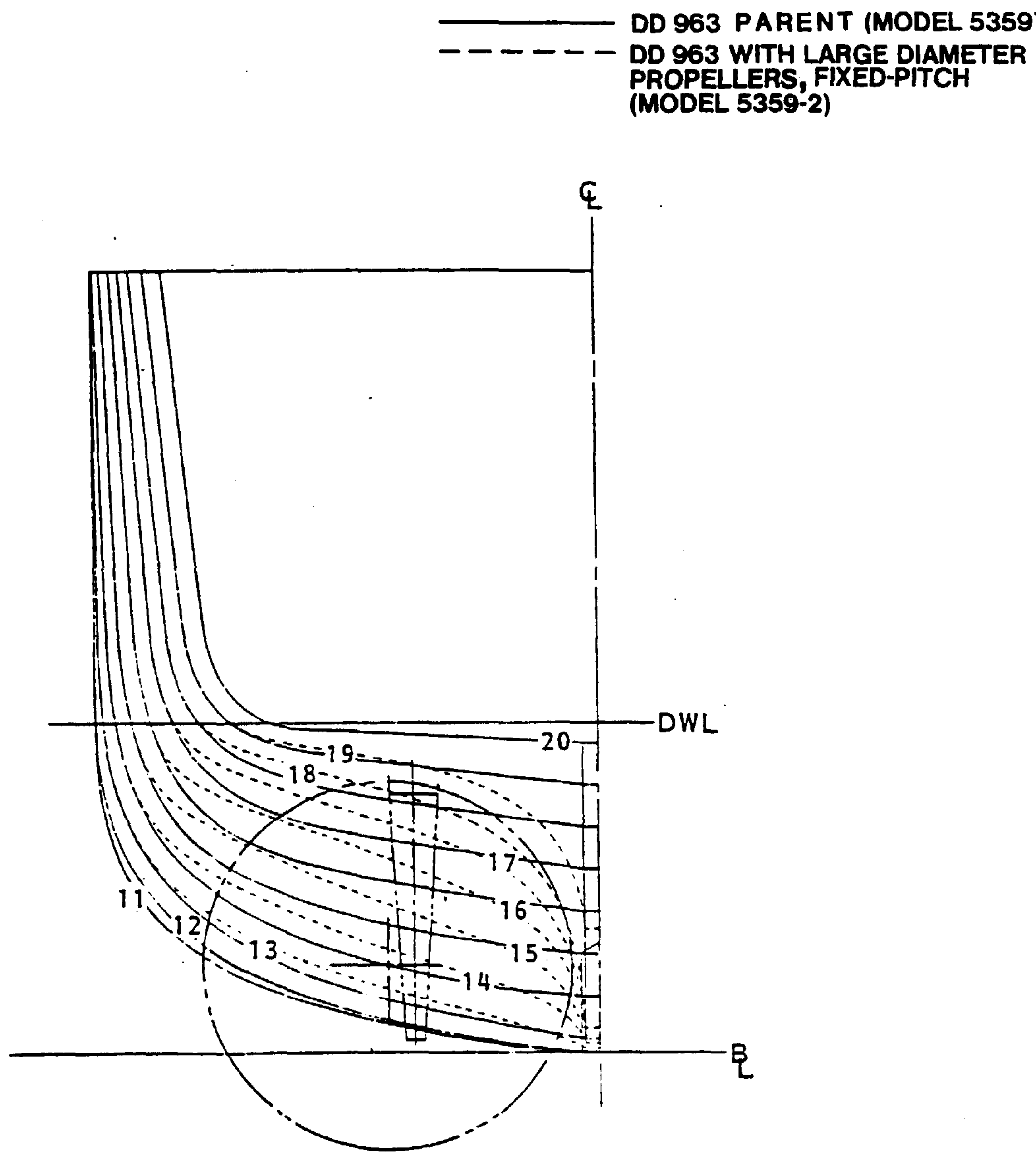


Figure A-7.4 - Comparison of Afterbody Sections of the Large Diameter Low Tip Clearance Propeller Configuration with Those of the Parent DD-963 Configuration, from Tomassoni and Slager (1980)

TWIN SHAFTLINE LARGE DIAMETER LOW TIP CLEARANCE FIXED-PITCH PROPELLERS

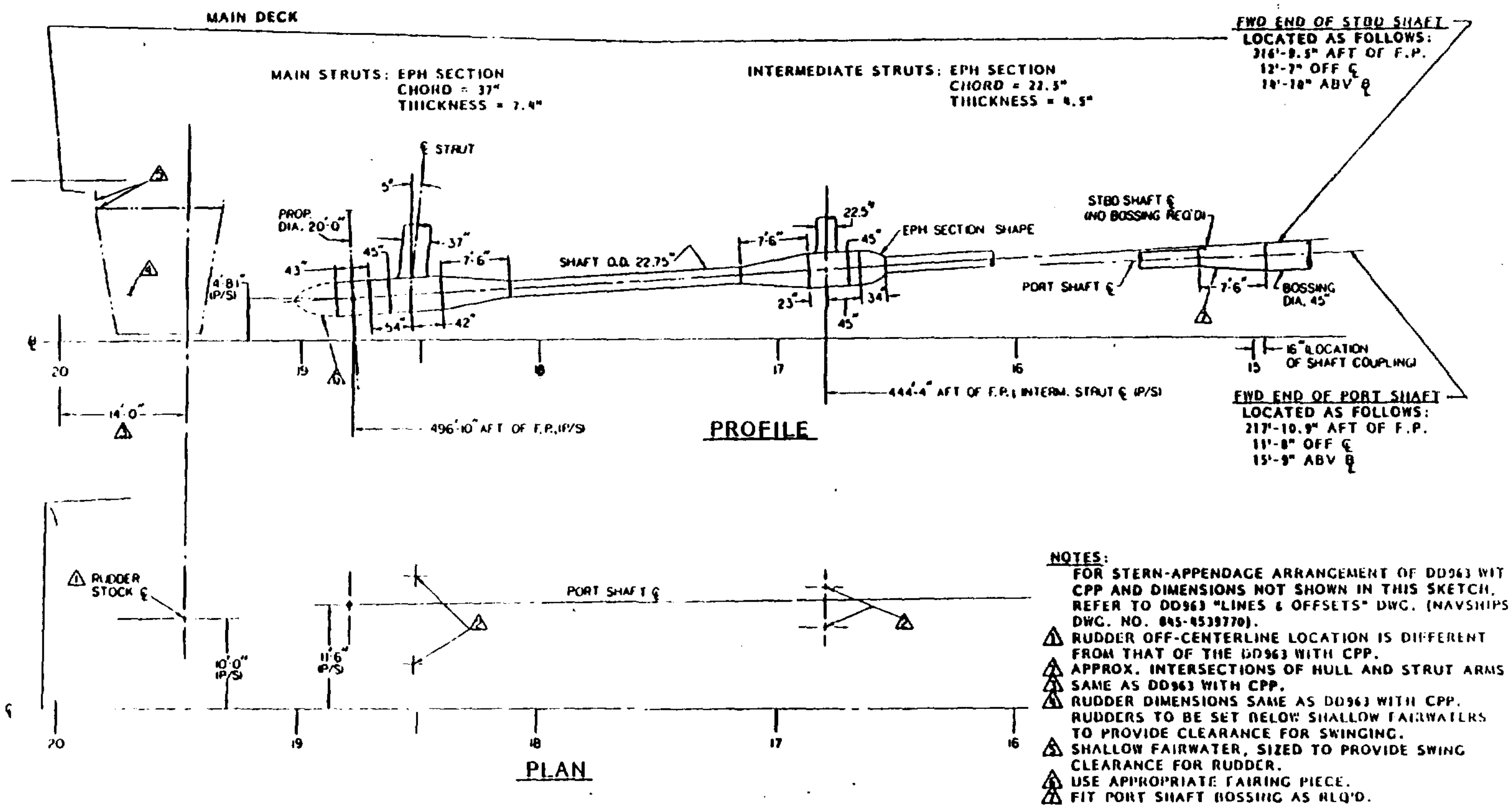
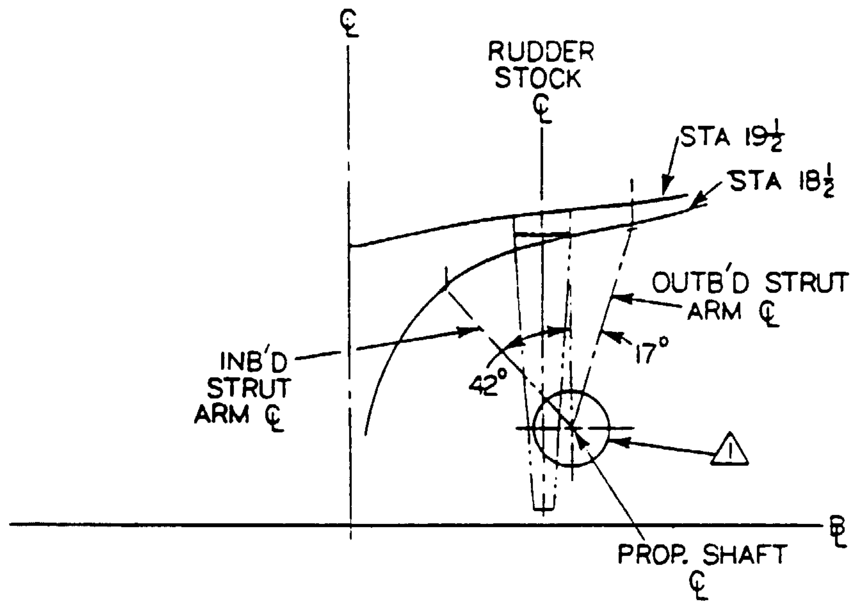


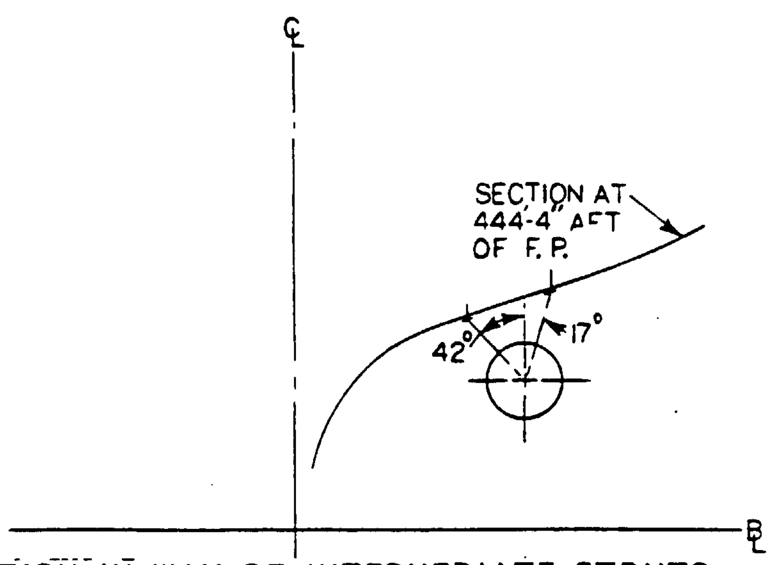
Figure A-7.5 - Stern Appendages of Large Diameter Low Tip Clearance Fixed-Pitch Propeller Configuration - Profile and Plan Views, from Tomassoni and Slager (1980)

TWIN SHAFTLINE LARGE DIAMETER LOW TIP CLEARANCE FIXED-PITCH PROPELLERS



SECTION IN WAY OF MAIN STRUTS & RUDDERS

NOTES:
MAIN & INTERMEDIATE STRUTS ARE IDENTICAL P&S EXCEPT AS REQ'D TO ACCOMMODATE DIFFERENCES IN SHAFT LOCATIONS.
⚠1 BARREL SECTION AT INTERSECTION OF SHAFT ℄ & STRUT ℄.



SECTION IN WAY OF INTERMEDIATE STRUTS

Figure A-7.6 - Stern Appendages of Large Diameter Low Tip Clearance Fixed-Pitch Propeller Configuration - Sectional Views, from Tomassoni and Slager (1980)

TWIN SHAFTLINE LARGE DIAMETER LOW TIP CLEARANCE FIXED-PITCH PROPELLERS

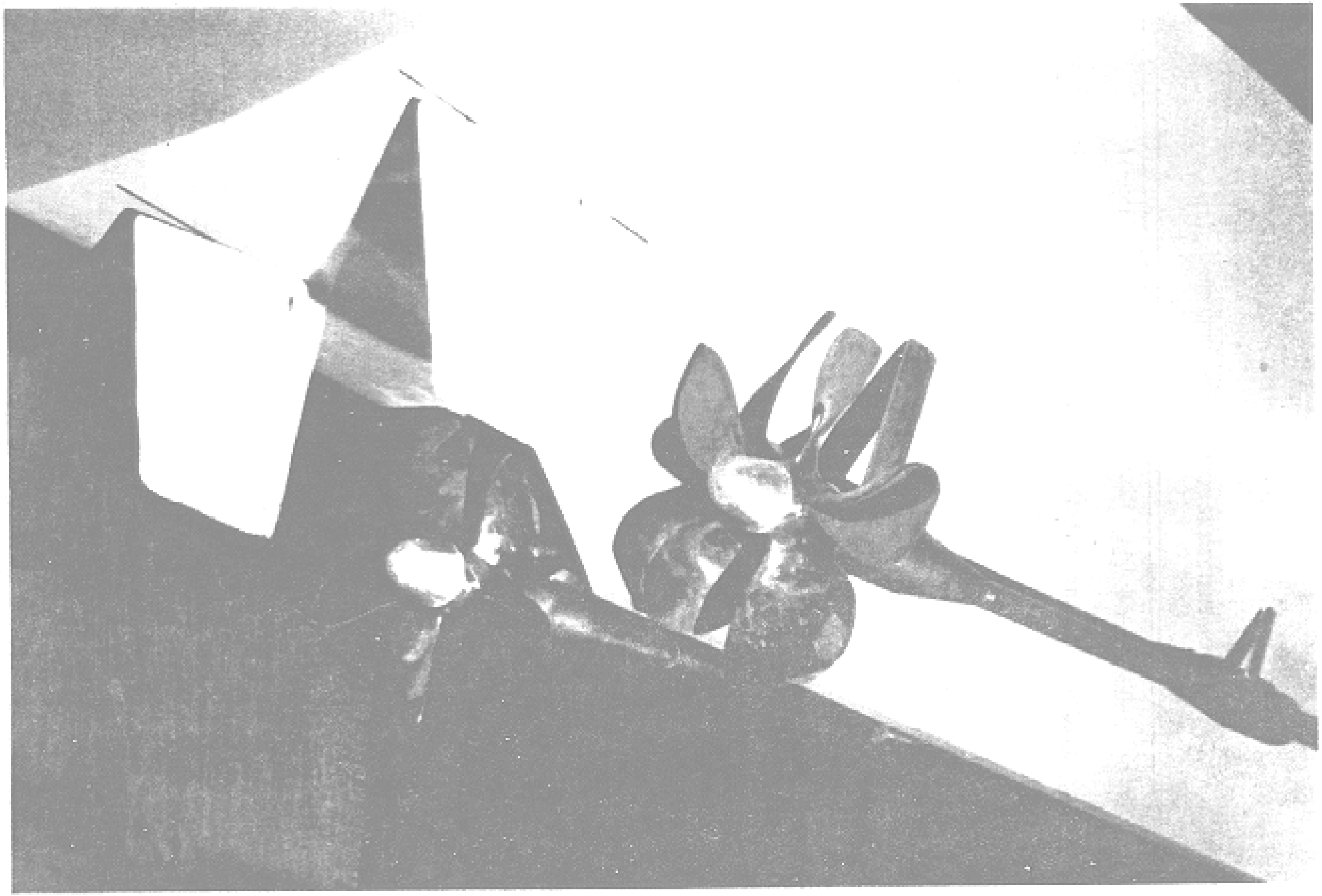


Figure A-7.7 - Photograph of Stern of Large Diameter Low Tip Clearance Fixed-Pitch Propeller Configuration (Model 5359-2)

TWIN SHAFTLINE TANDEM PROPELLERS

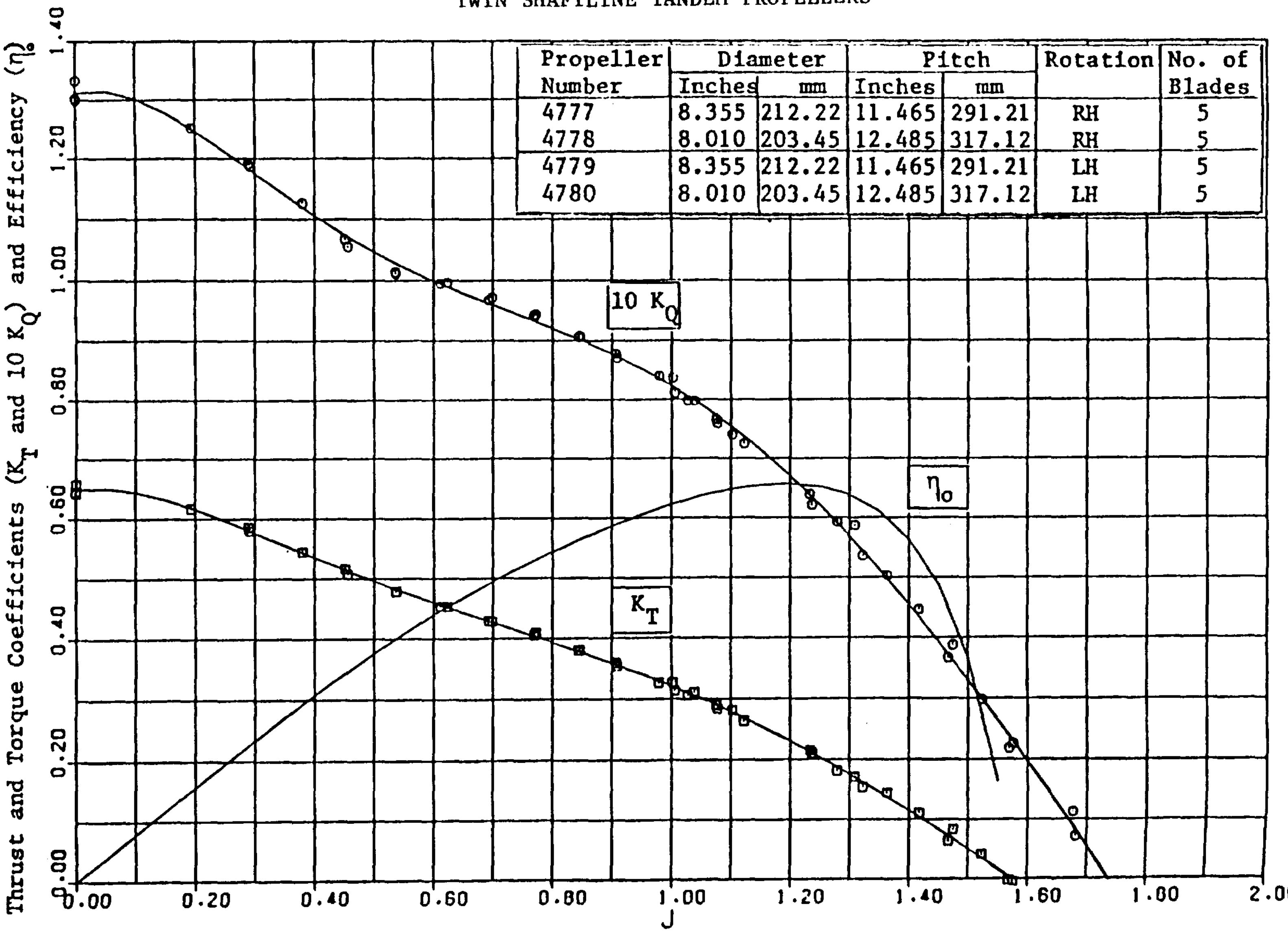
Afterbody - DD-963, unmodified (see Figure A-1.5) - Model 5359-1A

Rudders - Twin; same dimensions and locations as on DD-963

Propeller Shafts	
Number	2
O.D./I.D. Shafts in way of main strut bearing (inches)	21.875/14.50
O.D./I.D. of exposed shafts, forward of main strut (inches)	20.25 /13.50
Main Strut Arms	
Chord (inches)	35.0
Thickness (inches)	7.0
Intermediate Strut Arms	
Chord (inches)	22.5
Thickness (inches)	4.5
Propellers	
Type	F.P., Tandem (2 sets)
Number of blades, fwd/aft	5/5
D_p fwd/D_p aft (ft)	17.3/16.6
P/D $_{.7R}$ fwd/P/D $_{.7R}$ aft	1.35/1.55
E.A.R. fwd/E.A.R. aft	0.365/0.365
Weight, fwd/Weight, aft (lbs, approx.)*	24000 / 20900
RPM (approximately) at 20 knots	96.6
RPM (approximately) (design full power)	168
Longitudinal spacing between fwd and aft propeller	4.25 ft
Model propeller numbers	4777+4778/4779+4780

Figure A-8.1 - Afterbody, Appendage, and Propulsor Characteristics of the Twin Shafts and Struts Configuration with Tandem Propellers, from Tomassoni and Slager (1980)

TWIN SHAFTLINE TANDEM PROPELLERS



Propeller Number	Diameter Inches	Diameter mm	Pitch Inches	Pitch mm	Rotation	No. of Blades
4777	8.355	212.22	11.465	291.21	RH	5
4778	8.010	203.45	12.485	317.12	RH	5
4779	8.355	212.22	11.465	291.21	LH	5
4780	8.010	203.45	12.485	317.12	LH	5

Figure A-8.2 - Open Water Curves for Tandem Propellers 4777 & 4778 and 4779 & 4780

TWIN SHAFTLINE TANDEM PROPELLERS

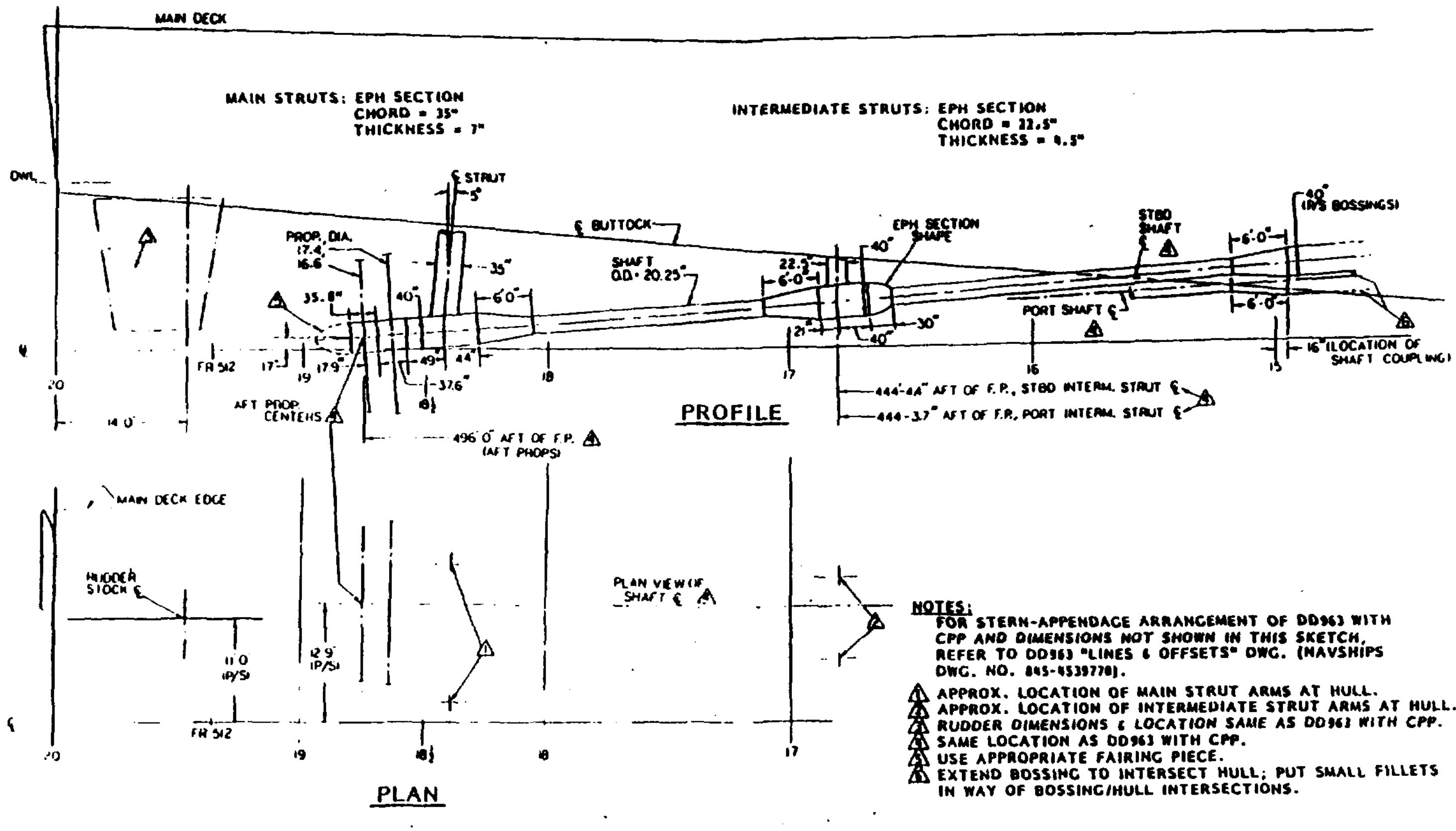


Figure A-8.3 - Stern Appendages of Twin Shafts and Struts Configuration with Tandem Propellers - Profile and Plan Views, from Tomassoni and Slager (1980)

TWIN SHAFTLINE TANDEM PROPELLERS

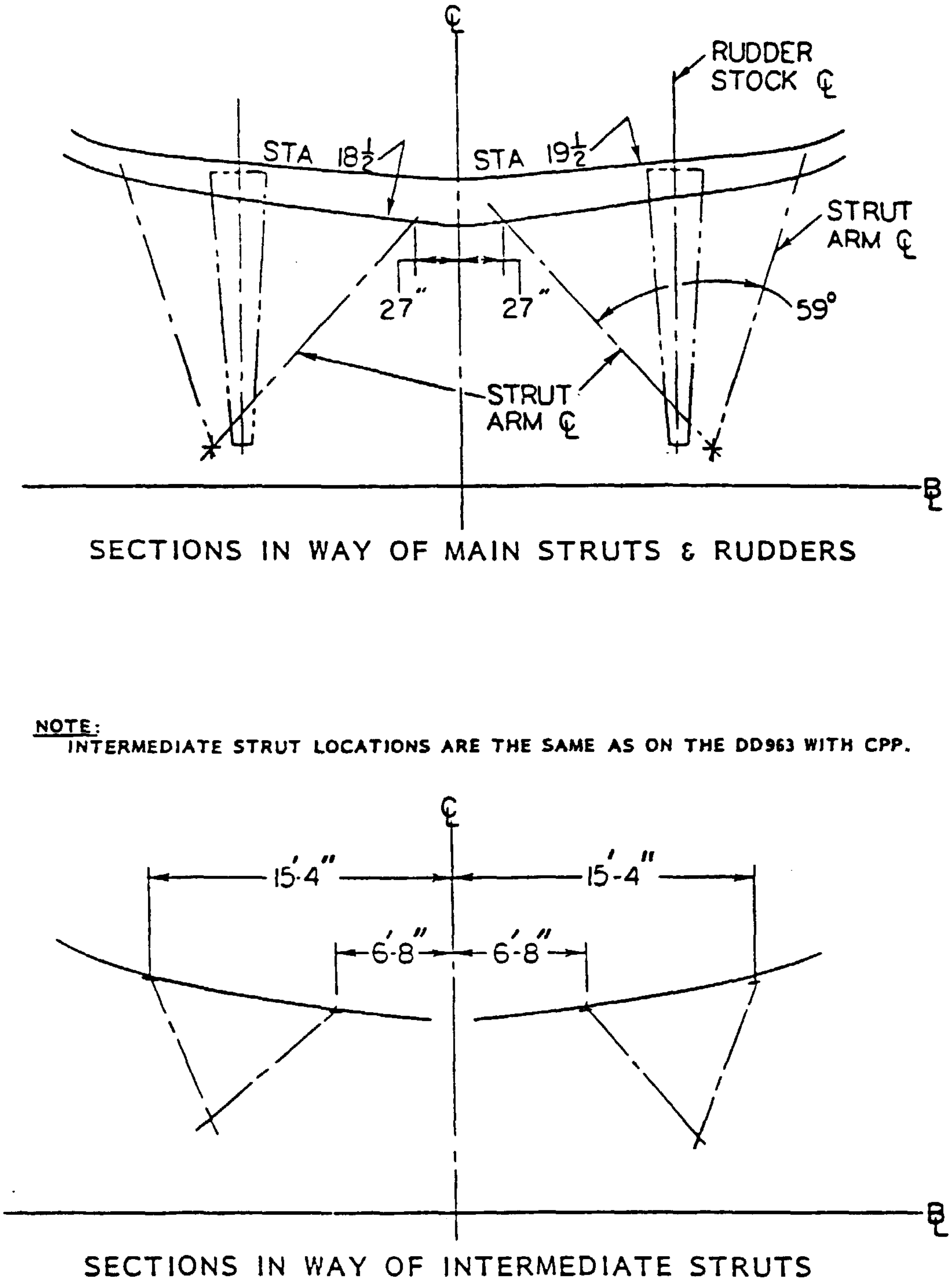


Figure A-8.4 - Stern Appendages of Twin Shafts and Struts Configuration with Tandem Propellers - Sectional Views, from Tomassoni and Slager (1980)

TWIN SHAFTLINE TANDEM PROPELLERS

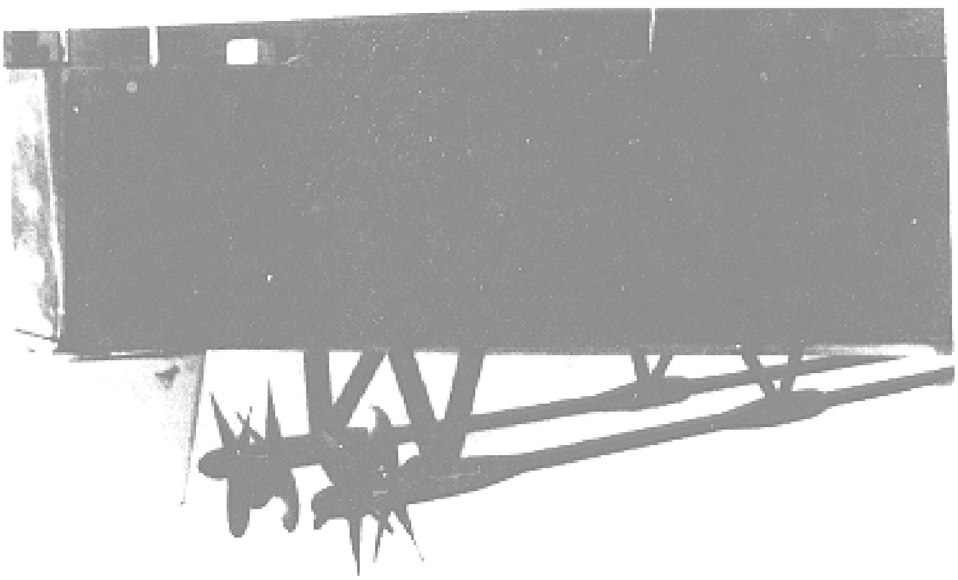


Figure A-8.5 - Photograph of Twin Shafts and Struts Configuration with Tandem Propellers (Model 5359-1A) - Stern Quarter View

Afterbody - DD-963, unmodified (see Figure A-1.5) - Model 5359

Rudders - Twin; same dimensions and location as on DD-963 - Wetted surface of two rudders is 648 ft^2

Propeller Shafts	
Number	2
O.D./I.D. Shafts in way of main strut bearing (inches)	26.25/–
O.D./I.D. of exposed shafts, forward of main strut (inches)	21.50/–
Main Strut Arms	
Chord (inches)	38.0
Thickness (inches)	7.6
Webbed surface of four struts	330.0 ft^2
Intermediate Strut Arms	
Chord (inches)	25.5
Thickness (inches)	5.1
Propellers	
Type	C.P.
Number of blades	5
Dp (ft)	17.0
$P/D_{.7R}$	1.54
E.A.R.	0.73
Weight (pounds each, approximate)	48,000
RPM (approximately) at 20 knots	96.6
RPM (approximately) (design full power)	168
Propeller model	4868;4869
Fairwaters	
Bullet Shape - L/D	1.00
Truncated Cone - L/D	0.50

Figure A-9.1 - Appendage, Afterbody, and Propulsor Characteristics of the Parent DD-963 Configuration - Twin Shafts and Struts with Controllable-Pitch Propellers and Revised Fairwater Shapes

TWIN SHAFTLINE CONTROLLABLE-PITCH PROPELLERS WITH REVISED FAIRWATERS

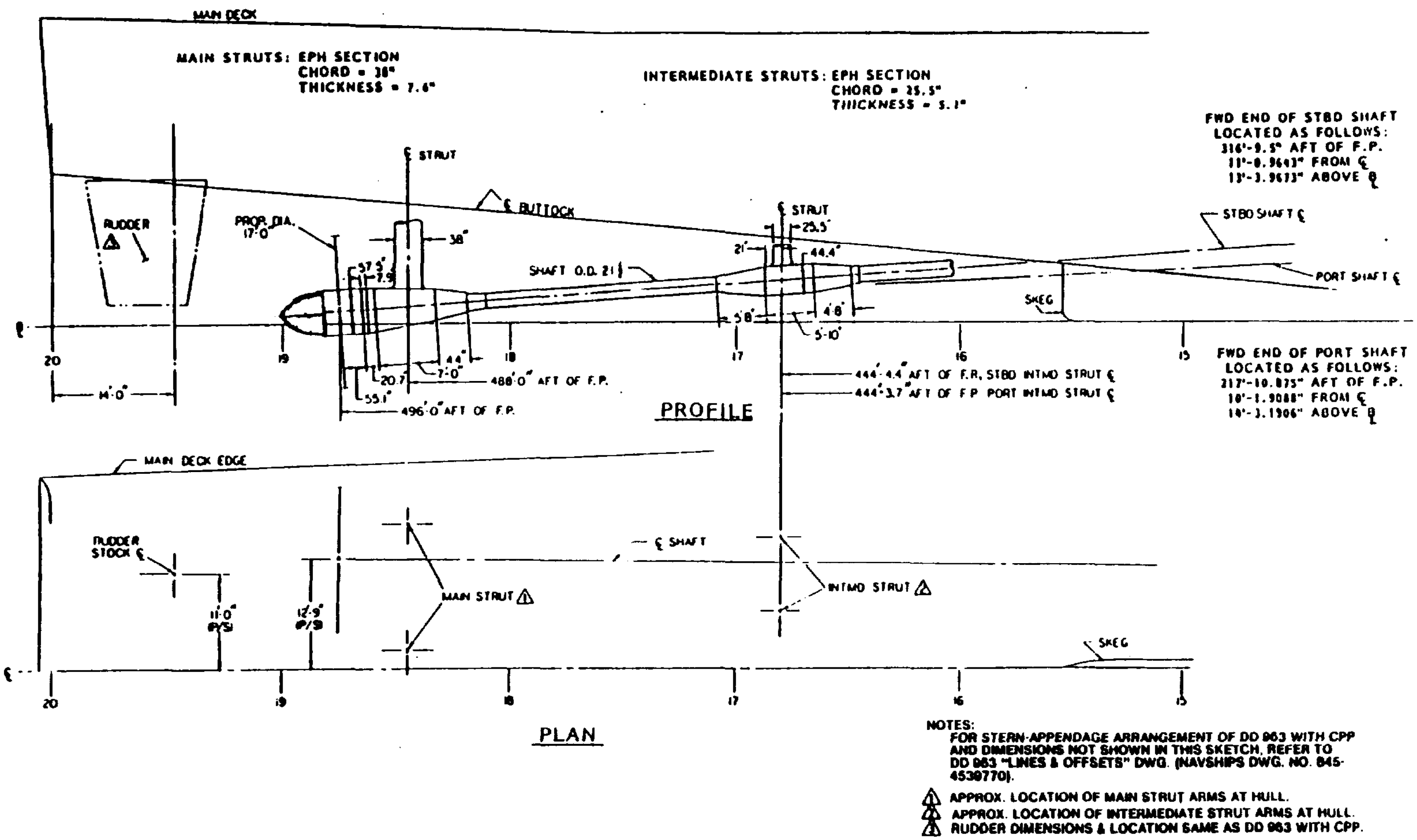


Figure A-9.2 - Stern Appendages of Twin Shafts and Struts Configuration with Controllable-Pitch Propellers and Revised Fairwater Shapes - Profile and Plan Views

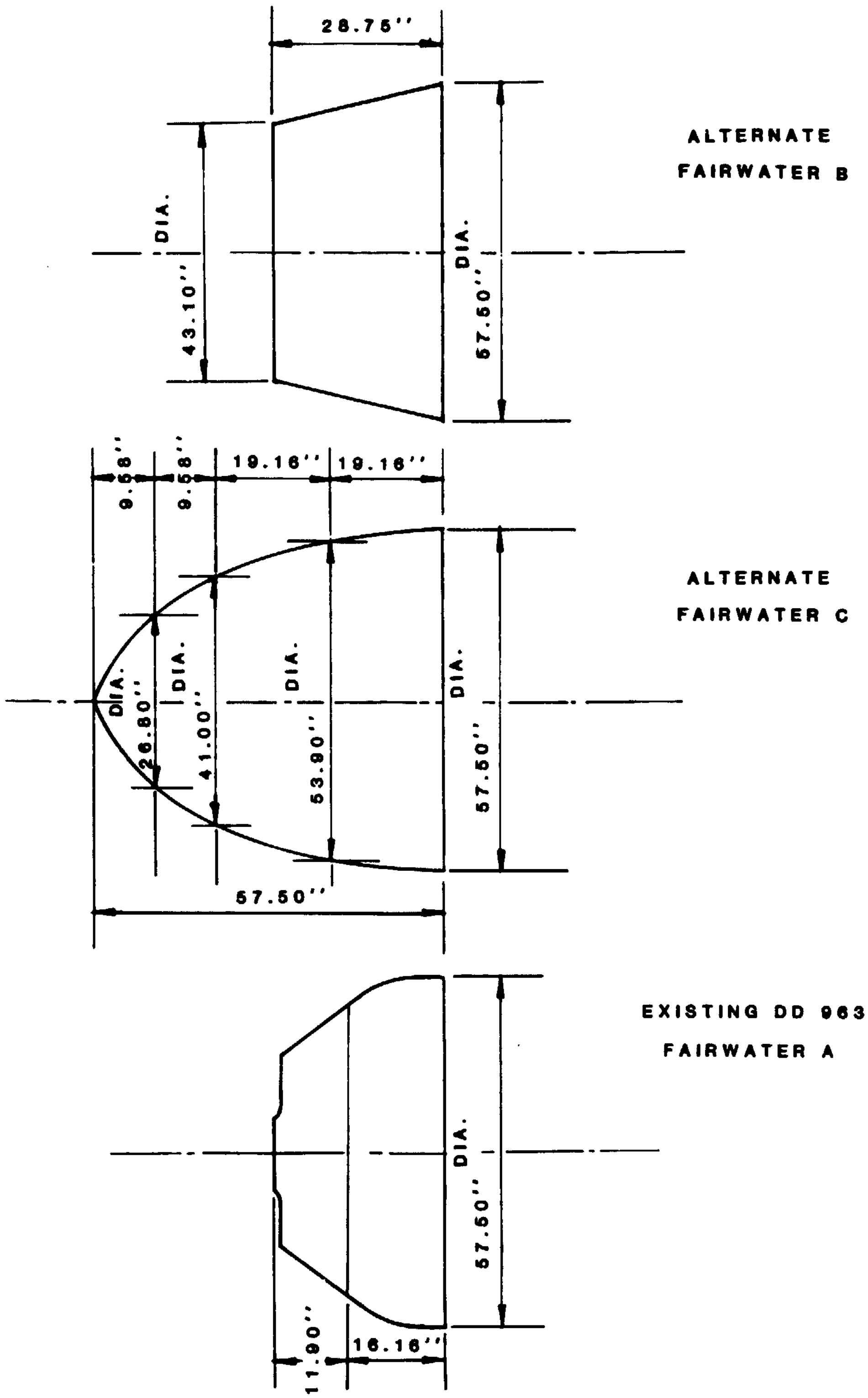


Figure A-9.3 - Details of the Existing DD-963 Fairwater Design (Labeled A) and Those of Two Alternate Low Drag Fairwater Shapes

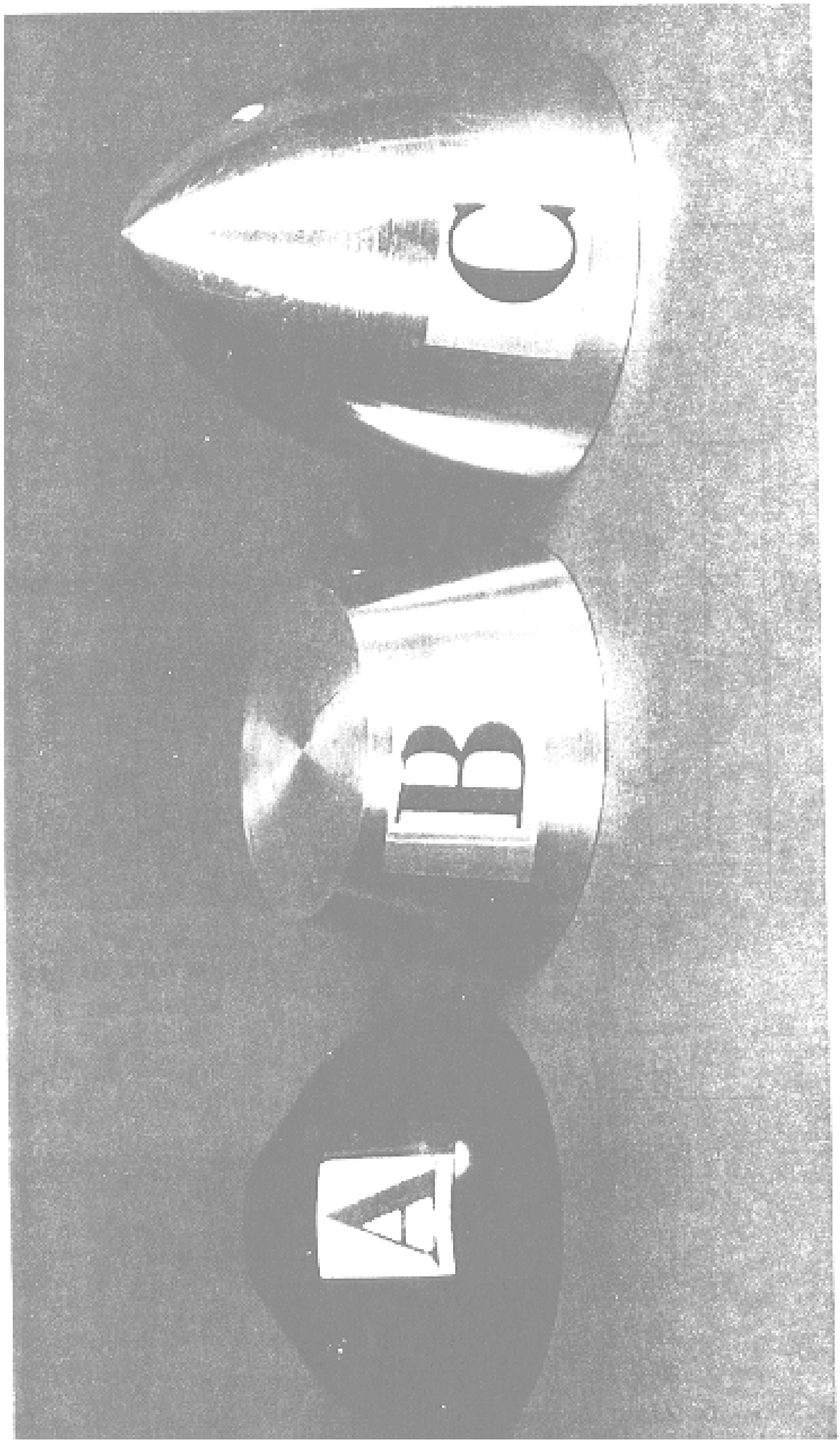


Figure A-9.4 - Photograph of a Model of the Existing DD-963 Fairwater Design (Labeled A) and of Two Alternate Low Drag Fairwater Shapes

TWIN SHAFTLINE LARGE DIAMETER OVERLAPPING PROPELLERS

Afterbody - Deep skeg with twin tunnels (see Figure A-10.4) - Model 5359-3

Rudders - Twin; same dimensions as on DD-963 athwartships and vertical locations different from DD-963, to suit modified lines and propeller centers. (see Figure A-10.5)

Propeller shafts	
Number	2
O.D./I.D. Shafts in way of main strut bearing (inches)	22.75/15.125
O.D./I.D. of exposed shafts, forward of main strut (inches)	22.75/15.125
Main Strut Arms	
Chord (inches)	37.0
Thickness (inches)	7.4
Intermediate Strut Arms	
Chord (inches)	22.5
Thickness (inches)	4.5
Propellers	
Type	F.P.; Overlapping
Number of blades	5
D_p (ft)	20.0
$P/D_{.7R}$	1.30
E.A.R. (approximate)	0.60
Weight (pounds each, approximate)	48000
Model propeller number	4751 and 4752

Figure A-10.1 - Afterbody, Appendage and Propulsor Characteristics for the Large Diameter Overlapping Propeller Configuration, from Tomassoni and Slager (1980)

TWIN SHAFTLINE LARGE DIAMETER OVERLAPPING PROPELLERS

SHIP AND MODEL DATA
FOR

MODEL
5359-3

APPENDAGES: Bow Sonar Dome and Centerline Skeg

DIMENSIONS	UNITS	SHIP	MODEL	LWL COEFFICIENTS			
LENGTH (LWL)	ft (m)	530.2 (161.6)	21.359 (6.510)	C_B	0.480	C_{WP}	0.736
LENGTH (LPP)	ft (m)	530.2 (161.6)	21.359 (6.510)	C_P	0.574	C_{WPA}	0.562
BEAM (B_X)	ft (m)	55.0 (16.8)	2.216 (0.675)	C_X	0.836	C_{WPF}	0.917
DRAFT (T)	ft (m)	19.5 (5.9)	0.786 (0.239)	C_{PF}	0.545	L_E/L	0.550
DISPLACEMENT (Δ)	tons (t)	7807 (7932)	0.496 (0.504)	C_{PA}	0.626	L_P/L	0.000
WETTED SURFACE	ft^2 (m^2)	34715 (3225.1)	56.334 (5.234)	C_{PE}	0.577	L_R/L	0.450
DESIGN VELOCITY	knots	30.0	6.021	C_{PR}	0.572	L/B	9.640
$\overline{FB}$/LWL 0.512	$\overline{FB}$/LPP 0.512	λ 24.824		C_{VP}	0.652	B_X/T	2.821
WATERLINE ENTRANCE HALF ANGLE 7.0°				C_{VPA}	0.562	$S/\sqrt{\Delta L}$	17.063
WETTED SURFACE OF TWO BILGE KEELS - 1497 ft^2				C_{VPF}	0.799	C_∇	0.001832
						f	0.289

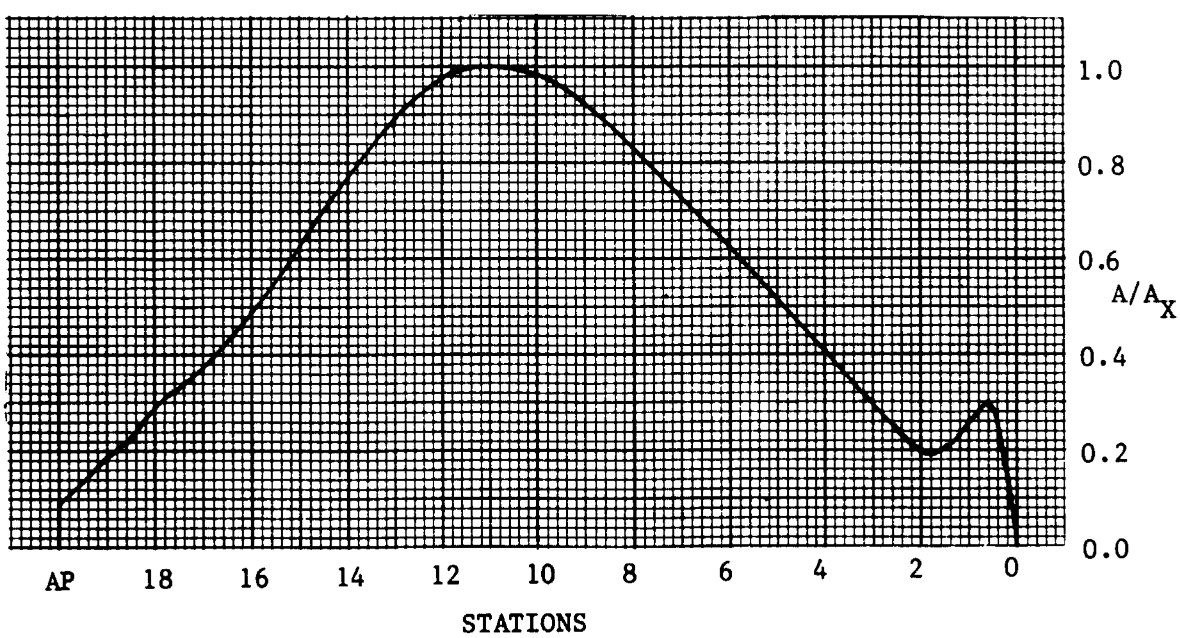


Figure A-10.2 - Ship and Model Data for the Large Diameter Overlapping Propeller Configuration Represented by Model 5359-3

TWIN SHAFTLINE LARGE DIAMETER OVERLAPPING PROPELLERS

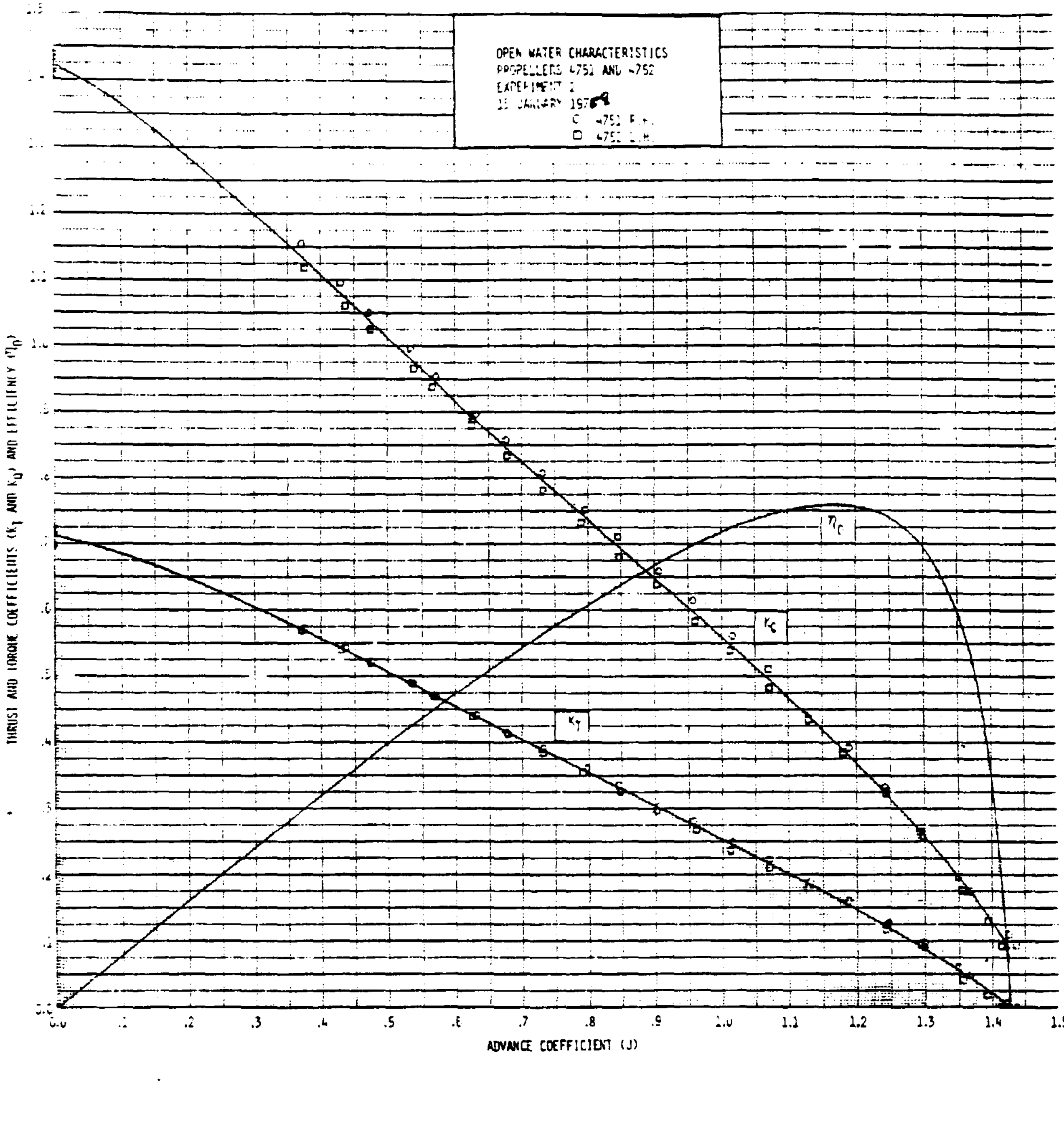


Figure A-10.3 - Open Water Curves for Propellers 4751 and 4752

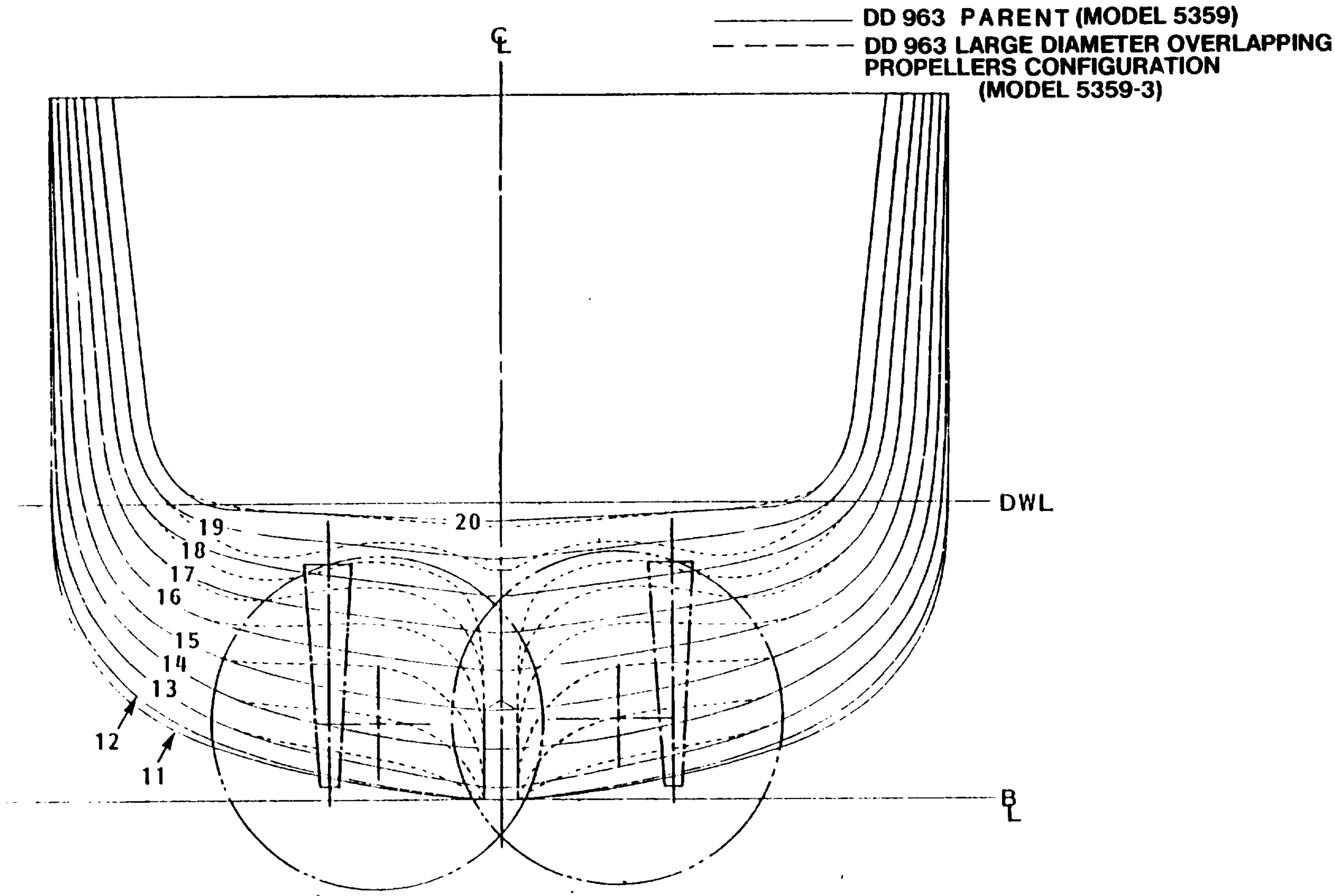


Figure A-10.4 - Comparison of Afterbody Sections of the Large Diameter Overlapping Propeller Configuration and the Parent DD-963 Hull Form, from Tomassoni and Slager (1980)

TWIN SHAFTLINE LARGE DIAMETER OVERLAPPING PROPELLERS

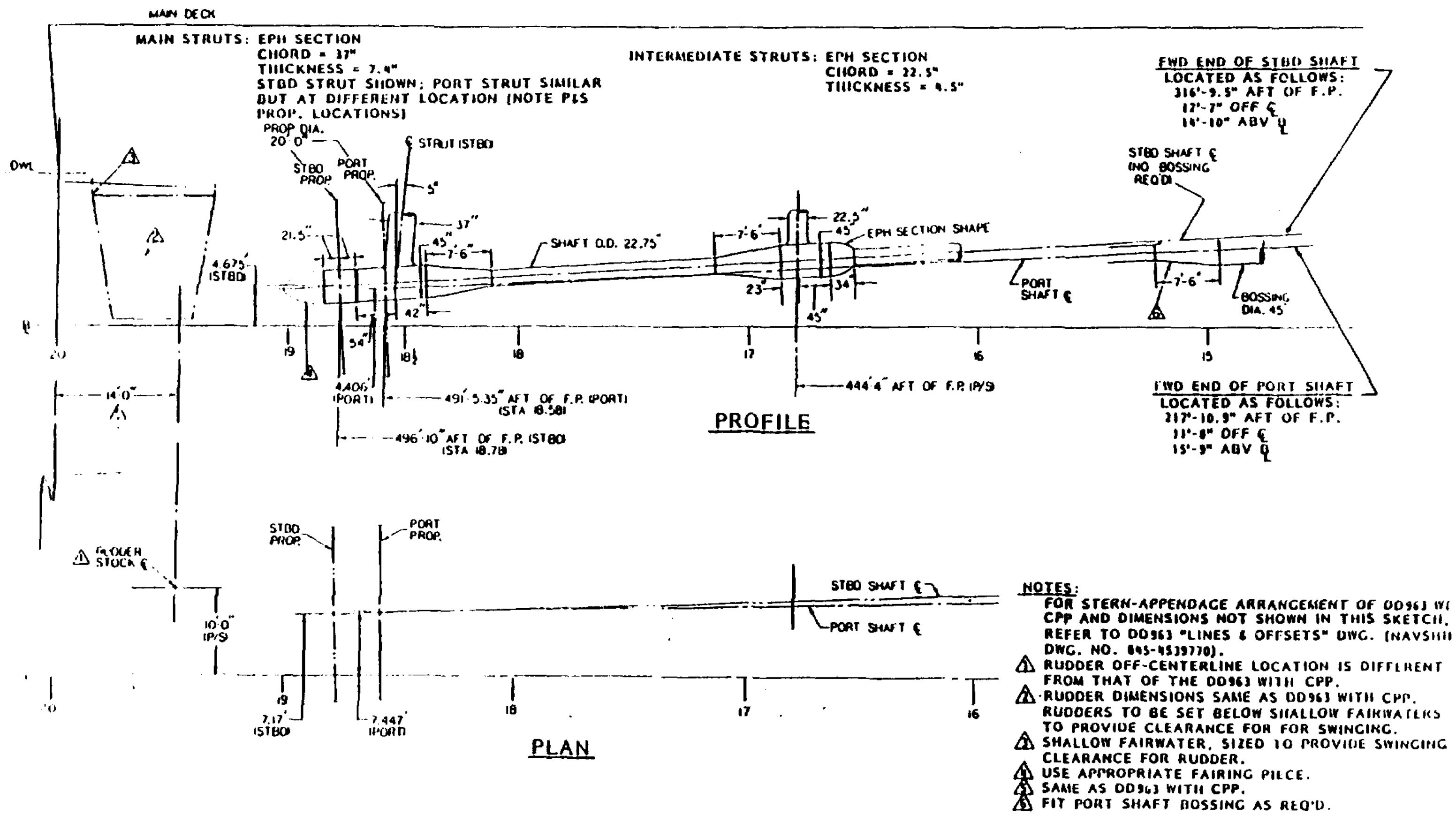


Figure A-10.5 - Stern Appendages of Large Diameter Overlapping Propeller Configuration - Profile and Plan Views, from Tomassoni and Slager (1980)

TWIN SHAFTLINE LARGE DIAMETER OVERLAPPING PROPELLERS

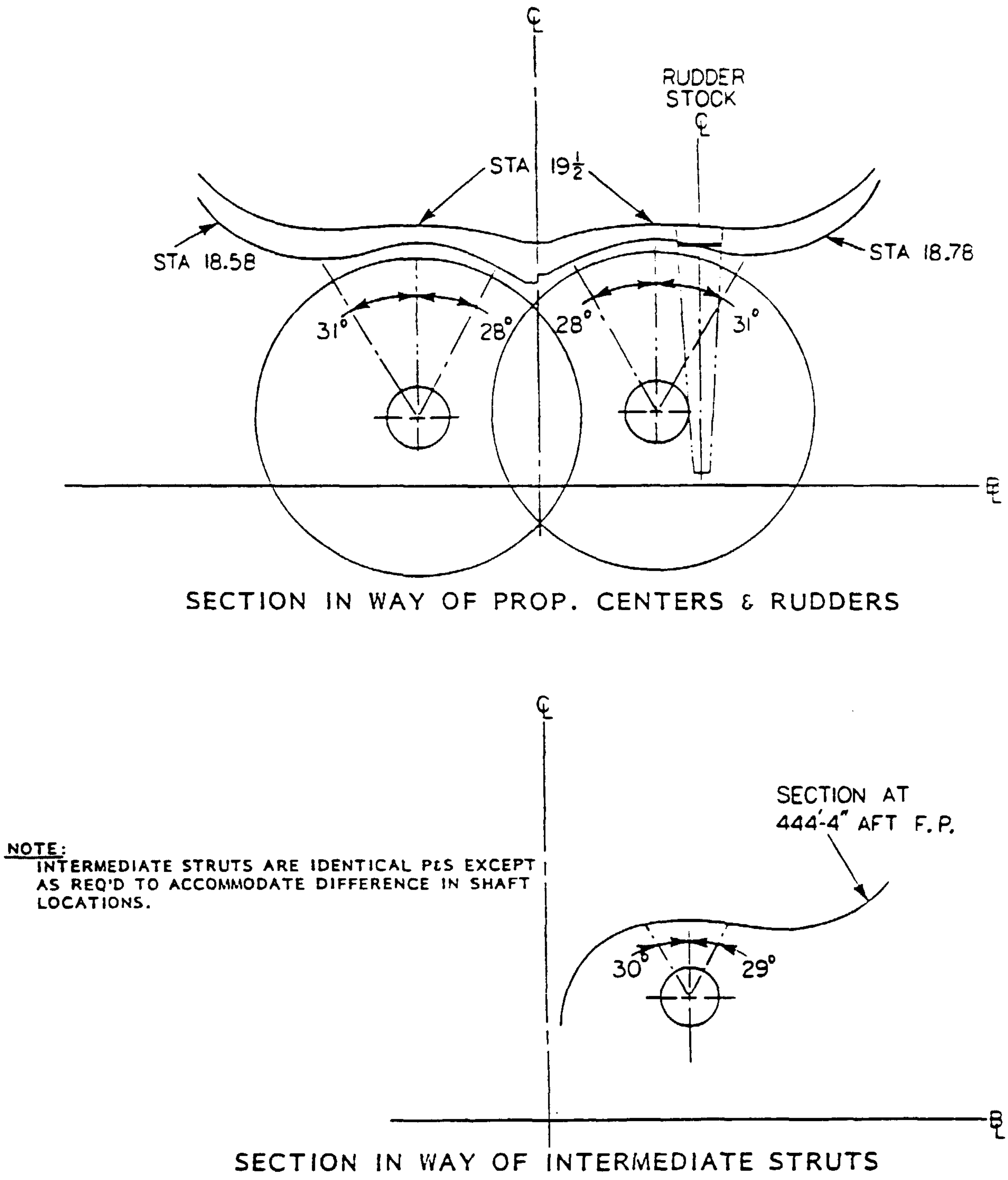


Figure A-10.6 - Stern Appendages of Large Diameter Overlapping Propeller Configuration - Sectional Views, from Tomassoni and Slager (1980)

TWIN SHAFTLINE LARGE DIAMETER OVERLAPPING PROPELLERS

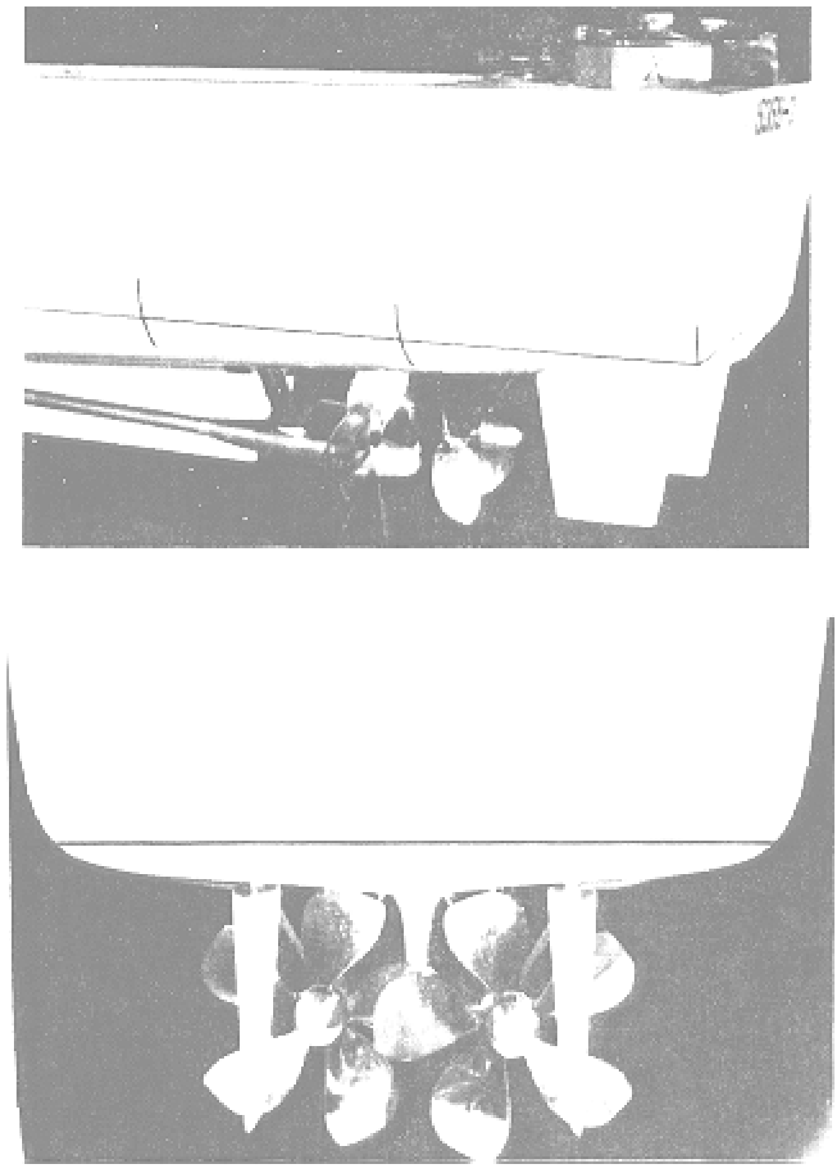


Figure A-10.7 - Photographs of Large Diameter Overlapping Propeller Configuration (Model 5359-3) - Stern Quarter and Stern View

TWIN SHAFTLINE LARGE DIAMETER LOW TIP CLEARANCE CONTROLLABLE-PITCH PROPELLERS

Afterbody - Deep skeg form with large fillet (see Figure A-7.4) - Model 5359-2A
- Same Afterbody as Model 5359-2

Rudders - Twin; same dimensions as on DD-963 athwartships and vertical locations different from DD-963, to suit modified lines and propeller centers. (see Figure A-11.3)

Propeller Shafts	
Number	2
O.D./I.D. Shafts in way of main strut bearing (inches)	31.50/21.00
O.D./I.D. of exposed shafts, forward of main strut (inches)	29.00/19.34
Main Strut Arms	
Chord (inches)	42.0
Thickness (inches)	8.4
Intermediate Strut Arms	
Chord (inches)	25.0
Thickness (inches)	5.0
Propellers	
Type	C.P.
Number of blades	5
D_p (ft)	20.0
$P/D_{.7R}$	1.30
E.A.R. (approximate)	0.60
Model propeller number	4751A; 4752A

Figure A-11.1 - Afterbody, Appendage, and Propulsor Characteristics of the Large Diameter Low Tip Clearance Controllable-Pitch Propeller Configuration, from Tomassoni and Slager (1980)

TWIN SHAFTLINE LARGE DIAMETER LOW TIP CLEARANCE CONTROLLABLE-PITCH PROPELLERS

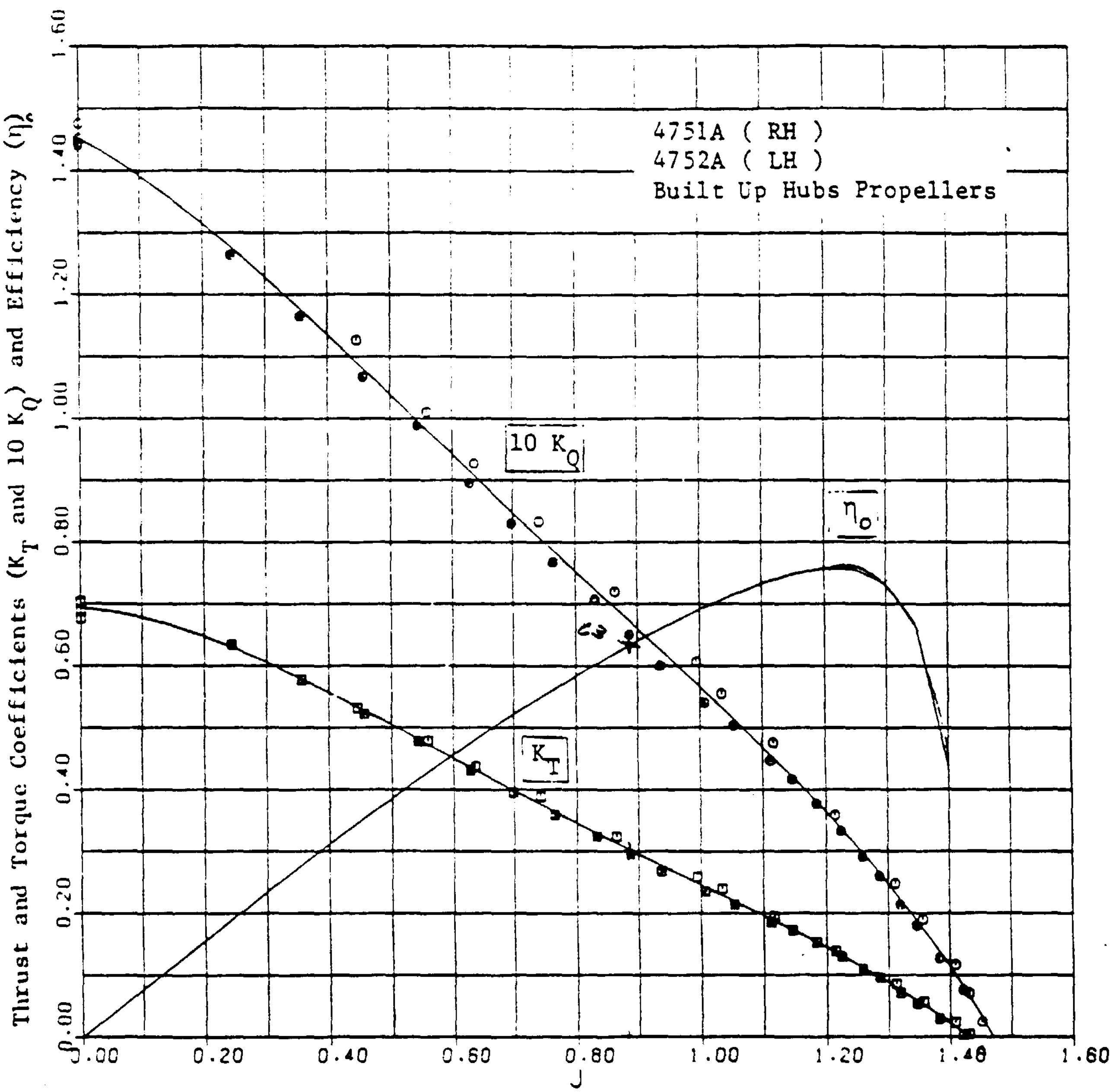


Figure A-11.2 - Open Water Curves for Propellers 4751A and 4752A

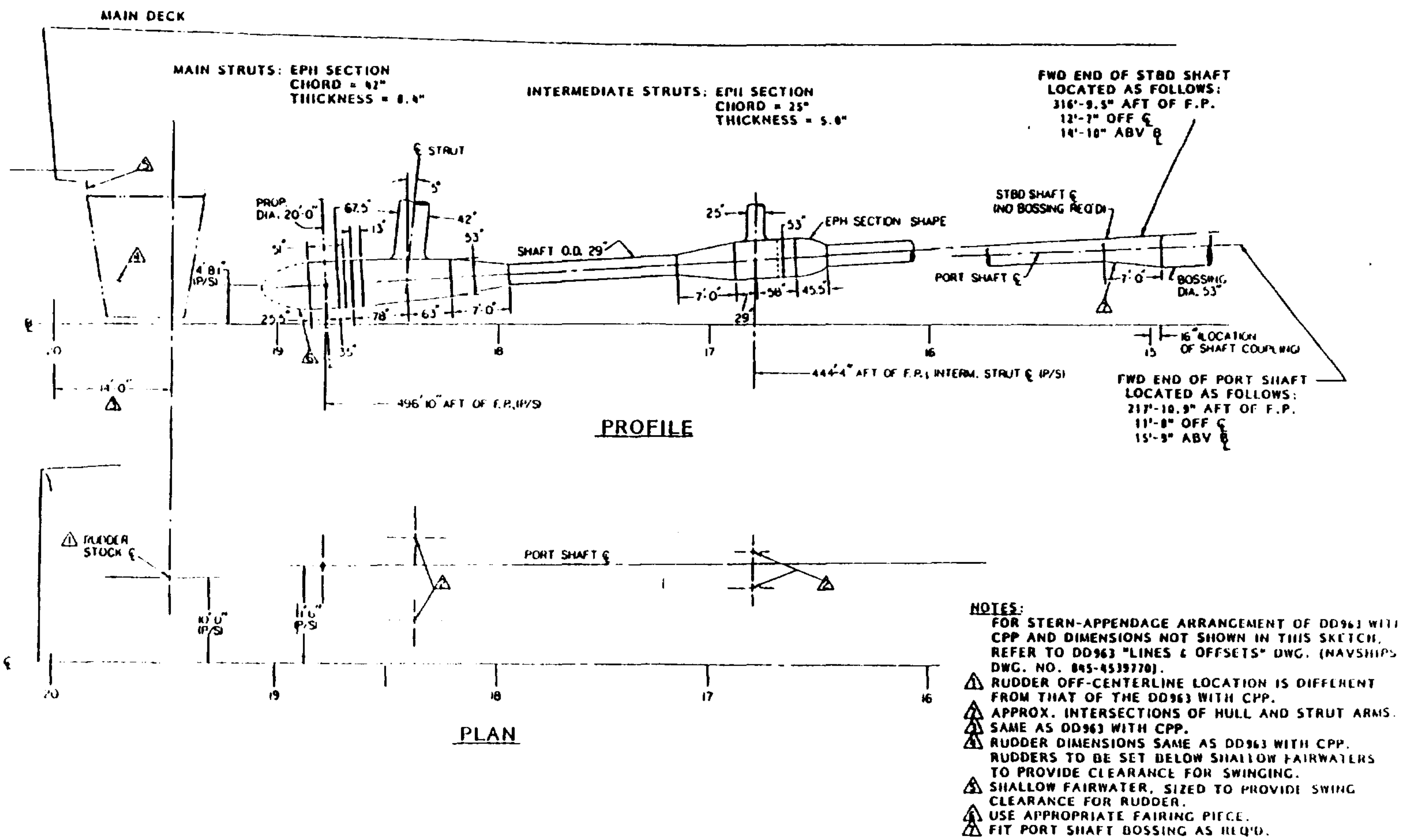
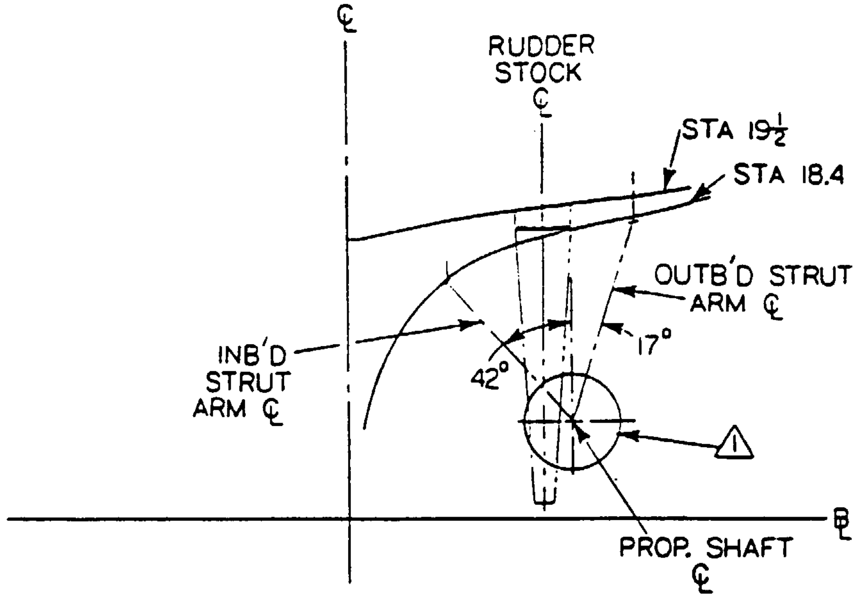
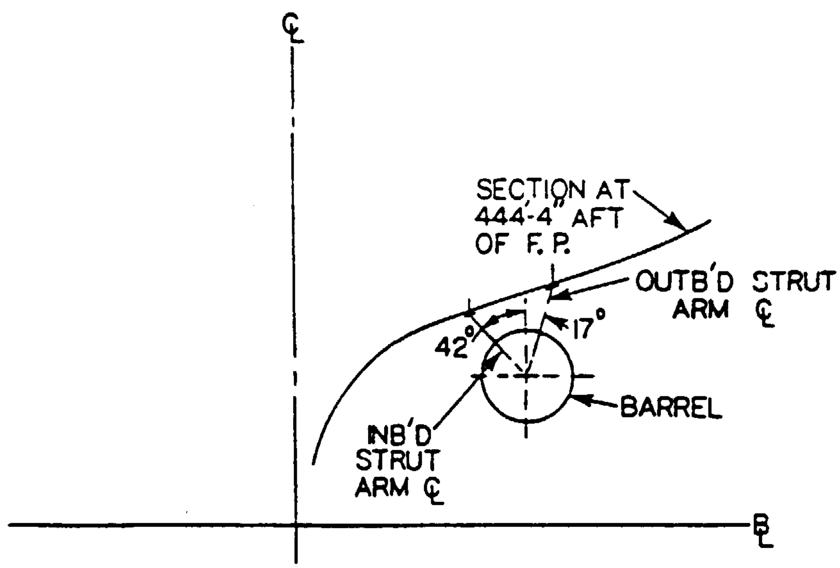


Figure A-11.3 - Stern Appendages of the Large Diameter Low Tip Clearance Controllable-Pitch Propeller Configuration - Profile and Plan Views, from Tomassoni and Slager (1980)



SECTION IN WAY OF MAIN STRUTS & RUDDERS

NOTES:
MAIN & INTERMEDIATE STRUTS ARE IDENTICAL P&S EXCEPT AS REQ'D TO ACCOMMODATE DIFFERENCES IN SHAFT LOCATIONS.
⚠1 BARREL SECTION AT INTERSECTION OF SHAFT ℄ & STRUT ℄.



SECTION IN WAY OF INTERMEDIATE STRUTS

Figure A-11.4 - Stern Appendages of the Large Diameter Low Tip Clearance Controllable-Pitch Propeller Configuration - Sectional Views, from Tomassoni and Slager (1980)

TWIN SHAFTLINE LARGE DIAMETER LOW TIP CLEARANCE CONTROLLABLE-PITCH PROPELLERS

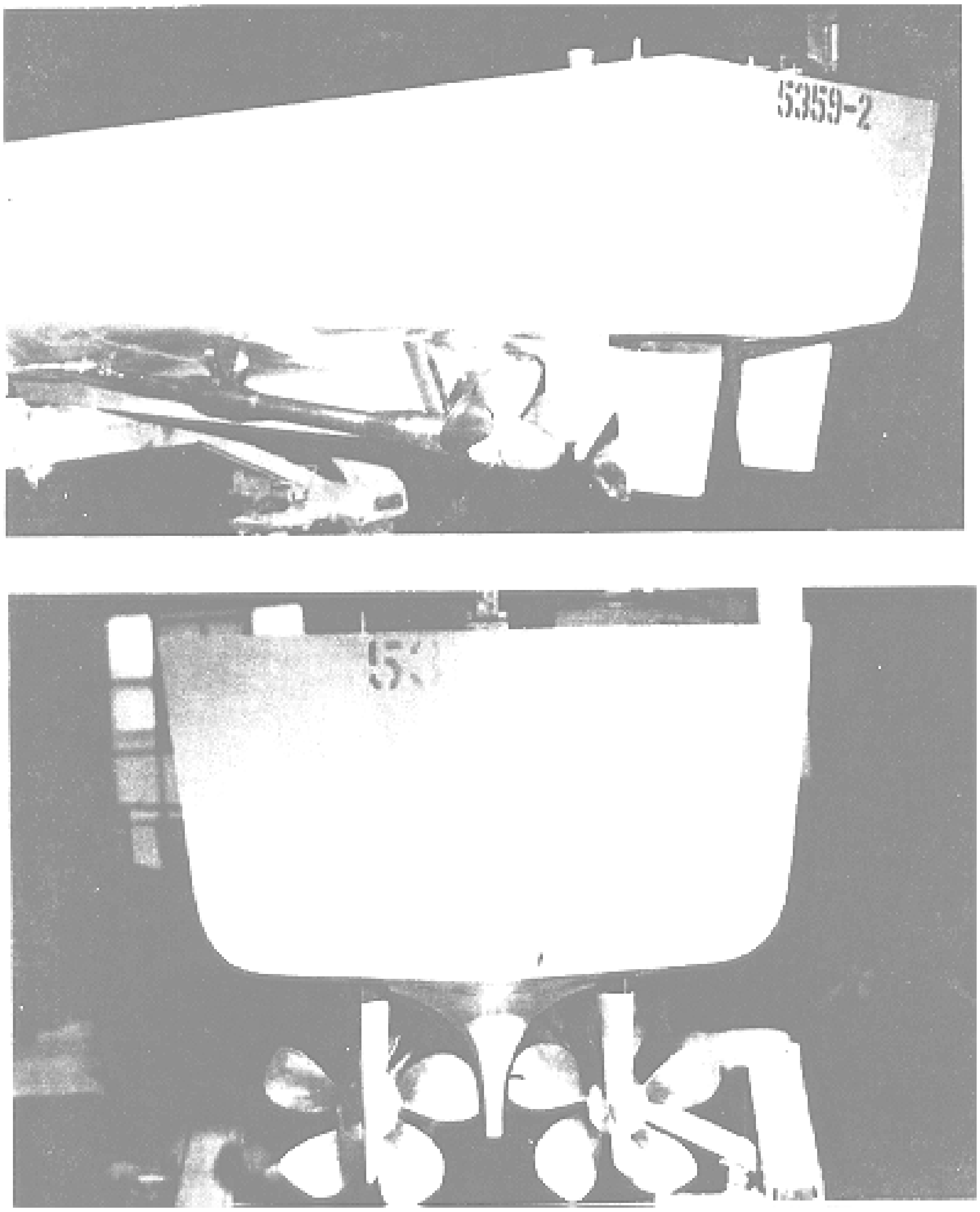


Figure A-11.5 - Photographs of Stern of Large Diameter Low Tip Clearance Controllable-Pitch Propeller Configuration (Model 5359-2A) - Stern Quartering and Stern Views

Afterbody - Modified DD-963 afterbody (see Figure A-12.4) - Model 5359-5

Rudders - Twin; same dimensions as on DD-963 athwartships and vertical location different from DD-963, to suit propeller location. (see Figure A-12.5)

Propeller Shafts

Shaft diameter inside main strut not specified.
(See shafting arrangement data, Figures A-12.5 and A-12.6.)

O.D. of outer shafts, forward of main strut (inches)	37.0

Main Strut Arms

Chord	(inches)	60.0
Thickness	(inches)	11.0

Skeg

Extends aft to about Station 16.
Incorporates 8.0' diameter "nacelle" to house shaft coupling.

Propellers

Type	F.P., Contrarotating (1 set)
Number of blades, fwd/aft	5/4
D_p fwd/D_p aft (ft)	20.7/19.3
P/D $_{.7R}$ fwd/P/D $_{.7R}$ aft	1.39/1.78
E.A.R. fwd/E.A.R. aft	0.45/0.45
Weight, fwd/Weight, aft (lbs. approx.)	40000/33000
RPM (approximately) at 20 knots	82.2
RPM (approximately) (design full power)	143.0
Model propeller number (FWD/AFT)	4859/4784

Figure A-12.1 - Afterbody, Appendage, and Propulsor Characteristics for the Single Shaftline Contrarotating Propeller Configuration, from Tomassoni and Slager (1980)

SINGLE SHAFTLINE CONTRAROTATING PROPELLERS

SHIP AND MODEL DATA

FOR

MODEL 5359-5

APPENDAGES : Bow Sonar Dome and Centerline Skeg

DIMENSIONS			L W L COEFFICIENTS	
	SHIP	MODEL	C_B 0.482	C_{WF} 0.56
LENGTH (LWL)	530.2	21.358	C_P 0.576	C_{WA} 0.91
LENGTH (LBP)	530.2	21.358	C_X 0.836	L_E/L 0.55
BEAM (B_X)	55.0	2.216	C_W 0.736	L_X/L
DRAFT (H)	19.5	0.786	C_{PF} 0.55	L_R/L 0.45
DISPL. IN TONS (.W.)	7820 sw	0.497fw	C_{PA} 0.63	L/B 9.64
WETTED SURF. SQ. FT.	34640	56.214	C_{PE} 0.58	B_X/H 2.82
DESIGN V IN KTS.	32	6.42	C_{PR} 0.57	$\Delta/(.01L)^3$ 51.01
LCB_{LWL} • AFT OF F.P.			C_{PV} 0.66	$S/\sqrt{\Delta L}$ 17.26
LCB_{LBP} • AFT OF F.P.			C_{PVA} 0.57	f
W.L. ENTRANCE HALF ANGLE •			C_{PVF} 0.80	f

WETTED SURFACE OF TWO BILGE KEELS - 1497 ft^2

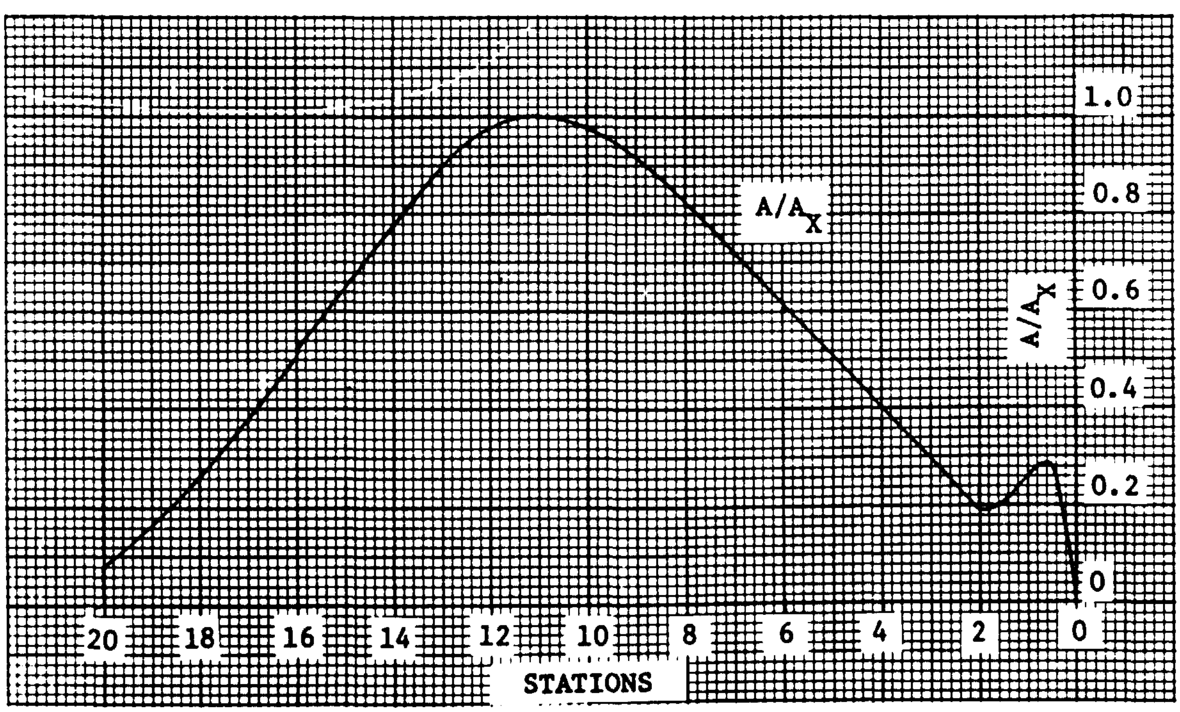
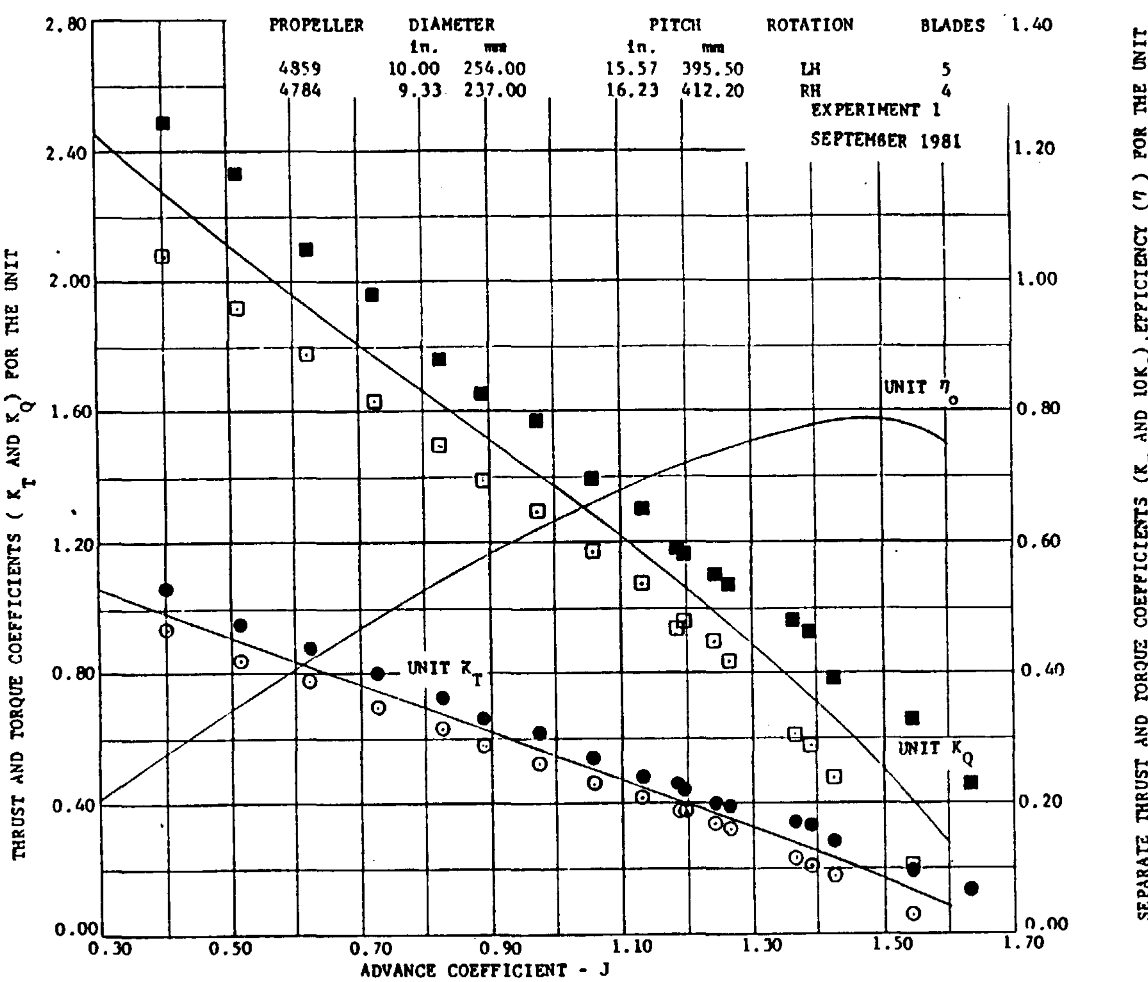


Figure A-12.2 - Ship and Model Data for the Single Shaftline Contrarotating Propeller Configuration Represented by Model 5359-5

SINGLE SHAFTLINE CONTRAROTATING PROPELLERS



CONTRAROTATING OPEN WATER CHARECTERISTICS OF PROPELLERS 4859 AND 4784

Figure A-12.3 - Open Water Curves for Contrarotating Propellers 4859 and 4784

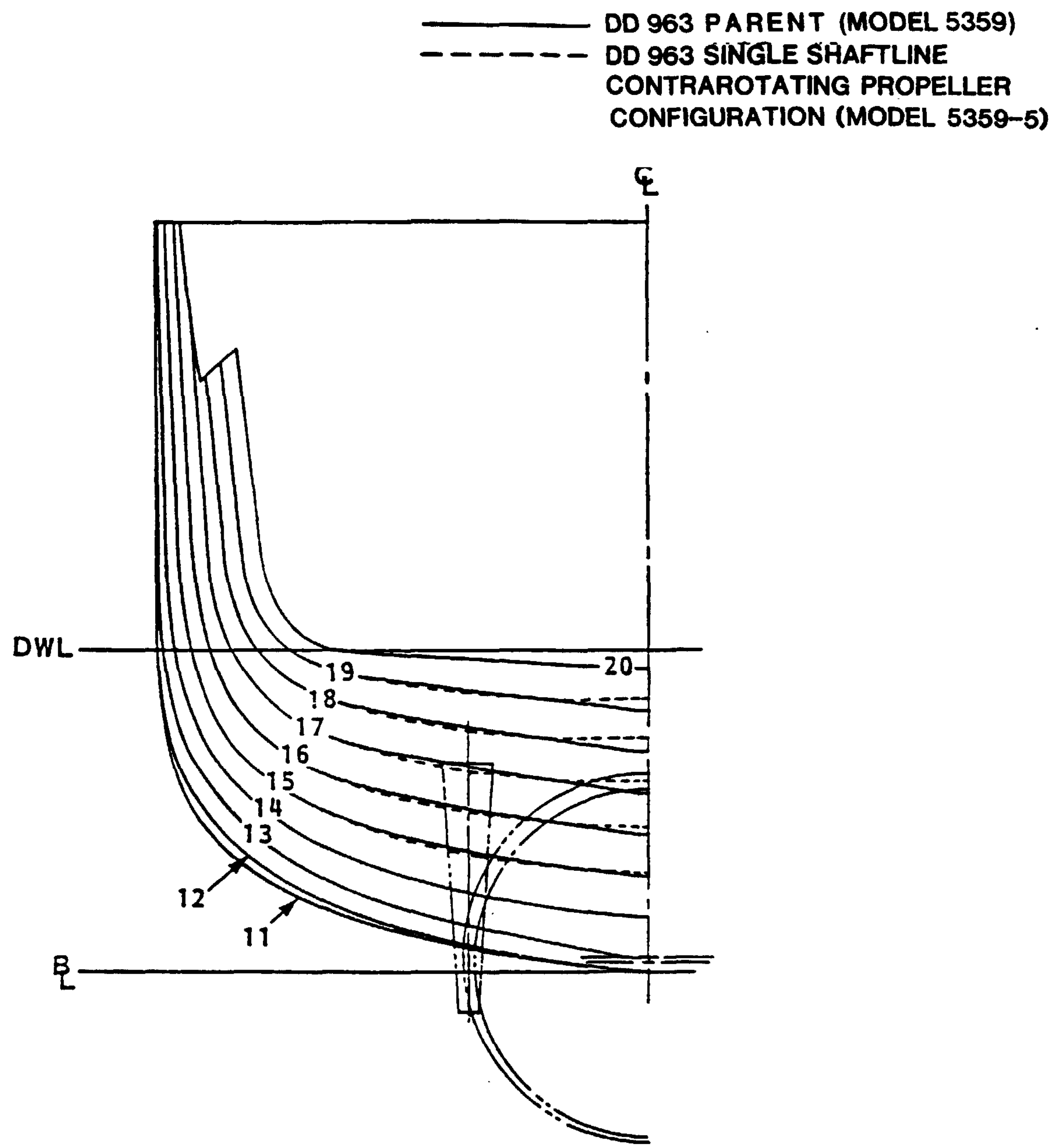


Figure A-12.4 - Comparision of Afterbody Sections of the Single Shaftline Contrarotating Propeller Configuration with Those of the Parent DD-963 Configuration, from Tomassoni and Slager (1980)

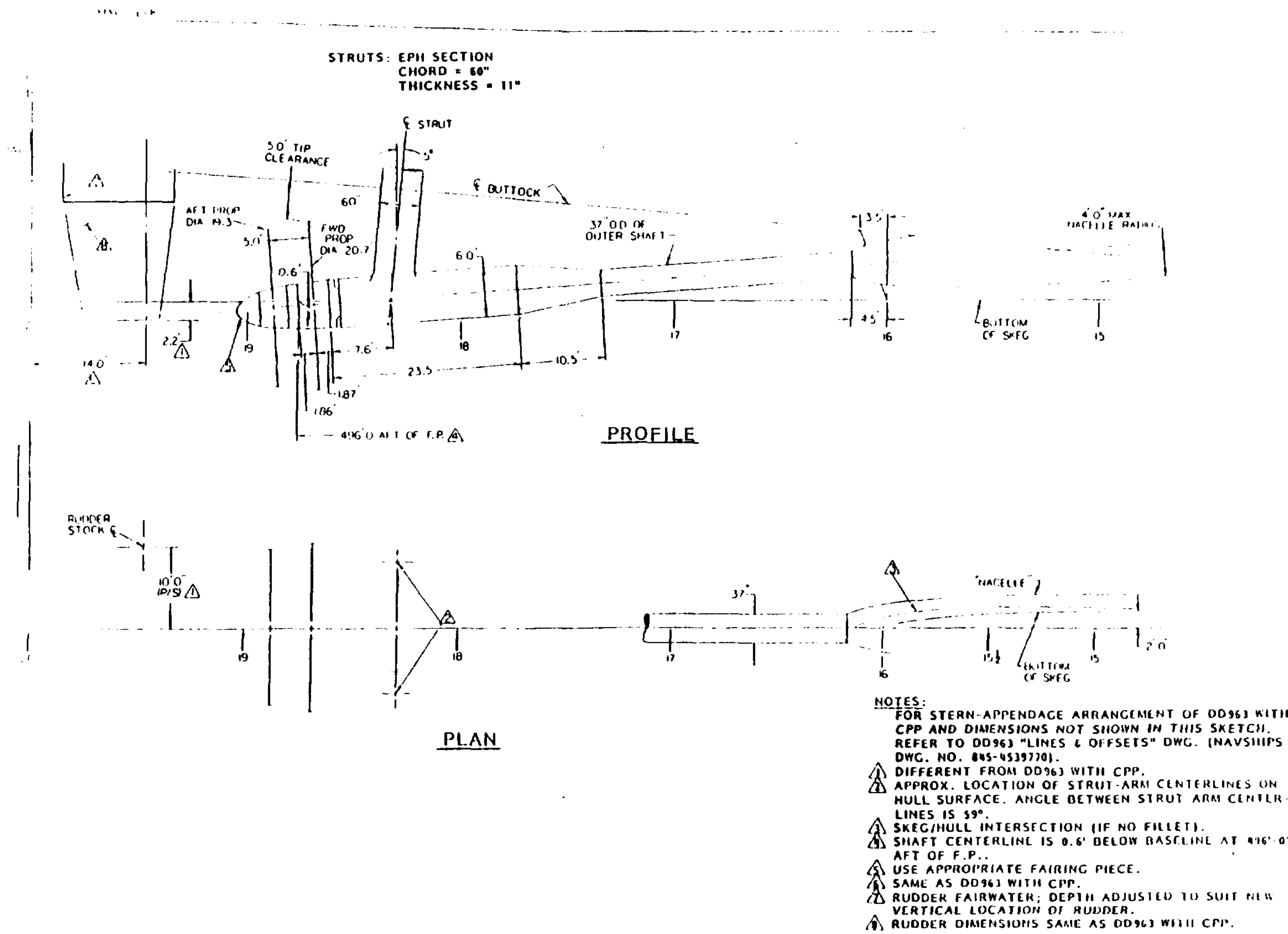


Figure A-12.5 - Stern Appendages of Single Shaftline Contrarotating Propeller Configuration - Profile and Plan Views, from Tomassoni and Slager (1980)

SINGLE SHAFTLINE CONTRAROTATING PROPELLERS

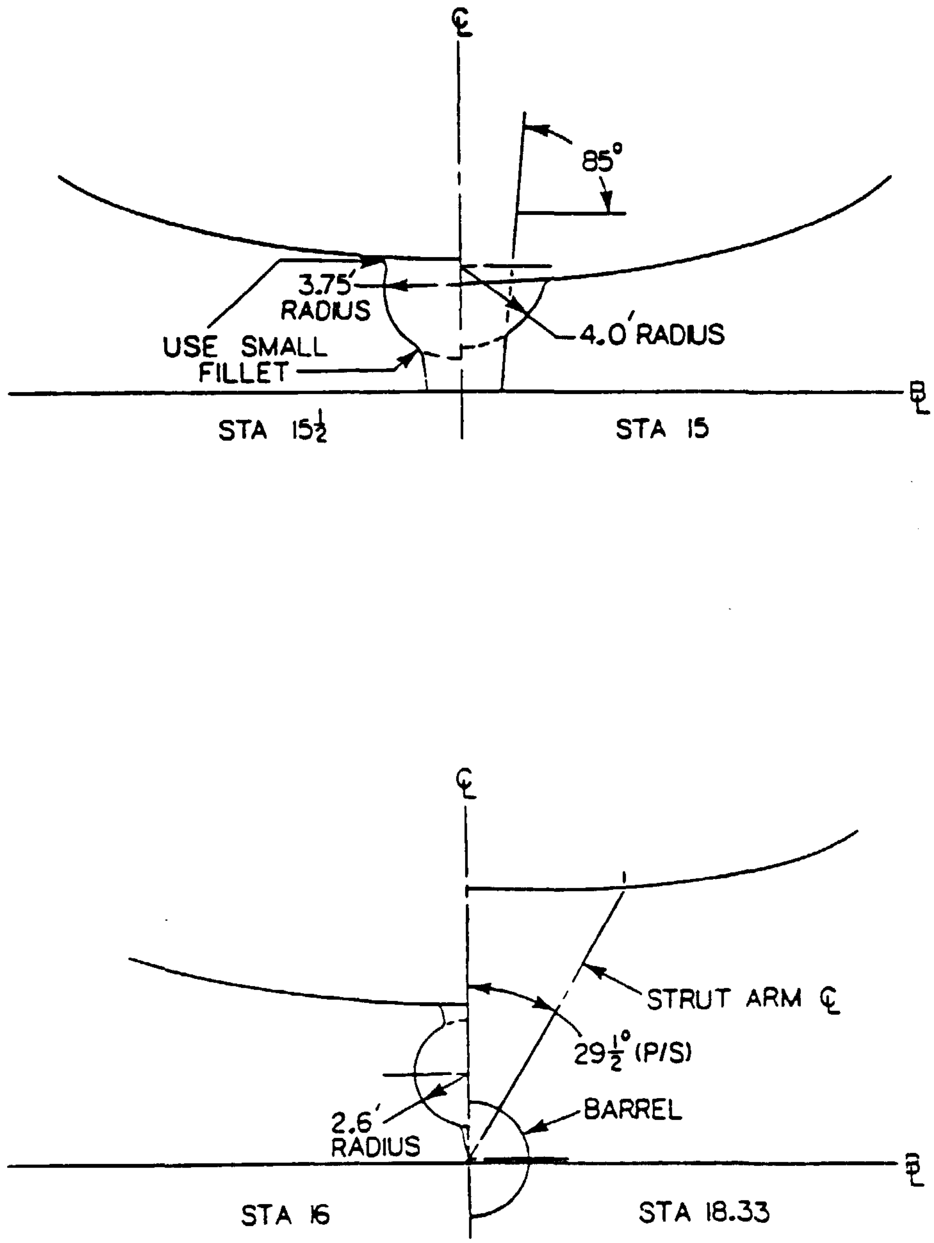


Figure A-12.6 - Stern Appendages of Single Shaftline Contrarotating Propeller Configuration - Section Views, from Tomassoni and Slager (1980)

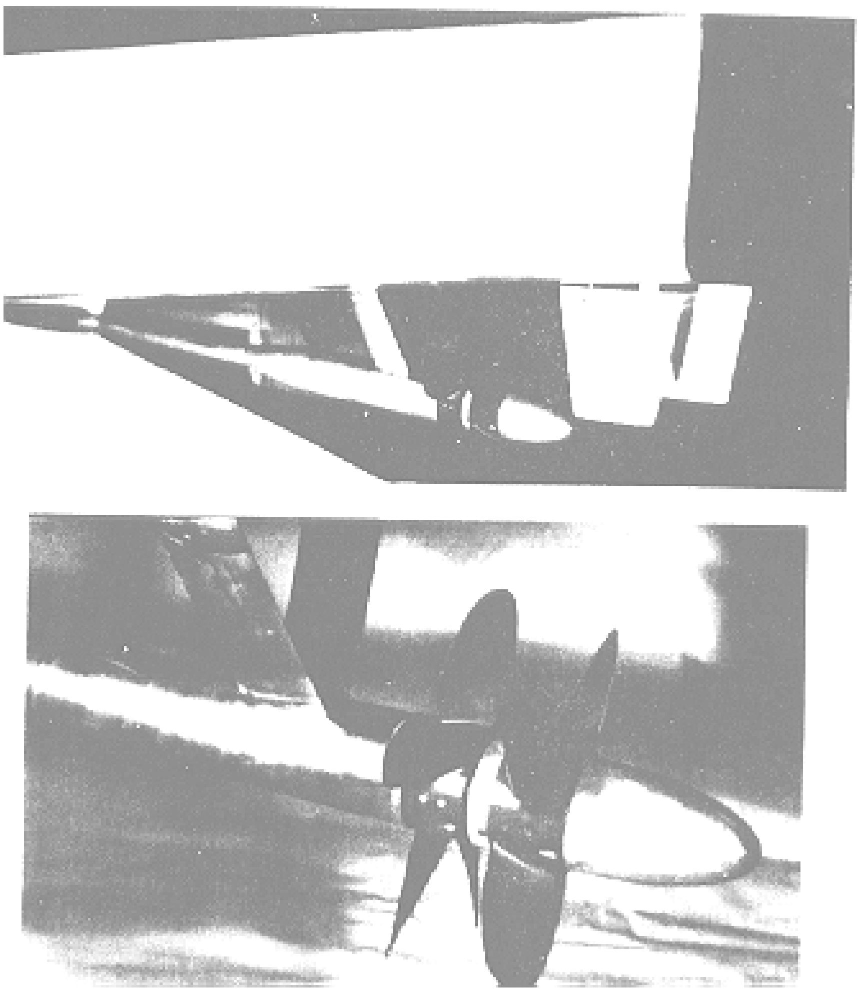


Figure A-12.7 - Photographs of Single Shaftline Contrarotating Propeller Configuration (Model 5359-5) - Profile Views

Afterbody - Modified DD-963 afterbody (see Figure A-12.4) - Model 5359-5A

Rudders - Twin; same dimensions as on DD-963 athwartships and vertical location different from DD-963, to suit propeller location. (see Figure A-13.3)

Propeller Shaft

Number	1
O.D./I.D. Shaft in way of main strut bearing (inches)	35.88/23.88
O.D./I.D. of exposed shaft, forward of main strut (inches)	33.50/22.33

Main Strut Arms

Chord (inches)	54.0
Thickness (inches)	10.0

Skeg

Extends aft to about Station 16.5.
Incorporates 6.6' diameter "nacelle" to house shaft coupling.

Propellers

Type	F.P., Tandem (1 set)
Number of blades, fwd/aft	5/5
D_p fwd/D_p aft (ft)	20.7/19.3
P/D $_{.7R}$ fwd/P/D $_{.7R}$ aft	1.37/1.72
E.A.R. fwd/E.A.R. aft	0.45/0.45
Weight, fwd/Weight, aft (lbs, approx.)	40000/33000
RPM (approximately) at 20 knots	82.2
RPM (approximately) (design full power)	143.0
Model propeller number	4781; 4782

Figure A-13.1 - Afterbody, Appendage, and Propulsor Characteristics for the Single Shaftline Tandem Propeller Configuration, from Tomassoni and Slager (1980)

SINGLE SHAFTLINE TANDEM PROPELLERS

Propeller Number	Diameter		Pitch	
	Inches	mm	Inches	mm
4781	9.984	253.59	13.63	346.20
4782	9.324	236.83	16.05	407.67

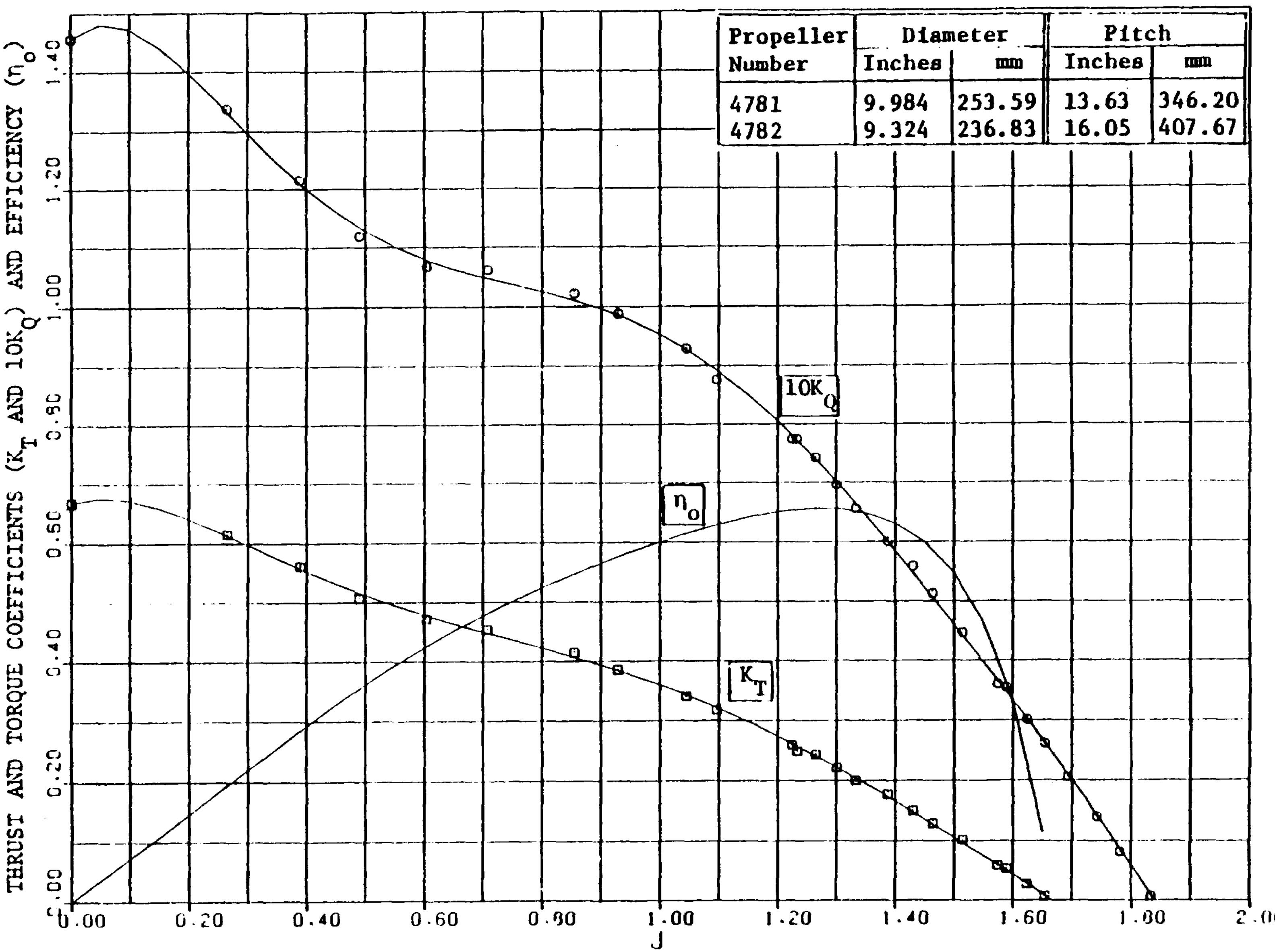


Figure A-13.2 - Open Water Curves for Tandem Propellers 4781 and 4782

SINGLE SHAFTLINE TANDEM PROPELLERS

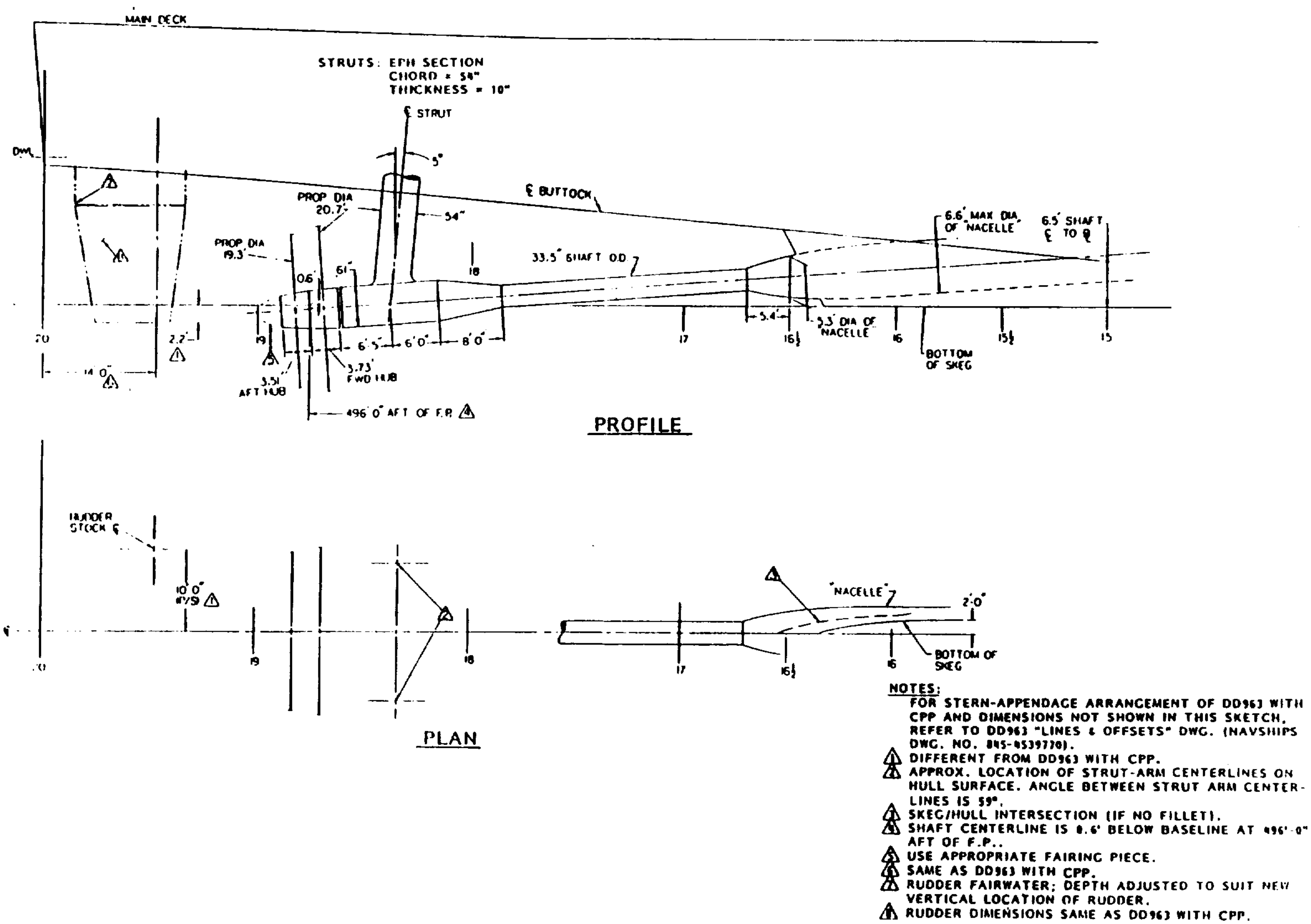


Figure A-13.3 - Stern Appendages of Single Shaftline Tandem Propeller Configuration - Profile and Plan Views, from Tomassoni and Slager (1980)

SINGLE SHAFTLINE TANDEM PROPELLERS

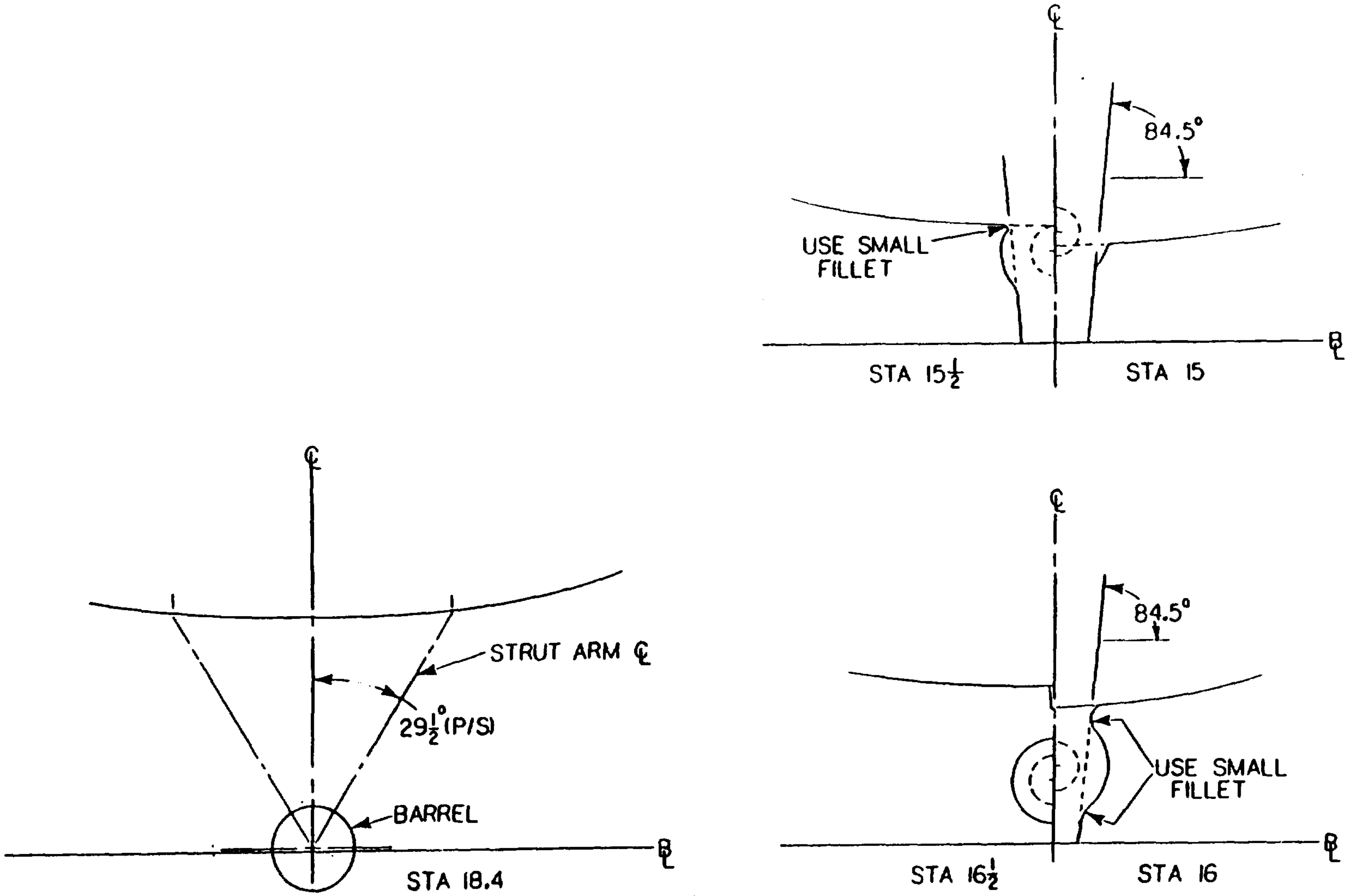
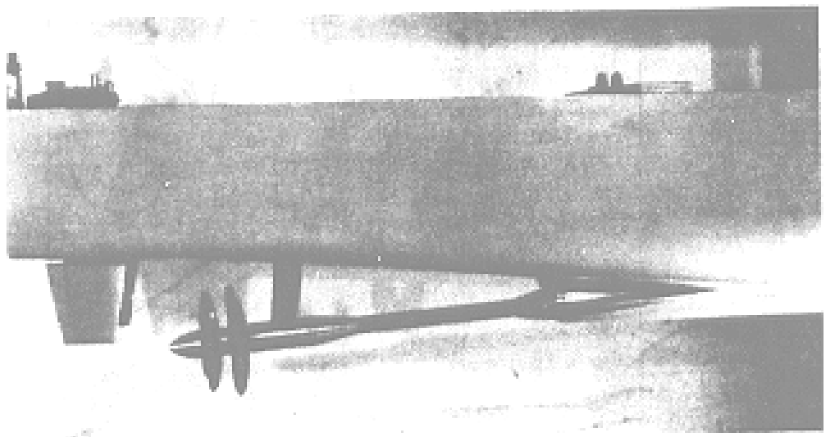


Figure A-13.4 - Stern Appendages of Single Shaftline Tandem Propeller Configuration - Sectional Views, from Tomassoni and Slager (1980)

SINGLE SHAFTLINE TANDEM PROPELLERS



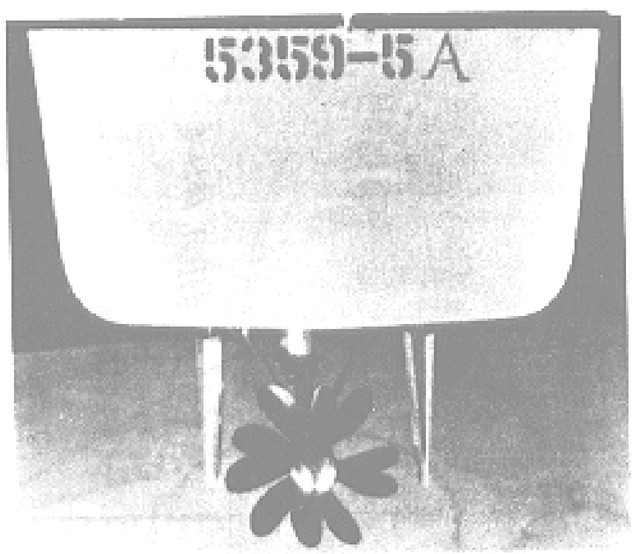


Figure A-13.5 - Photographs of Single Shaftline Tandem Propeller Configuration (Model 5359-5A) - Profile and Stern Views

APPENDIX B

RESULTS OF MODEL EXPERIMENTS TO CHARACTERIZE THE RESISTANCE AND PROPULSION PERFORMANCE OF A DESTROYER WITH THIRTEEN PROPULSION CONFIGURATIONS

CONTENTS - APPENDIX B

RESULTS OF MODEL EXPERIMENTS TO CHARACTERIZE THE RESISTANCE AND PROPULSION PERFORMANCE OF A DESTROYER WITH THIRTEEN PROPULSION CONFIGURATIONS

INTRODUCTION

This appendix comprises a presentation of the experimental data for all of the propulsor configurations covered in this report, and whose geometries are described in detail in Appendix A. The results in this appendix were obtained with what are called "stock" propulsors with the execption of the results for the parent DD-963 hull.

Stock propulsors are propellers that are either selected from an available library of propellers or designed to estimates of power, wake and thrust deduction. One then conducts a "stock" propulsion test, obtains more accurate measurements of the powering related factors and then either estimates "design" propulsor performance or actually designs, builds, and tests the model again with "design" propulsors.

For the purposes of the evaluations considered in this report, all of the stock propulsors were carefully designed around estimates of what was felt to be reasonable propulsion factors. These designs were then constructed and used for the experiments reported in this appendix. This procedure was followed because of the importance of the overall comparative results of the numerous configurations evaluated, and represents a special approach not usually taken. It is also noteworthy that, subjectively at least, this special approach enhances the general quality of the predicted "design" propulsor results presented in Appendix C.

Table B-1 presents a summary of the hull-propulsor configurations tested, along with the appropriate model and stock propeller identification information. The order in which the configurations are listed is consistent with the ordering utilized throughout the report; that is, the baseline configuration is followed by the other configurations in descending order of performance.

In all experiments the model was ballasted to a displacement of 7945 tonne (7820 ton), even keel. Model speeds of 2.0 to 6.4 knots, corresponding to ship speeds of 10 to 32 knots, were run in both resistance and propulsion experiments. A trip wire was fitted to the bow of the model at 5.0 percent of the load waterline length aft of the forward perpendicular on all configurations. In addition, sand roughness was applied to the forward portion of the sonar dome for all experiments. These turbulent stimulators were used to assure turbulent flow over the model for all speed conditions, including the very low model speeds corresponding to 10-16 knots full scale.

TABLE B-1 - SUMMARY OF HULL AND PROPELLER MODEL NUMBERS

Model Number	Propulsion Arrangement	Stock Propellers Used
5359	Twin Shafts and Struts - Controllable-Pitch	4660, 4661
5359-1C	Twin Pods - Contrarotating	4768, 4769, 4770, 4771 - First Set 4768, 4839, 4770, 4838 - Second Set
5359-0A1	Bearing-in-Rudder Post - Fixed-Pitch	4274, 4275 - First Set 4864, 4865 - Second Set
5359-1B	Twin Shafts and Struts - Contrarotating	4768, 4769, 4770, 4771 - First Set 4768, 4839, 4770, 4838 - Second Set
5359-1	Twin Shafts and Struts - Fixed-Pitch	4274, 4275 - First Set 4864, 4865 - Second Set
5359-0A, -0B, -0C	Bearing-in-Rudder Post - Controllable-Pitch	4660A, 4661A - Degraded Performance
5359-2	Twin Large Diameter Low Tip Clearance - Fixed-Pitch	4751, 4752
5359-1A	Twin Tandem	4777, 4778, 4779, 4780
5359	Twin Shafts and Struts - Controllable-Pitch Propellers with Revised Fairwaters	4868, 4869 - New Set of Design Propellers
5359-3	Overlapping Fixed-Pitch	4751, 4752
5359-2A	Twin Large Diameter Low Tip Clearance - Controllable-Pitch	4751A, 4752A - Built Up Hubs
5359-5	Single Shaftline - Contrarotating	4783, 4784 - First Set 4859, 4784 - Second Set
5359-5A	Single Shaftline - Tandem	4781, 4782

Resistance experiments were conducted on the parent model with and without bilge keels to determine the incremental resistance due to the bilge keels. The purpose of this experiment was to avoid the necessity of conducting lines-of-flow tests on and fitting bilge keels to subsequent variations of Model 5359. All propulsion experiments were conducted without bilge keels, but with the resistance of the bilge keels simulated. The resistance of the original bilge keels has been added to that of each new hull variation, and simulated during the propulsion experiments.

Model self-propulsion experiments were run at the ship-propulsion point for each speed. The ship propulsion point is reached by under-propelling the model an amount corresponding to the difference between ship and model frictional resistance calculated according to the 1957 I.T.T.C. Ship-Model Correlation Line using a correlation allowance (C_A) of 0.0005. The predictions of full-scale effective and delivered power in this appendix were made using the 1957 I.T.T.C. Correlation Line and a correlation allowance of 0.0005.

As discussed in detail in Appendix A, the DD-963 was built with shafts and struts which are smaller than those which would result from application of today's NAVSEA design standards. In order to account for this factor it was estimated that the difference would amount to an addition of 1.5 percent to the resistance; this, in fact, has been added to all parent DD-963 results in order to obtain what shall be consistently called the baseline DD-963 results.

The accuracies normally expected of model tests for surface ships conducted at DTNSRDC, for model speeds above two knots (for this ship, 10 knots, full scale) are ± 1.5 percent for effective power and ± 2.5 percent for delivered power measurements.

The first set of experiments with the new fiberglass Model 5359 were performed with the design controllable-pitch propellers. The results were compared with the data from experiments with Model 5265-1B and the same propellers, Lin and Murray (1975). Table B-2 compares the effective and delivered powers, and hull-propulsor interaction coefficients obtained with these two models. The table shows that at 20 knots the predicted effective powers agree within 1.1 percent. Delivered power predictions agree within 2.2 percent, and the hull-propulsor interaction coefficients agree within ± 0.005 in all cases. The agreement was better for the 32-knot condition, where the dynamometer accuracy is even better than at the lower speeds.

Table B-2 - COMPARISON OF POWERING PREDICTIONS FOR DD-963 FROM EXPERIMENTS WITH MODEL 5265-1B AND MODEL 5359, BOTH FITTED WITH CONTROLLABLE-PITCH PROPELLERS 4660 AND 4661

	Styrofoam Model Lin & Murray (1975)		Fiberglass Model Reed & Wilson (1980a)	
Model Number	5265-1B		5359	
Propeller Numbers	4660 & 4661		4660 & 4661	
Test Number	22		5	
Δ_s	7800 tons		7820 tons	
Wetted Surface	35040 ft^2		35780 ft^2	
C_A	0.0005		0.0005	
V_s	20 kts	32 kts	20kts	32 kts
P_E	9400	49190	9290	49220
P_D	13660	71920	13360	71330
rpm	97.2	164.6	96.9	164.0
η_D	0.690	0.685	0.695	0.690
η_O	0.750	0.750	0.750	0.750
η_H	0.965	0.945	0.965	0.950
η_R	0.950	0.965	0.955	0.970
1-t	0.960	0.960	0.960	0.960
$1-w_T$	0.995	1.015	0.990	1.010

In order to provide appropriate performance predictions for the various propulsion configurations, several sets of stock propellers were constructed (the propeller numbers used with the various concepts are given in Table B-1). Although the stock propellers were built to proper pitch and expanded area ratios, no consideration was given to detailed geometry such as camber and skew. In the interest of economy, these stock propellers were of simple construction with leading and trailing edges only roughly faired for experiments. Open water characterization was obtained for each propeller and in the case of tandem or contrarotating propellers, each set of propellers were tested as a unit and separately.

The remainder of this appendix presents the experimental results for each configuration tested. In each case the model and configuration details are discussed briefly along with the results, and in some instances, for reasons which will be explained, more than one set of experiments are discussed. Also, specific comparisons will be made of the performance of each configuration relative to the baseline configuration at both 20 and 32 knots. As necessary, discussions of confidence level in the results or any other issues affecting the practical exploitation of the configuration will be presented.

TWIN SHAFTLINE CONTROLLABLE-PITCH PROPELLERS
Model 5359, Propellers 4660 and 4661

Resistance and propulsion experiments were performed on Model 5359, with the design appendage suit taken from Model 5265-1B. Model propellers 4660 and 4661 represent the design controllable-pitch propellers for the DD-963 Class. The propellers were in good condition during these repeat experiments. The results of these experiments are reported in Reed and Wilson (1980a).

These powering results, with the original appendage suit, are presented in Table B-3, which will be referred to as the parent hull form results. As reported in Appendix A, the shafts and struts on Model 5359 are smaller than would result if they were designed today using standard Navy design practice. Since the shafts and struts for the other configurations have been designed using NAVSEA design guidelines, new, larger shafts and struts have been designed for the twin shafts and struts controllable-pitch propeller configuration. While the effects of these new, larger appendages have never been evaluated experimentally, it is estimated that their primary effect would be to increase the effective power by 1.5 percent. Therefore, a second powering table, Table B-4, has been prepared which reflects this increase in resistance. The effective and delivered powers presented in Table B-4 will be referred to as the baseline hull form results.

The results of the parent experiments with Model 5359 agree very well with the original experiments performed on Model 5265-1B, Lin and Murray (1975). The effective power, when these experiments were repeated, agreed within 1.1 and 0.1 percent at 20 and 32 knots, respectively; the delivered power agreed within 2.8 and 0.8 percent; the hull-propulsor interaction coefficients varied, but all coefficients agreed within ± 0.005.

It is noteworthy that, with two exceptions (which will be noted), the baseline results are used throughout this appendix for comparative purposes.

TABLE B-3 - POWERING PREDICTIONS FOR THE PARENT DD-963 HULL WITH TWIN CONTROLLABLE-PITCH PROPELLERS BASED ON EXPERIMENTS WITH MODEL 5359, FROM REED AND WILSON (1980a)

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1110	830	1600	1190	48.5
12	6.17	2010	1500	2900	2160	58.3
14	7.20	3250	2420	4670	3480	68.0
16	8.23	4830	3600	6950	5180	77.7
18	9.26	6840	5100	9840	7340	87.3
20	10.29	9290	6920	13360	9960	96.9
21	10.80	10660	7950	15340	11440	101.5
22	11.32	12160	9070	17500	13050	106.0
23	11.83	13780	10280	19830	14790	110.7
24	12.35	15550	11590	22370	16680	115.2
25	12.86	17480	13040	25160	18760	119.9
26	13.38	19690	14680	28330	21130	124.9
27	13.89	22540	16810	32430	24180	130.1
28	14.40	26240	19570	37810	28200	135.9
29	14.92	30870	23020	44490	33170	142.5
30	15.43	36280	27060	52350	39040	149.7
31	15.95	42490	31680	61400	45780	156.9
32	16.46	49220	36700	71330	53190	164.0
33	16.98	56530	42150	82160	61270	171.1
34	17.49	64090	47790	93560	69770	177.7

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-T	1-WT	1-WQ	JT
10	0.695	0.750	0.955	0.970	0.960	1.005	0.995	1.235
12	0.695	0.750	0.965	0.960	0.960	0.995	0.980	1.220
14	0.695	0.750	0.965	0.955	0.960	0.990	0.975	1.215
16	0.695	0.750	0.965	0.955	0.960	0.995	0.975	1.220
18	0.695	0.750	0.970	0.955	0.960	0.990	0.975	1.220
20	0.695	0.750	0.965	0.955	0.960	0.990	0.975	1.220
21	0.695	0.750	0.970	0.955	0.960	0.990	0.975	1.220
22	0.695	0.750	0.970	0.950	0.960	0.990	0.970	1.220
23	0.695	0.750	0.970	0.950	0.960	0.990	0.970	1.225
24	0.695	0.750	0.975	0.950	0.960	0.985	0.970	1.225
25	0.695	0.750	0.975	0.950	0.960	0.985	0.970	1.225
26	0.695	0.750	0.970	0.950	0.960	0.990	0.975	1.225
27	0.695	0.750	0.970	0.950	0.960	0.990	0.970	1.220
28	0.695	0.750	0.970	0.950	0.960	0.990	0.970	1.215
29	0.695	0.750	0.970	0.955	0.960	0.990	0.975	1.200
30	0.695	0.750	0.960	0.960	0.960	1.000	0.985	1.190
31	0.690	0.750	0.955	0.965	0.960	1.005	0.990	1.180
32	0.690	0.750	0.950	0.970	0.960	1.010	0.995	1.170
33	0.690	0.745	0.950	0.970	0.960	1.015	1.000	1.165
34	0.685	0.745	0.945	0.970	0.960	1.015	1.000	1.155

TABLE B-4 - POWERING PREDICTIONS FOR THE BASELINE DD-963 HULL WITH TWIN CONTROLLABLE-PITCH PROPELLERS

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1130	840	1620	1210	48.7
12	6.17	2040	1520	2940	2190	58.4
14	7.20	3290	2460	4740	3530	68.2
16	8.23	4900	3660	7050	5260	77.9
18	9.26	6940	5180	9990	7450	87.5
20	10.29	9430	7030	13560	10110	97.1
21	10.80	10820	8070	15570	11610	101.7
22	11.32	12350	9210	17760	13240	106.3
23	11.83	13990	10430	20130	15010	111.0
24	12.35	15780	11770	22700	16930	115.5
25	12.86	17750	13230	25530	19040	120.2
26	13.38	19990	14900	28750	21440	125.2
27	13.89	22880	17060	32910	24540	130.4
28	14.40	26640	19860	38370	28610	136.2
29	14.92	31340	23370	45170	33680	142.9
30	15.43	36830	27460	53180	39660	150.1
31	15.95	43120	32160	62360	46500	157.3
32	16.46	49960	37250	72430	54010	164.5
33	16.98	57380	42780	83500	62270	171.6
34	17.49	65050	48510	95040	70870	178.2

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	**JT**
10	0.695	0.750	0.955	0.970	0.960	1.005	0.995	1.230
12	0.695	0.750	0.965	0.960	0.960	0.995	0.980	1.220
14	0.695	0.750	0.970	0.955	0.960	0.990	0.975	1.215
16	0.695	0.750	0.965	0.955	0.960	0.995	0.975	1.215
18	0.695	0.750	0.970	0.955	0.960	0.990	0.975	1.215
20	0.695	0.750	0.970	0.955	0.960	0.990	0.975	1.215
21	0.695	0.750	0.970	0.955	0.960	0.990	0.975	1.220
22	0.695	0.750	0.970	0.950	0.960	0.990	0.970	1.220
23	0.695	0.750	0.970	0.950	0.960	0.990	0.970	1.220
24	0.695	0.750	0.975	0.950	0.960	0.985	0.970	1.220
25	0.695	0.750	0.975	0.950	0.960	0.985	0.970	1.225
26	0.695	0.750	0.970	0.950	0.960	0.990	0.970	1.225
27	0.695	0.750	0.970	0.950	0.960	0.990	0.970	1.220
28	0.695	0.750	0.970	0.950	0.960	0.990	0.970	1.210
29	0.695	0.750	0.970	0.955	0.960	0.990	0.975	1.200
30	0.690	0.750	0.960	0.960	0.960	1.000	0.985	1.190
31	0.690	0.750	0.955	0.965	0.960	1.005	0.990	1.180
32	0.690	0.750	0.950	0.970	0.960	1.010	0.995	1.170
33	0.685	0.745	0.950	0.970	0.960	1.015	1.000	1.160
34	0.685	0.745	0.945	0.970	0.960	1.015	1.000	1.155

TWIN PODS WITH CONTRAROTATING PROPELLERS

Model 5359-1C, Propellers 4768 & 4769 and 4770 & 4771 (First Set)
Propellers 4768 & 4839 and 4770 & 4838 (Second Set)

Resistance and propulsion experiments have been performed on Model 5359-1C, which represents the DD-963 hull form fitted with twin pods. The pods were 15.54 m (51 ft) in length, and 2.13 m (7 ft) in diameter full scale. The experiments were performed using two sets of stock contrarotating propellers. The first set of propellers were specified by Tomassoni and Slager (1980) to have a torque ratio of one at an rpm ratio of one. However, during the propulsion experiments on the twin shaftline contrarotating propeller configuration, these propellers were found to have a torque balance far from that which was expected, and their overall performance was inferior to that which was expected from contrarotating propellers. Therefore, a second set of stock propellers was developed, Nelka and Cox (1981), by redesigning the after propellers of the first contrarotating set. These new propellers were built and evaluated experimentally. Their performance was found to be much improved over that of the first set of contrarotating propellers. The results for both sets of contrarotating propellers are presented in Lin and Goldberg (1982).

The results of the resistance and propulsion experiments with the second set of contrarotating propellers are presented in Table B-5. These results indicate that the resistance of the twin pods is considerably lower than the resistance of the twin shafts and struts controllable-pitch propeller baseline configuration. In particular, at 20 knots the effective power is 6340 kW (8510 hp), and at 32 knots it is 34300 kW (46000 hp). This compares to 7030 kW and 37250 kW for the baseline at 20 and 32 knots, respectively, and represents a 9.8 percent reduction in effective power at 20 knots, and a 7.9 percent reduction at 32 knots.

Examination of the powering data shows that twin pods with stock contrarotating propellers require 8340 kW (11190 hp) at 20 knots and 45860 kW (61500 hp) at 32 knots. This compares to 10110 kW and 54010 kW for the baseline at 20 and 32 knots, respectively. This represents a 17.5 percent reduction in delivered power at 20 knots, and a 15.1 percent reduction at 32 knots.

The reliability of these experiments is fairly high. There is some possibility of scale effects affecting the resistance of the pods, due to the low Reynolds number of the flow over the pods. However, these effects should be no more significant than those which affect the drag of other appendage configurations. The propulsion experiments on the pods have employed a unique set of in-hub dynamometry driven through a right-angle drive to make both thrust and torque measurements. While there is little experience with the in-hub dynamometry, there have been side-by-side experiments using this system and the traditional solid shaft and hollow shaft transmission dynamometry on the twin shafts and struts contrarotating configuration. These experiments showed excellent correlation between the two dynamometry systems. Therefore, there is no reason to suspect that the model scale measurements with the pods are not reliable and of an accuracy comparable to that obtained using the traditional dynamometry.

TABLE B-5 - POWERING PREDICTIONS FOR THE DD-963 HULL FORM FITTED WITH TWIN PODS AND CONTRAROTATING PROPELLERS BASED ON EXPERIMENTS WITH MODEL 5359-1C, FROM LIN AND GOLDBERG (1982)

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	970	725	1290	960	35.8
12	6.17	1750	1300	2310	1730	43.2
14	7.20	2830	2110	3760	2800	50.5
16	8.23	4250	3170	5640	4200	57.8
18	9.26	6070	4530	8040	6000	64.9
20	10.29	8510	6340	11190	8340	72.2
21	10.80	9880	7370	13010	9700	75.5
22	11.32	11290	8420	14020	11050	78.9
23	11.83	12740	9500	16610	12390	82.3
24	12.35	14280	10650	18680	13930	85.6
25	12.86	16050	11970	20970	15630	89.1
26	13.38	18180	13550	23820	17760	92.7
27	13.89	20890	15580	27430	20450	96.5
28	14.40	24340	18150	31900	23790	100.9
29	14.92	28520	21270	37630	28060	105.5
30	15.43	33500	24980	44220	32980	110.4
31	15.95	39330	29330	52260	38970	115.9
32*	16.46	46000	34300	61500	45860	122.0

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	JT
10	0.755	0.790	0.940	1.015	0.920	0.980	0.985	1.600
12	0.755	0.795	0.940	1.015	0.920	0.980	0.985	1.590
14	0.755	0.795	0.940	1.010	0.920	0.980	0.985	1.585
16	0.755	0.795	0.940	1.010	0.920	0.980	0.985	1.580
18	0.755	0.795	0.940	1.010	0.920	0.980	0.980	1.580
20	0.760	0.795	0.945	1.010	0.920	0.975	0.975	1.575
21	0.760	0.795	0.955	1.000	0.925	0.970	0.970	1.570
22	0.760	0.795	0.955	1.000	0.925	0.970	0.965	1.570
23	0.765	0.795	0.955	1.010	0.920	0.965	0.970	1.570
24	0.765	0.795	0.945	1.015	0.910	0.960	0.965	1.570
25	0.765	0.795	0.945	1.020	0.905	0.960	0.965	1.570
26	0.765	0.795	0.945	1.015	0.905	0.960	0.965	1.570
27	0.760	0.795	0.945	1.010	0.905	0.960	0.960	1.560
28	0.765	0.800	0.945	1.010	0.910	0.960	0.960	1.550
29	0.760	0.800	0.950	1.000	0.910	0.960	0.965	1.540
30	0.755	0.800	0.950	1.000	0.915	0.965	0.965	1.535
31	0.755	0.800	0.940	1.000	0.915	0.975	0.975	1.515
32*	0.750	0.800	0.935	1.000	0.915	0.980	0.980	1.500

*The 32-knot results represent an extrapolation in speed. The experimental data went only to 31 knots due to dynamometry limitations.

TWIN BEARING-IN-RUDDER POST WITH FIXED-PITCH PROPELLERS
Model 5359-OA1, Propellers 4274 and 4275 (First Set)
Propellers 4864 and 4865 (Second Set)

Model 5359-OA1 represents the DD-963 hull form fitted with the bearing-in-rudder post configuration and shafting sized for fixed-pitch propellers. The first set of propellers included the propellers used in the original shafts and struts configuration experiments with the fixed-pitch propellers, Reed and Wilson (1980a). The rudder configuration was a modification of the straight rudder used in the controllable-pitch propeller bearing-in-rudder post configuration. During these first experiments, very little improvement was found with the bearing-in-rudder post over the shafts and struts with the same propellers. It was hypothesized that the lack of performance improvement was caused by the low pitch of these propellers, which resulted in little swirl being generated in the flow. Therefore, a second set of propellers, which would more closely represent the actual propellers which would be used on a modern destroyer, was developed and built. Both these new propellers and the first set were evaluated in a new set of experiments. These repeat experiments showed that the first set of bearing-in-rudder post experiments with propellers 4274 and 4275 was in error, so the results of the first set of experiments have never been published. The results from the second set of experiments are included in Lin and Wilson (in preparation).

The second set of propellers showed the lowest delivered power of the two sets of propellers tested. These results are presented in Table B-6. A comparison of the effective power for this configuration with that of the controllable-pitch propeller baseline configuration shows that this configuration requires 6390 kW (8560 hp) as opposed to 7030 kW for the baseline at 20 knots. At 32 knots, the comparison is 34700 kW (46530 hp) versus 37250 kW for the fixed-pitch bearing-in-rudder post compared to the baseline. This represents a reduction in effective power of 9.1 percent at 20 knots, and 6.8 percent at 32 knots.

A comparison of delivered power shows that the fixed-pitch bearing-in-rudder post requires 9030 kW (12110 hp) at 20 knots and 50280 kW (67430 hp) at 32 knots. This compares to delivered powers of 10110 kW and 54010 kW, and represents a drop in delivered power of 10.7 percent at 20 knots and a reduction of 6.9 percent at 32 knots.

These experiments seem to be without any significant problems. However, there is one point which should be made. That is, although these results represent a significant reduction in delivered power over the baseline configuration at 20 and 32 knots, these results do not represent a reduction in delivered power over that which could be obtained with shafts and struts and fixed-pitch propellers. In fact, at 20 knots, the bearing-in-rudder post with fixed-pitch propellers represents a small increase in delivered power over the shafts and struts configuration with the same propellers. (For further details, the reader is referred to Appendix E of this report.)

TABLE B-6 - POWERING PREDICTIONS FOR THE DD-963 HULL FORM FITTED WITH THE STRAIGHT RUDDER BEARING-IN-RUDDER POST CONFIGURATION AND TWIN FIXED-PITCH PROPELLERS BASED ON EXPERIMENTS WITH MODEL 5359-0A1, FROM LIN AND WILSON (IN PREPARATION)

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1000	750	1420	1060	45.5
12	6.17	1830	1360	2580	1930	55.2
14	7.20	2980	2220	4220	3140	64.7
16	8.23	4490	3350	6350	4740	74.1
18	9.26	6350	4740	8980	6700	83.3
20	10.29	8560	6390	12110	9030	92.2
21	10.80	9820	7330	13900	10360	96.6
22	11.32	11180	8340	15820	11800	101.0
23	11.83	12650	9430	17890	13340	105.4
24	12.35	14250	10630	20150	15030	109.8
25	12.86	16050	11970	22700	16930	114.3
26	13.38	18240	13600	25800	19240	119.1
27	13.89	21030	15690	29750	22190	124.4
28	14.40	24570	18320	34800	25950	130.4
29	14.92	28930	21570	41030	30590	136.9
30	15.43	34140	25460	48770	36370	143.9
31	15.95	40070	29880	57570	42930	151.2
32	16.46	46530	34700	67430	50280	158.8

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	JT
10	0.705	0.755	0.945	0.990	0.895	0.945	0.945	1.240
12	0.705	0.750	0.945	0.995	0.895	0.945	0.945	1.225
14	0.705	0.750	0.945	0.995	0.895	0.945	0.945	1.220
16	0.705	0.750	0.945	0.995	0.895	0.945	0.945	1.215
18	0.705	0.750	0.945	0.995	0.895	0.945	0.945	1.220
20	0.705	0.750	0.945	0.995	0.895	0.945	0.945	1.225
21	0.705	0.750	0.945	0.995	0.895	0.945	0.945	1.225
22	0.705	0.750	0.945	0.995	0.895	0.945	0.945	1.230
23	0.705	0.755	0.945	0.995	0.895	0.945	0.945	1.230
24	0.705	0.755	0.945	0.995	0.895	0.945	0.945	1.235
25	0.705	0.755	0.945	0.995	0.895	0.945	0.945	1.235
26	0.705	0.755	0.945	0.995	0.895	0.945	0.945	1.230
27	0.705	0.750	0.945	0.995	0.895	0.945	0.945	1.225
28	0.705	0.750	0.945	1.000	0.895	0.950	0.945	1.215
29	0.705	0.745	0.945	1.005	0.895	0.950	0.950	1.200
30	0.700	0.740	0.940	1.005	0.895	0.950	0.955	1.180
31	0.695	0.735	0.935	1.010	0.895	0.955	0.960	1.170
32	0.690	0.735	0.925	1.015	0.895	0.965	0.970	1.160

TWIN SHAFTLINE CONTRAROTATING PROPELLERS
Model 5359-1B, Propellers 4768 & 4769 and 4770 & 4771 (First Set)
Propellers 4768 & 4839 and 4770 & 4838 (Second Set)

These experiments were performed on a model of the DD-963 hull form with twin shafts and struts appendages sized for contrarotating propellers. The stock contrarotating propellers were designed to have a torque ratio of 1.0 at an rpm ratio of one. The first propellers did not achieve this major design goal, Lin (1980d), and they showed very poor performance. Their propulsion efficiencies increased by only about 4.0 percent over those of the baseline with the design controllable-pitch propellers. Because of this poor performance, a second set of stock propellers was designed, Nelka and Cox (1981). These new propellers were implemented by building new aft propellers for use with the forward propellers from the existing sets of stock contrarotating propellers. The new sets of contrarotating propellers were evaluated on the same model as the first sets, and significant performance improvements were achieved, including propulsion efficiencies which were between 10.0 and 11.0 percent above those of the baseline at 20 knots. These results are presented in Lin and Wilson (1983b).

The resistance and powering performance of this hull fitted with the second set of stock contrarotating propellers is presented in Table B-7. A comparison of the resistance of this configuration to that of the controllable-pitch baseline shows that the effective power is 6770 kW (9080 hp) versus 7030 kW at 20 knots and 36020 kW (48300 hp) versus 37250 kW at 32 knots. This represents a reduction in effective power with the twin shaftline contrarotating propeller configuration of 3.7 percent relative to the baseline at 20 knots and a reduction of 3.3 percent at 32 knots.

The delivered powers of the twin shaftline contrarotating configuration are 8780 kW (11780 hp) and 47120 kW (63190 hp) at 20 and 32 knots, respectively. The comparable baseline delivered powers are 10110 kW and 54010 kW, respectively. Thus, the twin shaftline contrarotating configuration provided a 13.2 percent reduction in delivered power at 20 knots, and a 12.8 percent reduction at 32 knots.

The twin shaftline contrarotating experiments have been repeated using two different dynamometry systems and two sets of stock propellers. The agreement between the two dynamometry systems was excellent, and the repeat of the experiments with the first set of stock propellers was also good. Therefore, this is one of the most reliable sets of experiments in this entire series, and the resulting predictions should be most accurate.

TABLE B-7 - POWERING PREDICTIONS FOR THE DD-963 HULL FORM FITTED WITH TWIN SETS OF CONTRAROTATING PROPELLERS BASED ON EXPERIMENTS WITH MODEL 5359-1B, FROM LIN AND WILSON (1983b)

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1060	790	1380	1030	36.8
12	6.17	1920	1430	2490	1860	44.1
14	7.20	3120	2330	4070	3030	51.5
16	8.23	4690	3500	6110	4550	58.9
18	9.26	6660	4970	8680	6470	66.3
20	10.29	9080	6770	11780	8780	73.5
21	10.80	10460	7800	13630	10170	77.2
22	11.32	11940	8900	15560	11610	80.7
23	11.83	13530	10090	17640	13160	84.3
24	12.35	15240	11370	19770	14750	87.6
25	12.86	17180	12810	22300	16630	91.2
26	13.38	19480	14520	25270	18840	94.9
27	13.89	22270	16610	28710	21410	98.6
28	14.40	25890	19300	33180	24740	102.9
29	14.92	30610	22820	39380	29370	107.7
30	15.43	35920	26790	46220	34460	112.5
31	15.95	41860	31210	54150	40380	118.1
32	16.46	48300	36020	63190	47120	123.5

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	JT
10	0.770	0.795	0.930	1.045	0.935	1.005	1.015	1.590
12	0.770	0.795	0.940	1.030	0.935	0.995	1.005	1.575
14	0.765	0.795	0.945	1.020	0.935	0.990	0.995	1.570
16	0.770	0.795	0.945	1.020	0.935	0.990	0.995	1.565
18	0.770	0.795	0.945	1.020	0.935	0.990	0.995	1.565
20	0.770	0.795	0.945	1.025	0.935	0.990	1.000	1.570
21	0.765	0.795	0.945	1.020	0.935	0.990	0.995	1.570
22	0.765	0.795	0.945	1.020	0.935	0.990	0.995	1.570
23	0.765	0.795	0.945	1.020	0.935	0.990	0.995	1.575
24	0.770	0.795	0.950	1.020	0.935	0.985	0.990	1.575
25	0.770	0.795	0.950	1.020	0.935	0.985	0.990	1.575
26	0.770	0.795	0.950	1.020	0.935	0.985	0.990	1.570
27	0.775	0.795	0.955	1.020	0.935	0.980	0.985	1.565
28	0.780	0.800	0.955	1.025	0.935	0.980	0.990	1.555
29	0.775	0.800	0.955	1.020	0.935	0.980	0.985	1.540
30	0.775	0.800	0.955	1.020	0.935	0.980	0.985	1.525
31	0.775	0.800	0.945	1.025	0.935	0.990	1.000	1.515
32	0.765	0.800	0.935	1.025	0.930	0.995	1.005	1.500

TWIN SHAFTLINE FIXED-PITCH PROPELLERS
Model 5359-1, Propellers 4274 and 4275 (First Set)
Propellers 4864 and 4865 (Second Set)

These experiments were performed on the DD-963 hull form fitted with twin shafts and struts sized for fixed-pitch propellers. The first set of propellers selected from the propeller library represented propellers of slightly smaller diameter and lower pitch diameter ratio than would be used if a set of propellers were specifically designed and built for this application. However, they were considered to be close enough to the ideal to suffice. The results with these propellers are reported in Reed and Wilson (1980a). During the fixed-pitch propeller bearing-in-rudder post experiments, a new set of fixed-pitch propellers was designed and built. Both the first set of propellers and this new, second set of propellers were used in a new set of experiments with twin shafts and struts. These repeat experiments showed that there had been an error in the first set of experiments, and the smaller diameter propellers had higher delivered power than was reported in Reed and Wilson. However, the second set of propellers did achieve delivered powers which were very close to the results published in Reed and Wilson, although at lower rpm.

The results of resistance and propulsion experiments with the second set of stock fixed-pitch propellers are given in Table B-8. These results show effective powers of 6450 kW (8650 hp) and 35170 kW (47160 hp) at 20 and 32 knots, respectively. The comparable baseline results are 7030 kW and 37250 kW. This represents an 8.2 percent reduction in effective power for the fixed-pitch appendage suit at 20 knots, and a 5.6 percent reduction at 32 knots.

The delivered power for the fixed-pitch propellers is 9000 kW (12070 hp) at 20 knots, and 50740 kW (68050 hp) at 32 knots. The baseline configuration requires 10110 kW at 20 knots and 54010 kW at 32 knots. This represents an 11.0 percent reduction at 20 knots and a 6.0 precent reduction at 32 knots. These resistance and propulsion experiments were straightforward. There were no complications associated with either the dynamometry or propulsors. Therefore, these experimental results should be quite reliable.

TABLE B-8 - POWERING PREDICTIONS FOR THE DD-963 HULL FORM FITTED WITH TWIN FIXED-PITCH PROPELLERS BASED ON EXPERIMENTS WITH MODEL 5359-1

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1020	760	1430	1070	45.5
12	6.17	1840	1380	2570	1920	55.1
14	7.20	2990	2230	4170	3110	64.5
16	8.23	4490	3350	6260	4670	73.8
18	9.26	6370	4750	8880	6620	83.0
20	10.29	8650	6450	12070	9000	92.0
21	10.80	9940	7410	13860	10340	96.5
22	11.32	11350	8460	15830	11800	100.9
23	11.83	12870	9590	17940	13380	105.4
24	12.35	14540	10840	20280	15120	109.8
25	12.86	16440	12260	22930	17100	114.4
26	13.38	18680	13930	26060	19430	119.2
27	13.89	21490	16020	30050	22410	124.5
28	14.40	24980	18630	35080	26160	130.4
29	14.92	29450	21960	41540	30980	137.1
30	15.43	34840	25980	49410	36850	144.5
31	15.95	40750	30390	58220	43410	151.9
32	16.46	47160	35170	68050	50740	159.1

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	JT
10	0.715	0.755	0.970	0.980	0.920	0.950	0.940	1.245
12	0.715	0.755	0.970	0.985	0.920	0.950	0.940	1.235
14	0.715	0.750	0.970	0.985	0.920	0.950	0.945	1.230
16	0.715	0.750	0.970	0.985	0.920	0.950	0.945	1.225
18	0.715	0.750	0.970	0.985	0.920	0.950	0.945	1.225
20	0.715	0.755	0.970	0.985	0.920	0.950	0.945	1.230
21	0.715	0.755	0.970	0.985	0.920	0.950	0.940	1.230
22	0.715	0.755	0.970	0.985	0.920	0.950	0.940	1.235
23	0.715	0.755	0.970	0.980	0.920	0.950	0.940	1.235
24	0.715	0.755	0.970	0.980	0.920	0.950	0.940	1.235
25	0.715	0.755	0.970	0.980	0.920	0.950	0.940	1.235
26	0.715	0.755	0.970	0.985	0.920	0.950	0.940	1.235
27	0.715	0.750	0.970	0.980	0.920	0.950	0.940	1.225
28	0.710	0.750	0.965	0.980	0.920	0.950	0.945	1.220
29	0.710	0.745	0.960	0.985	0.920	0.955	0.950	1.205
30	0.705	0.745	0.955	0.990	0.920	0.960	0.960	1.190
31	0.700	0.740	0.950	0.995	0.920	0.970	0.965	1.180
32	0.695	0.740	0.945	0.990	0.925	0.975	0.975	1.170

TWIN BEARING-IN-RUDDER POST WITH CONTROLLABLE-PITCH PROPELLERS
Models 5359-0A, -0B, and -0C, Propellers 4660A and 4661A

These experiments were performed on the DD-963 hull form using the shafting and intermediate struts from the parent model. The main struts and strut barrel were replaced with three bearing-in-rudder post configurations: a straight rudder (Model 5359-0A), a cambered or contraguide rudder (Model 5359-0B), and a contraguide rudder with Costa-bulb (Model 5359-0C). The propellers used were models of the DD-963 design controllable-pitch propellers. However, subsequent to the experiments, it was discovered that the performance of the propellers had degraded. Therefore, new open water data were obtained and used in the analysis of the propulsion data.

The data for these experiments were originally published by West (1981). However, it was discovered, after the fact, that the values of residuary resistance used in extrapolating to full scale were in error. In addition to the error in residuary resistance, West presented projections of powering performance with design propellers rather than actual experimental results. Therefore, the experimental data has been completely reanalyzed for presentation in this report. The results for the three rudder configurations are presented in Tables B-9, B-10, and B-11 for the straight, contraguide, and contraguide with Costa-bulb rudders, respectively.

As was stated earlier, the shafts and intermediate struts on this model were the same as those for the parent configuration. Therefore, the effective powers for these configurations must be compared with the parent effective power. Due to the fact that the propeller performance had deteriorated, neither the parent nor the baseline propulsion results are the correct ones to compare against, but rather a separate shafts and struts propulsion experiment with the degraded propellers is required. The results of these special shafts and struts propulsion experiments are presented in Appendix E.

Comparison of the effective powers for the three rudder configurations with that of the parent controllable-pitch propeller appendages shows power reductions of 8.0, 2.6, and 3.0 percent for the straight, contraguide, and contraguide with Costabulb rudders, respectively, at 20 knots. At 32 knots, the reductions are 5.2, 2.8, and 3.0 percent for the three rudders, respectively. Comparison of the delivered power for the three rudder configurations with that of the shafts and and struts configurations, all using the degraded propellers, shows 20-knot power reductions of 8.7, 5.7, and 4.9 percent for the respective rudders. At 32 knots, a similar comparison yields reductions in power of 5.7, 4.3, and 4.1 percent, respectively.

These resistance experiments were straightforward. Therefore, there does not appear to be any reason to suspect the accuracy of the effective power predictions, particularly when the small differences between the rudders are considered, and it is seen that the three rudders are ranked in the order which would be expected.

The use of a bearing mounted in the rudder post during the propulsion experiments renders the thrust measurements somewhat less precise than would be ideal, but it should not affect the torque measurements and the bottom line, delivered power. More recent experiments have shown that it is feasible to eliminate the bearing mounted in the rudder post. This more recent development, combined with the use of degraded propellers in these experiments, would seem to indicate that there could be some merit to repeating the controllable-pitch propeller bearing-in-rudder post experiments with new non-degraded propellers. This conclusion is in no way intended to cast any doubt on the validity of these experiments.

TABLE B-9 - POWERING PREDICTIONS FOR THE DD-963 HULL FORM FITTED WITH THE STRAIGHT RUDDER BEARING-IN-RUDDER POST CONFIGURATION AND TWIN CONTROLLABLE-PITCH PROPELLERS BASED ON EXPERIMENTS WITH MODEL 5359-0A

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	985	735	1460	1090	47.1
12	6.17	1810	1350	2680	2000	57.1
14	7.20	2960	2200	4380	3270	67.0
16	8.23	4440	3310	6590	4910	76.7
18	9.26	6300	4700	9340	6970	86.2
20	10.29	8550	6380	12630	9420	95.6
21	10.80	9840	7340	14610	10890	100.6
22	11.32	11250	8390	16630	12400	105.3
23	11.83	12810	9550	18930	14110	110.0
24	12.35	14490	10800	21410	15970	114.6
25	12.86	16300	12160	24120	17990	119.7
26	13.38	18440	13750	27230	20300	124.2
27	13.89	21160	15780	31330	23360	129.5
28	14.40	24750	18450	36830	27470	135.4
29	14.92	29040	21660	43210	32230	141.6
30	15.43	34100	25430	51020	38040	148.4
31	15.95	39960	29800	59910	44670	155.6
32	16.46	46680	34810	70090	52270	162.9
33	16.98	53780	40100	80780	60240	170.0
34	17.49	61130	45590	92300	68830	177.4

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	JT
10	0.670	0.690	0.945	1.030	0.900	0.950	0.960	1.200
12	0.675	0.690	0.945	1.030	0.900	0.950	0.960	1.190
14	0.675	0.690	0.945	1.030	0.900	0.950	0.960	1.185
16	0.675	0.690	0.945	1.030	0.900	0.950	0.960	1.180
18	0.675	0.690	0.945	1.030	0.900	0.950	0.960	1.180
20	0.675	0.690	0.945	1.035	0.900	0.950	0.965	1.185
21	0.675	0.690	0.940	1.035	0.900	0.955	0.970	1.190
22	0.675	0.690	0.940	1.040	0.900	0.955	0.970	1.190
23	0.675	0.690	0.940	1.040	0.900	0.955	0.970	1.190
24	0.675	0.690	0.940	1.040	0.900	0.955	0.970	1.190
25	0.675	0.690	0.935	1.045	0.900	0.960	0.975	1.195
26	0.675	0.690	0.945	1.040	0.900	0.955	0.970	1.190
27	0.675	0.690	0.945	1.035	0.900	0.955	0.970	1.185
28	0.670	0.690	0.950	1.025	0.905	0.955	0.965	1.175
29	0.670	0.690	0.950	1.020	0.910	0.955	0.965	1.165
30	0.670	0.690	0.950	1.015	0.915	0.960	0.965	1.155
31	0.665	0.690	0.950	1.015	0.915	0.965	0.970	1.145
32	0.665	0.690	0.950	1.015	0.920	0.970	0.975	1.135
33	0.665	0.690	0.950	1.015	0.925	0.975	0.980	1.125
34	0.660	0.690	0.945	1.015	0.930	0.985	0.990	1.125

TABLE B-10 - POWERING PREDICTIONS FOR THE DD-963 HULL FORM FITTED WITH THE CONTRAGUIDE RUDDER BEARING-IN-RUDDER POST CONFIGURATION AND TWIN CONTROLLABLE-PITCH PROPELLERS BASED ON EXPERIMENTS WITH MODEL 5359-0B

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1060	790	1520	1130	47.4
12	6.17	1940	1440	2780	2070	57.3
14	7.20	3150	2350	4530	3380	67.3
16	8.23	4730	3530	6810	5070	76.9
18	9.26	6680	4980	9610	7170	86.5
20	10.29	9050	6750	13040	9730	96.1
21	10.80	10390	7750	15000	11180	100.9
22	11.32	11830	8820	17120	12770	105.7
23	11.83	13390	9990	19410	14470	110.5
24	12.35	15110	11270	21900	16330	115.3
25	12.86	17040	12700	24730	18440	120.1
26	13.38	19210	14330	28000	20880	124.9
27	13.89	21880	16320	31940	23820	130.2
28	14.40	25550	19050	37410	27900	136.2
29	14.92	29970	22350	44080	32870	142.5
30	15.43	35290	26310	52050	38810	149.5
31	15.95	41210	30730	61050	45530	156.5
32	16.46	47830	35670	71070	53000	163.6
33	16.98	54810	40870	81800	61000	170.9
34	17.49	62140	46340	93020	69360	178.0

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-T	1-WT	1-WQ	JT
10	0.695	0.685	0.995	1.020	0.945	0.950	0.960	1.195
12	0.695	0.685	0.995	1.015	0.945	0.950	0.955	1.185
14	0.695	0.685	0.995	1.020	0.945	0.950	0.955	1.180
16	0.695	0.685	0.995	1.015	0.945	0.950	0.955	1.175
18	0.695	0.685	0.995	1.020	0.945	0.950	0.960	1.180
20	0.695	0.685	0.990	1.020	0.945	0.955	0.960	1.185
21	0.695	0.685	0.990	1.020	0.945	0.955	0.965	1.185
22	0.690	0.690	0.985	1.020	0.945	0.960	0.970	1.190
23	0.690	0.690	0.980	1.020	0.945	0.960	0.970	1.195
24	0.690	0.690	0.980	1.025	0.945	0.965	0.975	1.195
25	0.690	0.690	0.980	1.020	0.945	0.965	0.975	1.195
26	0.685	0.690	0.980	1.015	0.945	0.965	0.970	1.195
27	0.685	0.690	0.980	1.020	0.945	0.965	0.975	1.195
28	0.685	0.685	0.980	1.015	0.945	0.965	0.970	1.180
29	0.680	0.685	0.980	1.010	0.945	0.965	0.970	1.170
30	0.680	0.685	0.975	1.015	0.945	0.970	0.975	1.155
31	0.675	0.685	0.975	1.015	0.945	0.970	0.975	1.145
32	0.675	0.685	0.970	1.015	0.945	0.975	0.980	1.135
33	0.670	0.685	0.965	1.015	0.945	0.980	0.990	1.130
34	0.670	0.685	0.960	1.020	0.945	0.985	0.995	1.125

TABLE B-11 - POWERING PREDICTIONS FOR THE DD-963 HULL FORM FITTED WITH THE CONTRAGUIDE RUDDER AND COSTA BULB BEARING-IN-RUDDER POST CONFIGURATION AND TWIN CONTROLLABLE-PITCH PROPELLERS BASED ON EXPERIMENTS WITH MODEL 5359-0C

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1050	790	1530	1140	47.6
12	6.17	1860	1390	2700	2010	57.3
14	7.20	3130	2330	4570	3410	67.3
16	8.23	4690	3500	6850	5110	76.9
18	9.26	6640	4950	9650	7200	86.5
20	10.29	9010	6720	13150	9800	96.1
21	10.80	10340	7710	15100	11260	100.9
22	11.32	11760	8770	17170	12800	105.7
23	11.83	13310	9920	19420	14480	110.5
24	12.35	15020	11200	21930	16350	115.3
25	12.86	16920	12620	24700	18420	119.9
26	13.38	19140	14270	28020	20890	124.9
27	13.89	21890	16330	32150	23970	130.0
28	14.40	25560	19060	37590	28030	135.6
29	14.92	29990	22360	44360	33080	141.8
30	15.43	35380	26330	52150	38890	148.3
31	15.95	41180	30710	61190	45630	155.8
32	16.46	47750	35610	71270	53150	162.9
33	16.98	54830	40890	82090	61210	170.0
34	17.49	62170	46360	93490	69710	176.9

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-T	1-WT	1-WQ	JT
10	0.690	0.690	0.955	1.050	0.905	0.950	0.965	1.185
12	0.690	0.690	0.955	1.050	0.905	0.950	0.965	1.180
14	0.685	0.685	0.965	1.035	0.905	0.940	0.955	1.165
16	0.685	0.685	0.965	1.035	0.905	0.940	0.950	1.165
18	0.690	0.685	0.965	1.040	0.905	0.940	0.955	1.165
20	0.685	0.685	0.960	1.040	0.905	0.945	0.960	1.170
21	0.685	0.685	0.955	1.040	0.905	0.945	0.960	1.175
22	0.685	0.685	0.955	1.045	0.905	0.950	0.965	1.175
23	0.685	0.690	0.950	1.050	0.905	0.950	0.970	1.180
24	0.685	0.690	0.950	1.050	0.905	0.955	0.975	1.185
25	0.685	0.690	0.950	1.050	0.905	0.955	0.970	1.185
26	0.685	0.690	0.950	1.045	0.905	0.955	0.970	1.180
27	0.680	0.685	0.955	1.040	0.905	0.950	0.965	1.170
28	0.680	0.685	0.955	1.035	0.905	0.945	0.960	1.165
29	0.675	0.685	0.960	1.030	0.905	0.945	0.955	1.150
30	0.675	0.685	0.960	1.030	0.905	0.940	0.955	1.135
31	0.675	0.685	0.955	1.035	0.905	0.950	0.965	1.125
32	0.670	0.685	0.950	1.035	0.905	0.955	0.970	1.115
33	0.670	0.685	0.945	1.035	0.905	0.960	0.975	1.110
34	0.665	0.685	0.940	1.030	0.905	0.965	0.980	1.105

TWIN SHAFTLINE LARGE DIAMETER LOW TIP CLEARANCE FIXED-PITCH PROPELLERS
Model 5359-2, Propellers 4751 and 4752

These experiments were performed on a deep skeg hull form with a large fillet adjacent to the propeller. The 6.10 meter (20 ft) propellers had a hull-propeller tip clearance of 2.5 percent of the propeller diameter. The models of fixed-pitch propellers had hub diameters of 20.0 percent of the propeller diameter. The results of these experiments have been reported by Lin and Wilson (1980).

The experimental resistance and propulsion results with large diameter fixed-pitch propellers with low tip clearance are given in Table B-12. The effective powers for this configuration are 6530 kW (8750 hp) and 36420 kW (48840 hp) at 20 and 32 knots, respectively. These represent 7.1 and 2.2 percent reductions over the baseline effective powers of 7030 kW and 37250 kW at 20 and 32 knots, respectively.

The delivered powers for this configuration are 9470 kW (12700 hp) at 20 knots and 52100 kW (69870 hp) at 32 knots. These values compare with baseline results of 10110 kW and 54010 kW, and represent 6.3 and 3.5 percent reductions in delivered power over the baseline at 20 and 32 knots, respectively.

These experiments were straightforward and the experimental results were excellent. Therefore, these experimental results should be quite reliable. However, there is one noteworthy point with respect to these results: the significant 7.1 percent reduction in effective power which has been achieved with this configuration at 20 knots. This hull form has larger appendages than the controllable-pitch propeller baseline, which should cause higher appendage resistance than is found on the baseline configuration. The increase in appendage resistance due to larger size is somewhat offset by the smaller inclination of the shafting to the flow. This in turn reduces the length of the shafting and the struts, resulting in a situation where it is difficult to determine whether the appendage drag has increased or decreased. One fact which is certain is that the wetted surface of this configuration has increased 1.2 percent over that of the baseline. This should result in slightly higher viscous resistance.

Thus, while the source of the drag reduction is not clear, there is potential for a significant reduction in effective power with this hull form. In particular, the result of using the baseline controllable-pitch propeller appendage suit on this hull form with the large diameter propeller shaftline might have significant benefit in terms of reduced delivered power.

TABLE B-12 - POWERING PREDICTIONS FOR A CONTEMPORARY DESTROYER HULL FORM FITTED WITH TWIN LARGE DIAMETER LOW TIP CLEARANCE FIXED-PITCH PROPELLERS BASED ON EXPERIMENTS WITH MODEL 5359-2, FROM LIN AND WILSON (1980)

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1000	750	1520	1130	40.6
12	6.17	1810	1350	2720	2030	48.7
14	7.20	2930	2180	4350	3250	56.8
16	8.23	4380	3270	6460	4820	65.0
18	9.26	6240	4650	9120	6800	73.2
20	10.29	8750	6530	12700	9470	81.7
21	10.80	10210	7610	14780	11020	85.6
22	11.32	11710	8730	16880	12580	89.5
23	11.83	13290	9910	19100	14240	93.4
24	12.35	14960	11160	21470	16010	97.3
25	12.86	16900	12600	24180	18030	101.3
26	13.38	19140	14270	27310	20360	105.5
27	13.89	21990	16400	31320	23360	110.0
28	14.40	25660	19130	36550	27260	114.6
29	14.92	30200	22520	42950	32030	119.7
30	15.43	35680	26610	50760	37850	125.1
31	15.95	42000	31320	59830	44620	130.9
32	16.46	48840	36420	69870	52100	136.9
33	16.98	56170	41890	80590	60090	142.8
34	17.49	63670	47480	91740	68410	148.4

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-T	1-WT	1-WQ	JT
10	0.660	0.740	0.980	0.905	0.990	1.010	0.985	1.260
12	0.665	0.745	0.990	0.905	0.990	1.000	0.975	1.250
14	0.670	0.745	0.990	0.910	0.990	1.000	0.975	1.245
16	0.680	0.745	0.990	0.915	0.990	1.000	0.980	1.245
18	0.685	0.745	0.990	0.925	0.990	1.000	0.985	1.245
20	0.690	0.750	0.990	0.935	0.990	1.005	0.985	1.245
21	0.690	0.750	0.990	0.930	0.990	1.000	0.980	1.240
22	0.695	0.750	0.995	0.935	0.990	0.995	0.980	1.240
23	0.695	0.750	0.995	0.935	0.990	0.995	0.980	1.240
24	0.695	0.750	0.995	0.935	0.990	0.995	0.980	1.245
25	0.700	0.750	0.995	0.940	0.990	0.995	0.980	1.245
26	0.700	0.750	0.995	0.940	0.990	0.995	0.980	1.240
27	0.700	0.750	0.995	0.940	0.990	0.995	0.980	1.240
28	0.700	0.750	0.995	0.935	0.990	0.995	0.980	1.230
29	0.705	0.755	0.995	0.935	0.990	0.995	0.975	1.220
30	0.705	0.755	0.995	0.935	0.990	0.995	0.975	1.210
31	0.700	0.760	0.990	0.935	0.990	1.000	0.980	1.200
32	0.700	0.760	0.985	0.935	0.990	1.005	0.985	1.190
33	0.695	0.760	0.980	0.940	0.990	1.015	0.990	1.185
34	0.695	0.760	0.975	0.940	0.990	1.015	0.995	1.180

TWIN SHAFTLINE TANDEM PROPELLERS
Model 5359-1A, Propellers 4777 & 4778 and 4779 & 4780

These experiments have been conducted on the DD-963 hull form fitted with twin shafts and struts sized for tandem propellers. This configuration has only been evaluated with one set of propellers, and has been reported by Lin (1980a).

The resistance and propulsion results from Lin are reproduced in Table B-13. The effective power of the twin tandem configuration is 6500 kW (8710 hp) at 20 knots and 35280 kW (47310 hp) at 32 knots. These values represent 7.5 and 5.3 percent power reductions over the baseline values of 7030 kW and 37250 kW at 20 and 32 knots, respectively.

While the effective powers for the twin tandem configuration have shown substantial reductions relative to the baseline, the exact opposite is true of the delivered power results. The twin tandem configuration used in the experiments requires 11110 kW (14890 hp) at 20 knots, and 58700 kW (78720 hp) at 32 knots. This represents a 9.9 percent increase in delivered power at 20 knots relative to the baseline power of 10110 kW, and an increase of 8.7 percent relative to the baseline delivered power of 54010 kW at 32 knots.

While these resistance and propulsion experiments were straightforward and contained no complicating factors, these results should not be considered a good measure of the performance which might be expected from a twin tandem configuration. In particular, it should be noted that the propeller efficiency of 0.635 for this configuration is the lowest seen in this entire experimental program. This is probably due to an improper thrust distribution between the forward and aft propellers. Based on the experience with the contrarotating propellers, it is reasonable to expect a substantial increase in propeller efficiency from a proper redesign of these propellers. Such a redesign could also be expected to have a substantial beneficial effect on the hull-propulsor interaction coefficients. With improvements in propeller perfomance, the twin tandem configuration could be expected to perform as well as a set of design fixed-pitch propellers.

TABLE B-13 - POWERING PREDICTIONS FOR THE DD-963 HULL FORM FITTED WITH TWIN TANDEM PROPELLERS BASED ON EXPERIMENTS WITH MODEL 5359-1A, FROM LIN (1980a)

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1050	780	1820	1350	46.7
12	6.17	1890	1410	3260	2430	56.1
14	7.20	3050	2280	5260	3930	65.5
16	8.23	4550	3390	7820	5830	74.9
18	9.26	6440	4800	11020	8220	84.3
20	10.29	8710	6500	14890	11110	93.5
21	10.80	10000	7460	17060	12720	97.9
22	11.32	11390	8490	19410	14470	102.4
23	11.83	12910	9630	21960	16370	106.6
24	12.35	14620	10900	24770	18470	111.1
25	12.86	16520	12320	27910	20810	115.6
26	13.38	18710	13950	31500	23490	120.3
27	13.89	21500	16040	36140	26950	125.1
28	14.40	25010	18650	41900	31240	130.4
29	14.92	29450	21960	49250	36730	136.0
30	15.43	34740	25910	57910	43180	142.4
31	15.95	40740	30380	67900	50640	149.0
32	16.46	47310	35280	78720	58700	155.7
33	16.98	54290	40480	90180	67250	162.6
34	17.49	61520	45870	102020	76080	168.9

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-T	1-WT	1-WQ	JT
10	0.575	0.630	0.910	1.005	0.955	1.050	1.050	1.315
12	0.580	0.635	0.920	0.995	0.955	1.040	1.035	1.305
14	0.580	0.635	0.925	0.985	0.955	1.035	1.030	1.300
16	0.580	0.635	0.920	0.990	0.955	1.040	1.035	1.300
18	0.585	0.635	0.925	0.995	0.960	1.040	1.040	1.300
20	0.585	0.635	0.920	1.000	0.960	1.040	1.040	1.305
21	0.585	0.635	0.925	1.000	0.960	1.040	1.040	1.305
22	0.585	0.635	0.925	1.005	0.960	1.040	1.040	1.310
23	0.590	0.635	0.930	1.000	0.960	1.035	1.035	1.310
24	0.590	0.635	0.930	1.005	0.960	1.035	1.035	1.310
25	0.590	0.635	0.935	1.005	0.965	1.030	1.035	1.310
26	0.595	0.635	0.935	1.005	0.965	1.030	1.035	1.310
27	0.595	0.635	0.940	0.995	0.965	1.030	1.025	1.300
28	0.595	0.640	0.940	0.990	0.965	1.025	1.020	1.290
29	0.600	0.645	0.945	0.980	0.965	1.020	1.015	1.275
30	0.600	0.650	0.945	0.980	0.970	1.025	1.015	1.265
31	0.600	0.650	0.945	0.975	0.970	1.025	1.015	1.250
32	0.600	0.650	0.940	0.980	0.970	1.030	1.020	1.240
33	0.600	0.655	0.935	0.985	0.970	1.035	1.030	1.235
34	0.605	0.655	0.935	0.985	0.970	1.040	1.030	1.225

TWIN SHAFTLINE CONTROLLABLE-PITCH PROPELLERS WITH REVISED FAIRWATERS
Model 5359-2A, Propellers 4751A and 4752A
Model 5359, Propellers 4868 and 4869

Revised fairwater experiments have been performed on two models. The first experiments, which have not been reported, were resistance tests performed on the large diameter low tip clearance controllable-pitch propeller configuration. This model was chosen because of its large fairwater diameters which should have maximized the difference between the various fairwater shapes. Four fairwaters the DD-963 button shape, a long bullet shape, a short bullet shape, and a truncated cone) were evaluated at full-scale speeds of 20 and 32 knots using a statistical blocking technique to allow identification of small variations in resistance between the fairwater shapes. These experiments showed that the short bullet shape and the truncated cone both reduced the resistance of the model 3.0 to 3.5 percent. These results were significant enough to justify further experiments.

The second set of experiments was a series of resistance and propulsion tests. These experiments were performed on the DD-963 parent hull form with a new model set of design propellers (numbered 4868 and 4869); these propellers were built to the same design as the original models of the design propeller (numbered 4660 and 4661), whose performance had deteriorated significantly. Three fairwater shapes were used for these experiments: the original DD-963 button shape, a short bullet shape, and a truncated cone. These experiments were again performed at 20 and 32 knots full-scale, and employed blocking techniques to accurately distinguish between the performance of the three fairwaters. The results of these experiments are presented in Lin and Borda (1983).

Tables B-14 and B-15 present the results of these resistance and propulsion experiments. Table B-14 presents the resistance and effective power results for the three fairwaters at the two speeds, including standard deviations, and repeatability at 90 percent confidence levels. These results indicate that the truncated cone reduces the effective power by 2.6 percent at 20 knots, and 1.9 percent at 32 knots, relative to the parent configuration. The bullet shape reduces the effective power by 3.4 and 2.3 percent at 20 and 32 knots, respectively.

The delivered power results from Table B-15 are not nearly as encouraging. They indicate that the truncated cone reduces the delivered power by 1.3 and 0.6 percent relative to the parent hull form at 20 and 32 knots, respectively. The short bullet shape reduces the delivered power by 0.8 and 0.9 percent, respectively, indicating that the resistance benefits do not carry over to propulsion.

Due to the blocking technique, involving many repeat runs and randomized order for use of the fairwaters within the blocks, the accuracy of each set of data can be established with a high degree of precision. The repeatability of the 20-knot resistance measurement was between ± 0.59 and ± 0.66 percent; that of the effective power, between ± 0.74 and ± 0.80 percent; and that of the delivered power, between ± 1.40 and ± 1.67 percent. The 32-knot results were even more accurate, with resistance repeatability between ± 0.43 and ± 0.50 percent; effective power repeatability between ± 0.48 and ± 0.57 percent; and delivered power repeatability between ±0.71 and ± 1.12 percent. Thus, the confidence level for these results is very high.

An important point to note is the fact that the variations in fairwater shape have had a significant impact on the hull-propulsor interaction coefficients, particularly the thrust deduction factor. This is probably the major explanation for the fact that the propulsion results with the new fairwaters do not reflect the reduced effective power resulting from the fairwater variations.

TABLE B-14 - RESISTANCE MEASUREMENTS AND EFFECTICE POWER PREDICTIONS FOR THE PARENT DD-963 HULL FORM FITTED WITH THREE PROPELLER FAIRWATER SHAPES FROM EXPERIMENTS WITH MODEL 5359, FROM LIN AND BORDA (1983)

Fairwater	$\bar{R}_{TM}$ Lbs (N)	σR_{TM} Lbs (N)	R_{TM} Repeatability at a 90% Confidence Level Lbs / %	(N)	$\bar{P}_E$ HP (kw)	σP_E HP (kw)	P_E Repeatability at a 90% Confidence Level HP / %	(kw)	$\frac{(\bar{R}_{TM})_X}{(\bar{R}_{TM})_A}$	$\frac{(\bar{P}_E)_X}{(\bar{P}_E)_A}$
20 Knots Ship Speed										
A Button (Original)	11.281	0.0456	±0.075	(±0.334)	8879.9	43.23	±71.11	(±53.0)	1.000	1.000
	(50.2)	(0.203)	±0.66		(6621.7)	(32.2)	±0.80			
B Truncated Cone	11.040	0.0412	±0.068	(±0.302)	8645.1	38.83	±63.87	(±47.6)	0.979	0.974
	(49.1)	(0.183)	±0.61		(6446.7)	(29.0)	±0.74			
C Short Bullet	10.974	0.0396	±0.065	(±0.289)	8581.5	36.94	±60.77	(±45.3)	0.973	0.966
	(48.8)	(0.176)	±0.59		(6399.2)	(27.5)	±0.71			
32 Knots Ship Speed										
A Button (Original)	34.899	0.1055	±0.174	(±0.774)	46841.6	161.85	±266.2	(±198.5)	1.000	1.000
	(155.2)	(0.469)	±0.50		(34929.8)	(120.7)	±0.57			
B Truncated Cone	34.334	0.0911	±0.150	(±0.667)	45971.2	145.40	±239.2	(±178.3)	0.984	0.981
	(152.7)	(0.405)	±0.44		(34208.7)	(108.4)	±0.52			
C Short Bullet	34.204	0.0895	±0.147	(±654)	45766.5	133.84	±220.2	(±164.2)	0.980	0.977
	(152.1)	(0.398)	±0.43		(34128.1)	(99.8)	±0.48			

$\bar{R}_{TM}$ = Mean Measured Model Total Resistance
σR_{TM} = Standard Deviation of Model Total Resistance
$\bar{P}_E$ = Mean Total Effective Power
σP_E = Standard Deviation of Effective Power

TABLE B-15 - POWERING PREDICTIONS FOR THE PARENT DD-963 HULL FORM FITTED WITH TWIN CONTROLLABLE-PITCH PROPELLERS AND THREE PROPELLER FAIRWATER SHAPES BASED ON EXPERIMENTS WITH MODEL 5359, FROM LIN AND BORDA (1983)

Fairwater	$\bar{P}_D$ HP (kw)	σP_D HP (kw)	P_D Repeatability at a 90% Confidence Level HP (kw) %	η_D	η_O	η_H	η_R	1-t	1-w_T	$\frac{(P_E)_X}{(P_E)_A}$	$\frac{(P_D)_X}{(P_D)_A}$
20 Knots Ship Speed											
A Button (Original)	13137.4 (9796.6)	133.4 (99.5)	±219.4 (±163.6) ±1.67	0.695	0.762	0.972	0.938	0.972	0.999	1.000	1.000
B Truncated Cone	12967.9 (9670.2)	110.5 (82.4)	±181.8 (±135.6) ±1.40	0.686	0.761	0.956	0.943	0.954	0.998	0.974	0.987
C Short Bullet	13029.2 (9715.9)	116.0 (86.0)	±190.8 (±142.3) ±1.46	0.677	0.750	0.944	0.942	0.944	1.000	0.966	0.992
32 Knots Ship Speed											
A Button (Original)	71592.2 (53386.3)	442.8 (330.2)	±728.4 (±543.2) ±1.02	0.678	0.748	0.949	0.955	0.957	1.008	1.000	1.000
B Truncated Cone	71101.8 (53020.6)	305.7 (228.0)	±502.9 (±375.0) ±0.71	0.670	0.748	0.934	0.959	0.940	1.006	0.981	0.993
C Short Bullet	70895.9 (52867.1)	485.1 (361.7)	±798.0 (±595.1) ±1.12	0.670	0.748	0.931	0.961	0.938	1.007	0.977	0.990

$\bar{P}_D$ = Mean Total Delivered Power
σP_D = Standard Deviation of Delivered Power

TWIN SHAFTLINE LARGE DIAMETER OVERLAPPING PROPELLERS
Model 5359-3, Propellers 4751 and 4752

These experiments were performed on a twin tunnel hull form with a deep skeg and large fillet between the hull and skeg. The propellers were 6.10 m (20 ft) in diameter, and had a hull-propeller tip clearance of 2.5 percent of the propeller diameter. The results of these experiments are reported by Reed and Wilson (1980b)

The results of these resistance and propulsion experiments are presented in Table B-16. As was the case with the large diameter low tip clearance fixed-pitch propellers, the large diameter overlapping propellers configuration shows reduced effective power despite larger appendages and increased wetted surface relative to the baseline configuration. The large diameter overlapping configuration shows effective powers of 6650 kW (8920 hp) at 20 knots and 36340 kW (48730 hp) at 32 knots. This represents reductions in effective power of 5.4 and 2.4 percent at 20 and 32 knots, respectively, relative to the baseline values of 7030 kW and 37250 kW.

The delivered power, on the other hand, increases with stock propellers. At 20 knots, the large diameter overlapping configuration requires 10680 kW (14320 hp). This represents a 5.6 percent increase in delivered power over the baseline power of 10110 kW. The 32-knot results are similar, with this configuration requiring 55560 kW (74510 hp), as compared with the baseline, which requires 54010 kW, a 2.9 percent increase in delivered power.

Although there does not appear to be any error with these experiments, the results should not be considered representative of the performance which could be achieved with this configuration. This is indicated by the extremely low values of relative rotative efficiency, which is below 0.800 at 10 knots and only reaches 0.855 at 20 knots. These extremely low values are probably caused by the fact that the two propellers were operating at the same rpm, in each others wake. It is most likely that the aft propeller should have been operating at a somewhat higher rpm to account for the fact that it was operating in the accelerated velocity field of the forward propeller.

TABLE B-16 - POWERING PREDICTIONS FOR A CONTEMPORARY DESTROYER HULL FORM FITTED WITH TWIN LARGE DIAMETER OVERLAPPING FIXED-PITCH PROPELLERS BASED ON EXPERIMENTS WITH MODEL 5359-3, FROM REED AND WILSON (1980b)

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1020	760	1800	1340	40.1
12	6.17	1870	1390	3230	2410	48.3
14	7.20	3040	2270	5150	3840	56.5
16	8.23	4520	3370	7510	5600	64.8
18	9.26	6440	4810	10530	7850	73.2
20	10.29	8920	6650	14320	10680	81.5
21	10.80	10280	7670	16380	12210	85.6
22	11.32	11750	8760	18530	13820	89.6
23	11.83	13350	9960	20900	15580	93.4
24	12.35	15090	11260	23400	17450	97.1
25	12.86	17030	12700	26230	19560	100.9
26	13.38	19400	14460	29750	22180	105.0
27	13.89	22250	16590	34020	25370	109.3
28	14.40	25850	19280	39470	29440	114.1
29	14.92	30320	22610	46280	34510	119.4
30	15.43	35710	26630	54520	40660	124.9
31	15.95	42020	31330	64250	47910	130.9
32	16.46	48730	36340	74510	55560	136.9
33	16.98	55850	41650	85400	63690	142.9
34	17.49	63280	47190	96910	72270	148.8

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-T	1-WT	1-WQ	JT
10	0.570	0.745	0.975	0.780	0.960	0.985	0.915	1.245
12	0.580	0.750	0.980	0.785	0.960	0.980	0.910	1.235
14	0.590	0.755	0.980	0.800	0.960	0.980	0.915	1.230
16	0.600	0.750	0.975	0.820	0.960	0.985	0.930	1.235
18	0.610	0.750	0.970	0.840	0.960	0.990	0.940	1.235
20	0.625	0.750	0.970	0.855	0.960	0.995	0.950	1.235
21	0.630	0.750	0.970	0.865	0.960	0.995	0.955	1.235
22	0.635	0.750	0.970	0.870	0.960	0.995	0.955	1.235
23	0.640	0.750	0.970	0.875	0.960	0.990	0.955	1.235
24	0.645	0.750	0.975	0.880	0.960	0.985	0.950	1.235
25	0.650	0.750	0.980	0.885	0.960	0.985	0.950	1.235
26	0.650	0.750	0.980	0.885	0.960	0.980	0.950	1.230
27	0.655	0.755	0.980	0.885	0.960	0.980	0.950	1.225
28	0.655	0.755	0.980	0.885	0.960	0.980	0.950	1.220
29	0.655	0.755	0.975	0.885	0.960	0.985	0.950	1.210
30	0.655	0.760	0.975	0.885	0.960	0.990	0.950	1.200
31	0.655	0.760	0.970	0.890	0.960	0.995	0.955	1.190
32	0.655	0.760	0.960	0.895	0.960	1.000	0.965	1.185
33	0.655	0.760	0.955	0.900	0.960	1.010	0.970	1.180
34	0.655	0.760	0.945	0.905	0.960	1.015	0.980	1.175

TWIN SHAFTLINE LARGE DIAMETER LOW TIP CLEARANCE CONTROLLABLE-PITCH PROPELLERS
Model 5359-2A, Propellers 4751A and 4752A

These experiments were performed on a deep skeg hull form with a large fillet in way of the propeller. This is the same hull form used for the large diameter fixed-pitch propeller experiments. However, the propeller hubs have been built up to represent controllable-pitch propellers, and the size of the appendages has been increased accordingly. The results of these experiments have been reported by Lin and Wilson (1980).

The results of the resistance and propulsion experiments are reproduced in Table B-17. The effective power for this configuration is 6910 kW (9270 hp) at 20 knots and 37690 kW (50540 hp) at 32 knots. The corresponding baseline powers are 7030 kW and 37250 kW, respectively. These represent a 1.7 percent reduction in effective power at 20 knots and a 1.2 percent increase in effective power at 32 knots. The corresponding delivered powers for the large diameter controllable-pitch configuration are 10890 kW (14600 hp) and 57190 kW (76700 hp) at 20 and 32 knots. These represent increases in delivered power of 7.7 and 5.9 percent, respectively, compared to the baseline powers of 10110 kW and 54010 kW.

These experiments were straightforward and had no difficulties. Thus the experimental results are reliable. The cause of the poor performance of this configuration is probably the low clearance between the propeller hub and the hull, which obstructs the flow and causes a poor thrust deduction factor (1-t).

TABLE B-17 - POWERING PREDICTIONS FOR A CONTEMPORARY DESTROYER HULL FORM FITTED WITH TWIN LARGE DIAMETER LOW TIP CLEARANCE CONTROLLABLE-PITCH PROPELLERS BASED ON EXPERIMENTS WITH MODEL 5359-2A, FROM LIN AND WILSON (1980)

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1060	790	1660	1240	41.0
12	6.17	1900	1420	3000	2240	49.1
14	7.20	3100	2310	4890	3650	57.4
16	8.23	4660	3480	7360	5490	65.9
18	9.26	6610	4930	10410	7760	74.6
20	10.29	9270	6910	14600	10890	83.3
21	10.80	10850	8090	17040	12710	87.4
22	11.32	12480	9310	19510	14550	91.1
23	11.83	14140	10540	22050	16450	95.0
24	12.35	15920	11870	24690	18410	98.9
25	12.86	17910	13360	27690	20650	102.9
26	13.38	20280	15120	31200	23270	107.3
27	13.89	23260	17350	35620	26570	112.0
28	14.40	27080	20190	41350	30830	117.0
29	14.92	31780	23690	48290	36010	122.3
30	15.43	37430	27910	56800	42360	127.8
31	15.95	43700	32580	66310	49440	133.6
32	16.46	50540	37690	76700	57190	139.7
33	16.98	57930	43200	87900	65550	145.6
34	17.49	65690	48990	99680	74330	151.2

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-T	1-WT	1-WQ	JT
10	0.635	0.755	0.925	0.905	0.925	1.000	0.975	1.235
12	0.635	0.755	0.935	0.900	0.925	0.990	0.965	1.225
14	0.635	0.755	0.935	0.895	0.925	0.985	0.955	1.220
16	0.635	0.755	0.935	0.900	0.925	0.990	0.960	1.220
18	0.635	0.755	0.925	0.910	0.925	1.000	0.975	1.225
20	0.635	0.755	0.930	0.905	0.935	1.005	0.980	1.225
21	0.635	0.755	0.935	0.900	0.940	1.005	0.975	1.220
22	0.640	0.755	0.945	0.895	0.940	1.000	0.970	1.220
23	0.640	0.755	0.950	0.890	0.950	0.995	0.965	1.220
24	0.645	0.755	0.955	0.895	0.950	0.995	0.965	1.225
25	0.645	0.755	0.955	0.895	0.950	0.995	0.965	1.225
26	0.650	0.755	0.955	0.900	0.950	0.995	0.970	1.225
27	0.655	0.755	0.950	0.910	0.950	1.000	0.975	1.220
28	0.655	0.755	0.950	0.910	0.950	1.000	0.975	1.215
29	0.660	0.755	0.950	0.915	0.955	1.005	0.980	1.205
30	0.660	0.755	0.950	0.920	0.955	1.005	0.980	1.195
31	0.660	0.755	0.950	0.920	0.955	1.010	0.985	1.185
32	0.660	0.755	0.945	0.925	0.960	1.015	0.990	1.180
33	0.660	0.755	0.940	0.930	0.960	1.025	1.000	1.175
34	0.660	0.750	0.940	0.935	0.965	1.025	1.005	1.170

SINGLE SHAFTLINE CONTRAROTATING PROPELLERS

Model 5359-5, Propellers 4783 and 4784 (First Set)
Propellers 4859 and 4784 (Second Set)

These experiments were conducted on a prototype destroyer hull form fitted with a single shaftline appendage suit and a 6.10 meter (20 ft) diameter contrarotating propeller set. The first set of propellers was specified in Tomassoni and Slager (1980). The resistance of this hull form was very high, and the propulsive performance of this first set of propellers was very poor due to poor thrust and torque loading distribution between the two propellers, Lin (1980b). A second set of propellers was designed, Nelka and Cox (1981), and built using the existing after propeller from the first set of propellers to form the pair. The contrarotating propeller appendages were reinstalled on the model, and resistance and propulsion experiments were again performed. These repeat experiments gave significantly lower resistance than the first experiments, and the propulsion performance was much better, Lin and Wilson (1983a).

The results of these resistance and propulsion experiments are presented in Table B-18. The effective power for this configuration at 20 knots is 6340 kW (8510 hp) as opposed to the baseline power of 7030 kW. This represents a 9.8 percent reduction in effective power. At 32 knots, the single contrarotating configuration requires 35160 kW (47150 hp). This represents a 5.6 percent reduction over the baseline effective power of 37250 kW.

The delivered powers for this configuration are 8910 kW (11950 hp) and 49310 kW (66130 hp), at 20 and 32 knots, respectively. The corresponding powers for the baseline are 10110 kW and 54010 kW, respectively. These represent 11.9 and 8.7 percent reductions in delivered power.

These experiments were straightforward and no complications occurred. The only cause for any concern is the decrease in resistance which occurred between the first and second experiments. The appendages may have been better aligned for the second set of experiments, although it is not possible to check this. When, during the second experiment, it was discovered that the resistance was lower than during the first experiment, the resistance experiment was repeated and the second results seemed to be accurate and reliable.

A comment on the appendage suit seems appropriate here. The shape of the hull form and the restriction of full-scale shafting length to 24.4 m (80 ft) results in either extremely long strut bossings or long hull bossings for this configuration. A hull form redesigned with fewer artificial constraints would make possible the design of an appendage suit which would eliminate these large bossings and very likely result in a configuration with lower resistance and better propulsive performance.

TABLE B-18 - POWERING PREDICTIONS FOR A PROTOTYPE DESTROYER HULL FORM FITTED WITH A SINGLE SET OF CONTRAROTATING PROPELLERS BASED ON EXPERIMENTS WITH MODEL 5359-5, FROM LIN AND WILSON (1983a)

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1060	790	1490	1110	35.4
12	6.17	1880	1400	2650	1970	42.7
14	7.20	2990	2230	4210	3140	49.9
16	8.23	4440	3310	6250	4660	56.9
18	9.26	6250	4660	8810	6570	64.8
20	10.29	8510	6340	11950	8910	71.1
21	10.80	9770	7280	13720	10230	74.6
22	11.32	11230	8370	15770	11760	78.1
23	11.83	12700	9470	17940	13380	81.6
24	12.35	14480	10800	20280	15120	85.0
25	12.86	16370	12210	22930	17100	88.5
26	13.38	18520	13810	25900	19310	92.0
27	13.89	21270	15860	29630	22090	95.9
28	14.40	24960	18610	34520	25740	100.5
29	14.92	29390	21920	40660	30320	105.3
30	15.43	34510	25740	47930	35740	110.2
31	15.95	40350	30090	56440	42090	115.4
32	16.46	47150	35160	66130	49310	120.7

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-T	1-WT	1-WQ	JT
10	0.710	0.765	0.995	0.935	0.975	0.980	0.960	1.355
12	0.710	0.765	0.995	0.935	0.975	0.980	0.960	1.350
14	0.710	0.760	0.995	0.935	0.975	0.980	0.960	1.345
16	0.710	0.765	0.995	0.935	0.975	0.980	0.960	1.350
18	0.710	0.765	0.990	0.940	0.970	0.980	0.960	1.350
20	0.710	0.765	0.985	0.950	0.965	0.980	0.965	1.350
21	0.710	0.765	0.980	0.955	0.960	0.980	0.965	1.350
22	0.710	0.765	0.975	0.960	0.950	0.980	0.965	1.350
23	0.710	0.760	0.970	0.965	0.945	0.975	0.965	1.345
24	0.715	0.760	0.965	0.970	0.940	0.975	0.965	1.345
25	0.715	0.760	0.965	0.975	0.935	0.970	0.960	1.340
26	0.715	0.760	0.960	0.980	0.930	0.965	0.960	1.340
27	0.720	0.760	0.960	0.985	0.930	0.965	0.960	1.330
28	0.725	0.755	0.960	1.000	0.925	0.965	0.965	1.315
29	0.725	0.750	0.960	1.005	0.925	0.965	0.970	1.300
30	0.720	0.745	0.960	1.010	0.925	0.965	0.970	1.290
31	0.715	0.740	0.960	1.005	0.930	0.970	0.970	1.275
32	0.715	0.735	0.960	1.005	0.935	0.970	0.975	1.260

SINGLE SHAFTLINE TANDEM PROPELLERS
Model 5359-5A, Propellers 4781 and 4782

These experiments have been performed on a single shaftline destroyer hull form with the appendage suit sized appropriately for 6.10 meter (20 ft) diameter tandem propellers. The experiments were performed with no difficulties, though they showed poor performance. The experimental results are reported in Lin (1980c).

The results of these resistance and propulsion experiments are reported in Table B-19. The low resistance of this appendage suit results in effective powers of 5940 kW (7960 hp) at 20 knots, and 33670 kW (45160 hp) at 32 knots. These values represent 15.3 and 9.6 percent reductions over the respective baseline values of 7030 kW and 37250 kW at 20 and 32 knots, respectively.

Due to poor propulsor performance, the single tandem propellers achieved a net delivered power increase. The single shaftline tandem propellers required delivered powers of 10230 kW (13730 hp) and 57960 kW (77720 hp) at 20 and 32 knots, respectively. This represents increases in delivered power of 1.2 and 4.3 percent relative to the baseline values of 10110 kW at 20 knots and 54010 kW at 32 knots.

As was the case with the twin shaftline tandem propellers, the single shaftline tandem propeller performance was much poorer than would be expected with tandem propellers operating effectively. The propulsive efficiency of the single tandem is the lowest of the various propulsor configurations evaluated. It is not inconceivable that with a proper set of tandem propellers, the propulsive efficiency would be between 0.680 and 0.700, a 17 or 18 percent improvement in performance. Part of this improvement would be due to improved propeller efficiency. However, significant improvement in hull-propulsor interaction coefficients should also be expected. Thus, while there were no difficulties with these propulsion experiments, the experimental results do not accurately represent the performance which single shaftline tandem propellers should provide.

TABLE B-19 - POWERING PREDICTIONS FOR A PROTOTYPE DESTROYER HULL FORM FITTED WITH A SINGLE SET OF TANDEM PROPELLERS BASED ON EXPERIMENTS WITH MODEL 5359-5A, FROM LIN (1980c)

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	965	720	1660	1240	39.2
12	6.17	1730	1290	2980	2220	46.8
14	7.20	2780	2070	4780	3570	54.4
16	8.23	4130	3080	7120	5310	61.9
18	9.26	5840	4350	10070	7510	69.5
20	10.29	7960	5940	13730	10230	77.2
21	10.80	9180	6850	15830	11810	81.0
22	11.32	10490	7830	18190	13560	84.8
23	11.83	11930	8900	20750	15480	88.6
24	12.35	13530	10090	23530	17550	92.3
25	12.86	15330	11430	26520	19780	96.1
26	13.38	17400	12980	29850	22260	100.0
27	13.89	20050	14950	34160	25470	104.2
28	14.40	23510	17530	39910	29760	109.0
29	14.92	27710	20660	47050	35080	114.3
30	15.43	32790	24450	55860	41650	120.0
31	15.95	38750	28890	66240	49390	126.2
32	16.46	45160	33670	77720	57960	132.5
33	16.98	51910	38710	89820	66980	138.7
34	17.49	59170	44120	102900	76740	144.6

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-T	1-WT	1-WQ	JT
10	0.580	0.655	0.880	1.005	0.915	1.040	1.040	1.300
12	0.580	0.655	0.900	0.985	0.915	1.020	1.010	1.280
14	0.580	0.655	0.910	0.975	0.915	1.005	0.995	1.270
16	0.580	0.655	0.910	0.970	0.915	1.005	0.985	1.270
18	0.580	0.655	0.915	0.965	0.915	1.000	0.985	1.270
20	0.580	0.655	0.910	0.970	0.915	1.005	0.990	1.275
21	0.580	0.655	0.910	0.970	0.915	1.005	0.990	1.275
22	0.575	0.655	0.910	0.965	0.915	1.005	0.985	1.275
23	0.575	0.655	0.910	0.965	0.915	1.005	0.985	1,275
24	0.575	0.655	0.910	0.960	0.910	1.000	0.980	1.275
25	0.580	0.655	0.910	0.965	0.910	1.000	0.985	1.275
26	0.585	0.655	0.915	0.975	0.910	0.995	0.985	1.270
27	0.585	0.655	0.915	0.980	0.910	0.995	0.980	1.260
28	0.590	0.655	0.920	0.980	0.910	0.990	0.975	1.245
29	0.590	0.655	0.920	0.980	0.910	0.985	0.975	1.230
30	0.585	0.650	0.920	0.980	0.905	0.985	0.970	1.210
31	0.585	0.645	0.915	0.985	0.905	0.985	0.975	1.190
32	0.580	0.645	0.915	0.990	0.905	0.990	0.980	1.175
33	0.580	0.640	0.910	0.995	0.905	0.995	0.985	1.160
34	0.575	0.640	0.905	0.995	0.900	0.995	0.990	1.150

SUMMARY

A summary of the experimental results for the various propulsion configurations is provided for each of two ship speeds, 20 knots and 32 knots, in Tables B-20 and B-21, respectively. The first line of the table presents the results of powering experiments for the DD-963 baseline configuration with twin shafts and struts and controllable-pitch propellers. In this case the resistance of the parent hull with appendages has been increased by 1.5 percent to account for the resistance of larger shafting and struts required by NAVSEA design practice. The first two columns of the summary tables provide effective and delivered power predictions extrapolated from model test results. The following six columns present the propulsion efficiencies and propeller-hull interaction coefficients. Finally, the last two columns present the ratio of the effective and delivered powers measured with stock propellers for each particular configuration to that of the DD-963 baseline. In the summary tables the results from the best set of stock propellers are presented when more than one set of stock propellers were used on a configuration.

TABLE B-20 - SUMMARY OF POWERING PREDICTIONS FROM EXPERIMENTAL RESULTS FOR A SHIP SPEED OF 20 KNOTS

Coefficient and Power Ratio / Propulsion Arrangement	P_E	P_D	η_D	η_O	η_H	η_R	1-t	$1-w_T$	$\frac{P_{E_X}}{P_E 5359}$	$\frac{P_{D_X}}{P_D 5359}$
Twin Shaftline CP Baseline (5359)	9430*	13560*	0.695	0.750	0.965	0.955	0.960	0.990	1.000	1.000
Twin Pod CR (5359-1C)	8510	11190	0.760	0.795	0.945	1.010	0.920	0.975	0.902	0.825
Twin BRP-FP (5359-OA1)	8560	12110	0.705	0.750	0.945	0.995	0.895	0.945	0.908	0.893
Twin Shaftline CR (5359-1B)	9080	11780	0.770	0.795	0.945	1.025	0.935	0.990	0.963	0.869
Twin Shaftline FP (5359-1)	8650	12070	0.715	0.755	0.970	0.985	0.920	0.950	0.917	0.885
Twin BRP-CP (5359-OA)	8670*	13000*	0.667	0.685	0.969	1.005	0.925	0.955	0.919	0.958
Twin Shaftline, Large Dia. FP (5359-2)	8750	12700	0.690	0.750	0.990	0.935	0.990	1.005	0.928	0.937
Twin Shaftline Tandem (5359-1A)	8710	14890	0.585	0.635	0.920	1.000	0.960	1.040	0.924	1.098
Twin Shaftline CP with Revised Fairwaters (5359)	9180**	13380**	---	---	---	---	---	---	0.974	0.987
Twin Shaftline, Large Dia. Overlapping (5359-3)	8920	14320	0.623	0.750	0.969	0.855	0.962	0.993	0.946	1.056
Twin Shaftline, Large Dia. CP (5359-2A)	9270	14600	0.635	0.755	0.930	0.905	0.935	1.005	0.983	1.077
Single Shaftline CR (5359-5)	8510	11950	0.710	0.765	0.985	0.950	0.965	0.980	0.902	0.881
Single Shaftline Tandem (5359-5A)	7960	13730	0.580	0.655	0.910	0.970	0.915	1.005	0.844	1.013

Notes: CP = Controllable-Pitch Propellers; FP = Fixed-Pitch Propellers; CR = Contrarotating Propellers; BRP = Bearing-in-Rudder Post.
*These values were increased 1½% to reflect existing NAVSEA appendage design practice (see text).
**These values have been adjusted to maintain the same relationship to the parent configuration as shown in Lin and Borda (1983)

TABLE B-21 - SUMMARY OF POWERING PREDICTIONS FROM EXPERIMENTAL RESULTS FOR A SHIP SPEED OF 32 KNOTS

Coefficient and Power Ratio / Propulsion Arrangement	P_E	P_D	η_D	η_O	η_H	η_R	1-t	$1-w_T$	$\frac{P_{EX}}{P_E5359}$	$\frac{P_{DX}}{P_D5359}$
Twin Shaftline CP Baseline (5359)	49960*	72430*	0.690	0.749	0.951	0.969	0.960	1.009	1.000	1.000
Twin Pod CR (5359-1C)	46000	61500	0.750	0.800	0.935	1.000	0.915	0.980	0.921	0.849
Twin BRP-FP (5359-OA1)	46530	67430	0.690	0.735	0.925	1.015	0.895	0.965	0.931	0.931
Twin Shaftline CR (5359-1B)	48300	63190	0.765	0.800	0.935	1.025	0.930	0.995	0.967	0.872
Twin Shaftline FP (5359-1)	47160	68050	0.695	0.740	0.945	0.990	0.925	0.975	0.944	0.940
Twin BRP-CP (5359-OA)	49500*	75800*	0.653	0.685	0.949	1.005	0.925	0.975	0.990	1.047
Twin Shaftline, Large Dia. FP (5359-2)	48840	69870	0.700	0.760	0.985	0.935	0.990	1.005	0.978	0.965
Twin Shaftline Tandem (5359-1A)	47310	80190	0.590	0.655	0.915	0.985	0.930	1.015	0.947	1.107
Twin Shaftline CP with Revised Fairwaters (5359)	49010**	71920**	---	---	---	---	---	---	0.981	0.993
Twin Shaftline, Large Dia. Overlapping (5359-3)	48730	74510	0.654	0.760	0.960	0.896	0.968	1.015	0.975	1.029
Twin Shaftline, Large Dia. CP (5359-2A)	50540	76700	0.660	0.755	0.945	0.925	0.960	1.002	1.012	1.059
Single Shaftline CR (5359-5)	47150	66130	0.715	0.735	0.960	1.005	0.935	0.970	0.944	0.913
Single Shaftline Tandem (5359-5A)	45160	77720	0.580	0.645	0.915	0.990	0.905	0.990	0.904	1.073

Notes: CP = Controllable-Pitch Propellers; FP = Fixed-Pitch Propellers; CR = Contrarotating Propellers; BRP = Bearing-in-Rudder Post.
*These values were increased 1½% to reflect existing NAVSEA appendage design practice (see text).
**These values have been adjusted to maintain the same relationship to the parent configuration as shown in Lin and Borda (1983)

APPENDIX C

PROJECTED PROPULSION PERFORMANCE FOR FIFTEEN PROPULSION CONFIGURATIONS ON A DESTROYER

CONTENTS - APPENDIX C

PROJECTED PROPULSION PERFORMANCE FOR FIFTEEN PROPULSION CONFIGURATIONS ON A DESTROYER

INTRODUCTION

This appendix presents predictions of propulsion performance with design propellers for all of the configurations covered in this report. Given the model experimental results using stock propellers presented in Appendix B, and making assumptions regarding hull-propulsor interaction coefficients, the question, "What would be the configurations' performance with new 'well-designed' propellers?" will be answered. These results should be highly indicative of what one might expect as a near maximum for performance. By comparing these results for all of the configurations evaluated, a hierarchy of benefits will unfold from which management can make technology development and investment decisions.

A general description of how the performance predictions are made will be followed by a detailed description of the performance predictions with design propellers for each configuration on a case-by-case basis. Finally, a summary of these projections is presented. The order in which the configurations will be treated is consistent with that presented in Appendices A and B.

The predictions of design propeller powering performance are based upon experimental data from the stock propeller model experiments. In general the hull-propulsor interaction coefficients from these experiments are assumed to hold, Todd (1967), Karafiath and Wilson (1983). Using this information, estimated design propeller open water characteristics are generated. Lastly, these data are used to generate performance estimates over a speed range for each configuration with design propellers.

Some discussion of this procedure is in order. It is common practice to use the above approach when neither funds nor time are available to actually design, manufacture, and test a propeller. However, care must be taken when applying the assumption that the hull-propulsor interaction coefficients are identical for the stock and design propeller cases. Thus, where applicable in the discussion of the results for each individual propulsion configuration, coefficient variations and why they were taken will be discussed.

The resistance estimates are based on experimental results in all but two cases: the single shaftline fixed-pitch and single shaftline controllable-pitch propeller configurations. In these latter cases the results were inferred from the resistance results of those single shaftline configurations that were tested.

The one configuration where the above conclusions may not hold true is that of podded propulsion. The effective power used to make the performance prediction estimate for podded propulsion is based on experimental results, and is therefore reliable. The risk associated with pods is the uncertainty of pod size. Because pod size is highly dependent on the size of the machinery the pod encloses, and because of the uncertainty concerning the size of the machinery, there is a high probability that the size of the pod will change. The full-scale size of the pods which were evaluated experimentally [2.1 m (7 ft) diameter, 15.5 m (51 ft) length] was on the smaller end of the size scale for projected machinery arrangements. Therefore, there is a high probability that the pod size will increase, possibly resulting in significant increases in system resistance. This particular issue is discussed further in the main body of the report.

The details of the propeller performance estimates differ between the single rotation propeller cases (controllable-pitch, fixed-pitch, and tandem propellers) and the contrarotating propeller cases. The single rotation propeller studies were performed using the same criteria for strength and cavitation which were used in the design of the propellers which are employed on the DD-963. The results of these studies are reported by Majumdar and Krishnamoorthy (1980) and by Krishnamoorthy (1982). The report by Majumdar and Krishnamoorthy also includes predictions of propeller performance for both the single and twin shaftline contrarotating propeller configurations.

Majumdar and Krishnamoorthy's contrarotating propeller performance predictions were not used in this report; instead, new design studies were performed by the DTNSRDC Propulsor Technology Branch (Code 1544). These design studies employed a revised version of the DTNSRDC contrarotating propeller design program. This design program is an upgrade of the program reported by Caster and LaFone (1975), which is based on the theory of Morgan (1960). The upgrades of the Caster and LaFone program consist primarily of: 1) updating the lifting line program used to make the blade geometry calculations, and 2) improveing the induced velocity calculations used to determine the interaction between the two propellers of the contrarotating set.

In all of the propeller design calculations, the tips of the propellers have been unloaded by reducing the hydrodynamic pitch at the blade tip 10 percent relative to that at the 0.7 radius. This was done in order to reduce the propellers' susceptibility to tip vortex cavitation.

The blade section drag coefficient in all of the designs was assumed to be between 0.009 and 0.008 at the 0.7 radius. This is a conservative choice of drag coefficients and corresponds to values which would typically be found on model scale propellers. Full-scale section drag coefficients typically would be around 0.004 at the 0.7 radius, leading to yet higher propulsive efficiencies than are reported herein.

The powering performance predictions for the single rotation propellers have been prepared in the following manner. From the experimental hull-propulsor interaction coefficients, and the propeller efficiency (η_o) and rpm given in the reports by Majumdar and Krishnamoorthy (1980), and by Krishnamoorthy (1982), a thrust coefficient (K_T) and advance coefficient (J) were derived. The K_T, J, and η_o were then used to derive the corresponding torque coefficient (K_Q). In combination with the stock propeller open water characteristics and systematic propeller series data, these K_T, K_Q, and J values were used to develop an open water curve for the design propeller. This open water curve was used as input to the calculations of the delivered power and rpm over the speed range.

Although this is the general scheme which has been used to produce powering estimates for all single rotation propeller designs, deviations from this procedure do occur in the predictions of this report. Such deviations will be dealt with when the specific configurations, for which such deviations occur, are discussed.

The single rotation propeller designs are of relatively low risk in terms of their meeting the projected propeller efficiency. There is a somewhat higher risk with regard to the propellers meeting the design rpm at the operating point. Variations from the design operating point can be ignored unless they cause machinery difficulties through poor operating efficiency or unacceptable gearing of shafting loads. Such machinery problems can be resolved by performing a propeller redesign to correct the rpm problem.

In the case of tandem propellers, the chance that such a redesign will be required is almost certain. This is a result of the propeller designers' inability to properly account for the interaction between the two propellers. To compensate for this, it is standard practice with tandem propellers to build the model scale design propellers so that the axial spacing between the forward and aft propellers, and the relative angular rotation between the two propellers, can be varied to optimize the propeller efficiency and the cavitation performance.

The powering predictions for the contrarotating propeller configurations were prepared in a manner somewhat different from that of the single rotation propeller configurations. The predictions of optimum contrarotating propeller geometry result in predictions of optimum propeller efficiency behind rather than optimum propeller open water efficiency. Thus, because the relative rotative efficiency was not an input to the contrarotating propeller calculations, but rather an implied output, the design propeller open water characteristics must be derived independently of the propeller design program.

In order that the design propellers' open water performance could be derived, some assumptions had to be made. The details of how these calculations were performed for the three contrarotating configurations are given in Table C-1. This table shows the various efficiencies which contribute to propulsion efficiency for each of the configurations at the 20-knot propeller design speed. Within each efficiency block. three rows labeled Measured, Designed, and Projected are presented; they represent the results of model experiments (from Appendix B), the results of propeller parametric designs, and the values used in the projections presented herein, respectively.

The actual process presented in Table C-1 is as follows. The propulsion efficiency derived from the parametric design studies is used in conjunction with the hull efficiency to determine a propeller efficiency behind. This propeller efficiency behind is then further split into two terms, open water efficiency and relative rotative efficiency. Parametric studies of open water efficiency, Nelka and Cox (1981), and the experimental relative rotative efficiency values are used as guidance in determining this division. Once the open water and relative rotative efficiencies have been defined, the open water efficiency is used to derive an open water curve, and the process proceeds in the same fashion as was employed for the single rotation propeller configurations.

As with the single rotation propeller case, the individual assumptions and the deviations from the above outlined procedure will be detailed as part of the discussion of the individual configurations. Because there is no report on the parametric studies which were performed for the three contrarotating propeller cases, the results of each parametric study are given as part of their respective discussions.

TABLE C-1 - PROPULSION COEFFICIENTS FOR CONTRAROTATING PROPELLER CONFIGURATIONS AT 20 KNOTS

		Pods	Twin Shaftline	Single Shaftline
η_D	Measured	0.760	0.770	0.710
	Designed	0.783	0.769	0.777
	Projected	0.785	0.770	0.775
η_B	Measured	0.803	0.815	0.727
	Designed	0.829	0.814	0.789
	Projected	0.828	0.815	0.785
η_H	Measured	0.945	0.945	0.985
	Designed	0.945	0.945	0.985
	Projected	0.945	0.945	0.985
η_O	Measured	0.795	0.795	0.765
	Designed	---	---	---
	Projected	0.820	0.795	0.800
η_R	Measured	1.010	1.025	0.950
	Designed	---	---	---
	Projected	1.010	1.025	0.980

The contrarotating propeller design program and its predictions are somewhat more risky than the single rotation propeller designs. A very limited verification of a design developed for uniform flow indicates that the revised contrarotating propeller design program underpredicts the propeller efficiency by 1 to 2 percent. This validation also indicates that the program does not predict the pitch of the aft propeller correctly, which results in thrust and torque ratios at significant variance with those predicted for the propellers. Despite these uncertainties concerning the reliability of the contrarotating propeller design program, there is no doubt that, if an iterative design and experimental evaluation procedure is followed, contrarotating propellers can be designed successfully at the present time.

A second risk factor associated with the contrarotating propeller design predictions is the fact that the projected contrarotating propellers are much higher in pitch and consequently turn at much lower rpm than the stock propellers. It should be expected that with the higher pitch of the projected design propellers, the hull-propulsor interaction coefficients will differ significantly from those of the stock propeller experiments. While this is a risk factor, there is no reason to expect that the change in hull and propulsor interaction coefficients will result in a loss in achievable propulsive efficiencies. The major impact of this fact is that several iterations may be expected before a design which converges to optimum performance is realized.

This concludes the general discussion of the prediction methods which are used to make the performance estimates for the 15 propulsor configurations discussed in this report. The discussion of the individual configurations now follows. The discussion starts with the establishment of the baseline, which is derived from the DD-963 equipped with twin controllable-pitch propellers.

TWIN SHAFTLINE CONTROLLABLE-PITCH PROPELLERS (DD-963 BASELINE)

The parent configuration chosen for this study was the DD-963 hull form fitted with twin shafts and struts and controllable-pitch propellers. Because the shafting and appendage designs for all of the alternative propulsor configurations were developed using normal U.S. Navy design practices and standards, Tomassoni and Slager (1980), the appendages and shafting for the parent were redesigned using the same methods. The conclusion of this redesign was that the outside diameter of the full-scale shafting should be increased 38 mm (1.5 in), from 546 mm (21.5 in) to 584 mm (23 in). The baseline configuration is the DD-963 hull form fitted with these larger appendages. The estimated effect of this 7 percent increase in shafting diameter has been incorporated in the predicted performance of the baseline configuration as an increase in resistance over that of the parent DD-963.

The powering performance estimates for the controllable-pitch propeller baseline were produced by reanalyzing the original powering data with the resistance increased by 1.5 percent. This was accomplished by entering the hull-propulsor interaction coefficients [thrust deduction (1-t), wake fraction ($1-w_T$), and relative rotative efficiency (η_R)] into the powering performance prediction program along with the ship resistance and open water data for the DD-963 design propellers. A new operating point for the propellers was determined by the program along with the corresponding propeller efficiency and the resulting propulsion efficiency. The results of the above prediction for the controllable-pitch propeller baseline are presented in Table C-2.

The DD-963 with twin shafts and struts and controllable-pitch propellers has been evaluated experimentally a number of times with extremely consistent results. A number of these experiments have also involved increased displacements with an implied increase in resistance, which had little effect on the hull-propulsor interaction coefficients. From this, it can be concluded that the risks associated with the performance predictions for the controllable-pitch propeller baseline are extremely low.

TABLE C-2 - PROJECTED POWERING PERFORMANCE FOR THE BASELINE CONFIGURATION WITH TWIN CONTROLLABLE-PITCH PROPELLERS

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1130	840	1620	1210	48.7
12	6.17	2040	1520	2940	2190	58.4
14	7.20	3290	2460	4740	3530	68.2
16	8.23	4900	3660	7050	5260	77.9
18	9.26	6940	5180	9990	7450	87.5
20	10.29	9430	7030	13560	10110	97.1
21	10.80	10820	8070	15570	11610	101.7
22	11.32	12350	9210	17760	13240	106.3
23	11.83	13990	10430	20130	15010	111.0
24	12.35	15780	11770	22700	16930	115.5
25	12.86	17750	13230	25530	19040	120.2
26	13.38	19990	14900	28750	21440	125.2
27	13.89	22880	17060	32910	24540	130.4
28	14.40	26640	19860	38370	28610	136.2
29	14.92	31340	23370	45170	33680	142.9
30	15.43	36830	27460	53180	39660	150.1
31	15.95	43120	32160	62360	46500	157.3
32	16.46	49960	37250	72430	54010	164.5
33	16.98	57380	42780	83500	62270	171.6
34	17.49	65050	48510	95040	70870	178.2

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	J_T
10	0.695	0.750	0.955	0.970	0.960	1.005	0.995	1.230
12	0.695	0.750	0.965	0.960	0.960	0.995	0.980	1.220
14	0.695	0.750	0.970	0.955	0.960	0.990	0.975	1.215
16	0.695	0.750	0.965	0.955	0.960	0.995	0.975	1.215
18	0.695	0.750	0.970	0.955	0.960	0.990	0.975	1.215
20	0.695	0.750	0.970	0.955	0.960	0.990	0.975	1.215
21	0.695	0.750	0.970	0.955	0.960	0.990	0.975	1.220
22	0.695	0.750	0.970	0.950	0.960	0.990	0.970	1.220
23	0.695	0.750	0.970	0.950	0.960	0.990	0.970	1.220
24	0.695	0.750	0.975	0.950	0.960	0.985	0.970	1.220
25	0.695	0.750	0.975	0.950	0.960	0.985	0.970	1.225
26	0.695	0.750	0.970	0.950	0.960	0.990	0.970	1.225
27	0.695	0.750	0.970	0.950	0.960	0.990	0.970	1.220
28	0.695	0.750	0.970	0.950	0.960	0.990	0.970	1.210
29	0.695	0.750	0.970	0.955	0.960	0.990	0.975	1.200
30	0.690	0.750	0.960	0.960	0.960	1.000	0.985	1.190
31	0.690	0.750	0.955	0.965	0.960	1.005	0.990	1.180
32	0.690	0.750	0.950	0.970	0.960	1.010	0.995	1.170
33	0.685	0.745	0.950	0.970	0.960	1.015	1.000	1.160
34	0.685	0.745	0.945	0.970	0.960	1.015	1.000	1.155

TWIN PODS WITH CONTRAROTATING PROPELLERS

The performance of podded propulsors with contrarotating propellers fitted to the DD-963 hull form has been predicted in the manner discussed in the introduction to this appendix. The effective power from the stock propeller propulsion experiments with pods has been assumed to be valid. The wake fraction $(1-w_T)$ and thrust deduction (1-t) from the stock propeller propulsion experiments with pods, in conjunction with the model resistance and the wake survey data from the Escort Research Ship* (an unbuilt ship design fitted with a pod-like nacelle), have been combined to provide the information necessary as input to the contrarotating propeller design program. This program has been used to perform a series of parametric studies of propulsive efficiency as a function of propeller diameter and rpm. The results of this study are shown in Figure C-1.

As can be seen from Figure C-1, the optimum contrarotating propellers for podded propulsion on the DD-963 are 5.18 m (17 ft) in diameter and turn 65 rpm at 20 knots. The propulsion efficiency of these propellers is predicted to be 0.783, neglecting the effect of relative rotative efficiency on the propeller efficiency behind. From the shape and position of the curves for the other two propeller diameters of the parametric study, it can be seen that the 5.18 meter (17 ft) propeller diameter chosen is very close to the optimum propeller diameter for the selected pods.

The details of the derivation of the hull-propulsor interaction coefficients for podded propulsion at 20 knots are given in the first column of Table C-1. The projected values have been derived from the design values by applying the experimental relative rotative efficiency to the design propulsive efficiency to obtain the projected propulsive efficiency. Based on the geometric characteristics of the optimum propeller from the parametric studies and the results of the generic parametric studies contained in Nelka and Cox (1981), it was determined that the optimum propeller open water efficiency would be 0.820. This is consistent with the propeller efficiency of 0.828 behind and the

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* From a report of higher classification by Yeh and Gawlik.

experimental relative rotative efficiency of 1.010.

The performance predictions for podded propulsion with contrarotating propellers are given in Table C-3 for speeds between 10 and 32 knots. At 20 knots podded propulsion requires a delivered power of 8110 kW (10870 hp), as compared to the baseline, which requires 10110 kW, a 19.8 percent reduction in delivered power. At 32 knots, a delivered power of 45080 kW (60450 hp) is required, as compared to the baseline, which required 54010 kW. This is a 16.5 percent reduction in delivered power over that of the baseline configuration.

The expanded area ratios (EAR) for the optimum propellers in the parametric study were 0.399 as opposed to the value of 0.365 for both forward and aft stock propellers. These values of EAR were chosen based on cavitation considerations at 32 knots and on propeller strength. The 20-knot rotational speed of the design propellers is 66 rpm, which compares to 72 rpm for the stock propellers and 97 rpm for the DD-963 design controllable-pitch propellers at the same ship speed. This reflects the very high pitch-diameter ratio (P/D), 2.037 for the forward design propeller and 2.036 for the aft design propeller, as opposed to the values of 1.65 and 1.89 for the forward and aft stock propellers, respectively.

The higher EAR and P/D for the design propellers is certain to have some effect on the hull-propulsor interaction coefficients. However, this effect is unknown, and is most likely not going to affect the propulsion efficiency of the system significantly. As with most similar issues, the only way in which the exact effects could be determined would be to perform a wake survey and to design and build design propellers so that they can be evaluated experimentally.

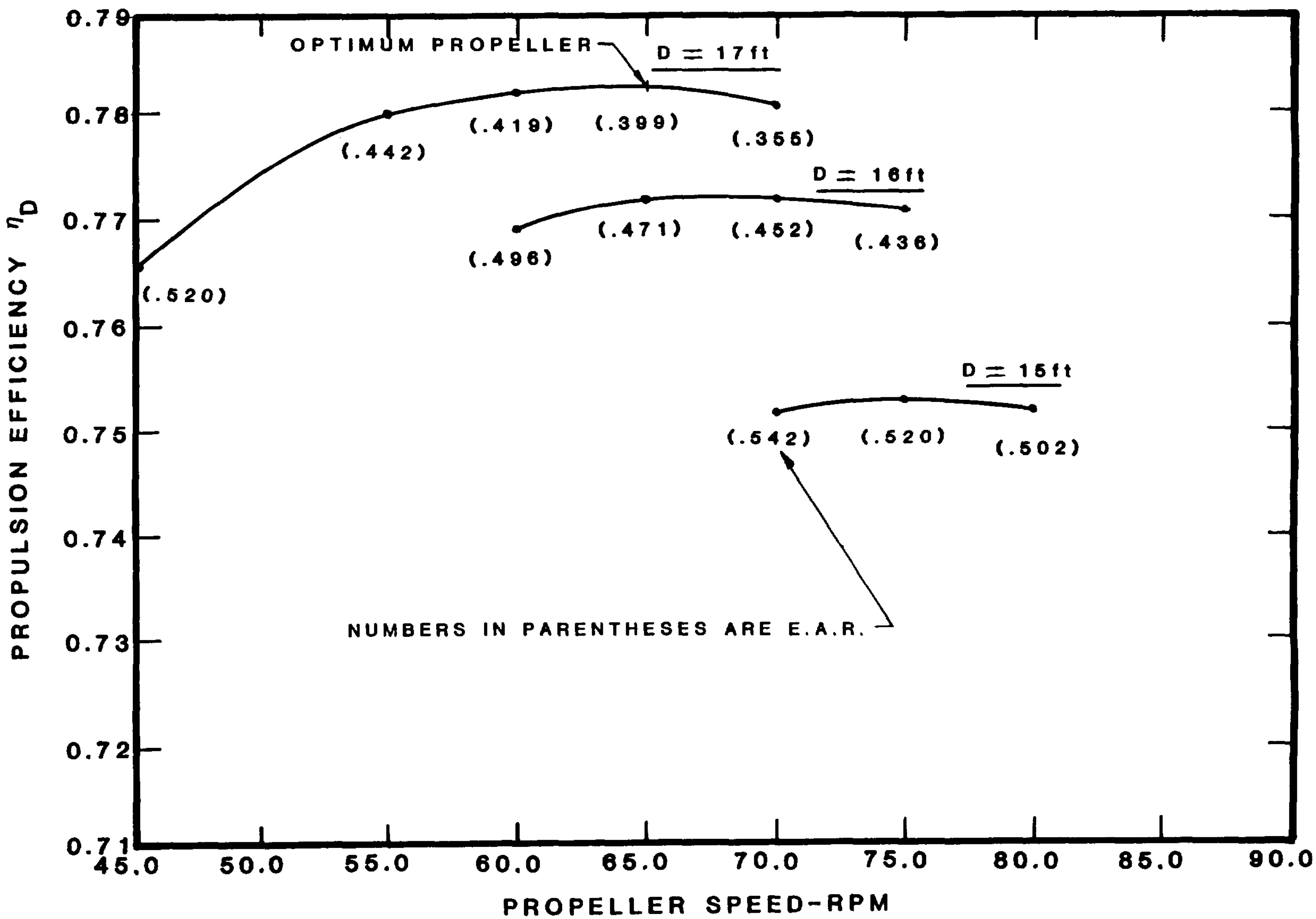

Figure C-1 - Propulsion Efficiency for Contrarotating Propellers on Twin Pods: Results of a Parametric Study

TABLE C-3 - PROJECTED POWERING PERFORMANCE FOR THE DD-963 HULL FORM FITTED WITH TWIN PODS AND CONTRAROTATING PROPELLERS

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	970	725	1240	920	32.2
12	6.17	1750	1300	2240	1670	38.8
14	7.20	2830	2110	3630	2710	45.4
16	8.23	4250	3170	5450	4070	51.9
18	9.26	6070	4530	7800	5820	58.8
20	10.29	8510	6340	10870	8110	65.0
21	10.80	9880	7370	12600	9400	67.9
22	11.32	11290	8420	14370	10720	71.1
23	11.83	12740	9500	16170	12060	74.0
24	12.35	14280	10650	18120	13520	76.8
25	12.86	16050	11970	20370	15200	80.0
26	13.38	18180	13550	23090	17230	83.5
27	13.89	20890	15580	26610	19850	87.0
28	14.40	24340	18150	31090	23200	90.8
29	14.92	28520	21270	36840	27480	94.6
30	15.43	33500	24980	43400	32380	99.3
31	15.95	39330	29330	51540	38450	104.4
32	16.46	46000	34300	60450	45080	109.4

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	J_T
10	0.785	0.820	0.940	1.015	0.920	0.980	0.985	1.774
12	0.780	0.820	0.940	1.015	0.920	0.980	0.985	1.762
14	0.780	0.820	0.940	1.010	0.920	0.980	0.985	1.757
16	0.780	0.820	0.940	1.010	0.920	0.980	0.985	1.757
18	0.780	0.820	0.940	1.010	0.920	0.980	0.980	1.746
20	0.785	0.820	0.945	1.010	0.920	0.975	0.975	1.746
21	0.785	0.820	0.955	1.000	0.925	0.970	0.970	1.746
22	0.785	0.820	0.955	1.000	0.925	0.970	0.970	1.746
23	0.790	0.820	0.955	1.010	0.920	0.965	0.970	1.746
24	0.790	0.820	0.945	1.015	0.910	0.960	0.965	1.746
25	0.790	0.820	0.945	1.020	0.905	0.960	0.965	1.746
26	0.785	0.820	0.945	1.015	0.905	0.960	0.965	1.740
27	0.785	0.820	0.945	1.010	0.905	0.960	0.960	1.735
28	0.785	0.820	0.945	1.010	0.910	0.960	0.960	1.724
29	0.775	0.815	0.950	1.000	0.910	0.960	0.960	1.712
30	0.770	0.815	0.950	1.000	0.915	0.965	0.965	1.696
31	0.765	0.815	0.940	1.000	0.915	0.975	0.975	1.685
32	0.760	0.815	0.935	1.000	0.915	0.980	0.980	1.668

TWIN BEARING-IN-RUDDER POST WITH FIXED-PITCH PROPELLERS

The case of bearing-in-rudder post with fixed-pitch propellers applied to the DD-963 hull form provides a difficult case for prognostication. As described in Appendix E, two sets of fixed-pitch propellers [4.79 m (15.8 ft) and 5.18 m (17 ft) in diameter] were evaluated experimentally with both shafts and struts and bearing-in-rudder post appendage suits. In all cases, the performance of the smaller pair of propellers was inferior to that of the larger set of propellers. However, in the bearing-in-rudder post configuration, the smaller set of propellers requires 2 to 3 percent less power, depending on speed, than the same set of propellers in the shafts and struts configurations. In the bearing-in-rudder post configuration, the larger set of propellers requires, depending on speed, between 1 percent more and 1 percent less delivered power than the same set of propellers in the shafts and struts configuration. Thus, if the performance of the bearing-in-rudder post configuration with fixed-pitch propellers were to be predicted based on the experiments with the small diameter propellers, the bearing-in-rudder post configuration would show a 2 to 3 percent better performance than that of the fixed-pitch propellers with shafts and struts. However, the corresponding predictions for shafts and struts do not follow, in that the predicted results would be several percent worse than the results achieved experimentally with the best set of propellers.

On the other hand, if the results of the experiments with the large diameter propellers are used as the basis of the fixed-pitch bearing-in-rudder post predictions, then there would be no difference in performance between the bearing-in-rudder post and shafts and struts configurations, although the shafts and struts performance would be close to the optimum attainable.

In the predictions which are made herein for bearing-in-rudder post configurations with fixed-pitch propellers, a mixed approach is chosen. The fixed-pitch propeller performance with shafts and struts is assumed to be attainable based on the experiments with the large diameter fixed-pitch propellers. The bearing-in-rudder post performance is then assumed to be 2 to 3 percent better than the shafts and struts performance, based on the experimental results with the small diameter propellers. In order to achieve this prediction, the hull-propulsor interaction coefficients for the large diameter propeller shafts and struts configurations were modified based on the differences between results for the small diameter propellers in the shafts and struts and bearing-in-rudder post configurations.

The performance predictions for the DD-963 hull form fitted with bearing-in-rudder post and fixed-pitch propellers are given in Table C-4, for speeds between 10 and 32 knots. At 20 knots the DD-963 hull form with bearing-in-rudder post and fixed-pitch propellers requires a delivered power of 8590 kW (11510 hp), as compared to the DD-963 baseline, which requires 10110 kW, a 15.0 percent reduction in delivered power. At 32 knots, a delivered power of 48530 kW (65080 hp) is required, as compared to the DD-963 baseline, which required 54010 kW. This represents a 10.1 percent reduction in delivered power over that of the baseline configuration.

The risks associated with this prediction are relatively high, in that the bearing-in-rudder post and the mechanics of its improved performance relative to shafts and struts are little understood. Because of this lack of understanding, the practicality of achieving the artificially projected improvements in performance with the fixed-pitch propeller bearing-in-rudder post configuration is unknown. However, if one is to judge from the great number of propellers evaluated on the PC, PCC, and EPC ship classes before a satisfactory propeller design was achieved, and from the great range of hull-propulsor interaction coefficients obtained from these experiments, it would seem that if sufficient resources are invested, the projections are probably achievable. The real issue which must be resolved is whether the 3 percent improvement over shafts and struts with fixed-pitch propellers is worth the increased technical risks associated with bearing-in-rudder post.

Table C-4 - PROJECTED POWERING PERFORMANCE FOR THE DD-963 HULL FORM FITTED WITH BEARING-IN-RUDDER POST CONFIGURATION WITH TWIN FIXED-PITCH PROPELLERS

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1000	750	1350	1000	40.8
12	6.17	1830	1360	2450	1830	49.5
14	7.20	2980	2220	4010	2990	58.1
16	8.23	4490	3350	6050	4510	66.5
18	9.26	6350	4740	8550	6380	74.7
20	10.29	8560	6390	11510	8590	82.7
21	10.80	9820	7330	13200	9850	86.7
22	11.32	11180	8340	15020	11200	90.6
23	11.83	12650	9430	16980	12660	94.5
24	12.35	14250	10630	19120	14250	98.4
25	12.86	16050	11970	21530	16050	102.5
26	13.38	18240	13600	24480	18260	106.8
27	13.89	21030	15690	28280	21090	111.6
28	14.40	24570	18320	33190	24750	117.1
29	14.92	28930	21570	39270	29280	122.9
30	15.43	34140	25460	46710	34830	129.3
31	15.95	40070	29880	55360	41290	136.0
32	16.46	46530	34700	65080	48530	142.8

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	J_T
10	0.745	0.765	0.955	1.020	0.905	0.945	0.955	1.385
12	0.745	0.765	0.955	1.020	0.905	0.945	0.955	1.370
14	0.745	0.760	0.955	1.020	0.905	0.945	0.955	1.360
16	0.745	0.760	0.955	1.020	0.905	0.945	0.955	1.355
18	0.745	0.760	0.955	1.020	0.905	0.945	0.955	1.360
20	0.745	0.765	0.955	1.020	0.905	0.945	0.955	1.365
21	0.745	0.765	0.955	1.020	0.905	0.945	0.955	1.365
22	0.745	0.765	0.955	1.020	0.905	0.945	0.955	1.370
23	0.745	0.765	0.955	1.020	0.905	0.945	0.955	1.375
24	0.745	0.765	0.955	1.020	0.905	0.945	0.955	1.375
25	0.745	0.765	0.955	1.020	0.905	0.945	0.955	1.375
26	0.745	0.765	0.955	1.020	0.905	0.945	0.955	1.375
27	0.745	0.765	0.955	1.020	0.905	0.945	0.955	1.365
28	0.740	0.760	0.950	1.025	0.900	0.950	0.960	1.350
29	0.735	0.760	0.950	1.025	0.900	0.950	0.960	1.335
30	0.730	0.755	0.945	1.025	0.900	0.950	0.965	1.315
31	0.725	0.750	0.940	1.025	0.900	0.955	0.970	1.300
32	0.715	0.750	0.935	1.025	0.900	0.965	0.980	1.290

TWIN SHAFTLINE CONTRAROTATING PROPELLERS

Performance predictions for the DD-963 hull form fitted with twin shaftline contrarotating propellers are extremely straightforward and of low risk. The resistance from the stock propeller experiments has been assumed to hold. This resistance, in conjunction with the wake fraction $(1-w_T)$ and thrust deduction $(1-t)$ from the stock propeller propulsion experiments, and the wake survey data from the DD-963 parent fitted with shafts and struts and controllable-pitch propellers, Day (1975), have been used to perform a parametric study of optimum contrarotating propeller performance. Figure C-2 shows the predicted propulsion efficiency as a function of propeller rpm for three diameters.

As can be seen from Figure C-2, the optimum propeller from this study would be 5.17 m (17 ft) in diameter, resulting in a propulsion efficiency of 0.769 and operating at 64 rpm. The relative location of the optimum rpms on the curves for the other two diameters would indicate that yet higher efficiency might be attainable with a larger diameter propeller. However, a larger diameter propeller could not easily be employed on this hull without modifying the hull form or having the propeller extend an unacceptable distance below the hull.

The details of the derivation of the hull-propulsor interaction coefficient for twin shaftline contrarotating propellers at 20 knots are given in the second column of Table C-1. In this case, the powering prediction from the parametric study (Design) and the experimental results are extremely close. Therefore, experimental results have been used as the projected results, with the exception that the propeller rpms have been adjusted to correspond to those which would be given by the new propeller design.

The performance predictions for the DD-963 fitted with twin shafts and struts and contrarotating propellers are given in Table C-5 for speeds between 10 and 32 knots. At 20 knots the twin shaftline contrarotating propeller configuration requires a delivered power of 8780 kW (11780 hp), as compared to the baseline, which requires 10110 kW, a 13.2 percent reduction is delivered power. At 32 knots, this configuration requires 47120 kW (63190 hp), as compared to the 54080 kW, required by the baseline. This represents a 12.9 percent reduction in deliverd power.

These design propellers have a higher expanded area ratio (0.424 on each) than the stock propellers (0.365 on each), and they have a higher pitch-diameter ratio (2.07 - 2.11) than the stock propellers (1.65 forward and 1.89 aft). The result of these tradeoffs is, according to Nelka and Cox (1981), that these propellers should have an open water efficiency of 0.82 rather than the 0.80 value which has been assumed. This means that the propeller efficiencies assumed are conservative, and that most likely the efficiency of the total system would be higher than that projected. Thus these projections would seem to be of low risk. However, as discussed earlier, this is conditional on the effects of the higher expanded area ratio and pitch-diameter ratio on the hull-propulsor interaction coefficients.

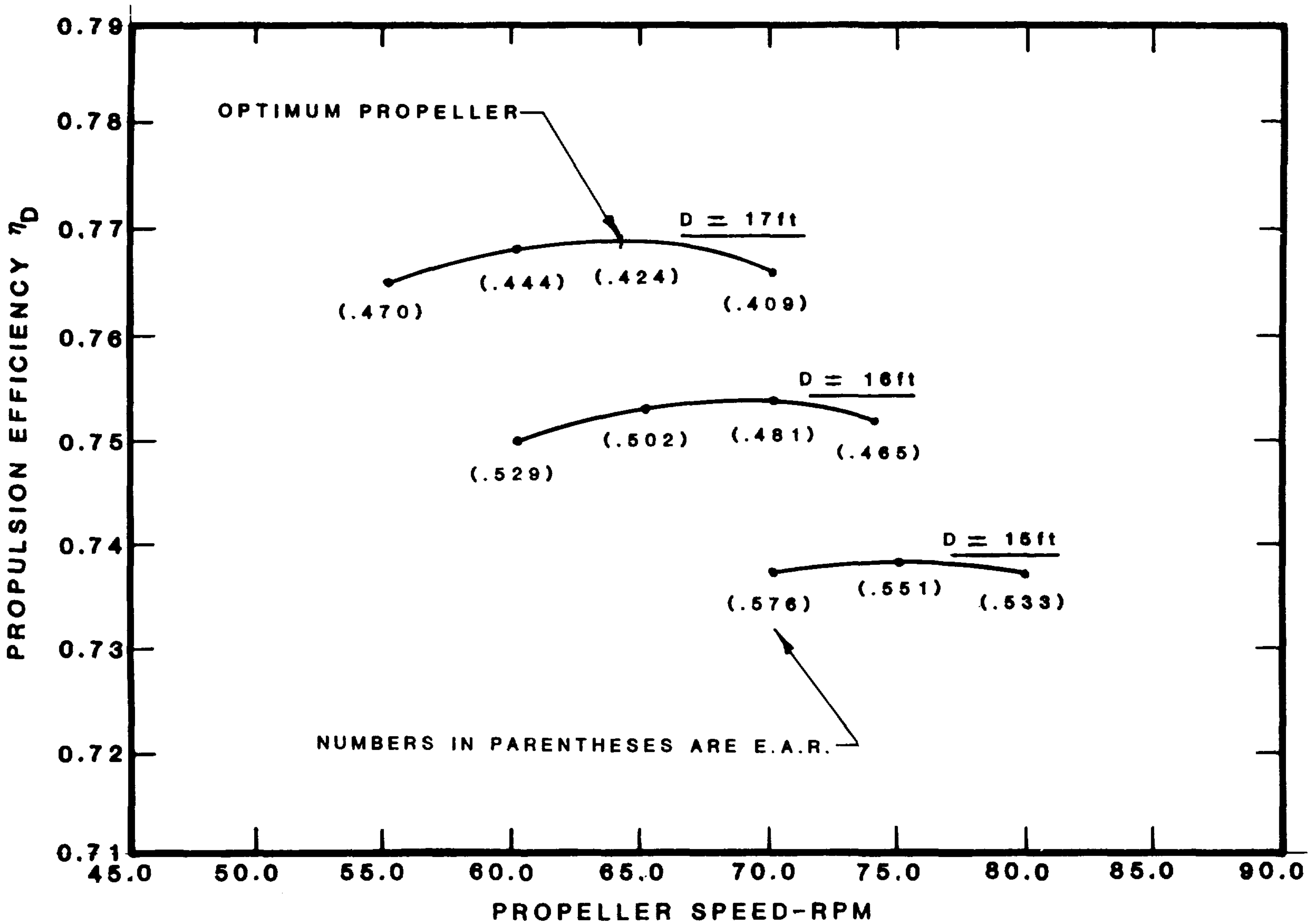

Figure C-2 - Propulsion Efficiency of Twin Shaftline Contrarotating Propellers: Results of a Parametric Study

TABLE C-5 - PROJECTED POWERING PERFORMANCE FOR THE DD-963 HULL FORM FITTED WITH TWIN SETS OF CONTRAROTATING PROPELLERS

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1060	790	1380	1030	32.1
12	6.17	1920	1430	2490	1860	38.5
14	7.20	3120	2330	4070	3030	44.8
16	8.23	4590	3500	6110	4550	51.4
18	9.26	6660	4970	8600	6470	57.8
20	10.29	9080	6770	11790	8790	64.0
21	10.80	10450	7800	13630	10170	67.2
22	11.32	11940	8900	15560	11610	70.4
23	11.83	13530	10090	17640	13160	73.4
24	12.35	15240	11370	19770	14750	76.2
25	12.86	17190	12910	22300	16630	79.4
26	13.38	19430	14520	25270	18840	82.8
27	13.89	22270	16610	28710	21410	86.4
28	14.40	25890	19300	33180	24740	89.6
29	14.92	30610	22820	39390	29370	93.7
30	15.43	35920	26790	46220	34450	97.8
31	15.95	41860	31210	54150	40380	102.8
32	16.46	48300	36020	63190	47120	107.7

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	J_T
10	0.770	0.795	0.930	1.045	0.935	1.005	1.015	1.823
12	0.770	0.795	0.940	1.030	0.935	0.995	1.005	1.806
14	0.765	0.795	0.945	1.020	0.935	0.990	0.995	1.801
16	0.770	0.795	0.945	1.020	0.935	0.990	0.995	1.795
18	0.770	0.795	0.945	1.020	0.935	0.990	0.995	1.795
20	0.770	0.795	0.945	1.025	0.935	0.990	1.000	1.801
21	0.765	0.795	0.945	1.020	0.935	0.990	0.995	1.801
22	0.765	0.795	0.945	1.020	0.935	0.990	0.995	1.801
23	0.765	0.795	0.945	1.020	0.935	0.990	0.995	1.806
24	0.770	0.795	0.950	1.020	0.935	0.985	0.990	1.806
25	0.770	0.795	0.950	1.020	0.935	0.985	0.990	1.806
26	0.770	0.795	0.950	1.020	0.935	0.985	0.990	1.801
27	0.775	0.795	0.955	1.020	0.935	0.980	0.985	1.783
28	0.780	0.800	0.955	1.025	0.935	0.980	0.990	1.783
29	0.775	0.800	0.955	1.020	0.935	0.980	0.985	1.766
30	0.775	0.800	0.955	1.020	0.935	0.980	0.985	1.749
31	0.775	0.800	0.945	1.025	0.935	0.990	1.000	1.737
32	0.765	0.800	0.935	1.025	0.930	0.995	1.005	1.720

TWIN SHAFTLINE FIXED-PITCH PROPELLERS

The predictions of powering performance for the DD-963 hull form fitted with twin shafts and struts as well as fixed-pitch propellers are made using a straightforward extrapolation of the model data from the stock propulsion experiments (Appendix B). The experimental resistance and hull-propulsor interaction coefficients, along with the propeller characteristics from Krishnamoorthy (1982), are used to generate the powering predictions with design propellers.

These powering predictions for speeds between 10 and 32 knots with design fixed-pitch propellers are given in Table C-6. At 20 knots, the fixed-pitch configuration requires a delivered power of 8870 kW (11890 hp), as compared with the baseline, which requires 10110 kW, a reduction in delivered power of 12.3 percent. At 32 knots the fixed-pitch configuration requires 50040 kW (67110 hp) while the baseline configuration requires 54010 kW. This represents a reduction in delivered power of 7.4 percent.

These reductions in delivered power are substantially greater than the power reduction which was initially anticipated. The distribution of the powering reduction is composed of reductions in effective power of 9.1 and 5.6 percent at 20 and 32 knots, respectively, and increases in the propulsion coefficient of 4.5 and 1.8 percent at 20 and 32 knots, respectively. The reduction in effective power at 32 knots is much smaller than at 20 knots, due to the fact that the appendage drag is a much smaller fraction of total drag at 32 knots than it is at 20 knots.

TABLE C-6 - PROJECTED POWERING PERFORMANCE FOR THE DD-963 HULL FORM FITTED WITH TWIN FIXED-PITCH PROPELLERS

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1020	760	1410	1050	41.2
12	6.17	1840	1380	2540	1890	49.8
14	7.20	2990	2230	4110	3070	58.4
16	8.23	4490	3350	6170	4600	66.8
18	9.26	6370	4750	8750	6530	75.1
20	10.29	8650	6450	11890	8870	83.2
21	10.80	9940	7410	13670	10190	87.3
22	11.32	11350	8460	15610	11640	91.3
23	11.83	12870	9590	17700	13200	95.3
24	12.35	14540	10840	20000	14910	99.3
25	12.86	16440	12260	22610	16860	103.5
26	13.38	18680	13930	25700	19160	107.8
27	13.89	21490	16020	29620	22090	112.6
28	14.40	24980	18630	34570	25780	118.0
29	14.92	29450	21960	40930	30520	124.1
30	15.43	34840	25980	48690	36310	130.8
31	15.95	40750	30390	57390	42800	137.5
32	16.46	47160	35170	67110	50040	144.1

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	J_T
10	0.725	0.765	0.970	0.980	0.920	0.950	0.940	1.375
12	0.725	0.765	0.970	0.985	0.920	0.950	0.940	1.365
14	0.725	0.765	0.970	0.985	0.920	0.950	0.940	1.355
16	0.725	0.765	0.970	0.985	0.920	0.950	0.940	1.355
18	0.725	0.765	0.970	0.985	0.920	0.950	0.940	1.355
20	0.725	0.765	0.970	0.985	0.920	0.950	0.940	1.360
21	0.725	0.765	0.970	0.985	0.920	0.950	0.940	1.360
22	0.725	0.765	0.970	0.985	0.920	0.950	0.940	1.365
23	0.725	0.765	0.970	0.980	0.920	0.950	0.940	1.365
24	0.725	0.765	0.970	0.980	0.920	0.950	0.940	1.370
25	0.725	0.765	0.970	0.980	0.920	0.950	0.940	1.365
26	0.725	0.765	0.970	0.985	0.920	0.950	0.940	1.365
27	0.725	0.765	0.970	0.980	0.920	0.950	0.940	1.355
28	0.725	0.760	0.965	0.980	0.920	0.950	0.945	1.345
29	0.720	0.760	0.960	0.985	0.920	0.955	0.950	1.330
30	0.715	0.75[illegible]	0.955	0.990	0.920	0.960	0.955	1.315
31	0.710	0.750	0.950	0.995	0.920	0.970	0.965	1.300
32	0.705	0.750	0.945	0.990	0.925	0.975	0.970	1.290

TWIN BEARING-IN-RUDDER POST WITH CONTROLLABLE-PITCH PROPELLERS

Extrapolation of the experimental results for bearing-in-rudder post with controllable-pitch propellers on the DD-963 hull form to account for design propeller performance resulted in a reduction in delivered power of 15.5 percent at 20 knots compared to the baseline. This result is in excess of the improvement provided by any of the bearing-in-rudder post configurations evaluated thus far* and seems too optimistic. Analysis of these results concluded that two adjustments to the experimental results were appropriate. First, as in the case of the controllable-pitch propeller baseline, the shafting on the model was smaller than the shafting which resulted from application of Navy design practice. Therefore, the resistance of the model was increased by 1.5 percent to account for this required increase in shaft diameter. Second, the experimental relative rotative efficiency (η_R) was lowered to values which better reflected that which could be reliably obtained. For example, at 20 knots, η_R has been reduced from 1.035 to 1.020. These two changes result in a delivered power reduction of 11.9 percent relative to the baseline at 20 knots. This is a much more credible benefit than that which resulted from the initial extrapolation.

Delivered power predictions for the DD-963 hull form fitted with bearing-in-rudder post and controllable-pitch propellers are presented in Table C-7 for speeds between 10 and 34 knots. At 20 knots, the bearing-in-rudder post with controllable-pitch propellers requires 8910 kW (11950 hp), as compared with the baseline, which requires 10110 kW. This represents a reduction of 11.9 percent in delivered power. At 32 knots, the bearing-in-rudder post configuration with controllable-pitch propellers requires 49460 kW (66330 hp), while the baseline requires 54010 kW, a reduction in delivered power of 8.4 percent.

These performance predictions for the bearing-in-rudder post configuration with controllable-pitch propellers contain a large degree of judgment. However, the adjustments which have been made are in a conservative direction, and result in power reductions which are comparable to those which were obtained experimentally on models of the PG-84 and PCG.* Thus, these predictions are of relatively low risk, and it is likely that these projected gains could be obtained experimentally with design propellers.

* See Appendix E.

TABLE C-7 - PROJECTED POWERING PERFORMANCE FOR THE DD-963 HULL FORM FITTED WITH BEARING-IN-RUDDER POST CONFIGURATION WITH TWIN CONTROLLABLE-PITCH PROPELLERS

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	995	740	1370	1020	46.3
12	6.17	1850	1380	2540	1900	56.3
14	7.20	3010	2240	4140	3090	66.0
16	8.23	4510	3360	6210	4630	75.4
18	9.26	6400	4770	8810	6570	84.8
20	10.29	8680	6470	11950	8910	94.1
21	10.80	9990	7450	13750	10260	99.0
22	11.32	11420	8520	15720	11720	103.6
23	11.83	13000	9700	17810	13280	108.3
24	12.35	14710	10970	20150	15030	112.9
25	12.86	16550	12340	22780	16990	117.9
26	13.38	18720	13960	25740	19190	122.3
27	13.89	21480	16020	29650	22110	127.5
28	14.40	25120	18730	34770	25930	133.3
29	14.92	29480	21980	40870	30480	139.3
30	15.43	34510	25740	47960	35760	146.0
31	15.95	40560	30240	56600	42200	153.1
32	16.46	47380	35330	66330	49460	160.3
33	16.98	54590	40710	76550	57080	167.2
34	17.49	62050	46270	87940	65570	174.5

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	J_T
10	0.725	0.750	0.945	1.020	0.900	0.950	0.955	1.220
12	0.725	0.750	0.945	1.020	0.900	0.950	0.955	1.205
14	0.725	0.750	0.945	1.020	0.900	0.950	0.955	1.200
16	0.725	0.750	0.945	1.020	0.900	0.950	0.955	1.200
18	0.725	0.750	0.945	1.020	0.900	0.950	0.955	1.200
20	0.725	0.750	0.945	1.020	0.900	0.950	0.955	1.205
21	0.725	0.750	0.940	1.025	0.900	0.955	0.965	1.205
22	0.725	0.750	0.940	1.025	0.900	0.955	0.965	1.210
23	0.730	0.750	0.940	1.030	0.900	0.955	0.965	1.210
24	0.730	0.750	0.940	1.030	0.900	0.955	0.965	1.210
25	0.725	0.750	0.935	1.030	0.900	0.960	0.970	1.210
26	0.725	0.750	0.945	1.025	0.900	0.955	0.965	1.210
27	0.725	0.750	0.945	1.020	0.900	0.955	0.960	1.205
28	0.725	0.750	0.950	1.015	0.905	0.955	0.960	1.195
29	0.720	0.750	0.950	1.010	0.910	0.955	0.960	1.185
30	0.720	0.750	0.950	1.010	0.915	0.960	0.965	1.175
31	0.715	0.750	0.950	1.010	0.915	0.965	0.970	1.165
32	0.715	0.745	0.950	1.010	0.920	0.970	0.975	1.155
33	0.715	0.745	0.950	1.010	0.925	0.975	0.980	1.145
34	0.705	0.745	0.945	1.005	0.930	0.985	0.985	1.145

TWIN SHAFTLINE LARGE DIAMETER LOW TIP CLEARANCE FIXED-PITCH PROPELLERS

The predictions of delivered power for a contemporary destroyer hull form fitted with large diameter low tip clearance fixed-pitch propellers involve straightforward powering predictions. The prognostications are made using the predicted design propeller characteristics from Majumdar and Krishnamoorthy (1980) and the experimentally derived hull-propulsor interaction coefficients. This results in a set of highly reliable powering predictions.

The powering predictions for the hull form fitted with large diameter low tip clearance fixed-pitch propellers are given in Table C-8 for speeds between 10 and 34 knots. At 20 knots, the large diameter low tip clearance fixed-pitch propeller configuration requires a delivered power of 3980 kW (12040 hp), as compared to the 10110 kW required by the baseline ship. This constitutes an 11.2 percent reduction in delivered power. At 32 knots, this configuration requires 49620 kW (66549 hp), compared to 54010 kW for the baseline. This represents an 8.1 percent reduction in power relative to the baseline ship.

These predictions are probably conservative due to the low propeller-efficiency behind (η_B) which is predicted. The low η_B is probably caused by the large hub of the propeller, and possibly by a propeller design which is inappropriate for the in-flow to the propeller. In any case, it is likely that with design, wake-adapted propellers, higher η_B's than those projected could be obtained.

An important point, which should be noted concerning this hull form with large diameter low tip clearance fixed-pitch propellers, is the low effective power of this hull considering the large appendage suit. With a set of shafting which is only 6 mm (0.25 in) smaller in diameter than the projected shaft diameter for the controllable-pitch baseline, 0.578 m diameter versus 0.584 m diameter, the large diameter low tip clearance fixed-pitch propeller hull and appendage suit has 7.1 percent lower resistance than the baseline at 20 knots, and 2.2 percent lower resistance at 32 knots. Due to the fact that the resistance of this hull form was not measured without the appendages, it is not possible to tell whether the reduced resistance of this hull is due to hull form modification or to a reduction in appendage drag.

Despite the lack of bare hull resistance data, two observations can be made relating to the lower effective power of the large diameter low tip clearance hull form. First, the large diameter low tip clearance hull form has a wetted surface which is 1.5 percent greater than that of the baseline hull form. Thus, the large diameter hull form could be expected to have a greater viscous resistance than the baseline. However, this must be traded off against the drag caused by the sharp juncture between the hull and skeg on the baseline hull. The secondary flow which is probably generated at this juncture may cause even greater drag on the baseline hull form than does the increased wetted surface on the large diameter low tip clearance hull form. Secondly, the low tip clearance and the unusual hull form associated with the constant tip clearance appear to result in much better alignment between the flow and the shafting than is found on the baseline hull form. This could result in lower appendage resistance for the large diameter low tip clearance hull form than is found on the baseline ship.

TABLE C-8 - PROJECTED POWERING PERFORMANCE FOR A CONTEMPORARY DESTROYER HULL FORM FITTED WITH TWIN LARGE DIAMETER LOW TIP CLEARANCE FIXED-PITCH PROPELLERS

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1000	750	1440	1080	33.3
12	6.17	1810	1350	2570	1920	39.9
14	7.20	2930	2180	4120	3070	46.7
16	8.23	4380	3270	6130	4570	53.4
18	9.26	6240	4650	8640	6450	60.0
20	10.29	8750	6530	12040	8980	67.2
21	10.80	10210	7610	14030	10460	70.3
22	11.32	11710	8730	15920	11870	73.4
23	11.93	13290	9910	18080	13480	76.7
24	12.35	14960	11160	20260	15110	79.9
25	12.86	16900	12600	22880	17060	83.2
26	13.38	19140	14270	25900	19320	86.6
27	13.89	21990	16400	29700	22150	90.3
28	14.40	25660	19130	34760	25920	94.2
29	14.92	30200	22520	40810	30430	98.4
30	15.43	35690	26610	48150	35910	102.8
31	15.95	42000	31320	55940	42460	107.7
32	16.46	48840	36420	66540	49620	112.6
33	16.98	56170	41890	76910	57350	117.9
34	17.49	63670	47480	87230	65050	122.2

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-T	1-WT	1-WQ	J_T
10	0.695	0.785	0.980	0.905	0.990	1.010	0.985	1.535
12	0.705	0.785	0.990	0.905	0.990	1.000	0.975	1.520
14	0.710	0.790	0.990	0.910	0.990	1.000	0.975	1.520
16	0.715	0 790	0.990	0.915	0.990	1.000	0.975	1.520
18	0.720	0.790	0.990	0.925	0.990	1.000	0.980	1.520
20	0.725	0.790	0.985	0.935	0.990	1.005	0.985	1.515
21	0.730	0.790	0.990	0.930	0.990	1.000	0.980	1.510
22	0.735	0.790	0.995	0.935	0.990	0.995	0.975	1.510
23	0.735	0.790	0.995	0.935	0.990	0.995	0.975	1.510
24	0.740	0 790	0.995	0.940	0.990	0.995	0.980	1.515
25	0.740	0.790	0.995	0.940	0.990	0.995	0.980	1.515
26	0.740	0.790	0.995	0.940	0.990	0.995	0.980	1.510
27	0.740	0.790	0.995	0.940	0.990	0.995	0.980	1.505
28	0.740	0.795	0.995	0.935	0.990	0.995	0.975	1.495
29	0.740	0.795	0.995	0.935	0.990	0.995	0.975	1.485
30	0.740	0 [illegible]	0.995	0.935	0.990	0.995	0.975	1.470
31	0.740	0.795	0.990	0.935	0.990	1.000	0.975	1.455
32	0.735	0.795	0.985	0.935	0.990	1.005	0.980	1.445
33	0.730	0.795	0.975	0.940	0.990	1.015	0.990	1.440
34	0.730	0.795	0.975	0.940	0.990	1.015	0.990	1.430

TWIN SHAFTLINE TANDEM PROPELLERS

As with most of the previous powering projections, the powering projection for the DD-963 hull form fitted with twin shaftline tandem propellers is straightforward. These projections require elementary powering estimates using design propeller performance and experimentally derived resistances and hull-propulsor interaction coefficients.

The powering predictions for the twin shaftline tandem propeller configuration are given in Table C-9. At 20 knots, this table shows that the twin tandem configuration requires a delivered power of 9290 kW (12460 hp), as compared with the baseline, which requires 10110 kW. This constitutes a reduction in delivered power of 8.1 percent. At 32 knots, the tandem configuration requires 50350 kW (67520 hp), as compared to the 54010 kW of the baseline ship, a reduction of 6.8 percent.

These predictions are reliable, and in fact probably somewhat conservative, particularly at the lower speeds where the hull efficiency is low. As is mentioned in the discussion of experimental results, Appendix B, the low efficiency of the stock tandem propellers is probably due to a significant mismatch between the propellers of this compound propulsor. This mismatch probably has a strong negative impact on the hull-propulsor interaction coefficients. A tandem propeller design with a better match between the forward and aft propellers should have higher efficiency, and could very well have increased hull efficiency due to improved hull-propulsor interaction coefficients.

TABLE C-9 - PROJECTED POWERING PERFORMANCE FOR THE DD-963 HULL FORM FITTED WITH TWIN TANDEM PROPELLERS

Ship Speed		Effective Power (P_E)		**Delivered Power (P_D)**		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1050	780	1510	1130	48.4
12	6.17	1890	1410	2720	2030	58.0
14	7.20	3050	2280	4420	3300	67.7
16	8.23	4550	3390	6590	4910	77.6
18	9.26	6440	4800	9240	6890	87.2
20	10.29	8710	6500	12460	9290	96.6
21	10.80	10000	7460	14300	10660	101.3
22	11.32	11390	8490	16220	12100	106.0
23	11.83	12910	9630	18390	13710	110.3
24	12.35	14620	10900	20690	15430	115.0
25	12.86	16520	12320	23220	17310	119.4
26	13.38	18710	13950	26240	19560	124.2
27	13.89	21500	16040	30420	22690	129.6
28	14.40	25010	18650	35290	26320	134.8
29	14.92	29450	21960	41690	31090	140.5
30	15.43	34740	25910	49360	36810	147.4
31	15.95	40740	30390	58160	43370	154.0
32	16.46	47310	35280	67520	50350	161.0
33	16.98	54290	40480	77550	57830	168.0
34	17.49	61520	45870	88390	65910	174.9

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	**ETAO**	ETAH	ETAR	1-T	1-WT	1-WQ	J_T
10	0.690	0.755	0.910	1.005	0.955	1.050	1.050	1.295
12	0.695	0.760	0.920	0.995	0.955	1.040	1.040	1.280
14	0.690	0.760	0.925	0.985	0.955	1.035	1.030	1.275
16	0.690	0.760	0.920	0.990	0.955	1.040	1.035	1.275
18	0.695	0.760	0.925	0.995	0.960	1.040	1.040	1.280
20	0.700	0.760	0.925	1.000	0.960	1.040	1.040	1.280
21	0.700	0.755	0.925	1.005	0.960	1.040	1.040	1.285
22	0.700	0.755	0.925	1.005	0.960	1.040	1.040	1.285
23	0.700	0.755	0.930	1.000	0.960	1.035	1.035	1.285
24	0.705	0.755	0.930	1.005	0.960	1.035	1.035	1.285
25	0.710	0.755	0.935	1.005	0.965	1.030	1.030	1.285
26	0.715	0.755	0.935	1.005	0.965	1.030	1.030	1.285
27	0.705	0.760	0.935	0.995	0.965	1.030	1.030	1.280
28	0.710	0.760	0.940	0.990	0.965	1.025	1.020	1.270
29	0.705	0.760	0.950	0.980	0.965	1.020	1.010	1.255
30	0.705	0.760	0.945	0.980	0.970	1.025	1.015	1.245
31	0.700	0.760	0.945	0.975	0.970	1.025	1.015	1.230
32	0.700	0.760	0.940	0.980	0.970	1.030	1.020	1.220
33	0.700	0.760	0.935	0.985	0.970	1.035	1.030	1.210
34	0.695	0.760	0.935	0.985	0.970	1.040	1.035	1.205

TWIN SHAFTLINE CONTROLLABLE-PITCH PROPELLERS WITH REVISED FAIRWATERS

Due to the lack of experimental resistance and powering data over the entire speed range, only the effective and delivered power have been predicted for the baseline with controllable-pitch propellers and revised fairwater shapes. The experimental results showed significant changes in the hull-propulsor interaction coefficients, particularly the thrust deduction (1-t) with changes in fairwater shape. Therefore, it seemed imprudent to produce tables of hull-propulsor interaction coefficients based solely on experimental data at 20 and 32 knots.

The experimental data showed that the effective power for the baseline with the bullet-shaped fairwater was reduced by about 3.5 percent at 20 knots and 2.5 percent at 32 knots, compared to the baseline configuration with the button shaped fairwater. On the other hand, the experimental delivered power was only reduced by 1 percent at both speeds, compared to the baseline configuration.

The effective and delivered power curves for the baseline with controllable-pitch propellers and revised fairwater shapes have been produced by reducing the baseline hull form's effective power by 3.5 percent at 20 knots, and gradually reducing this to 2.5 percent at 32 knots. The delivered power values have been produced by reducing the delivered power of the baseline hull form by 1 percent across the entire speed range.

The effective and delivered powers for the DD-963 with controllable-pitch propellers and revised fairwaters are given in Table C-10 for speeds between 10 and 34 knots. At 20 knots, the revised fairwaters require 10010 kW (13420 hp), as opposed to the baseline, which required 10110 kW. At 32 knots, the revised fairwaters required 53470 kW (71710 hp), while the baseline required 54010 kW.

The accuracy of these powering predictions should be quite high due to the high precision of the experiments which were performed, except for the possibility of scale effects. The area where a large degree of uncertainty exists is that of the hull-propulsor interaction coefficients. The wake fraction ($1-w_T$) remained relatively unaffected by the change in fairwater. However, the thrust deduction (1-t) changed quite singificantly with the change in fairwater shape. Specifically, at 20 knots the wake fraction changed from 0.999 to 1.000 with the change from the button fairwater to the bullet fairwater. Meanwhile, the thrust deduction changed from 0.972 to 0.944, a 2.9 percent reduction, with the same change in fairwater shape.

TABLE C-10 - PROJECTED POWERING PERFORMANCE FOR THE BASELINE CONFIGURATION WITH TWIN CONTROLLABLE-PITCH PROPELLERS FITTED WITH IMPROVED FAIRWATERS

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)	
Knots	m/sec	Hp	kW	Hp	kW
10	5.14	1090	810	1600	1200
12	6.17	1970	1470	2910	2170
14	7.20	3170	2360	4690	3500
16	8.23	4720	3520	6980	5200
18	9.26	6700	5000	9890	7380
20	10.29	9100	6790	13420	10010
21	10.80	10440	7790	15410	11490
22	11.32	11920	8890	17580	13110
23	11.83	13510	10070	19930	14860
24	12.35	15260	11380	22470	16760
25	12.86	17180	12810	25280	18850
26	13.38	19370	14440	27320	20370
27	13.89	22190	16550	32980	24590
28	14.40	25870	19290	37990	28330
29	14.92	30460	22710	44720	33350
30	15.43	35840	26730	52650	39260
31	15.95	42000	31320	61740	46040
32	16.46	48700	36320	71710	53470
33	16.98	55950	41720	82660	61640
34	17.49	63420	47290	94090	70160

TWIN SHAFTLINE LARGE DIAMETER OVERLAPPING PROPELLERS

The propulsion predictions, for a hull form fitted with large diameter overlapping propllers result from a straightforward extrapolation of experimental results which reflect design propeller performance. These predictions were made using the resistance and hull-propulsor interaction coefficient values from the stock propeller model experiments and synthesized open water characteristics for a design propeller. These open water characteristics were based on the projected propeller performance presented in Majumdar and Krishnamoorthy (1980).

The results of these predictions for speeds between 10 and 34 knots are given in Table C-11. At 20 knots, the large diameter overlapping configuration requires a delivered power of 10170 kW (13640 hp), as compared to the 10110 kW required by the baseline configuration. This represents an increase in delivered power of 0.6 percent. At 32 knots, the delivered power of the large diameter overlapping configuration is 53100 kW (71210 hp), compared to the 54010 kW required by the baseline configuration. This represents a 1.7 percent reduction in delivered power.

These predictions are probably very conservative due to the poor hull-propulsor interaction coefficients which are obtained with this configuration, model scale. At 20 knots the efficiency of the propellers behind is 15 percent lower than the efficiency of the propellers in open water. This large discrepancy is probably due to the fact that the after propeller should be operating at a higher rpm than the forward propeller for an identical set of propellers, or at a higher pitch for the same rpm.

Another means of analyzing the poor projected propulsive performance of the large diameter overlapping configuration with the stock propeller hull-propulsor interaction coefficients is to compare the effective powers for this configuration and the controllable-pitch baseline to the delivered powers. At 20 knots, the large diameter overlapping configuration requires 5.4 percent less effective power than the controllable-pitch baseline, yet it requires 0.6 percent more delivered power. Thus the projected propulsion characteristics of the large diameter overlapping configuration are 6.0 percent poorer with the stock propeller hull-propulsor interaction coefficients than are those of the baseline configuration. At the same time, the efficiency of the large diameter propeller is higher.

TABLE C-11 - PROJECTED POWERING PERFORMANCE FOR A CONTEMPORARY DESTROYER HULL FORM FITTED WITH LARGE DIAMETER OVERLAPPING PROPELLERS

Ship Speed		Effective Power (P_E)		**Delivered Power (P_D)**		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1020	760	1700	1270	32.9
12	6.17	1870	1390	3070	2290	39.7
14	7.20	3040	2270	4880	3640	45.4
16	8.23	4520	3370	7120	5310	53.2
18	9.26	6440	4810	9980	7440	60.1
20	10.29	8920	6650	13640	10170	67.1
21	10.80	10280	7670	15550	11590	70.5
22	11.32	11750	8760	17660	13170	73.7
23	11.83	13350	9960	19850	14810	76.8
24	12.35	15090	11260	22200	16550	79.7
25	12.86	17030	12700	24900	18570	83.0
26	13.38	19400	14460	28190	21020	86.2
27	13.89	22250	16590	32300	24090	89.8
28	14.40	25850	19280	37480	27950	93.7
29	14.92	30320	22610	44130	32910	98.2
30	15.43	35710	26630	52220	38940	103.0
31	15.95	42020	31330	61410	45790	107.9
32	16.46	48730	36340	71210	53100	112.8
33	16.98	55850	41650	82010	61160	118.0
34	17.49	63280	47190	92930	69390	122.7

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-T	1-WT	1-WQ	J_T
10	0.600	0.790	0.975	0.780	0.960	0.985	0.910	1.515
12	0.610	0.795	0.980	0.785	0.960	0.980	0.905	1.500
14	0.620	0.795	0.980	0.800	0.960	0.980	0.910	1.495
16	0.635	0.795	0.975	0.820	0.960	0.985	0.925	1.500
18	0.645	0.795	0.970	0.840	0.960	0.990	0.935	1.500
20	0.655	0.795	0.965	0.855	0.960	0.995	0.945	1.500
21	0.660	0.795	0.965	0.865	0.960	0.995	0.950	1.500
22	0.665	0.790	0.965	0.870	0.960	0.995	0.955	1.505
23	0.675	0.795	0.970	0.875	0.960	0.990	0.950	1.500
24	0.680	0.795	0.975	0.880	0.960	0.985	0.945	1.500
25	0.685	0.795	0.975	0.885	0.960	0.985	0.950	1.500
26	0.690	0.795	0.980	0.885	0.960	0.980	0.945	1.495
27	0.690	0.795	0.980	0.885	0.960	0.980	0.945	1.490
28	0.690	0.795	0.980	0.885	0.960	0.980	0.940	1.480
29	0.685	0.795	0.975	0.885	0.960	0.985	0.945	1.470
30	0.685	0.795	0.970	0.885	0.960	0.990	0.950	1.460
31	0.685	0.795	0.965	0.890	0.960	0.995	0.955	1.445
32	0.685	0.795	0.960	0.895	0.960	1.000	0.960	1.435
33	0.680	0.795	0.950	0.900	0.960	1.010	0.970	1.430
34	0.680	0.795	0.945	0.905	0.960	1.015	0.975	1.425

TWIN SHAFTLINE LARGE DIAMETER LOW TIP CLEARANCE CONTROLLABLE-PITCH PROPELLERS

The contemporary destroyer hull form, which was fitted with large diameter low tip clearance fixed-pitch propellers, was also fitted with large diameter low tip clearance controllable-pitch propellers. The powering predictions for this configuration fitted with the large diameter low tip clearance controllable-pitch propellers result from a straightforward extrapolation of stock propeller results using the projected open water characteristics of a design propeller.

The results of this extrapolation are given in Table C-12. At 20 knots this projection indicates that a delivered power of 10740 kW (14410 hp) is required, as compared to 10110 kW for the DD-963 baseline. This represents a 6.2 percent increase in delivered power. The delivered power for the large diameter low tip clearance configuration is 55720 kW (74730 hp) at 32 knots. This compares to 54010 kW for the DD-963 baseline, and represents a 3.2 percent increase in delivered power.

Due to the extremely large hub, which results from the use of the large diameter low tip clearance controllable-pitch propellers and the close proximity of the hub to the hull, extremely adverse hull-propulsor interaction coefficients result. In turn, these adverse hull-propulsor interaction coefficients result in poor propulsive performance, as shown by the 20-knot hull efficiency of 0.93 and by the propeller efficiency behind of 0.69.

TABLE C-12 - PROJECTED POWERING PERFORMANCE FOR A CONTEMPORARY DESTROYER HULL FORM FITTED WITH TWIN LARGE DIAMETER LOW TIP CLEARANCE CONTROLLABLE-PITCH PROPELLERS

Ship Speed		Effective Power (P_E)		**Delivered Power (P_D)**		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1060	790	1660	1240	32.8
12	6.17	1900	1420	2960	2210	39.3
14	7.20	3100	2310	4820	3590	45.8
16	8.23	4660	3480	7240	5400	52.6
18	9.26	6610	4930	10280	7660	59.6
20	10.29	9270	6910	14410	10740	66.6
21	10.80	10850	8090	16860	12570	70.0
22	11.32	12480	9310	19390	14460	73.0
23	11.83	14140	10540	21750	16220	75.9
24	12.35	15920	11870	24390	18190	79.1
25	12.86	17910	13360	27450	20470	82.3
26	13.38	20280	15120	30880	23030	85.7
27	13.89	23260	17350	35170	26230	89.6
28	14.40	27080	20190	40810	30430	93.5
29	14.92	31780	23690	47500	35420	97.9
30	15.43	37430	27910	55490	41380	102.3
31	15.95	43700	32580	65010	48480	107.0
32	16.46	50540	37690	74730	55720	111.7
33	16.98	57930	43200	86000	64130	116.8
34	17.49	65690	48990	96500	71960	121.0

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-T	1-WT	1-WQ	J_T
10	0.635	0.760	0.925	0.905	0.925	1.000	0.970	1.545
12	0.640	0.765	0.935	0.900	0.925	0.990	0.955	1.530
14	0.645	0.765	0.940	0.895	0.925	0.985	0.950	1.525
16	0.645	0.765	0.935	0.900	0.925	0.990	0.955	1.525
18	0.645	0.765	0.925	0.910	0.925	1.000	0.970	1.530
20	0.645	0.765	0.930	0.905	0.935	1.005	0.975	1.530
21	0.645	0.765	0.935	0.900	0.940	1.005	0.970	1.525
22	0.645	0.765	0.940	0.895	0.940	1.000	0.965	1.525
23	0.650	0.765	0.955	0.890	0.950	0.995	0.960	1.525
24	0.655	0.765	0.955	0.895	0.950	0.995	0.960	1.530
25	0.655	0.765	0.955	0.895	0.950	0.995	0.960	1.530
26	0.655	0.765	0.955	0.900	0.950	0.995	0.960	1.530
27	0.660	0.765	0.950	0.910	0.950	1.000	0.970	1.525
28	0.665	0.770	0.950	0.910	0.950	1.000	0.970	1.515
29	0.670	0.770	0.950	0.915	0.955	1.005	0.975	1.505
30	0.675	0.770	0.950	0.920	0.955	1.005	0.975	1.490
31	0.670	0.775	0.945	0.920	0.955	1.010	0.980	1.480
32	0.675	0.775	0.945	0.925	0.960	1.015	0.985	1.470
33	0.675	0.775	0.935	0.930	0.960	1.025	0.995	1.465
34	0.680	0.775	0.940	0.935	0.965	1.025	1.000	1.460

SINGLE SHAFTLINE CONTRAROTATING PROPELLERS

The powering performance for a single shaftline destroyer equipped with contrarotating propellers has been predicted using the experimental resistance values and hull-propulsor interaction coefficients from the stock propeller experiments. The open water characteristics which were used as input to the powering performance prediction program were synthesized from the results of a parametric study.

The parametric study of single shaftline contrarotating propeller performance is summarized in Figure C-3. The results shown in this figure were generated using the wake fraction $(1-w_T)$ and the thrust deduction (1-t) from the stock propeller propulsion experiments in conjunction with the wake survey results from the FF-1052, Lin and Hurwitz (1974). Figure C-3, which shows propulsion efficiency as a function of rpm for three propeller diameters, was generated using the DTNSRDC contrarotating propeller design program. As can be seen from the figure, the optimum propeller is 6.1 m (20 ft) in diameter and operates at 56 rpm at 20 knots. The forward propeller of this set has a pitch-diameter ratio (P/D) of 2.15; the after propeller has a P/D of 2.13; these compare with the respective values of 1.39 and 1.78 for the stock propellers. The expanded area ratio of both propellers is 0.594, which compares with 0.45 for the stock propellers.

Table C-1 shows how the hull-propulsor interaction coefficients for the single shaftline contrarotating propellers were derived at the design speed of 20 knots. As can be seen from the table, the predicted relative rotative efficiency (η_R) has been increased relative to the experimental results in order to bring the propeller efficiency behind into agreement with the value which is predicted by the propeller design program. This modest increase in η_R, from 0.950 to 0.980, is difficult to assure. However, with design propellers, some increase in η_R is attainable in most cases.

Table C-13 presents predictions of delivered power for the single shaftline destroyer fitted with contrarotating propellers for speeds between 10 and 32 knots. At 20 knots, the single shaftline contrarotating configuration requires 8230 kW (11030 hp), as compared to the DD-963 baseline, which requires 10110 kW. This represents an 18.6 percent reduction in delivered power. At 32 knots, the single shaftline contrarotating configuration requires a delivered power of 45900 kW (61550 hp), as compared to 54010 kW for the baseline. This represents a reduction in power of 15.0 percent for the single shaftline contrarotating configuration.

With the exception of the increase in relative rotative efficiency, which is assumed to be attainable, the reliability of these predictions is high. The propeller design calculations are conservative in their margins of blade area and section drag coefficient. Therefore, the performance of the propeller should be easily achieved, resulting in the predicted reduction in delivered power.

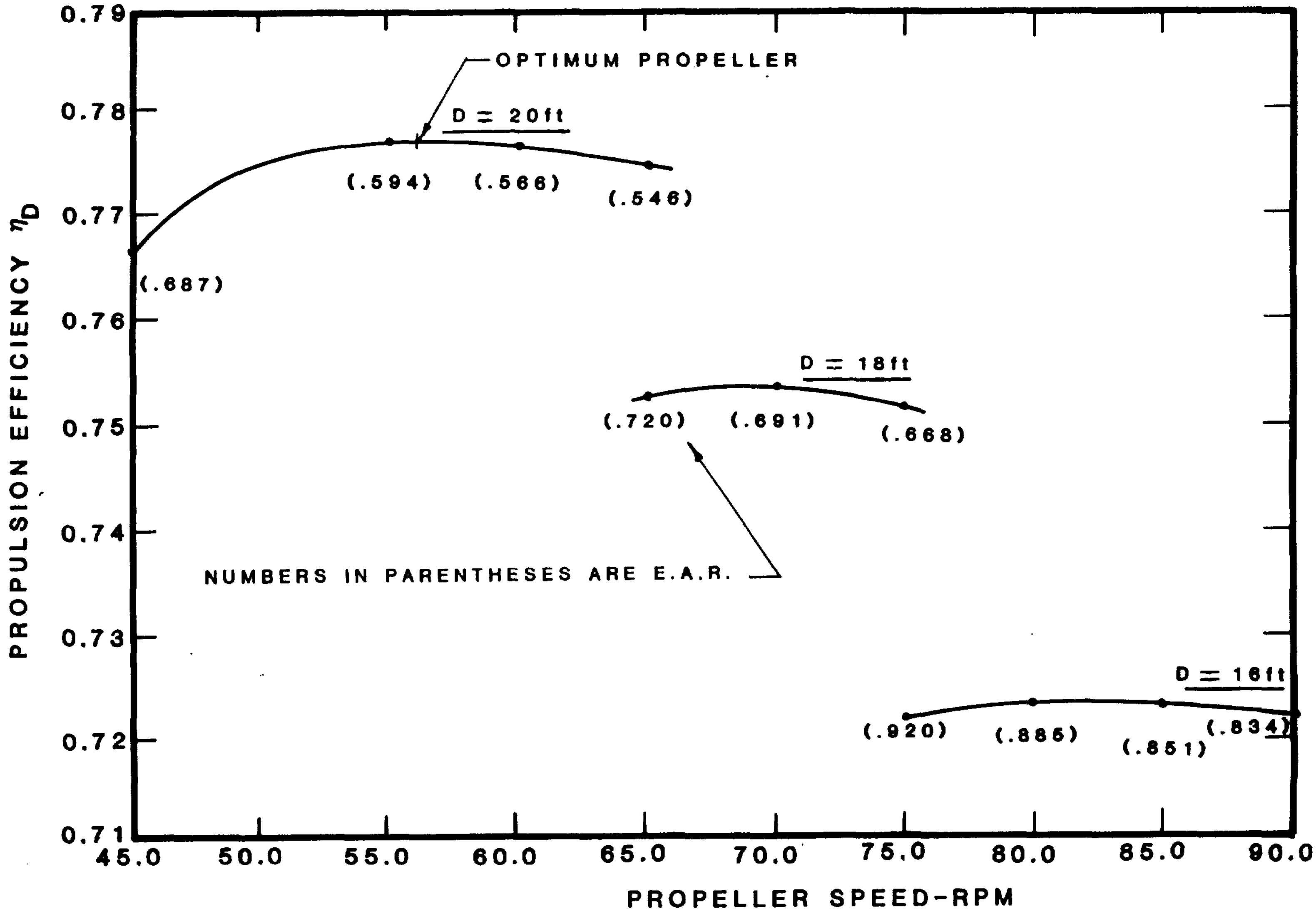

Figure C-3 - Propulsion Efficiency of Single Shaftline Contrarotating Propellers: Results of a Parametric Study

TABLE C-13 - PROJECTED POWERING PERFORMANCE FOR A PROTOTYPE DESTROYER HULL FORM FITTED WITH A SINGLE SET OF CONTRAROTATING PROPELLERS

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1060	790	1370	1020	27.9
12	6.17	1880	1400	2440	1820	33.7
14	7.20	2990	2230	3880	2900	39.3
16	8.23	4440	3310	5760	4290	44.8
18	9.26	6250	4660	8100	6040	50.5
20	10.29	8510	6340	11000	8200	56.0
21	10.80	9770	7280	12640	9430	58.8
22	11.32	11230	8370	14520	10830	61.5
23	11.83	12780	9530	16530	12320	64.3
24	12.35	14480	10800	18770	14000	67.0
25	12.86	16370	12210	21160	15780	69.7
26	13.38	18520	13810	23880	17810	72.4
27	13.89	21270	15860	27450	20470	75.6
28	14.40	24960	18610	32000	23860	79.1
29	14.92	29460	21970	37710	28120	82.9
30	15.43	34510	25740	44070	32860	86.8
31	15.95	40350	30090	51170	38150	90.8
32	16.46	47150	35160	59790	44580	94.9

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	J_T
10	0.770	0.800	0.995	0.965	0.975	0.980	0.970	1.777
12	0.770	0.800	0.995	0.965	0.975	0.980	0.970	1.767
14	0.770	0.800	0.995	0.965	0.975	0.980	0.970	1.767
16	0.770	0.800	0.995	0.965	0.975	0.980	0.970	1.767
18	0.770	0.800	0.990	0.970	0.970	0.980	0.970	1.772
20	0.775	0.800	0.985	0.980	0.965	0.980	0.975	1.772
21	0.775	0.800	0.980	0.985	0.960	0.980	0.975	1.772
22	0.775	0.800	0.975	0.990	0.950	0.980	0.975	1.767
23	0.775	0.800	0.970	0.995	0.945	0.975	0.975	1.767
24	0.770	0.800	0.965	0.995	0.940	0.975	0.970	1.762
25	0.775	0.800	0.965	1.000	0.935	0.970	0.970	1.762
26	0.775	0.800	0.960	1.005	0.930	0.965	0.970	1.752
27	0.775	0.800	0.960	1.005	0.930	0.965	0.965	1.742
28	0.780	0.800	0.960	1.015	0.925	0.965	0.970	1.728
29	0.780	0.800	0.960	1.020	0.925	0.965	0.975	1.708
30	0.785	0.795	0.960	1.025	0.925	0.965	0.975	1.693
31	0.790	0.795	0.960	1.035	0.930	0.970	0.985	1.673
32	0.790	0.790	0.960	1.035	0.935	0.970	0.985	1.658

SINGLE SHAFTLINE FIXED-PITCH PROPELLER

No model experiments have been performed on a single shaftline fixed-pitch propeller configuration under this program. Therefore, both the effective power and the hull-propulsor interaction coefficients must be estimated as part of these projections of delivered power. This renders the prediction process more complicated and increases the risks associated with these projections.

The effective power estimates have been developed based on experimental data for the single tandem configuration and the twin tandem and fixed-pitch configurations. The assumption which has been made is that the ratio of the resistance of the single tandem configuration to that of a single fixed-pitch configuration will be the same as the ratio of the resistances of the twin tandem configuration to those of the twin fixed-pitch configuration. Based on this, the resistance of the single shaftline fixed-pitch propeller configuration has been estimated for speeds from 10 to 32 knots, using the following formula:

$$P_E \text{ - single FP} = \frac{P_E \text{ - single tandem}}{\dfrac{P_E \text{ - twin tandem}}{P_E \text{ - twin FP}}}$$

The hull-propulsor interaction coefficients for a single shaftline fixed-pitch propeller configuration have been estimated by assuming that they will match the coefficients of the FF-1052 Class, Hankley and West (1964). The only way in which the coefficients have been scaled to account for the variations of the coefficients with ship size and shape is through the selection of the speeds at which data were obtained and used. The interaction coefficients have been speed scaled using the Froude hypothesis, with the square root of the ratio of the lengths of the ships as the speed constant of proportionality.

Due to the fact that there are no experimental data for this configuration, no design propeller calculations were performed. Therefore, the propeller characteristics were estimated based on the parametric propeller design studies reported by Nelka and Cox (1981). Based on the results of this investigation, open water curves for fixed-pitch propellers were developed. The open water characteristics were used as input to the propulsor performance prediction program, along with the

the resistances and hull-propulsor interaction coefficients mentioned above.

Powering predictions for a single shaftline configuration fitted with fixed-pitch propellers are presented in Table C-14 for speeds between 10 and 32 knots. At 20 knots this configuration requires an effective power of 5900 kW (7910 hp) and a delivered power of 8470 kW (11360 hp). These values compare to 7030 kW and 10110 kW for the baseline configuration, respectively. This represents a 16.1 percent reduction in effective power and a 16.2 percent reduction in delivered power. At 32 knots, the same comparisons show an effective power of 33570 kW (45010 hp) and a delivered power of 50660 kW (67930 hp). These compare with values of 37250 kW and 54010 kW for the baseline configuration and represent a 9.9 percent reduction in effective power and a 6.2 reduction in delivered power.

Although the risks associated with these predictions are difficult to quantify, the resistance predictions seem reasonable when compared to the model experiments for the single shaftline tandem and contrarotating configurations. It is difficult to assure that a given set of hull-propulsor interaction coefficients will result from a given hull-appendage configuration. However, the chosen values are certainly attainable in that they have been copied directly from the results for a particular ship. The same comments apply to the selection of propeller characteristics; the estimated propeller efficiencies are obtainable with propellers which can satisfy the cavitation and strength criteria. Thus, while the confidence level of these predictions is lower than that associated with the configurations for which there are model experiments, these are not unduly optimistic predictions.

TABLE C-14 - PROJECTED POWERING PERFORMANCE FOR A PROROTYPE DESTROYER HULL FORM FITTED WITH A SINGLE FIXED-PITCH PROPELLER

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	940	700	1320	980	37.1
12	6.17	1680	1260	2380	1770	45.0
14	7.20	2730	2030	3870	2880	52.9
16	8.23	4080	3040	5820	4340	60.6
18	9.26	5780	4310	8270	6160	68.3
20	10.29	7910	5900	11360	8470	76.0
21	10.80	9130	6800	13130	9790	79.9
22	11.32	10450	7790	15020	11200	83.6
23	11.83	11890	8870	17090	12740	87.3
24	12.35	13460	10030	19350	14430	91.1
25	12.86	15260	11380	21950	16370	95.0
26	13.38	17460	13020	25180	18780	99.2
27	13.89	20040	14940	29000	21630	103.6
28	14.40	23480	17510	34220	25520	108.8
29	14.92	27710	20660	40730	30370	114.4
30	15.43	32890	24520	48910	36470	120.7
31	15.95	38760	28910	58100	43330	127.0
32	16.46	45010	33570	67930	50660	133.1

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	J_T
10	0.715	0.755	1.000	0.945	0.960	0.960	0.925	1.310
12	0.710	0.750	0.990	0.955	0.950	0.960	0.930	1.295
14	0.705	0.745	0.980	0.965	0.940	0.960	0.940	1.285
16	0.700	0.745	0.970	0.970	0.930	0.960	0.940	1.285
18	0.700	0.745	0.965	0.975	0.925	0.960	0.945	1.285
20	0.695	0.745	0.960	0.975	0.925	0.970	0.950	1.290
21	0.695	0.750	0.955	0.975	0.925	0.970	0.955	1.290
22	0.695	0.750	0.955	0.975	0.925	0.970	0.955	1.295
23	0.695	0.750	0.955	0.975	0.925	0.970	0.955	1.295
24	0.695	0.750	0.955	0.975	0.925	0.970	0.955	1.295
25	0.695	0.750	0.955	0.975	0.925	0.970	0.955	1.295
26	0.695	0.745	0.955	0.975	0.925	0.970	0.955	1.290
27	0.690	0.745	0.955	0.975	0.925	0.970	0.955	1.280
28	0.685	0.740	0.955	0.975	0.925	0.970	0.955	1.265
29	0.680	0.735	0.955	0.975	0.925	0.970	0.955	1.245
30	0.670	0.725	0.950	0.975	0.925	0.975	0.955	1.225
31	0.665	0.720	0.950	0.975	0.930	0.980	0.955	1.210
32	0.665	0.715	0.950	0.975	0.930	0.980	0.960	1.195

SINGLE SHAFTLINE TANDEM PROPELLERS

The delivered power projections for a contemporary single shaftline destroyer fitted with tandem propellers evolve from a straightforward extrapolation of experimental data. The experimental effective power and hull-propulsor interaction coefficients have been used to derive the characteristics of the design propeller, Majumdar and Krishnamoorthy (1980). The design propeller's characteristics and operating point at the design speed of 20 knots have been used to derive the open water curve which was used to make the powering predictions.

The powering characteristics for the single shaftline tandem configuration for speeds between 10 and 34 knots are presented in Table C-15. At 20 knots, this configuration requires a delivered power of 9210 kW (12350 hp), as compared to the baseline, which requires 10110 kW, a reduction in delivered power of 8.9 percent. At 32 knots, the single shaftline tandem configuration requires 52280 kW (70110 hp), while the baseline requires 54010 kW. This represents a 3.2 percent reduction in delivered power.

These predictions are of low risk, and in fact, are probably very conservative due to the poor hull-propulsor interaction coefficients which this configuration shows. These poor hull and relative rotative efficiencies are probably a result of poor stock-propeller performance. It is quite likely that if the redesign efforts made for the contrarotating propeller configurations were made for the stock tandem propellers, those coefficients would be significantly higher, as would the predicted performance of the configuration.

TABLE C-15 - PROJECTED POWERING PERFORMANCE FOR A PROTOTYPE DESTROYER HULL FORM FITTED WITH A SINGLE SET OF TANDEM PROPELLERS

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	960	720	1490	1110	41.7
12	6.17	1730	1290	2680	2000	49.8
14	7.20	2780	2070	4260	3200	57.7
16	8.23	4130	3080	6410	4780	65.9
18	9.26	5840	4350	9060	6760	73.9
20	10.29	7960	5940	12350	9210	82.2
21	10.80	9180	6850	14250	10620	86.3
22	11.32	10490	7830	16360	12200	90.2
23	11.83	11930	8900	18600	13870	94.2
24	12.35	13530	10090	21220	15820	98.1
25	12.86	15330	11430	23910	17830	102.3
26	13.38	17400	12980	25750	19950	106.3
27	13.89	20050	14950	30690	22880	111.0
28	14.40	23510	17530	35890	26760	115.1
29	14.92	27710	20660	42260	31510	121.5
30	15.43	32790	24450	50560	37710	127.9
31	15.95	38750	28890	59850	44530	134.4
32	16.46	45160	33670	70110	52280	141.1
33	16.98	51910	38710	80970	60380	147.6
34	17.49	59170	44120	93380	69630	154.8

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-T	1-WT	1-WQ	JT
10	0.645	0.730	0.880	1.005	0.915	1.040	1.045	1.265
12	0.645	0.730	0.895	0.985	0.915	1.020	1.010	1.245
14	0.650	0.730	0.910	0.975	0.915	1.005	0.990	1.235
16	0.645	0.730	0.910	0.970	0.915	1.005	0.990	1.235
18	0.645	0.730	0.915	0.965	0.915	1.000	0.980	1.235
20	0.645	0.730	0.910	0.970	0.915	1.005	0.990	1.240
21	0.645	0.730	0.910	0.970	0.915	1.005	0.990	1.240
22	0.640	0.730	0.910	0.965	0.915	1.005	0.985	1.240
23	0.640	0.730	0.910	0.965	0.915	1.005	0.985	1.240
24	0.640	0.730	0.910	0.960	0.910	1.000	0.975	1.240
25	0.640	0.730	0.910	0.965	0.910	1.000	0.980	1.235
26	0.650	0.730	0.915	0.975	0.910	0.995	0.980	1.230
27	0.655	0.730	0.915	0.980	0.910	0.995	0.985	1.225
28	0.655	0.725	0.920	0.980	0.910	0.990	0.990	1.210
29	0.655	0.725	0.925	0.980	0.910	0.985	0.970	1.190
30	0.650	0.720	0.920	0.980	0.905	0.985	0.970	1.170
31	0.645	0.715	0.920	0.985	0.905	0.985	0.975	1.150
32	0.645	0.710	0.915	0.990	0.905	0.990	0.985	1.135
33	0.640	0.710	0.910	0.995	0.905	0.995	0.990	1.125
34	0.635	0.705	0.905	0.995	0.900	0.995	0.990	1.110

SINGLE SHAFTLINE CONTROLLABLE-PITCH PROPELLER

As in the case of the single shaftline fixed-pitch propeller configuration, no propulsion experiments have been performed on this configuration as part of this program. Therefore, both effective power and hull-propulsor interaction coefficients had to be estimated so that the delivered power could be predicted.

The method for predicting the effective power is similar to that employed in the case of the single shaftline fixed-pitch configuration, except that the ratio of the effective power of the twin tandem configuration to that of the twin shaftline controllable-pitch propeller baseline is used in the formula:

$$P_E \text{ - single CP} = \frac{P_E \text{ - single tandem}}{\dfrac{P_E \text{ - twin tandem}}{P_E \text{ - twin CP}}}$$

The hull-propulsor interaction coefficientss have been assumed to agree with those of the FFG-7 Class, Woo, Karafiath, and Borda (1983), with the appropriate Froude scaling of the speed. As in the case of the single fixed-pitch configuration, the propeller design point was selected from the parametric study of Nelka and Cox (1981), which was used to develop the open water characteristics used in the powering performance predictions.

The effective and delivered powers for the single shaftline configuration for speeds between 10 and 32 knots are presented in Table C-16. At 20 knots, the effective and delivered powers are 6430 kW (8620 hp) and 9210 kW (12350 hp), respectively. These values compare with 7030 kW and 10110 kW for the baseline, and represent reductions of 8.5 percent and 8.9 percent in effective and delivered power, respectively. At 32 knots, the single shaftline controllable-pitch propeller configuration requires an effective power of 35560 kW (47690 hp) and a delivered power of 52910 kW (70950 hp). The respective values for the baseline are 37250 kW and 54010 kW. This represents a reduction of 4.5 percent in effective power and 2.0 percent in delivered power.

As was the case with the single shaftline fixed-pitch propeller predictions, these projections represent a higher degree of uncertainty than found in those predictions where model experiments were performed using stock propellers. However, these predictions are based on model data, albeit for a mixture of configurations, and should be reasonably reliable.

TABLE C-16 - PROJECTED POWERING PERFORMANCE FOR A PROTOTYPE DESTROYER HULL FORM FITTED WITH A SINGLE CONTROLLABLE-PITCH PROPELLER

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1040	770	1490	1110	42.5
12	6.17	1870	1390	2690	2010	51.5
14	7.20	3010	2240	4320	3220	60.0
16	8.23	4450	3320	6380	4760	68.5
18	9.26	6300	4690	8990	6710	76.9
20	10.29	8620	6430	12350	9210	85.4
21	10.80	9930	7410	14290	10650	89.6
22	11.32	11370	8480	16420	12250	93.9
23	11.83	12920	9640	18780	14000	98.3
24	12.35	14610	10890	21260	15850	102.4
25	12.86	16460	12280	23900	17820	106.6
26	13.38	18680	13930	27030	20160	111.0
27	13.89	21330	15910	30820	22980	115.6
28	14.40	25040	18670	36210	27000	121.1
29	14.92	29480	21980	42570	31740	126.7
30	15.43	34760	25920	50500	37660	133.3
31	15.95	41020	30590	60260	44940	140.2
32	16.46	47690	35560	70950	52910	147.0

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	J_T
10	0.695	0.745	0.970	0.965	0.930	0.960	0.945	1.145
12	0.695	0.740	0.970	0.965	0.930	0.960	0.945	1.135
14	0.695	0.740	0.975	0.965	0.930	0.955	0.940	1.130
16	0.695	0.740	0.975	0.965	0.930	0.955	0.940	1.130
18	0.700	0.740	0.975	0.970	0.930	0.955	0.940	1.130
20	0.700	0.740	0.975	0.965	0.930	0.955	0.940	1.130
21	0.695	0.740	0.975	0.965	0.930	0.955	0.940	1.135
22	0.690	0.740	0.970	0.960	0.930	0.955	0.940	1.135
23	0.690	0.740	0.970	0.955	0.930	0.960	0.940	1.140
24	0.685	0.745	0.970	0.955	0.930	0.960	0.940	1.140
25	0.690	0.740	0.970	0.960	0.925	0.960	0.940	1.140
26	0.690	0.740	0.970	0.965	0.925	0.955	0.940	1.135
27	0.690	0.740	0.965	0.970	0.920	0.955	0.940	1.125
28	0.690	0.735	0.965	0.975	0.915	0.950	0.935	1.110
29	0.695	0.730	0.970	0.980	0.915	0.945	0.935	1.095
30	0.690	0.725	0.965	0.985	0.915	0.950	0.940	1.080
31	0.680	0.720	0.960	0.985	0.910	0.950	0.940	1.065
32	0.670	0.715	0.950	0.985	0.905	0.955	0.945	1.050

SUMMARY

The performance predictions for the 11 twin shaftline and four single shaftline configurations are summarized in Tables C-17 and C-18. Table C-17 presents the effective and delivered powers, the hull-propulsor interaction coefficients, and the ratios of each configuration's effective and delivered powers to those of the respective baseline power at 20 knots. The same quantities at 32 knots are collected in Table C-18. After the first configuration (the baseline), it can be seen that the 20-knot delivered powers of the twin shaftline configurations increase monotonically down the table, followed by the single shaftline configurations in order of increasing power. In fact, it has been the order of these 20-knot projections of delivered power which has determined the order in which the various configurations have been presented throughout this report.

As can be seen by examining Table C-17, the top three configurations in terms of reduced delivered power at 20 knots are twin pods with contrarotating propellers, single shaftline contrarotating propellers, and single fixed-pitch propellers. These respective configurations show delivered power reductions of 20, 19, and 16 percent, relative to the controllable-pitch propeller baseline.

TABLE C-17 - SUMMARY OF DELIVERED POWER PROJECTIONS FOR FIFTEEN PROPULSOR CONFIGURATIONS ON A 7945 TONNE DESTROYER AT 20 KNOTS

Propulsion Arrangement	P_E (Hp)	P_D (Hp)	η_D	η_O	η_H	η_R	1-t	$1-W_T$	$\frac{P_{E-X}}{P_{E-Baseline}}$	$\frac{P_{D-X}}{P_{D-Baseline}}$
Twin CP	9430	13560	0.695	0.750	0.970	0.955	0.960	0.990	1.000	1.000
Twin Pod CR	8510	10870	0.785	0.820	0.945	1.010	0.920	0.975	0.902	0.802
Twin BRP-FP	8560	11510	0.745	0.765	0.955	1.020	0.905	0.945	0.908	0.849
Twin CR	9080	11790	0.770	0.795	0.945	1.025	0.935	0.990	0.963	0.869
Twin FP	8650	11890	0.725	0.765	0.970	0.985	0.920	0.950	0.917	0.877
Twin BRP-CP	8680	11950	0.725	0.750	0.945	1.020	0.900	0.950	0.920	0.881
Twin LD-FP	8750	12040	0.725	0.790	0.985	0.935	0.990	1.005	0.928	0.888
Twin Tandem	8710	12460	0.700	0.760	0.925	1.000	0.960	1.040	0.924	0.919
Twin CP-New Fairwater	9100	13420	---	---	---	---	---	---	0.965	0.990
Twin LD-Overlapping	8920	13640	0.655	0.795	0.965	0.855	0.960	0.995	0.946	1.006
Twin LD-CP	9270	14410	0.645	0.765	0.930	0.905	0.935	1.005	0.983	1.063
Single CR	8510	11000	0.775	0.800	0.985	0.980	0.965	0.980	0.902	0.811
Single FP	7910	11360	0.695	0.745	0.960	0.975	0.925	0.970	0.839	0.838
Single Tandem	7960	12350	0.645	0.730	0.910	0.970	0.915	1.005	0.844	0.911
Single CP	8620	12350	0.700	0.740	0.975	0.965	0.930	0.955	0.914	0.911

Notes: CP = Controllable-Pitch Propeller, FP = Fixed-Pitch Propeller, CR = Contrarotating Propellers, BRP = Bearing-In-Rudder Post, LD = Large Diameter

TABLE C-18 - SUMMARY OF DELIVERED POWER PROJECTIONS FOR FIFTEEN PROPULSOR CONFIGURATIONS ON A 7945 TONNE DESTROYER AT 32 KNOTS

Propulsion Arrangement	P_E (Hp)	P_D (Hp)	η_D	η_O	η_H	η_R	1-t	$1-W_T$	$\frac{P_{E\text{-}X}}{P_{E\text{-Baseline}}}$	$\frac{P_{D\text{-}X}}{P_{D\text{-Baseline}}}$
Twin CP	49960	72430	0.690	0.750	0.950	0.970	0.960	1.010	1.000	1.000
Twin Pod CR	46000	60450	0.760	0.815	0.935	1.000	0.915	0.980	0.921	0.835
Twin BRP-FP	46530	65080	0.715	0.750	0.935	1.025	0.900	0.965	0.931	0.899
Twin CR	48300	63190	0.765	0.800	0.935	1.025	0.930	0.995	0.967	0.872
Twin FP	47160	67110	0.705	0.750	0.945	0.990	0.925	0.975	0.944	0.927
Twin BRP-CP	47380	66330	0.715	0.745	0.950	1.010	0.920	0.970	0.948	0.916
Twin LD-FP	48840	66540	0.735	0.795	0.985	0.935	0.990	1.005	0.978	0.919
Twin Tandem	47310	67520	0.700	0.760	0.940	0.980	0.970	1.030	0.947	0.932
Twin CP-New Fairwater	48700	71710	---	---	---	---	---	---	0.975	0.990
Twin LD-Overlapping	48730	71210	0.685	0.795	0.960	0.895	0.960	1.000	0.975	0.983
Twin LD-CP	50540	74730	0.675	0.775	0.945	0.925	0.960	1.015	1.012	1.032
Single CR	47150	59790	0.790	0.790	0.960	1.035	0.935	0.970	0.944	0.825
Single FP	45010	67930	0.665	0.715	0.950	0.975	0.930	0.980	0.901	0.938
Single Tandem	45160	70110	0.645	0.710	0.915	0.990	0.905	0.990	0.904	0.968
Single CP	47690	70950	0.670	0.715	0.950	0.985	0.905	0.955	0.955	0.980

Notes: CP = Controllable-Pitch Propeller, FP = Fixed-Pitch Propeller, CR = Contrarotating Propellers, BRP = Bearing-In-Rudder Post, LD = Large Diameter

APPENDIX D

BRIEF SUMMARY OF RESEARCH ON PODDED PROPULSION

CONTENTS - APPENDIX D

BRIEF SUMMARY OF RESEARCH ON PODDED PROPULSION

INTRODUCTION

In the early 1970s, struts and pods* with high power were advocated as a means of propelling surface-effect ships, and studies with both right angle drives and enclosed motors were undertaken. In the late 1970s pods were first advocated for use on conventional combatants. One of these later studies showed great potential for ship weight reduction and fuel savings. At the same time, another study undertook the first experimental evaluation of propulsion pods. These studies led to a number of additional analytical and experimental efforts covering subjects ranging from resistance through contrarotating propulsion, and maneuvering.

SHIP IMPACT

The first studies of podded propulsion were those of Strom-Tejsen and Day (1971) and Roddy.** These efforts developed algorithms for use in predicting the performance of propulsion pods on surface-effect ships. Strom-Tejsen and Day concentrated on right angle drives, while Roddy concentrated on encapsulated superconducting motors. Both models included the sizing of the pods based on the size of the equipment which had to be enclosed within the pod; these efforts then continued to estimate pod drag and propulsion performance.

The first, and only, efforts to look at the impact of pods on the total ship design where those of Levedahl (1978 and 1980). In his work Levedahl shows that through proper selection of machinery components and their arrangement, significant reductions in ship size, installed power and fuel consumption can be achieved for a destroyer, without impacting payload, range, speed, margins, or stability. These gains are attained through synergistic effects among a number of systems such as gas turbines, electric drive, energy storage and contrarotating propulsion. Levedahl's highest leverage system uses all of the above concepts, with the gas turbines placed higher in the ship to reduce the volume of the ship dedicated to ducting, and with the electric motors placed in pods, which serves to reduce the length of shafting and its associated weight. Thus, Levedahl obtains results which indicate that the full load displacement of a destroyer thus equipped could

* For brevity, we shall refer to this strut-pod combination as a pod.
** Reported informally as Roddy, R.F. (1973), "Hydrodynamic Performance of a Propulsion Pod," NSRDC Ship Performance Department Technical Note TN-237.

be reduced some 35 percent relative to a conventional destroyer fitted with controllable-pitch propellers.

The publication of Levedahl's paper inaugurated a virtual flood of research on the pod concept, covering resistance, propulsion, and maneuvering. These efforts, some of which cover more than one of the above categories, will be discussed in the above order.

RESISTANCE

The first resistance experiments with pods were performed on a model of the DD-963 and reported by Kowalyshyn and Kirkman (1979). These studies involved resistance tests on a DD-963 hull fitted with shafts and struts, and two pod configurations -- one a pusher configuration, and the other a tractor configuration. The same pod was used for both the pusher and tractor experiments. It was just rotated end for end on the strut to change from one configuiration to the other. During the change from one configuration to the other, the propeller fairwaters were changed, as were the caps on the other end of the pod. These changes resulted in a tractor pod which was slightly longer than the pusher pod. The shapes of the strut barrels on the shafts and struts configuration varied slightly from those of the DD-963, while other details of the shafts and struts configuration cannot be assessed for their accuracy. All three configurations were fitted with the DD-963 spade rudders.

The results from Kowalyshyn and Kirkman show that the pusher pod has resistance which is 0.7 percent higher than the shafts and struts version at 20 knots, and 4.5 percent lower at 32 knots. The tractor pods have 2.1 percent higher and 2.3 percent lower resistance than the shafts and struts configuration at 20 and 32 knots, respectively. Thus, on the basis of this limited comparison, it can be concluded that these tractor pods have marginally higher resistance than pusher pods. This result is consistent with the tractor pods having slightly greater length and wetted surface than the pusher pods.

Roddy (1982) developed an analytical model for predicting the resistance of propulsion pods. His efforts are based on the empirical methods of Hoerner (1965) and employ the resistance data for streamlined bodies of revolution from Series 58, Gertler (1960). Roddy builds his results up as a series of drags and interferences between components. Thus he computes the drag of the body and the strut, and the interference between the strut and body and between the strut and the hull. He also includes some terms for pod-pod interaction.

Roddy compares the predictions of pod drag from his method to the experimental results from Kowalyshyn and Kirkman (1979). These comparisons, which oscillate, show that Roddy's method under-predicts the appendage drag due to the strut-pod configuration by as much as 41 percent at 22 knots and over-predicts the drag by as much as 18 percent at 34 knots. Roddy contends that, because all of his formulas depend on a flat plate friction line which is monotonic, the errors must be due to the wavemaking resistance of the hull-strut-pod combination.

Pod resistance is further studied in the experiments reported in Roddy (1983). In these experiments a series of four pods which represent different states-of-the-art in electric machinery design were mounted on a ground board and towed to determine their resistance as a function of pod-to-pod interference on pod resistance. These experiments found that the resistance varied strongly as a function of pod submergence. Again, these results were attributed to wave resistance. Roddy did find that for deeply submerged pods the analytical model, Roddy (1982), did do a reasonable job of predicting the resistance of pods. However, he concludes that it is not likely that forseeable pod designs will be deeply enough submerged for the free-surface effects to be negligible.

Fisher (1981b) carried out a series of experiments with a single pod located on the centerline of the DD-963 hull form at four longitudinal positions. He performed both traditional resistance experiments to determine residuary resistance, and longitudinal wave cuts to determine the wave pattern resistance. At 20 knots, Fisher's resistance experiments found that the addition of a pod could increase the total resistance of a bare hull by 11 percent, and that this varied by at most 1.5 percent with variations in pod location. Similarly, the residuary resistance of a bare hull increased by 31 percent, and varying the pod location changed this influence by ± 3 percent. He found, however, that the addition of a pod could increase the wave resistance of a bare hull model by an average of 22 percent, and that this value varied by ± 16 percent as the pod locaton was moved fore and aft. Two of Fisher's conclusions are of significance: first, the pod location which minimized the wave resistance due to the pod maximized the total resistance penalty due to the pod. Second, the use of the traditional wave resistance and bulb design techniques based on longitudinal wave cuts do not lead to proper guidance as to the location where the pod should be placed to minimize wave resistance. In conclusion, Fisher's experiments would indicate that the issue of pod location should not be treated by wave resistance theory, but rather must be treated by examining the total resistance of the ship-pod combination.

Motivated by Fisher's results, Kim (1983) performed an analysis of the wave-making resistance of pods mounted on ships. Using the traditional thin ship theory to represent the ship and a slender body representation of the pod, Kim attempted to analytically reproduce the experimental results produced by Fisher. Kim's results parallel Fisher's results in that he also concludes that the usual linearized wave resistance theory is not capable of predicting the experimental results, although Kim does conclude that the character of Fisher's results would seem to indicate that the variations in residuary resistance are due to wave-making.

PROPULSION

The first efforts in pod propulsion were those of Kowalyshyn and Kirkman (1979). They propelled the model of the DD-963 discussed above with shafts and struts and with both pusher and tractor pods using single rotation propellers. These experiments were conducted with a right angle drive mounted in the pod and with the transmission dynamometer mounted in the hull. Thus only torque could be measured. Because of this the hull-propulsor interaction coefficients for the pods had to be derived via torque identities. This in no way invalidates their results, but it does make comparisons with conventionally derived hull-propulsor interaction coefficients less meaningful. If we compare Kowalyshyn and Kirkman's accurately measured delivered power with pods to that with shafts and struts, we find that at 20 knots the pusher pod required 3.8 percent more delivered power than the shafts and struts configuration. Likewise, the tractor pod required 1.8 percent more power. At 32 knots, they found that the pusher pod required 3.2 percent less power and the tractor pod 2.3 percent less power than the shafts and struts configuration. Based on these results, one could conclude that the differences between tractor and pusher pods are not significant, and the benefits of pods over shafts and struts are negligible over the speed range. However, before one draws these conclusions, one should realize that the same set of propellers was used with all three configurations, and that these were models of the design propellers for the shafts and struts configuration. It is highly unlikely that the design propellers for the shafts and struts configurations would be the optimal propellers for use with either the tractor or pusher pod configurations, and the proper choice of propeller for the pod configurations could reduce the delivered power by 5 percent or more.

The next efforts in pod propulsion are those of Roddy (1982). He extended his analytical model development for pod resistance to include the prediction of hull-propulsor interaction coefficients and propeller performance. This resulted in a method for predicting delivered power for both pusher and tractor pods fitted with either single rotation or contrarotating propellers. Although this method is highly empirical in nature, it is based on much experimental data for submarines and does seem to include the known effects of interaction between the pods and propellers in a reasonable fashion. Thus, it would seem that this is a reasonable model to use for parametric studies as to the effects of various pod parameters on an overall ship design.

In addition to the resistance characteristics of four pod configurations, Roddy (1983) presents the results of propeller characterization performed on these pods at different depths of submergence. Valuable information on the variation of hull-propulsor interaction coefficients with pod proportions and propeller-to-hull clearance can be derived from this report.*

One useful comparison is to look at the differences in performance between pusher and tractor pods. Table D-1 presents a comparison of the performance of tractor and pusher pods at peak propeller efficiency.

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* The reader is warned to be cautious with the notation of this report. In Figures 21-25 Roddy uses the notations of K_T, K_Q, and η_O to denote the thrust and torque coefficients and efficiency behind the pod, rather than the traditional open-water thrust and torque coefficient and open-water efficiency. In Tables 21-25 Roddy uses K_T, K_Q, and η to denote the thrust and torque coefficients and efficiency behind the pod. In both of these cases, a better notation would be K_{TB}, K_{QB}, and η_B to denote the thrust and torque coefficients and efficiency behind, respectively.

TABLE D-1 - COMPARISON OF TRACTOR AND PUSHER POD PERFORMANCE

	Tractor Pod	Pusher Pod	$\frac{\eta\ (\text{Tractor})}{\eta\ (\text{Pusher})}$
η_O	0.738	0.684	1.0789
η_B	0.769	0.712	1.0801
η_{NET}	0.654	0.634	1.0315

As can be seen from the first line, the open water efficiency of the tractor propeller is 7.9 percent higher than that of the pusher propeller. The propeller efficiency behind the pod is 8.0 percent higher for the tractor pod, comparable to the open water efficiency ratio. However, if we look at η_{NET}, the efficiency based on the net thrust provided by the pod, we see that the efficiency of the tractor pod is reduced to 3.2 percent greater than that of the pusher pod. Thus, if open water efficiency of the pusher propeller were comparable to that of the tractor propeller, the pusher pod would provide 4.7 percent more useful thrust at the same power. This is not to say that, when other issues such as cavitation are considered, the pusher pod would still be superior, but it does give some measure of relative propulsive performance.

The only complete set of propulsion experiments with pods are those reported in Lin and Goldberg (1982). These experiments incorporated both thrust and torque measurements, and used contrarotating propellers to propel a model fitted with twin pusher pods, 15.54 m (51 ft) in length and 2.13 m (7 ft) in diameter, full-scale. This was accomplished by the use of a unique set of in-hub dynamometers which, in combination with slip rings and right angle drives, allowed the entire instrumentation package to be fitted into a model scale pod less than 0.63 m (2 ft) in length, and less than 0.086 m (0.28 ft) in diameter. This pod configuration had effective powers of 6340 kW (8510 hp) and 29330 kW (39330 hp) at 20 and 31* knots, respectively. This compares to the corresponding effective powers

* These comparisons are made at 31 knots rather than 32 knots because the model could not achieve speeds corresponding to 32 knots due to dynamometry limitations.

of 7030 kW (9430 hp) and 32160 kW (43120 hp) for the baseline, and represents reductions of 9.8 and 8.8 percent in effective power at speeds of 20 and 31 knots, respectively. The delivered powers for this configuration were 8340 kW (11190 hp) and 38970 kW (52260 hp) at 20 and 31 knots, respectively. These are 17.5 and 16.2 percent below the 10110 kW (13560 hp) and 46500 kW (62360 hp) delivered powers for the baseline configuration at 20 and 31 knots. These powering results represent the best of two sets of propellers which were used in the experiments. As is discussed in other parts of this report, it is expected that a set of design propellers could produce even better propulsive performance for a ship equipped with pods and contrarotating propellers.

MANEUVERING

There has been one maneuvering report on pods to date, by Motter. * In his study, Motter evaluates the maneuvering performance of three pod configurations fitted to the DD-963 hull form. Two of the pod configurations involved pods 18.3 m (60 ft) long and 2.4 m (8 ft) in diameter. One of these was a pusher pod with a separate rudder, and the second was a tractor pod with an integral rudder. The third configuration was a pusher pod 27.0 m (88.5 ft) long and 2.9 m (9.5 ft) in diameter, and fitted with a separate rudder. Motter evaluated these configurations by conducting maneuvering simulations using a modified version of the maneuvering simulation developed for the DD-963. Based on these studies, he concludes that the placement of and size of the strut supporting the pod are much more important than the pod itself to the maneuvering performance of the ship. His conclusions concerning the performance of the individual configurations are as follows. The short pusher pod will require a rudder 18 percent larger than the current DD-963 rudder in order to achieve the same maneuvering performance as the DD-963. He concludes that the tractor pod, with its strut placed further aft, will have poorer maneuvering performance than the current DD-963 for any reasonable rudder size, whether the rudder be a flap at the trailing edge of the strut or a separate rudder. Finally, due to the very low aspect ratio on the strut of the large pod, Motter concludes that its maneuvering performance would be about the same as that of the DD-963 with the same size rudder as is on the DD-963. Motter

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* In a report of higher classification.

is careful to note that all of these results must be confirmed by means of model tests before any design decisions are reached.

CONCLUSION

The summary of pod research presented above indicates that there is a modest-sized, but significant data base which shows that pods could have significant beneficial effects on the perfromance of surface combatants thus outfitted. Though much research still needs to be performed on pod hydrodynamics, machinery, structure, and ship systems integration, pods need to be treated carefully and postive ly. Pods should certainly not be rejected out-of-hand.

APPENDIX E

HISTORY OF BEARING-IN-RUDDER POST: APPLICATIONS AND EXPERIMENTS

CONTENTS - APPENDIX E

HISTORY OF BEARING-IN-RUDDER POST:
APPLICATIONS AND EXPERIMENTS

INTRODUCTION

At the start of the Energy Program in 1977, two model scale applications of the bearing-in-rudder post configuration were known. These applications were on models of two patrol craft: the PG-84 Class and an early design of the PCG Class. Thus, it came as somewhat of a surprise to discover in late 1982 that more than 50 years earlier the Coast Guard had had a class of 18 patrol boats fitted with bearing-in-rudder post. This discovery prompted a thorough search of model-test records dating back to the Experimental Model Basin (EMB). This search turned up five early experimental investigations relating to the bearing-in-rudder post, and led to the discovery that during the Second World War, the U.S. Navy built close to 200 patrol craft fitted with bearing-in-rudder post.

This appendix is intended to provide a brief history of the bearing-in-rudder post configuration. It starts with the earliest application of the bearing-in-rudder post to Coast Guard patrol boats in the 1930s and continues through to the present to include the experiments with two pairs of fixed-pitch propellers applied to the DD-963 hull form.

165-FOOT COAST GUARD PATROL BOAT

The earliest application found of the bearing-in-rudder post configuration was on the 165-foot Coast Guard patrol boat. Eighteen of these craft were built by Bath Iron Works between 1931 and 1934. They had a length on the water line of 49.00 m (160.75 ft), a maximum beam of 7.24 m (23.75 ft), and a draft of 2.13 m (7.0 ft) at a displacement of 299 tonne (294 tons). These vessels had twin shafts and fixed-pitch propellers powered by twin diesels; total shaft power was 999 kW (1340 hp). One of these vessels, the ELECTRA, was renamed the POTOMAC and became the Presidential Yacht.

The only published record concerning this class was the article by Johnson (1982), which motivated the search whose results are reported herein. A search of EMB records did show that a model of this class, Model 3076, was built and tested at the EMB, though no report was ever issued. The appendage configuration is shown in Figure E-1. Both bare hull and appended resistance experiments were performed. The bare hull resistance results are shown in Table E-1, while the appended resistance and propulsion characteristics with two pairs of propellers are given in Tables E-2 and E-3. From this data, an estimate of the appendage drag factor (appended resistance/bare hull resistance) can be obtained. This experimental data shows that the appendage drag factor varied from 1.21 at the low speed to 1.13 at the top speed. There were no shafts and struts experiments, so it is not possible to assess the differences in performance between the shafts and struts and bearing-in-rudder post configurations for this vessel. With the first set of propellers, numbered 1112 and 1113, the propeller efficiencies are somewhat lower than might be found with today's propellers. However, both the hull and relative rotative efficiencies are quite respectable, comparable to those on the DD-963 models. With the second set of propellers, numbered 1145 and 1146, the propeller efficiencies are higher. However, the hull efficiency falls off significantly. Therefore, both sets of propellers achieve propulsion efficiencies between 0.630 and 0.640.

The only full-scale performance data available is that which can be derived from the article by Johnson. He states that the vessels reached speeds of 16 knots during trials. A second and very valuable piece of information he offers is that these vessels had no vibration problems. This is important, in that one of the issues affecting the viability of the bearing-in-rudder post configuration is the issue of cavitation induced vibration.

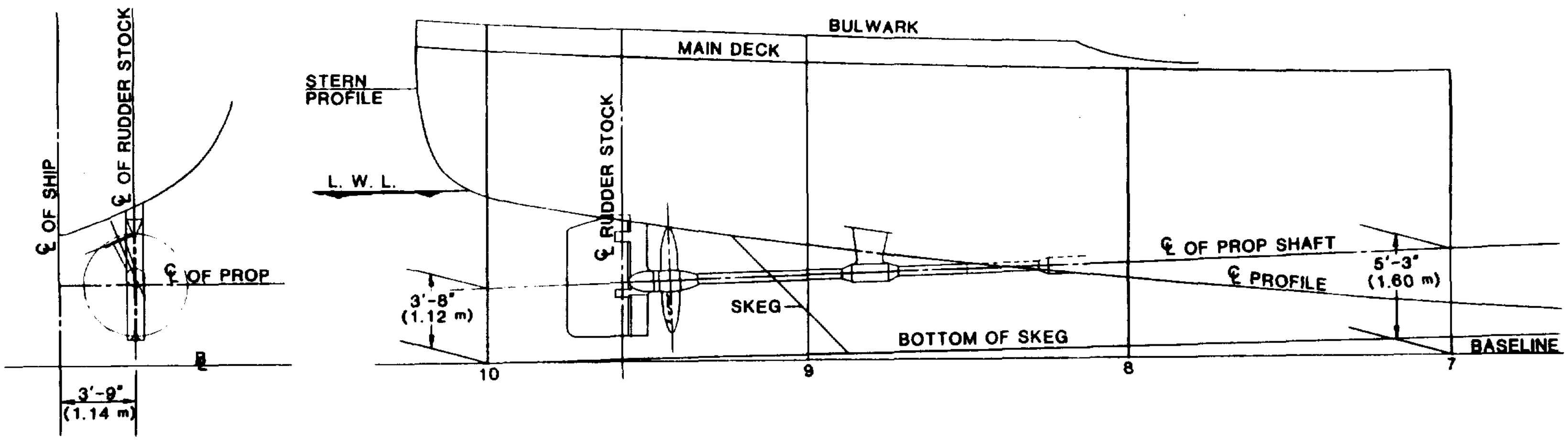

Figure E-1 Stern Appendages of the Bearing-in-Rudder Post Configuration Fitted on a 165-Foot Coast Guard Patrol Boat, Model 3076

TABLE E-1 - BARE HULL EFFECTIVE POWER PREDICTIONS FOR A 165-FOOT COAST GUARD PATROL BOAT, MODEL 3076

	SHIP	MODEL
LENGTH	160 FT (48.8 M)	16.00 FT (4.877 M)
WETTED SURFACE	3582 SQ FT (333 SQ M)	35.82 SQ FT (3.33 SQ M)
DISPLACEMENT	293 TONS (298 T)	.29 TONS (.29 T)
RHO	1.9905 (31.885 $N\text{-}S^2/m^4$)	1.9373 (31.033 $N\text{-}S^2/m^4$)
NU (E+5)	1.2817 (.11907 SQ M/SEC)	1.1287 (.10486 SQ M/SEC)

LINEAR RATIO 10.000
ITTC FRICTION LINE
CORRELATION ALLOWANCE (CA) .00040

VS		Effective Power		Frictional Power		FN	V-L	1000CR
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)			
3.32	1.71	3.1	2.3	3.0	2.2	0.078	0.263	0.109
4.79	2.47	9.1	6.8	8.5	6.4	0.113	0.379	0.178
6.47	3.33	23.0	17.2	20.2	15.1	0.152	0.512	0.336
7.94	4.08	42.8	31.9	36.4	27.2	0.187	0.628	0.409
9.46	4.86	74.9	55.8	60.3	45.0	0.222	0.748	0.552
11.13	5.73	130.5	97.3	96.6	72.1	0.262	0.880	0.787
12.75	6.56	213.4	159.1	143.2	106.7	0.300	1.008	1.087
14.18	7.30	322.4	240.4	194.6	145.1	0.334	1.121	1.437
15.13	7.78	431.1	321.5	234.6	175.0	0.356	1.196	1.819
15.65	8.05	515.1	384.1	258.8	193.0	0.368	1.238	2.144
15.81	8.13	551.2	411.0	266.4	198.7	0.372	1.250	2.312
16.10	8.28	604.0	450.4	280.5	209.2	0.379	1.273	2.489
16.89	8.69	809.1	603.3	322.3	240.3	0.397	1.335	3.244
17.23	8.87	900.7	671.7	341.8	254.9	0.405	1.363	3.503
17.82	9.17	1095.9	817.2	376.5	280.8	0.419	1.409	4.080
18.26	9.39	1235.9	921.6	404.2	301.4	0.430	1.444	4.382
18.52	9.52	1337.4	997.3	420.6	313.6	0.436	1.464	4.635

TABLE E-2 - POWERING PREDICTIONS FOR A 165-FOOT COAST GUARD PATROL BOAT WITH BEARING-IN-RUDDER POST APPENDAGE SUIT, MODEL 3076 WITH PROPELLERS 1112 AND 1113

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10.5	5.42	135	100	225	165	249.6
11.2	5.78	170	130	280	210	267.1
11.9	6.10	205	155	340	255	284.8
12.5	6.42	250	185	410	305	302.0
13.4	6.89	320	240	515	385	326.0
14.2	7.29	390	290	620	460	346.8
14.8	7.61	465	345	725	540	363.8
15.4	7.92	560	420	875	655	385.3
15.9	8.16	660	495	1050	780	403.5
16.5	8.50	830	620	1310	980	431.4
17.2	8.83	1020	760	1620	1210	458.5
17.8	9.16	1230	920	2010	1500	488.9

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	JT
10.5	0.610	0.655	0.935	0.995	0.835	0.895	0.890	0.740
11.2	0.605	0.655	0.940	0.980	0.830	0.885	0.875	0.730
11.9	0.605	0.655	0.925	0.995	0.820	0.890	0.885	0.725
12.5	0.610	0.655	0.925	1.005	0.825	0.890	0.890	0.720
13.4	0.625	0.655	0.945	1.010	0.845	0.895	0.895	0.720
14.2	0.630	0.655	0.950	1.010	0.855	0.895	0.900	0.720
14.8	0.645	0.655	0.960	1.020	0.850	0.885	0.900	0.705
15.4	0.640	0.655	0.960	1.020	0.855	0.890	0.905	0.695
15.9	0.630	0.650	0.955	1.015	0.845	0.885	0.895	0.680
16.5	0.635	0.645	0.955	1.025	0.850	0.885	0.905	0.665
17.2	0.630	0.640	0.960	1.025	0.850	0.885	0.905	0.650
17.8	0.615	0.630	0.935	1.040	0.830	0.890	0.915	0.635

TABLE E-3 - POWERING PREDICTIONS FOR A 165-FOOT COAST GUARD PATROL BOAT WITH BEARING-IN-RUDDER POST APPENDAGE SUIT, MODEL 3076 WITH PROPELLERS 1114 AND 1145

Ship Length	160.0 Feet (48.8 Meters)
Ship Displacement	292 Tons (297 Metric Tons)
Ship Wetted Surface	3785 Sq Ft (352 Sq Meters)
Correlation Allowance	.00040 ITTC Friction Used

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
9.8	5.05	105	80	180	135	236.1
10.9	5.59	150	110	255	190	264.6
11.6	5.95	185	140	315	235	282.1
12.2	6.26	225	165	375	280	299.8
12.8	6.56	270	200	445	330	315.2
13.8	7.11	360	265	565	420	344.6
14.2	7.29	390	290	615	460	353.0
14.6	7.53	440	325	695	515	366.6
15.3	7.85	530	395	840	625	387.6
15.8	8.12	635	475	995	740	406.9
16.4	8.46	805	600	1250	930	436.4
17.0	8.75	965	720	1530	1140	461.7
17.2	8.84	1020	760	1570	1170	465.9

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	**JT**
9.8	0.590	0.690	0.895	0.955	0.815	0.910	0.890	0.745
10.9	0.595	0.690	0.880	0.980	0.805	0.915	0.905	0.735
11.6	0.595	0.690	0.880	0.975	0.795	0.900	0.890	0.725
12.2	0.595	0.690	0.875	0.985	0.795	0.910	0.900	0.725
12.8	0.605	0.690	0.895	0.975	0.815	0.910	0.895	0.720
13.8	0.630	0.690	0.910	1.010	0.825	0.910	0.915	0.715
14.2	0.635	0.690	0.910	1.010	0.825	0.905	0.910	0.715
14.6	0.630	0.685	0.905	1.015	0.820	0.905	0.915	0.710
15.3	0.635	0.685	0.910	1.020	0.820	0.900	0.915	0.695
15.8	0.640	0.680	0.920	1.020	0.835	0.905	0.915	0.685
16.4	0.645	0.675	0.920	1.035	0.840	0.910	0.930	0.670
17.0	0.635	0.665	0.910	1.050	0.820	0.905	0.935	0.650
17.2	0.650	0.665	0.940	1.035	0.855	0.905	0.930	0.655

EPC-618 CLASS

The next examples of bearing-in-rudder post were also unpublished. They were the PC-452, PC-776, PC-1193, PCC, and EPC-618 Classes represented by Model 3585. Approximately 200 of these vessels were built at various shipyards throughout the United States, with the first one delivered in late 1941. These ships displaced about 386 tonnes (380 tons), were 51.82 m (170 ft) in length, had a beam of 6.86 m (22.5 ft), and a mean draft of 2.07 m (6.8 ft). They were twin shafted and had an installed power of 2088 kW (2800 hp), and reportedly were capable of speeds in excess of 20 knots. The bearing-in-rudder post on these vessels was supported by a single strut on each rudder which extended from the shaft centerline to the hull centerline. The majority of these craft which survived the war were transferred to other navies and the last one left the U.S. Navy in 1965.

The powering characteristics of one of these vessels, the EPC-618 Class, are given in Table E-4. (There are no comparable shafts and struts data.) These characteristics indicate that the hull-propulsor interaction coefficients are quite respectable, with excellent propeller efficiencies, and hull and relative rotative efficiencies of 0.900 and 1.015, respectively, in the mid-speed range. These results are quite remarkable considering the correlation allowance of 0.00298, which is at least six times higher than the usually accepted values. (This will be discussed further in the next paragraph.) Examination of the model test records shows that this excellent propulsive performance was not attained without some effort. At least seven different propeller designs were evaluated on this hull form before the best set of propellers was determined.

Full-scale trials data exist for the EPC-618 Class. These data were used to determine the correlation allowance of 0.00298. The trials records for these trials indicate the presence of a masker belt, and the fact that the hull condition was poor. Thus, this high correlation allowance should not be considered as characteristic of bearing-in-rudder post.

TABLE E-4 - POWERING PREDICTIONS FOR EPC-618 CLASS WITH BEARING-IN-RUDDER POST APPENDAGE SUIT, MODEL 3585 WITH PROPELLERS 2156 AND 2157

Ship Length	170.0 Feet (51.8 Meters)
Ship Displacement	378 Tons (384 Metric Tons)
Ship Wetted Surface	4283 Sq Ft (398 Sq Meters)
Correlation Allowance	.00298 ITTC Friction Used

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
6	3.09	55	40	75	55	99.9
7	3.60	85	65	115	90	116.7
8	4.12	130	95	175	130	133.4
9	4.63	185	140	255	190	149.4
10	5.14	260	190	360	270	167.9
11	5.66	350	260	490	365	185.5
12	6.17	460	340	645	480	203.2
13	6.69	600	445	860	640	222.2
14	7.20	765	570	1110	830	241.7
15	7.72	960	715	1390	1030	259.8
16	8.23	1220	910	1780	1330	280.0
17	8.75	1570	1170	2310	1730	304.2
18	9.26	2050	1530	3070	2290	330.7

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	JT
6	0.735	0.715	1.005	1.025	0.945	0.940	0.950	0.855
7	0.735	0.715	1.000	1.025	0.940	0.940	0.955	0.860
8	0.730	0.715	1.000	1.025	0.940	0.940	0.950	0.855
9	0.725	0.710	1.010	1.010	0.935	0.925	0.930	0.850
10	0.715	0.710	0.990	1.015	0.930	0.940	0.945	0.850
11	0.710	0.710	0.990	1.010	0.930	0.940	0.945	0.845
12	0.710	0.710	0.985	1.015	0.925	0.940	0.945	0.845
13	0.695	0.705	0.980	1.010	0.920	0.940	0.945	0.835
14	0.690	0.705	0.970	1.015	0.920	0.950	0.955	0.835
15	0.695	0.705	0.970	1.015	0.920	0.950	0.955	0.830
16	0.690	0.700	0.980	1.005	0.930	0.950	0.950	0.825
17	0.680	0.695	0.975	1.000	0.940	0.965	0.965	0.820
18	0.665	0.690	0.975	0.990	0.950	0.975	0.970	0.805

160-FOOT COAST GUARD PATROL CRAFT WPC

The next record of a bearing-in-rudder post was from a set of experiments performed on Model 4619, a proposed 160-foot Coast Guard patrol craft WPC, Beal (1956). This vessel was to have a length of 48.77 m (160 ft), a beam of 7.48 m (24.54 ft), and a draft of 2.13 m (7.0 ft). It was to displace 383 tonnes (377 tons and to attain a speed of 24 knots. This design was not pursued full scale because the decision was made to build a larger, 210-foot ship.

Beal also gives the results of bare hull and appended effective power experiments. At 20 knots the appendage drag factor due to the shafting and rudders was about 1.08, at least 4 percent lower than would be expected from the same hull with shafts and struts. As with the previous cases, there are no shafts and struts experimental data for this model. The powering data show propulsion efficiencies around 0.65 in the upper speed range. The thrust deduction is about 0.90, and the wake fraction is 0.97, resulting in a hull efficiency of 0.93. The propeller efficiency is 0.695, and the relative rotative efficiency is 1.01. This propulsion efficiency is respectable for a ship of this size with a propeller of this vintage.

83- AND 95-FOOT COAST GUARD PATROL BOATS

Cavanaugh (1960) reports on the next set of bearing-in-rudder post experiments, on Model 4429. This model represents two geometrically similar Coast Guard patrol boats, 83 and 95 feet in length, respectively. The smaller boat was equipped with shafts and struts, while the larger vessel was fitted with bearing-in-rudder post. At the heavy displacement, the 83-foot boat had a length of 22.26 m (73.03 ft), a beam of 4.87 m (15.99 ft), a draft of 1.80 m (5.89 ft), and a displacement of 69.5 tonnes (68.4 tons). The larger, 95-foot patrol boat had a waterline length of 27.44 m (90.04 ft), a beam of 5.62 m (18.45 ft), a draft of 2.06 m (6.76 ft), and a displacement of 107 tonnes (105 tons). Both vessels attained speeds between 30 and 32 knots, although no information on the full-scale performance of these vessels is available.

Cavanaugh's experiments were intended to study the effects of stern wedges on the performance of these craft. Therefore, only one appendage configuration, bearing-in-rudder post, was built and evaluated. The effect of the wedges on the two sizes of vessels was studied by analyzing the experimental data from one set of experiments with two scale ratios. Cavanaugh states explicitly that this is acceptable because the difference in performance between the shafts and struts configuration and the bearing-in-rudder post configuration "will be negligibly small." The data which will be presented later in this appendix shows this to be a naive assumption.

The hull-propulsor interaction coefficients which Cavanaugh reports show the highest propulsion efficiencies at 30 to 34 knots. The range of propulsion efficiencies which is presented varies between 0.58 and 0.67. These trends are followed by the hull, propeller, and relative rotative efficiencies, and are probably not unexpected for a craft such as this.

210-FOOT COAST GUARD PATROL CRAFT WPC

The next design with bearing-in-rudder post is a 210-foot Coast Guard Patrol Craft WPC, whose performance is presented in three reports published in 1961. This ship, represented by Model 4868, had a length of 60.96 m (200 ft) on the waterline, a beam of 10.06 m (33 ft), and a draft of 2.97 m (9.75 ft) at amidships. It displaced 945 tonnes (930 tons) and was to attain a speed of 20 or 21 knots.

West (1961a) reports on effective power experiments on the model, bare hull, and with both bearing-in-rudder post and shafts and struts. This is the first set of experiments found where there was any comparison between bearing-in-rudder post and shafts and struts. A comparison of the appendage drag factors shows factors of 1.133 and 1.194 for bearing-in-rudder post and shafts and struts, respectively, at 15 knots. Similar comparison at 21 knots shows factors of 1.070 and 1.084, respectively. Thus at 15 knots, bearing-in-rudder post provides a 5.1 percent reduction in effective power as compared to shafts and struts. A similar comparison at 21 knots shows a reduction of 1.3 percent. Only the shafts and struts configuration was used for propulsion experiments, West (1961b).

The significant experiments on Model 4868 were a series of maneuvering tests, Surber (1961). These experiments showed that the bearing-in-rudder post configuration had turning rates of about one half of those of the model equipped with shafts and struts. In addition, the bearing-in-rudder post responded much more slowly to rudder deflections during random maneuvers. This was, in fact, why the decision was made to perform the propulsion experiments and ultimately to build the ship with the shafts and struts configuration. However, it should be noted that the bearing-in-rudder post rudder had an area that was only 59 percent of that of the shafts and struts configuration. Thus it should not come as a significant surprise that the turning rate with the bearing-in-rudder post was significantly less than that with the conventional shafts and struts configuration. In fact, it is likely that if the areas of the two rudders were the same, the turning rates would be close to identical.

PG-84 CLASS

The first set of experiments where comparative data for both bearing-in-rudder post and shafts and struts were obtained was on Model 4950, Hoekzema (1964). This model represents a prototype for a 154-foot patrol boat, which became the PG-84 Class. These vessels had a length of 46.94 m (154.0 ft) on the waterline, a beam of 6.68 m (21.9 ft), a draft of 1.52 m (5.0 ft), and a displacement of 216.9 tonnes (213.5 tons). The PG-84 Class had an installed power of 8950 kW (12000 hp), and was capable of achieving speeds in excess of 40 knots. This is the first example of bearing-in-rudder post to employ the contraguide feature in the design of the rudder.

Hoekzema's original experimental data has been reanalyzed and is presented here. Table E-5 presents the shafts and struts data, and Table E-6 presents the bearing-in-rudder post data. A comparison of the data for these two configurations shows that the bearing-in-rudder reduced the effective power by 6.5 percent at 20 knots and 2.8 percent at 32 knots, relative to the shafts and struts configuration. Bearing-in-rudder post reduced the delivered power by 15.4 percent at 20 knots, and by 12.6 percent at 32 knots. This 32-knot improvement is representative of the 12 to 13 percent delivered power reduction which is available throughout the range of speeds between 26 and 40 knots, and illustrates conclusively the improvement in performance which is possible with bearing-in-rudder post.

TABLE E-5 - POWERING PREDICTIONS FOR PG-84 CLASS WITH TWIN SHAFTS AND STRUTS APPENDAGE SUIT, MODEL 4950 WITH PROPELLERS 4056 AND 4057

Ship Length	154.0 Feet (46.9 Meters)
Ship Displacement	213 Tons (217 Metric Tons)
Ship Wetted Surface	3205 Sq Ft (298 Sq Meters)
Correlation Allowance	.00040 ITTC Friction Used

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
18	9.26	980	730	1670	1250	328
20	10.29	1380	1030	2340	1750	368
22	11.32	1770	1320	2970	2210	404
24	12.35	2180	1630	3640	2710	436
26	13.38	2630	1960	4380	3270	466
28	14.40	3110	2320	5150	3840	495
30	15.43	3670	2740	6020	4490	524
32	16.46	4290	3200	6990	5210	553
34	17.49	4980	3710	8080	6030	582
36	18.52	5790	4320	9300	6930	612
38	19.55	6680	4980	10580	7890	642
40	20.58	7640	5700	11980	8930	672

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	JT
18	0.585	0.720	0.905	0.900	0.925	1.020	0.960	1.035
20	0.590	0.720	0.900	0.910	0.930	1.030	0.975	1.035
22	0.595	0.725	0.890	0.920	0.930	1.045	1.000	1.050
24	0.600	0.730	0.890	0.920	0.930	1.045	1.000	1.060
26	0.600	0.735	0.890	0.920	0.925	1.040	0.995	1.070
28	0.605	0.735	0.890	0.920	0.920	1.035	0.995	1.080
30	0.610	0.740	0.895	0.920	0.925	1.030	0.990	1.085
32	0.615	0.740	0.905	0.915	0.925	1.025	0.985	1.095
34	0.615	0.745	0.910	0.910	0.930	1.025	0.980	1.100
36	0.625	0.745	0.915	0.915	0.935	1.020	0.980	1.105
38	0.630	0.745	0.920	0.920	0.935	1.015	0.980	1.110
40	0.640	0.750	0.925	0.925	0.940	1.015	0.980	1.110

TABLE E-6 - POWERING PREDICTIONS FOR PG-84 CLASS WITH BEARING-IN-RUDDER POST APPENDAGE SUIT, MODEL 4950 WITH PROPELLERS 4056 AND 4057

Ship Length	154.0 Feet (46.9 Meters)
Ship Displacement	213 Tons (217 Metric Tons)
Ship Wetted Surface	3205 Sq Ft (298 Sq Meters)
Correlation Allowance	.00040 ITTC Friction Used

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
18	9.26	920	685	1390	1040	316
20	10.29	1290	960	1980	1480	354
22	11.32	1690	1260	2560	1910	388
24	12.35	2130	1590	3160	2360	418
26	13.38	2580	1920	3810	2840	448
28	14.40	3050	2270	4500	3360	476
30	15.43	3570	2660	5260	3920	502
32	16.46	4170	3110	6110	4560	532
34	17.49	4850	3620	7080	5280	561
36	18.52	5580	4160	8090	6030	589
38	19.55	6370	4750	9250	6900	618
40	20.58	7260	5410	10530	7850	648

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	JT
18	0.660	0.720	0.945	0.975	0.925	0.980	0.965	1.025
20	0.650	0.715	0.935	0.970	0.925	0.985	0.970	1.025
22	0.660	0.720	0.935	0.980	0.920	0.985	0.975	1.030
24	0.675	0.720	0.945	0.995	0.920	0.970	0.970	1.030
26	0.675	0.720	0.940	0.995	0.915	0.970	0.970	1.035
28	0.680	0.725	0.940	0.995	0.910	0.970	0.965	1.050
30	0.680	0.730	0.945	0.985	0.910	0.960	0.950	1.055
32	0.685	0.735	0.945	0.985	0.910	0.965	0.955	1.065
34	0.685	0.735	0.945	0.985	0.910	0.960	0.955	1.075
36	0.690	0.735	0.950	0.985	0.910	0.960	0.950	1.080
38	0.690	0.740	0.950	0.980	0.910	0.960	0.950	1.085
40	0.690	0.740	0.945	0.985	0.910	0.960	0.955	1.090

PCG CLASS

The next example of the application of bearing-in-rudder post is on a design of another patrol boat, Model 5300, representing an early version of the PCG. This model also has data for shafts and struts, Grant (1973), and bearing-in-rudder post, Hampton & Weaver (1973). In addition to the bearing-in-rudder post data of Hampton and Weaver, which were for a bearing-in-rudder post with support strut, data for bearing-in-rudder post without a support strut have been found and are presented here for the first time.

The PCG represented in these experiments had a waterline length of 67.06 m (220 ft), a beam of 8.38 m (27.5 ft), and a draft of 2.44 m (8.0 ft). Its displacement was 649 tonnes (639 tons). It was intended to reach speeds of 30 to 32 knots with installed power of about 14,900 kW (20,000 hp).

The powering characteristics of Model 5300 equipped with shafts and struts is presented in Table E-7 and those of the bearing-in-rudder post with a support strut extending from the rudder horn to the hull are presented in Table E-8. As stated above, an examination of the model test folder showed that this model had also been evaluated with the normal unsupported bearing-in-rudder post; the powering performance of this configuration is presented in Table E-9. A comparison of the results with shafts and struts to those with the two bearing-in-rudder post configurations shows that the bearing-in-rudder post with support strut reduced the effective power by 1.0 percent over the speed range, while the bearing-in-rudder post without support strut reduced the effective power by 2.5 percent over the speed range. The bearing-in-rudder post with strut reduced the delivered power by 8.2 percent at 20 knots, and 6.3 percent at 32 knots. The bearing-in-rudder post without strut reduced the delivered power by 11.3 percent at 20 knots and 9.7 percent at 32 knots.

TABLE E-7 - POWERING PREDICTIONS FOR A 220-FOOT PATROL CRAFT FITTED WITH TWIN SHAFTS AND STRUTS APPENDAGE SUIT, MODEL 5300 WITH PROPELLERS 4415 AND 4416, FROM GRANT (1973)

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	245	185	405	300	131.4
12	6.17	440	330	725	540	158.8
14	7.20	730	545	1200	895	186.9
16	8.23	1130	845	1860	1390	215.4
18	9.26	1660	1240	2770	2070	245.0
20	10.29	2540	1890	4260	3180	279.0
22	11.32	3780	2820	6390	4760	315.5
24	12.35	5170	3860	8740	6520	349.1
26	13.38	6600	4920	11170	8330	378.4
28	14.40	8060	6010	13570	10120	405.4
30	15.43	9640	7190	16120	12020	431.3
32	16.46	11360	8470	18740	13970	455.2

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	JT
10	0.606	0.753	0.888	0.907	0.880	0.991	0.963	0.955
12	0.606	0.752	0.887	0.908	0.880	0.992	0.964	0.950
14	0.606	0.751	0.884	0.913	0.880	0.995	0.968	0.944
16	0.604	0.750	0.880	0.914	0.880	1.000	0.972	0.940
18	0.600	0.750	0.875	0.915	0.881	1.008	0.980	0.938
20	0.597	0.747	0.871	0.917	0.888	1.020	0.990	0.925
22	0.592	0.744	0.866	0.919	0.897	1.035	1.005	0.914
24	0.592	0.742	0.865	0.922	0.904	1.045	1.015	0.910
26	0.591	0.742	0.867	0.918	0.907	1.046	1.014	0.910
28	0.594	0.744	0.872	0.916	0.912	1.046	1.013	0.914
30	0.598	0.745	0.878	0.913	0.917	1.044	1.011	0.919
32	0.606	0.747	0.892	0.910	0.926	1.038	1.005	0.924

TABLE E-8 - POWERING PREDICTIONS FOR A 220-FOOT PATROL CRAFT FITTED WITH BEARING-IN-RUDDER POST WITH SUPPORTING STRUT APPENDAGE SUIT, MODEL 5300 WITH PROPELLERS 4415 AND 4416, FROM HAMPTON AND WEAVER (1973)

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	275	205	430	320	134.4
12	6.17	450	335	705	525	160.1
14	7.20	710	530	1110	830	186.8
16	8.23	1080	805	1600	1190	214.5
18	9.26	1600	1190	2520	1880	243.7
20	10.29	2480	1850	3910	2920	276.5
22	11.32	3780	2820	5970	4450	312.1
24	12.35	5120	3820	8100	6040	343.8
26	13.38	6550	4880	10380	7740	373.8
28	14.40	8050	6000	12760	9520	401.6
30	15.43	9540	7110	15140	11290	427.8
32	16.46	11080	8260	17590	13120	454.2

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	JT
10	0.640	0.750	0.874	0.976	0.872	0.998	0.991	0.939
12	0.638	0.752	0.872	0.973	0.872	1.000	0.992	0.947
14	0.637	0.752	0.871	0.973	0.872	1.001	0.993	0.949
16	0.636	0.752	0.868	0.975	0.872	1.005	0.998	0.948
18	0.635	0.751	0.864	0.979	0.872	1.009	1.003	0.942
20	0.634	0.747	0.863	0.984	0.872	1.010	1.005	0.924
22	0.633	0.740	0.862	0.993	0.872	1.012	1.010	0.902
24	0.632	0.737	0.859	0.998	0.872	1.015	1.014	0.896
26	0.631	0.738	0.856	1.000	0.872	1.019	1.019	0.896
28	0.631	0.739	0.855	0.999	0.872	1.020	1.020	0.899
30	0.630	0.741	0.853	0.996	0.872	1.022	1.021	0.906
32	0.630	0 744	0.849	0.997	0.872	1.027	1.026	0.915

TABLE E-9 - POWERING PREDICTIONS FOR A 220-FOOT PATROL CRAFT FITTED WITH BEARING-IN-RUDDER POST APPENDAGE SUIT, MODEL 5300 WITH PROPELLERS 4415 AND 4416

Ship Length	220.0 Feet (67.1 Meters)
Ship Displacement	640 Tons (650 Metric Tons)
Ship Wetted Surface	5510 Sq Ft (605 Sq Meters)
Correlation Allowance	.00050 ITTC Friction Used

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
20	10.29	2460	1840	3780	2820	276.4
22	11.32	3680	2740	5640	4210	310.1
24	12.35	5080	3780	7780	5800	342.1
26	13.38	6470	4820	9920	7400	370.7
28	14.40	7880	5880	12090	9020	397.5
29	14.92	8630	6430	13230	9860	410.5
30	15.43	9400	7010	14420	10750	423.5
31	15.95	10190	7600	15660	11680	436.1
32	16.46	11000	8200	16920	12620	448.6

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	JT
20	0.650	0.765	0.910	0.940	0.930	1.025	1.000	0.935
22	0.650	0.760	0.910	0.945	0.930	1.025	1.000	0.920
24	0.650	0.755	0.910	0.945	0.930	1.025	1.000	0.910
26	0.650	0.755	0.910	0.945	0.930	1.025	1.000	0.910
28	0.650	0.755	0.910	0.945	0.930	1.025	1.000	0.910
29	0.650	0.755	0.910	0.945	0.930	1.025	1.000	0.915
30	0.650	0.760	0.910	0.945	0.930	1.025	1.000	0.915
31	0.650	0.760	0.910	0.945	0.930	1.020	1.000	0.920
32	0.650	0.760	0.910	0.945	0.925	1.020	1.000	0.920

DD-963 HULL FORM

The final data are for two sets of bearing-in-rudder post experiments performed on the DD-963 hull form. The first of these was performed with three different rudder configurations, Models 5359-0A, -0B, -0C, using models of the DD-963 design controllable-pitch propellers, numbered 4660 and 4661, albeit these propellers were in a deteriorated condition. The three rudders were a straight rudder (5359-0A); a cambered, contraguide rudder (5359-0B); and a contraguide rudder with bulbous extension of the propeller hub, Costa bulb (5359-0C). The second set of experiments was performed with two pairs of fixed-pitch propellers, numbered 4274 & 4275 and 4864 & 4865, on Model 5359-0A1, which was fitted with a straight rudder.

Models 5359-0 and 5359-1 represent the DD-963 hull form, which has a waterline length of 161.6 m (530.2 ft), a beam of 16.76 m (55.0 ft), and a draft of 5.94 m (19.5 ft). This ship has a displacement of 7945 tonnes (7820 tons). The parent DD-963 has an installed power of 60 mW (80,000 hp) and a design speed of 32 knots.

Controllable-Pitch Propellers

The results of the bearing-in-rudder post experiments with three rudder configurations and controllable-pitch propellers were first reported in West (1981). However, after this report was published, it was discovered that an incorrect set of residuary resistance coefficients had been used in calculating the effective power. It was also discovered that the open water performance of the propellers had degraded significantly. Thus it was necessary to completely reanalyze the bearing-in-rudder post with controllable-pitch propeller experimental data. The fact that the model controllable-pitch propeller had degraded meant that the parent DD-963 results, Reed and Wilson (1980a), were not the correct basis against which to compare these bearing-in-rudder post results. Therefore, the shafts and struts experiments were repeated with the degraded propellers, which have been designated propellers 4660A and 4661A.

The powering performance of the parent DD-963 with degraded controllable-pitch propellers is given in Table E-10. The propulsion performances with the straight, contraguide, and contraguide with Costa bulb configurations are given in Tables E-11, E-12, and E-13, respectively. The powering benefit provided by bearing-in-rudder post in these three cases must be looked at as due to two separate improvements: one, a reduction in effective power, and two, an increase in propulsion efficiency. Table E-14 presents a summary of these two benefits and the aggregate delivered power.

As can be seen by examining Table E-14, the straight rudder provided the greatest reduction in effective power and the smallest increase in propulsion efficiency. The contraguide rudder provided the smallest reduction in effective power and the largest increase in propulsion efficiency. The contraguide rudder with Costa bulb provided reductions intermediate between the other two rudders. The bottom line for these three configurations is that the effective power reduction with the straight rudder is great enough that it overcomes the better propulsion efficiency of the other configurations and results in a reduction in delivered power which is 3 percent greater than that of the contraguide rudder and 3.8 percent greater than that of the contraguide rudder with Costa bulb, at 20 knots. The results at 32 knots are similar, although the differences are smaller.

TABLE E-10 - POWERING PREDICTIONS FOR THE PARENT DD-963 FITTED WITH TWIN SHAFTS AND STRUTS APPENDAGE SUIT AND DESIGN CONTROLLABLE-PITCH PROPELLERS IN DEGRADED CONDITION, MODEL 5359 WITH PROPELLERS 4660A AND 4661A

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1110	830	1660	1230	48.5
12	6.17	2010	1500	2990	2230	58.7
14	7.20	3250	2420	4840	3610	68.7
16	8.23	4830	3600	7190	5360	78.4
18	9.26	6840	5100	10180	7590	88.2
20	10.29	9290	6930	13830	10320	97.8
21	10.80	10660	7950	15880	11840	102.5
22	11.32	12160	9070	18120	13510	107.3
23	11.83	13780	10280	20540	15310	112.0
24	12.35	15550	11600	23180	17280	116.7
25	12.86	17480	13030	26060	19430	121.5
26	13.38	19690	14680	29350	21890	126.4
27	13.89	22540	16810	33650	25090	131.9
28	14.40	26240	19570	39170	29210	137.9
29	14.92	30870	23020	46130	34400	144.5
30	15.43	36280	27050	54300	40490	151.3
31	15.95	42490	31680	63790	47570	158.4
32	16.46	49220	36700	74300	55400	165.7

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-T	1-WT	1-WQ	JT
10	0.670	0.685	0.980	1.000	0.960	0.980	0.980	1.205
12	0.670	0.685	0.980	1.000	0.960	0.980	0.980	1.195
14	0.670	0.685	0.980	1.000	0.960	0.980	0.980	1.190
16	0.670	0.685	0.980	1.000	0.960	0.980	0.980	1.190
18	0.670	0.685	0.980	1.000	0.960	0.980	0.980	1.190
20	0.670	0.685	0.980	1.000	0.960	0.980	0.980	1.195
21	0.670	0.685	0.980	1.000	0.960	0.980	0.980	1.195
22	0.670	0.685	0.980	1.000	0.960	0.980	0.980	1.195
23	0.670	0.685	0.980	1.000	0.960	0.980	0.980	1.200
24	0.670	0.685	0.980	1.000	0.960	0.980	0.980	1.200
25	0.670	0.685	0.980	1.000	0.960	0.980	0.980	1.200
26	0.670	0.685	0.980	1.000	0.960	0.980	0.980	1.200
27	0.670	0.685	0.980	1.000	0.960	0.980	0.980	1.200
28	0.670	0.685	0.975	1.000	0.960	0.985	0.985	1.190
29	0.670	0.685	0.975	1.000	0.960	0.985	0.985	1.180
30	0.670	0.685	0.975	1.000	0.960	0.985	0.985	1.165
31	0.665	0.685	0.970	1.000	0.960	0.990	0.990	1.155
32	0.660	0.685	0.965	1.000	0.960	0.995	0.995	1.145

TABLE E-11 - POWERING PREDICTIONS FOR THE DD-963 HULL FORM FITTED WITH STRAIGHT RUDDER BEARING-IN-RUDDER POST APPENDAGE SUIT AND CONTROLLABLE-PITCH PROPELLERS, MODEL 5359-OA WITH PROPELLERS 4660A AND 4661A

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	985	735	1460	1090	47.1
12	6.17	1810	1350	2680	2000	57.1
14	7.20	2960	2200	4380	3270	67.0
16	8.23	4440	3310	6590	4910	76.7
18	9.26	6300	4700	9340	6970	86.2
20	10.29	8550	6380	12630	9420	95.6
21	10.80	9840	7340	14610	10890	100.6
22	11.32	11250	8390	16630	12400	105.3
23	11.83	12810	9550	18930	14110	110.0
24	12.35	14490	10800	21410	15970	114.6
25	12.86	16300	12160	24120	17990	119.7
26	13.38	18440	13750	27230	20300	124.2
27	13.89	21160	15780	31330	23360	129.5
28	14.40	24750	18450	36830	27470	135.4
29	14.92	29040	21660	43210	32230	141.6
30	15.43	34100	25430	51020	38040	148.4
31	15.95	39960	29800	59910	44670	155.6
32	16.46	46680	34810	70090	52270	162.9
33	16.98	53780	40100	80780	60240	170.0
34	17.49	61130	45590	92300	68830	177.4

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	JT
10	0.670	0.690	0.945	1.030	0.900	0.950	0.960	1.200
12	0.675	0.690	0.945	1.030	0.900	0.950	0.960	1.190
14	0.675	0.690	0.945	1.030	0.900	0.950	0.960	1.185
16	0.675	0.690	0.945	1.030	0.900	0.950	0.960	1.180
18	0.675	0.690	0.945	1.030	0.900	0.950	0.960	1.180
20	0.675	0.690	0.945	1.035	0.900	0.950	0.965	1.185
21	0.675	0.690	0.940	1.035	0.900	0.955	0.970	1.190
22	0.675	0.690	0.940	1.040	0.900	0.955	0.970	1.190
23	0.675	0.690	0.940	1.040	0.900	0.955	0.970	1.190
24	0.675	0.690	0.940	1.040	0.900	0.955	0.970	1.190
25	0.675	0.690	0.935	1.045	0.900	0.960	0.975	1.195
26	0.675	0.690	0.945	1.040	0.900	0.955	0.970	1.190
27	0.675	0.690	0.945	1.035	0.900	0.955	0.970	1.185
28	0.670	0.690	0.950	1.025	0.905	0.955	0.965	1.175
29	0.670	0.690	0.950	1.020	0.910	0.955	0.965	1.165
30	0.670	0.690	0.950	1.015	0.915	0.960	0.965	1.155
31	0.665	0.690	0.950	1.015	0.915	0.965	0.970	1.145
32	0.665	0.690	0.950	1.015	0.920	0.970	0.975	1.135
33	0.665	0.690	0.950	1.015	0.925	0.975	0.980	1.125
34	0.660	0.690	0.945	1.015	0.930	0.985	0.990	1.125

TABLE E-12 - POWERING PREDICTIONS FOR THE DD-963 HULL FORM FITTED WITH CONTRA-GUIDE RUDDER BEARING-IN-RUDDER POST APPENDAGE SUIT AND CONTROLLABLE-PITCH PROPELLERS, MODEL 5359-OB WITH PROPELLERS 4660A AND 4661A

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1060	790	1520	1130	47.4
12	6.17	1940	1440	2780	2070	57.3
14	7.20	3150	2350	4530	3380	67.3
16	8.23	4730	3530	6810	5070	76.9
18	9.26	6680	4980	9610	7170	86.5
20	10.29	9050	6750	13040	9730	96.1
21	10.80	10390	7750	15000	11180	100.9
22	11.32	11830	8820	17120	12770	105.7
23	11.83	13390	9990	19410	14470	110.5
24	12.35	15110	11270	21900	16330	115.3
25	12.86	17040	12700	24730	18440	120.1
26	13.38	19210	14330	28000	20880	124.9
27	13.89	21880	16320	31940	23820	130.2
28	14.40	25550	19050	37410	27900	136.2
29	14.92	29970	22350	44080	32870	142.5
30	15.43	35290	26310	52050	38810	149.5
31	15.95	41210	30730	61050	45530	156.5
32	16.46	47830	35670	71070	53000	163.6
33	16.98	54810	40870	81800	61000	170.9
34	17.49	62140	46340	93020	69360	178.0

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-T	1-WT	1-WQ	JT
10	0.695	0.685	0.995	1.020	0.945	0.950	0.960	1.195
12	0.695	0.685	0.995	1.015	0.945	0.950	0.955	1.185
14	0.695	0.685	0.995	1.020	0.945	0.950	0.955	1.180
16	0.695	0.685	0.995	1.015	0.945	0.950	0.955	1.175
18	0.695	0.685	0.995	1.020	0.945	0.950	0.960	1.180
20	0.695	0.685	0.990	1.020	0.945	0.955	0.960	1.185
21	0.695	0.685	0.990	1.020	0.945	0.955	0.965	1.185
22	0.690	0.690	0.985	1.020	0.945	0.960	0.970	1.190
23	0.690	0.690	0.980	1.020	0.945	0.960	0.970	1.195
24	0.690	0.690	0.980	1.025	0.945	0.965	0.975	1.195
25	0.690	0.690	0.980	1.020	0.945	0.965	0.975	1.195
26	0.685	0.690	0.980	1.015	0.945	0.965	0.970	1.195
27	0.685	0.690	0.980	1.020	0.945	0.965	0.975	1.195
28	0.685	0.685	0.980	1.015	0.945	0.965	0.970	1.180
29	0.680	0.685	0.980	1.010	0.945	0.965	0.970	1.170
30	0.680	0.685	0.975	1.015	0.945	0.970	0.975	1.155
31	0.675	0.685	0.975	1.015	0.945	0.970	0.975	1.145
32	0.675	0.685	0.970	1.015	0.945	0.975	0.980	1.135
33	0.670	0.685	0.965	1.015	0.945	0.980	0.990	1.130
34	0.670	0.685	0.960	1.020	0.945	0.985	0.995	1.125

TABLE E-13 - POWERING PREDICTIONS FOR THE DD-963 HULL FORM FITTED WITH CONTRA-GUIDE RUDDER AND COSTA BULB BEARING-IN-RUDDER POST APPENDAGE SUIT AND CONTROLLABLE-PITCH PROPELLERS, MODEL 5359-OC AND PROPELLERS 4660A AND 4661A

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1050	790	1530	1140	47.6
12	6.17	1860	1390	2700	2010	57.3
14	7.20	3130	2330	4570	3410	67.3
16	8.23	4690	3500	6850	5110	76.9
18	9.26	6640	4950	9650	7200	86.5
20	10.29	9010	6720	13150	9800	96.1
21	10.80	10340	7710	15100	11260	100.9
22	11.32	11760	8770	17170	12800	105.7
23	11.83	13310	9920	19420	14480	110.5
24	12.35	15020	11200	21930	16350	115.3
25	12.86	16920	12620	24700	18420	119.9
26	13.38	19140	14270	28020	20890	124.9
27	13.89	21890	16330	32150	23970	130.0
28	14.40	25560	19060	37590	28030	135.6
29	14.92	29990	22360	44360	33080	141.8
30	15.43	35380	26330	52150	38890	148.3
31	15.95	41180	30710	61190	45630	155.8
32	16.46	47750	35610	71270	53150	162.9
33	16.98	54830	40890	82090	61210	170.0
34	17.49	62170	46360	93490	69710	176.9

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-T	1-WT	1-WQ	JT
10	0.690	0.690	0.955	1.050	0.905	0.950	0.965	1.185
12	0.690	0.690	0.955	1.050	0.905	0.950	0.965	1.180
14	0.685	0.685	0.965	1.035	0.905	0.940	0.955	1.165
16	0.685	0.685	0.965	1.035	0.905	0.940	0.950	1.165
18	0.690	0.685	0.965	1.040	0.905	0.940	0.955	1.165
20	0.685	0.685	0.960	1.040	0.905	0.945	0.960	1.170
21	0.685	0.685	0.955	1.040	0.905	0.945	0.960	1.175
22	0.685	0.685	0.955	1.045	0.905	0.950	0.965	1.175
23	0.685	0.690	0.950	1.050	0.905	0.950	0.970	1.180
24	0.685	0.690	0.950	1.050	0.905	0.955	0.975	1.185
25	0.685	0.690	0.950	1.050	0.905	0.955	0.970	1.185
26	0.685	0.690	0.950	1.045	0.905	0.955	0.970	1.180
27	0.680	0.685	0.955	1.040	0.905	0.950	0.965	1.170
28	0.680	0.685	0.955	1.035	0.905	0.945	0.960	1.165
29	0.675	0.685	0.960	1.030	0.905	0.945	0.955	1.150
30	0.675	0.685	0.960	1.030	0.905	0.940	0.955	1.135
31	0.675	0.685	0.955	1.035	0.905	0.950	0.965	1.125
32	0.670	0.685	0.950	1.035	0.905	0.955	0.970	1.115
33	0.670	0.685	0.945	1.035	0.905	0.960	0.975	1.110
34	0.665	0.685	0.940	1.030	0.905	0.965	0.980	1.105

TABLE E-14 - PERCENTAGE IMPROVEMENT IN EFFECTIVE POWER, PROPULSION EFFICIENCY, AND DELIVERED POWER FOR THREE BEARING-IN-RUDDER POST CONFIGURATIONS FITTED TO THE DD-963 HULL FORM WITH CONTROLLABLE-PITCH PROPELLERS AT 20 AND 32 KNOTS

	P_E		η_D		P_D	
Speed / Rudder Configuration	20	32	20	32	20	32
Straight	8.0%	5.2%	0.8%	0.5%	8.7%	5.7%
Contraguide	2.6%	2.8%	3.3%	1.6%	5.7%	4.3%
Contraguide with Costa Bulb	3.0%	3.0%	2.0%	1.1%	4.9%	4.1%

Fixed-Pitch Propellers

The bearing-in-rudder post experiments with fixed-pitch propellers were performed using a modified version of the straight rudder used in the controllable-pitch propeller experiments just discussed. The rudder was modified by reducing the diameter of the fairing between the propeller hub and the rudder to the diameter of the fixed-pitch propeller hub.

The first set of propellers, numbered 4274 and 4275, were existing propellers from the propeller library and represent five-bladed fixed-pitch propellers 4.81 m (15.77 ft) in diameter. These propellers have a pitch-diameter ratio of 1.216 and an expanded area ratio of 0.80. The second set of propellers, numbered 4864 and 4865, was custom stock, designed for use on the DD-963 hull form with fixed-pitch propellers. These are four-bladed propellers, 5.18 m (17 ft) in diameter. They have a pitch-diameter ratio of 1.527 and an expanded area ratio of 0.736.

The results of the fixed-pitch propeller propulsion experiments with shafts and struts and propellers 4274 and 4275 were given in Reed and Wilson (1981a). However, these results have since been determined to be in error. The experiments with these propellers were repeated at the time of the shafts and struts experiments with propellers 4864 and 4865. The bearing-in-rudder post experiments with both sets of propellers are reported in Lin and Wilson (In Preparation). The results of the shafts and struts and bearing-in-rudder post experiments with propellers 4274 and 4275 are given in Tables E-15 and E-16, respectively; the shafts and struts and bearing-in-rudder post results with propellers 4864 and 4865 are given in Tables E-17 and E-18, respectively.

The results with bearing-in-rudder post and fixed-pitch propellers on the DD-963 hull form show significantly less performance improvement than has been shown with the various controllable-pitch propeller configurations. Table E-19 shows the percent reduction in effective and delivered power with the two sets of propellers. As can be seen in the table, the effective power has been reduced by 1.0 to 1.3 percent by application of the bearing-in-rudder post configuration. This reduction in effective power is about one-third of the reduction seen with the typical controllable-pitch propeller application. This is probably due to the reduced base drag of the fixed-pitch propeller hub compared to that of the controllable-pitch propeller hub. The reduced base drag is directly related to the differences in the hub diameter for the two propeller types.

The delivered power comparison for the two sets of propellers, given in Table E-19, shows that the first set of propellers has a modest power reduction with the bearing-in-rudder post configuration. The second set of propellers shows a negligible delivered power increase with bearing-in-rudder post at 20 knots, and a small power reduction at 32 knots. These anomalous results with bearing-in-rudder post and fixed-pitch propellers, compared to controllable-pitch propellers, serve to illustrate the lack of understanding which exists with regard to the performance of the bearing-in-rudder post configuration.

TABLE E-15 - POWERING PREDICTIONS FOR THE DD-963 HULL FORM FITTED WITH TWIN SHAFTS AND STRUTS APPENDAGE SUIT AND FIXED-PITCH PROPELLERS, MODEL 5359-1 AND PROPELLERS 4274 AND 4275

Ship Length	530.2 Feet (161.6 Meters)
Ship Displacement	7812 Tons (7940 Metric Tons)
Ship Wetted Surface	35775 Sq Ft (3324 Sq Meters)
Correlation Allowance	.00050 ITTC Friction Used

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1020	760	1510	1120	59.8
12	6.17	1840	1380	2710	2020	72.3
14	7.20	2990	2230	4400	3280	84.6
16	8.23	4490	3350	6600	4920	96.8
18	9.26	6370	4750	9360	6980	108.8
20	10.29	8650	6450	12720	9490	120.7
21	10.80	9940	7410	14620	10900	126.6
22	11.32	11350	8460	16690	12450	132.5
23	11.83	12870	9590	18920	14110	138.3
24	12.35	14540	10840	21380	15940	144.2
25	12.86	16440	12260	24170	18030	150.2
26	13.38	18680	13930	27480	20490	156.5
27	13.89	21490	16020	31600	23560	163.2
28	14.40	24980	18630	36730	27390	170.5
29	14.92	29450	21960	43310	32300	178.6
30	15.43	34840	25980	51230	38200	187.2
31	15.95	40750	30390	60110	44820	196.1
32	16.46	47160	35170	69760	52020	205.5

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	J_T
10	0.680	0.740	0.945	0.970	0.925	0.980	0.970	1.050
12	0.680	0.740	0.945	0.970	0.925	0.980	0.965	1.045
14	0.680	0.745	0.945	0.970	0.925	0.980	0.965	1.040
16	0.680	0.745	0.945	0.970	0.925	0.980	0.965	1.040
18	0.680	0.745	0.945	0.970	0.925	0.980	0.965	1.040
20	0.680	0.745	0.945	0.970	0.925	0.980	0.965	1.040
21	0.680	0.740	0.945	0.970	0.925	0.980	0.965	1.040
22	0.680	0.740	0.945	0.970	0.925	0.980	0.965	1.045
23	0.680	0.740	0.945	0.970	0.925	0.980	0.965	1.045
24	0.680	0.740	0.945	0.970	0.925	0.980	0.965	1.045
25	0.680	0.740	0.945	0.970	0.925	0.980	0.965	1.045
26	0.680	0.740	0.945	0.970	0.925	0.980	0.965	1.045
27	0.680	0.745	0.945	0.970	0.925	0.980	0.965	1.040
28	0.680	0.745	0.945	0.965	0.925	0.980	0.965	1.030
29	0.680	0.745	0.945	0.965	0.925	0.980	0.965	1.020
30	0.680	0.745	0.945	0.965	0.925	0.980	0.965	1.010
31	0.680	0.745	0.940	0.970	0.925	0.985	0.970	1.000
32	0.675	0.745	0.935	0.975	0.930	0.995	0.980	0.995

TABLE E-16 - POWERING PREDICTIONS FOR THE DD-963 HULL FORM FITTED WITH BEARING-IN-RUDDER POST APPENDAGE SUIT AND FIXED-PITCH PROPELLERS, MODEL 5359-OA1 AND PROPELLERS 4274 AND 4275, FROM LIN AND WILSON (IN PREPARATION)

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1000	750	1450	1080	59.4
12	6.17	1830	1360	2630	1960	71.9
14	7.20	2980	2220	4290	3200	84.3
16	8.23	4490	3350	6460	4820	96.5
18	9.26	6350	4740	9140	6820	108.4
20	10.29	8560	6390	12320	9190	120.1
21	10.80	9820	7330	14140	10540	125.9
22	11.32	11180	8340	16090	12000	131.7
23	11.83	12650	9430	18200	13570	137.5
24	12.35	14250	10630	20500	15290	143.2
25	12.86	16050	11970	23160	17270	149.1
26	13.38	18240	13600	26360	19660	155.3
27	13.89	21030	15690	30480	22730	162.1
28	14.40	24570	18320	35610	26550	169.5
29	14.92	28930	21570	42040	31350	177.5
30	15.43	34140	25460	49770	37110	186.2
31	15.95	40070	29880	58670	43750	195.0
32	16.46	46530	34700	68420	51020	204.0

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	**JT**
10	0.695	0.740	0.925	1.010	0.895	0.965	0.970	1.045
12	0.695	0.745	0.925	1.005	0.895	0.965	0.970	1.035
14	0.695	0.745	0.925	1.005	0.895	0.965	0.970	1.030
16	0.695	0.745	0.925	1.005	0.895	0.965	0.970	1.030
18	0.695	0.745	0.925	1.005	0.895	0.965	0.970	1.030
20	0.695	0.745	0.925	1.005	0.895	0.965	0.970	1.030
21	0.695	0.745	0.925	1.005	0.895	0.965	0.970	1.035
22	0.695	0.745	0.925	1.010	0.895	0.965	0.970	1.035
23	0.695	0.745	0.925	1.010	0.895	0.965	0.970	1.035
24	0.695	0.745	0.925	1.010	0.895	0.965	0.970	1.040
25	0.695	0.745	0.925	1.005	0.895	0.965	0.965	1.040
26	0.690	0.745	0.925	1.005	0.895	0.965	0.965	1.035
27	0.690	0.745	0.925	1.000	0.895	0.965	0.965	1.030
28	0.690	0.745	0.925	1.000	0.895	0.965	0.965	1.025
29	0.690	0.745	0.930	0.995	0.895	0.965	0.965	1.015
30	0.685	0.745	0.930	0.990	0.900	0.970	0.965	1.005
31	0.685	0.745	0.925	0.990	0.900	0.975	0.970	0.995
32	0.680	0.745	0.925	0.990	0.905	0.980	0.970	0.985

TABLE E-17 - POWERING PREDICTIONS FOR THE DD-963 HULL FORM FITTED WITH TWIN SHAFTS AND STRUTS APPENDAGE SUIT AND FIXED-PITCH PROPELLERS, MODEL 5359-1 AND PROPELLERS 4864 AND 4865

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1020	760	1430	1070	45.5
12	6.17	1840	1380	2570	1920	55.1
14	7.20	2990	2230	4170	3110	64.5
16	8.23	4490	3350	6260	4670	73.8
18	9.26	6370	4750	8880	6620	83.0
20	10.29	8650	6450	12070	9000	92.0
21	10.80	9940	7410	13860	10340	96.5
22	11.32	11350	8460	15830	11800	100.9
23	11.83	12870	9590	17940	13380	105.4
24	12.35	14540	10840	20280	15120	109.8
25	12.86	16440	12260	22930	17100	114.4
26	13.38	18680	13930	26060	19430	119.2
27	13.89	21490	16020	30050	22410	124.5
28	14.40	24980	18630	35080	26160	130.4
29	14.92	29450	21960	41540	30980	137.1
30	15.43	34840	25980	49410	36850	144.5
31	15.95	40750	30390	58220	43410	151.9
32	16.46	47160	35170	68050	50740	159.1

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	JT
10	0.715	0.755	0.970	0.980	0.920	0.950	0.940	1.245
12	0.715	0.755	0.970	0.985	0.920	0.950	0.940	1.235
14	0.715	0.750	0.970	0.985	0.920	0.950	0.945	1.230
16	0.715	0.750	0.970	0.985	0.920	0.950	0.945	1.225
18	0.715	0.750	0.970	0.985	0.920	0.950	0.945	1.225
20	0.715	0.755	0.970	0.985	0.920	0.950	0.945	1.230
21	0.715	0.755	0.970	0.985	0.920	0.950	0.940	1.230
22	0.715	0.755	0.970	0.985	0.920	0.950	0.940	1.235
23	0.715	0.755	0.970	0.980	0.920	0.950	0.940	1.235
24	0.715	0.755	0.970	0.980	0.920	0.950	0.940	1.235
25	0.715	0.755	0.970	0.980	0.920	0.950	0.940	1.235
26	0.715	0.755	0.970	0.985	0.920	0.950	0.940	1.235
27	0.715	0.750	0.970	0.980	0.920	0.950	0.940	1.225
28	0.710	0.750	0.965	0.980	0.920	0.950	0.945	1.220
29	0.710	0.745	0.960	0.985	0.920	0.955	0.950	1.205
30	0.705	0.745	0.955	0.990	0.920	0.960	0.960	1.190
31	0.700	0.740	0.950	0.995	0.920	0.970	0.965	1.180
32	0.695	0.740	0.945	0.990	0.925	0.975	0.975	1.170

TABLE E-18 - POWERING PREDICTIONS FOR THE DD-963 HULL FORM FITTED WITH BEARING-IN-RUDDER POST APPENDAGE SUIT AND FIXED-PITCH PROPELLERS, MODEL 5359-0A1 AND PROPELLERS 4864 AND 4865, FROM LIN AND WILSON (IN PREPARATION)

Ship Speed		Effective Power (P_E)		Delivered Power (P_D)		Propeller Revolutions Per Minute
(knots)	(m/sec)	(horsepower)	(kilowatts)	(horsepower)	(kilowatts)	
10	5.14	1000	750	1420	1060	45.5
12	6.17	1830	1360	2580	1930	55.2
14	7.20	2980	2220	4220	3140	64.7
16	8.23	4490	3350	6350	4740	74.1
18	9.26	6350	4740	8980	6700	83.3
20	10.29	8560	6390	12110	9030	92.2
21	10.80	9820	7330	13900	10360	96.6
22	11.32	11180	8340	15820	11800	101.0
23	11.83	12650	9430	17890	13340	105.4
24	12.35	14250	10630	20150	15030	109.8
25	12.86	16050	11970	22700	16930	114.3
26	13.38	18240	13600	25800	19240	119.1
27	13.89	21030	15690	29750	22190	124.4
28	14.40	24570	18320	34600	25950	130.4
29	14.92	28930	21570	41030	30590	136.9
30	15.43	34140	25460	48770	36370	143.9
31	15.95	40070	29880	57570	42930	151.2
32	16.46	46530	34700	67430	50280	158.8

Ship Speed (knots)	Efficiencies (ETA)				Thrust Deduction and Wake Factors			Advance Coef.
	ETAD	ETAO	ETAH	ETAR	1-THDF	1-WFTT	1-WFTQ	J_T
10	0.705	0.755	0.945	0.990	0.895	0.945	0.945	1.240
12	0.705	0.750	0.945	0.995	0.895	0.945	0.945	1.225
14	0.705	0.750	0.945	0.995	0.895	0.945	0.945	1.220
16	0.705	0.750	0.945	0.995	0.895	0.945	0.945	1.215
18	0.705	0.750	0.945	0.995	0.895	0.945	0.945	1.220
20	0.705	0.750	0.945	0.995	0.895	0.945	0.945	1.225
21	0.705	0.750	0.945	0.995	0.895	0.945	0.945	1.225
22	0.705	0.750	0.945	0.995	0.895	0.945	0.945	1.230
23	0.705	0.755	0.945	0.995	0.895	0.945	0.945	1.230
24	0.705	0.755	0.945	0.995	0.895	0.945	0.945	1.235
25	0.705	0.755	0.945	0.995	0.895	0.945	0.945	1.235
26	0.705	0.755	0.945	0.995	0.895	0.945	0.945	1.230
27	0.705	0.750	0.945	0.995	0.895	0.945	0.945	1.225
28	0.705	0.750	0.945	1.000	0.895	0.950	0.945	1.215
29	0.705	0.745	0.945	1.005	0.895	0.950	0.950	1.200
30	0.700	0.740	0.940	1.005	0.895	0.950	0.955	1.180
31	0.695	0.735	0.935	1.010	0.895	0.955	0.960	1.170
32	0.690	0.735	0.925	1.015	0.895	0.965	0.970	1.160

TABLE E-19 - PERCENT POWER REDUCTION FOR BEARING-IN-RUDDER POST VERSUS SHAFTS AND STRUTS WITH TWO SETS OF FIXED-PITCH PROPELLERS, NUMBERED 4274 & 4275 AND 4864 & 4865, AT 20 AND 32 KNOTS

Propeller Numbers / Speed (Kts)	P_E	P_D	
		4274 & 75	4864 & 65
20	1.0 %	3.1%	-0.3%
32	1.3%	1.9%	0.9%

SUMMARY

Figures E-2 and E-3 summarize the performance benefits which have been achieved with the application of the bearing-in-rudder post configuration. Figure E-2 gives the effective power with bearing-in-rudder post relative to that with shafts and struts. With the exception of the DD-963 with controllable-pitch propellers, the effective power reductions in the upper speed range are between 1 and 3 percent. The DD-963 as built shows reductions which are twice this large. However, if the DD-963 parent calculations are repeated using a shafts and struts configuration with improved fairwater shapes as baseline, the DD-963 controllable-pitch propeller bearing-in-rudder post results fall in line with the results from tests on the other models which have been evaluated.

Figure E-3 shows a comparison of the delivered power measurements with bearing-in-rudder post to those measurements with shafts and struts. As can be seen, there is a much greater spread in improvement than is seen in effective power. In summary, the greatest improvements are seen in the case of the PG-84 and PCG classes, while the least improvement is seen with the two fixed-pitch propeller applications just discussed. If the two fixed-pitch propeller applications are neglected, it can be seen that the minimum improvement at 20 knots is 6 percent and ranges up to 15 percent. At 32 knots, the improvement ranges from 4 percent to 13 percent.

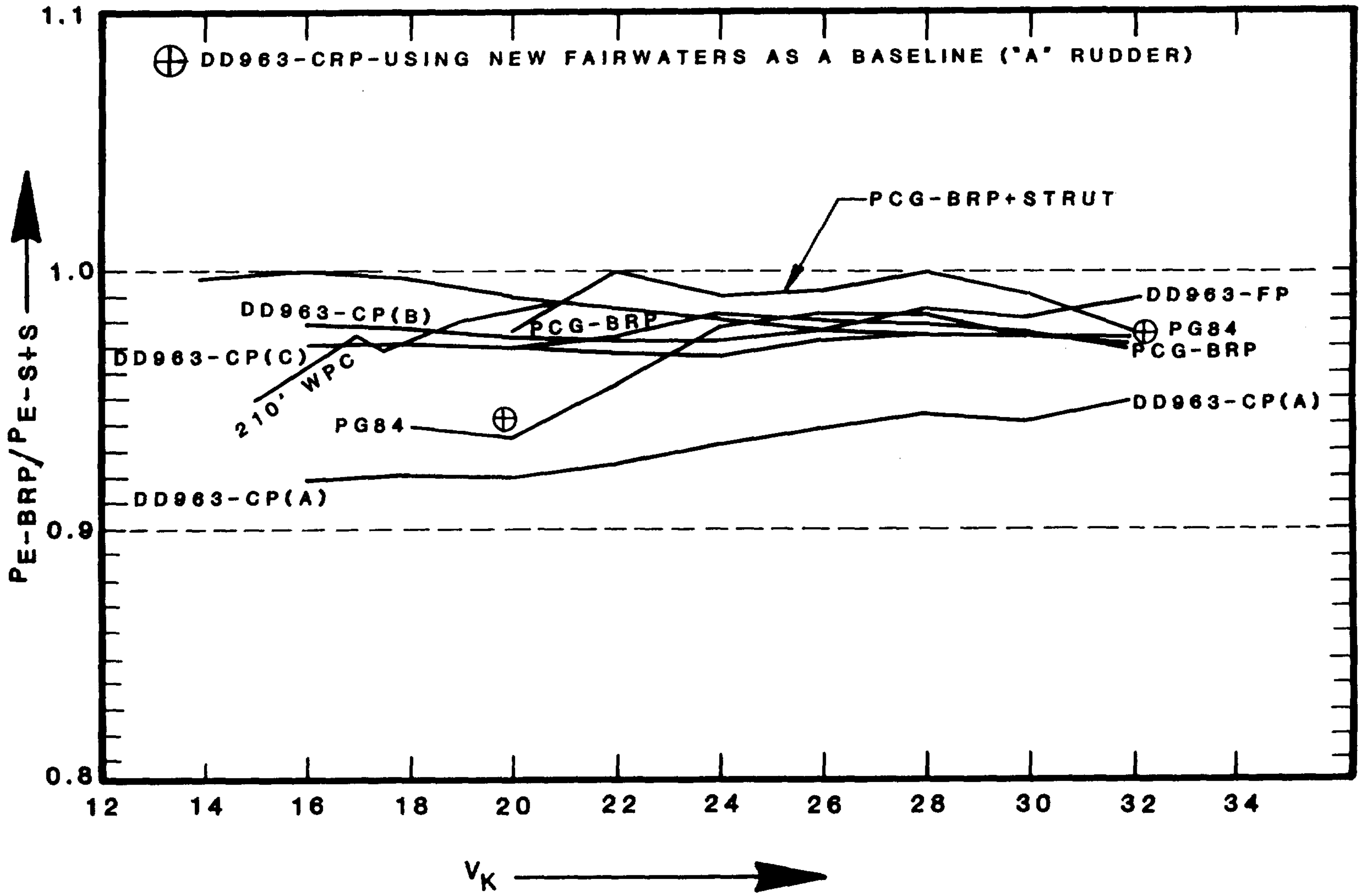

Figure E-2 - Comparison of Effective Power with Bearing-in-Rudder Post to that with Shafts and Struts for Seven Models, as a Function of Speed

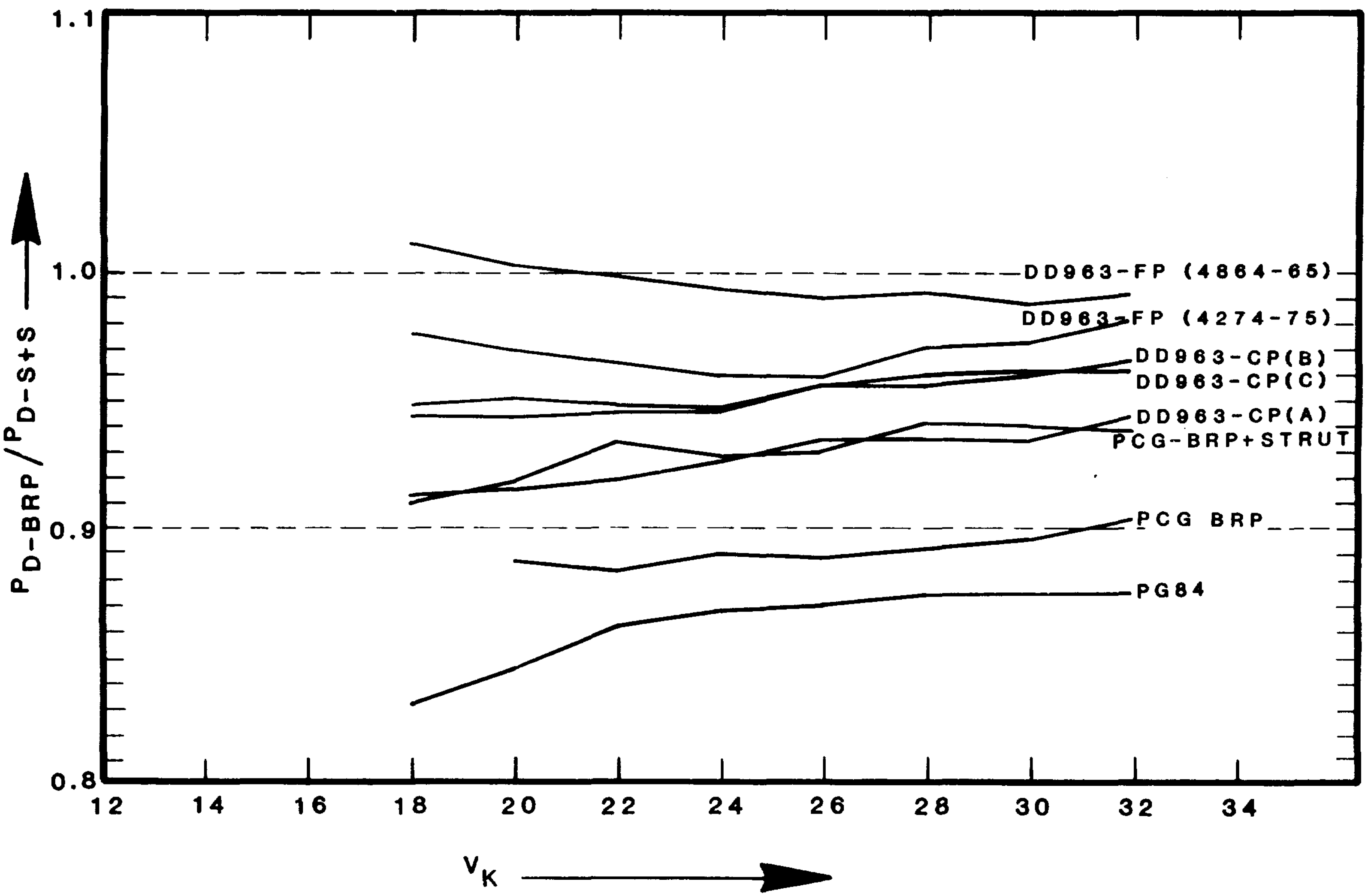

Figure E-3 - Comparison of Delivered Power with Bearing-in-Rudder Post to that with Shafts and Struts for Eight Models, as a Function of Speed

REFERENCES

Bau, F. et al (1981), "Propeller Design Optimization: An Integral Theoretical and Experimental Procedure," Propellers '81, Society of Naval Architects and Marine Engineers, New York, pp. 379-405.

Beal, A.L. (1956), "Resistance and Propulsion Characteristics of a 160-Foot Patrol Vessel," David Taylor Model Basin Report 1087.

Caster, E.B. and T.A. LaFone (1975), "A Computer Program for the Preliminary Design of Contrarotating Propellers," Ship Performance Department Report DTNSRDC/SPD-596-01.

Cavanaugh, M.G. (1960), "Effect of Transom Wedges on Trim and Powering for 83- and 95-Foot Coast Guard Patrol Boats Represented by Model 4429," David Taylor Model Basin Report 1471.

Day, W.G. (1975), "Effect of Speed on the Wake in Way of the Propeller Plane for the DD-963 Class Destroyer Represented by Model 5265-1B," Ship Performance Department Report DTNSRDC/SPD-311-37.

Fisher, S.C. (1981a), "An Analysis of the Propulsion Experiments Performed on a Model Representing the Stretched PONCE DE LEON (SPDL) Class RO/RO Ship Fitted with Two Sets of Design Contrarotating Propellers (Model 5362; Propellers 4731 & 4732 and 9019 & 9020)," Ship Performance Department Report DTNSRDC/SPD-141-19.

Fisher, S.C. (1981b), "Effects of Propulsion Pod Longitudinal Location on the Resistance Characteristics of a Ship," Ship Performance Department Report DTNSRDC/SPD-1011-01.

Gertler, M. (1960), "Resistance Experiments on a Systematic Series of Streamlined Bodies of Revolution - for Application to the Design of High-Speed Submarines," David Taylor Model Basin Report C-297.

Grant, J.W. (1973), "Powering Predictions for a Patrol Craft (PC) with a Conventional Appendage Configuration Represented by Model 5300," NSRDC Ship Performance Department Evaluation Report 528-H-02.

Greger, O. (1961), "Testing the Costa Propulsion Bulb with a View to its Use on Modern Ships," International Shipbuilding Progress, Vol. 8, No. 77, pp. 43-53.

Hampton, G.A. and A.H. Weaver (1973), "Powering Predictions for a Patrol Craft Represented by Model 5300," NSRDC Ship Performance Department Evaluation Report 528-H-01 (Revised).

Hankley, D.W. and E.E. West (1964), "Powering Characteristics, Flow Patterns and Recommended Strut Angles for DE-1052 Represented by Model 4989," DTMB Hydromechanics Laboratory Test and Evaluation Report 011-H-02.

Hoekzema, D.R. (1964), "Powering Characteristics for a 154-Foot High-Speed PGM from Tests of Models 4932, 4942, and 4950," David Taylor Model Basin Report 1652.

Hoerner, S.F. (1965), Fluid-Dynamic Drag, Published by the Author.

Jenkins, D.S. (1980), "Exploratory Frigate Design for Improved Energy Efficiency Based on FFG-7 Hull Form," Ship Performance Department Report DTNSRDC/SPD-0829-01.

Johnson, H.F. (1982), "New Patrol Boats for the U.S. Coast Guard, "Naval Engineers Journal, Vol. 94, No. 5, pp. 89-92.

Karafiath, G., and C.J. Wilson (1983), "Comparative Performance of Stock and Design Propellers Derived from Propulsion Experiments," Proceedings of 20th ATTC, Stevens Institute of Technology, Hoboken, N.J.

Kim, Y.H. (1983), "Analytical Investigation of the Effect of Pod on Surface Ship Wavemaking Resistance and Effective Power," Ship Performance Department Report DTNSRDC/SPD-1011-02.

Kowalyshyn, R. and K.L. Kirkman (1979), "Model Tests of DD-963 Class Destroyer with Conventional and Pod-Strut Propulsion Appendages," Hydronautics, Inc. Technical Report 7982-1.

Krishnamoorthy, V. (1982), "A Study of DD-963 Alternative Propulsion Systems," Hydronautics, Inc. Technical Report 8210-1.

Leveldahl, W.J. (1978), "Integrated Ship Machinery Systems Which Result in Small, Efficient Destroyers," Propulsion and Auxiliary Systems Department Evaluation Report PAS-78-46.

Leveldahl, W.J. (1980), "Integrated Ship Machinery Which Result in Small, Efficient Destroyers," Naval Engineers Journal, Vol. 92, No. 2, pp. 271-278.

Lin, A.C.M. (1980a), "Preliminary Powering Investigation for a DD-963 Class Destroyer Fitted with Twin Tandem Propulsion Arrangement Represented by Model 5359-1A," Ship Performance Department Report DTNSRDC/SPD-0829-08.

Lin, A.C.M. (1980b), "Preliminary Powering Investigation for a DD-963 Class Destroyer Prototype with a Single Contrarotating Coaxial Propulsion Arrangement Represented by Model 5359-5," Ship Performance Department Report DTNSRDC/SPD 0829-07.

Lin, A.C.M. (1980c), "Preliminary Powering Investigation for a DD-963 Class Destroyer Prototype with a Single Tandem Propeller Arrangement Represented by Model 5359-5A," Ship Performance Department Report DTNSRDC/SPD-0829-09.

Lin, A.C.M. (1980d), "Preliminary Powering Investigation for a DD-963 Class Destroyer Fitted with a Twin Coaxial Contrarotating Propulsion Arrangement Represented by Model 5359-1B," Ship Performance Department Report DTNSRDC/SPD-0829-11.

Lin, A.C.M. and G.G. Borda (1983), "An Experimental Investigation of the Effect of Propeller Fairwater Shapes on Powering of DD-963 Class Ships Represented by Model 5359," Ship Performance Department Report DTNSRDC/SPD-0829-26.

Lin, A.C.M. and R.S. Goldberg (1982), "Twin Pod Propulsion with Contrarotating Propellers for DD-963 Class Destroyer Represented by Model 5359-1C," Ship Performance Department Report DTNSRDC/SPD-0829-18.

Lin, A.C.M. and R.B. Hurwitz (1974), "Velocity Survey Data for DE-1052 Class Ship Represented by Model 5324," NSRDC Ship Performance Department Evaluation Report 011-H-12.

Lin, A.C.M. and L.O. Murray (1975), "Powering Predictions for DD-963 Class Destroyer Represented by Model 5265-1B," Ship Performance Department Report DTNSRDC/SPD-311-34.

Lin, A.C.M. and C.J. Wilson (1980), "Comparisons of the Powering Requirements for the Existing DD-963 Class (Model 5359) with those for a Modified Hull Having Large Diameter Low Tip Clearance - Models 5359-2 (Fixed-Pitch) and 5359-2A (Controllable-Pitch)," Ship Performance Department Report DTNSRDC/SPD-0829-10.

Lin, A.C.M. and C.J. Wilson (1983a), "Comparison of Powering Requirements for Model 5359-5 with Original and Second Stock Single Contrarotating Propellers and the Existing DD-963 Class (Model 5359) with Twin Controllable-Pitch Propellers," Ship Performance Department Report DTNSRDC/SPD-0829-21.

Lin, A.C.M. and C.J. Wilson (1983b), "Stock Propeller Powering Investigation for a DD-963 Class Destroyer Fitted with a Twin Coaxial Contrarotating Propulsion Arrangement with New After Propellers Represented by Model 5359-1B and Propellers 4768 and 4839 (Port), and 4770 and 4838 (Starboard)," Ship Performance Department Report DTNSRDC/SPD-0829-22.

Lin, A.C.M. and C.J. Wilson (In Preparation), "Predicted Powering Requirements for a DD-963 Class Prototype with Twin Fixed-Pitch Propellers and Main V-Struts Replaced by a Bearing-in-Rudder Post Arrangement Represented by Model 5359-0A1," Ship Performance Department Report DTNSRDC/SPD-0829-25.

Majumdar, P. and V. Krishnamoorthy (1980), "A Study of Alternative Propeller Configurations for a Contemporary Destroyer-Type Ship," Hydronautics, Inc. Technical Report 7925.09-1.

Morgan, W.B. (1960), "The Design of Counter-rotating Propellers Using Lerbs' Theory," Transactions, Society of Naval Architects and Marine Engineers, New York, Vol. 68, pp. 6-38.

Nelka, J.J. and B.D. Cox (1981), "Parameteric Calculations of Contrarotating Propeller Performance," Hydrodynamics Research Associates, Inc., Report 8103.

Pien, P.C. and J. Strom-Tejsen (1968), "A Hull Form Design Procedure for High-Speed Displacement Ships," Proceedings 1968 Diamond Jubilee International Meeting, Society of Naval Architects and Marine Engineers, New York, pp. 13-1 through 13-27.

Reed, A.M. et al (1982), "Summary Report of the Controllable-Pitch Propeller Research Program," DTNSRDC Report 81/065.

Reed, A.M. and C.J. Wilson (1980a), "Comparison of the Powering Requirements for the DD-963 Class when Fitted with Controllable-Pitch and with Fixed-Pitch Propellers as Predicted from Experiments with Models 5359 and 5359-1," Ship Performance Department Report DTNSRDC/SPD-0829-06. (Revision in Preparation).

Reed, A.M. and C.J. Wilson (1980b), "Comparison of the Powering Requirements of the Existing DD-963 Class (Model 5359) with those for a Modified Hull Having Large Diameter Overlapping Propellers (Low Tip Clearance and Fixed-Pitch, Model 5359-3)," Ship Performance Department Report DTNSRDC/SPD-0829-13.

Roddy, R.F. (1980), "Novel Stern Shapes for Improved Energy Conservation for Naval Surface Combatants," Ship Performance Department Report DTNSRDC/SPD-0829-05.

Roddy, R.F. (1982), "Hydrodynamic Performance of Propulsion Pods - Analytical Model," Ship Performance Department Report DTNSRDC/SPD-0829-14.

Roddy, R.F. (1983), "Hydrodynamic Performance of Propulsion Pods: Results of Experiments with a Groundboard and Correlation with Analytical Predictions," Ship Performance Department Report DTNSRDC/SPD-0829-24.

Saunders, H.E. (1957), Hydrodynamics in Ship Design, Society of Naval Architects and Marine Engineers, New York, Vol. 2, pp. 729-735.

Scragg, C.A. (1980), "Wake Scale Effects and Propeller Hull Interactions: State-of-the-Art," Ship Performance Department Report DTNSRDC/SPD-0829-02.

Strom-Tejsen, J. and W.G. Day (1971), "Study of Air Cushion Vehicle Propulsion System - Part 3 - Transmission Design and Performance," NSRDC Ship Performance Department Evaluation Report 378-H-08.

Strom-Tejsen, J. and R.F. Roddy (1972), "Performance of Container Ship with Overlapping Propeller Arrangement," Naval Ship Research and Development Center Report 3750.

Surber, W.G. (1961), "Turning and Maneuvering Tests of Model 4868 Representing the U.S. Coast Guard 210-Foot Patrol Craft WPC," David Taylor Model Basin Report 1503.

Todd, F.H. (1967), "Resistance and Propulsion," in Principles of Naval Architecture, J.P. Comstock (Editor), Society of Naval Architects and Marine Engineers, New York, p. 393.

Tomassoni, C.A. and J.J. Slager (1980), "Development of Alternate Afterbody Appendage/Propulsor Configurations for a Contemporary Destroyer-Type Ship," NAVSEA Report 3213-80-3.

West, E.E. (1961a), "Effective Horsepower Predictions for a U.S. Coast Guard 210-Foot Patrol Craft WPC," David Taylor Model Basin Report 1504.

West, E.E. (1961b), "Powering Predictions for a U.S. Coast Guard 210-Foot Patrol Craft WPC Model 4868," David Taylor Model Basin Report 1504-2.

West, E.E. (1981), "Preliminary Powering Investigation for a DD-963 Class Destroyer with Main V-Struts Replaced by Various Types of Bearing-in-Rudder Post Arrangements Represented by Models 5359-OA, 5359-OB, and 5359-OC," Ship Performance Department Report DTNSRDC/SPD-0829-17.

Wilson, C.J. (1969), "Powering Characteristics for DE-1052 Represented by Model 4989 Fitted with CRP Propeller 4402," NSRDC Hydromechanics Laboratory Test and Evaluation Report 001-H-06.

Woo, E.L., G. Karafiath and G.G. Borda (1983), "Ship-Model Correlation of Powering Performance on USS OLIVER HAZARD PERRY, FFG-7 Class," Marine Technology, Vol. 20, No. 1, pp. 35-52.

Zeno, G. (1953), "The Costa Propulsion Bulb," Schiff und Hafen, Vol. 5, No. 6, pp. 358-360 [In German].