No. 168
February 1975

FEASIBILITY OF SAILING SHIPS FOR THE AMERICAN MERCHANT MARINE

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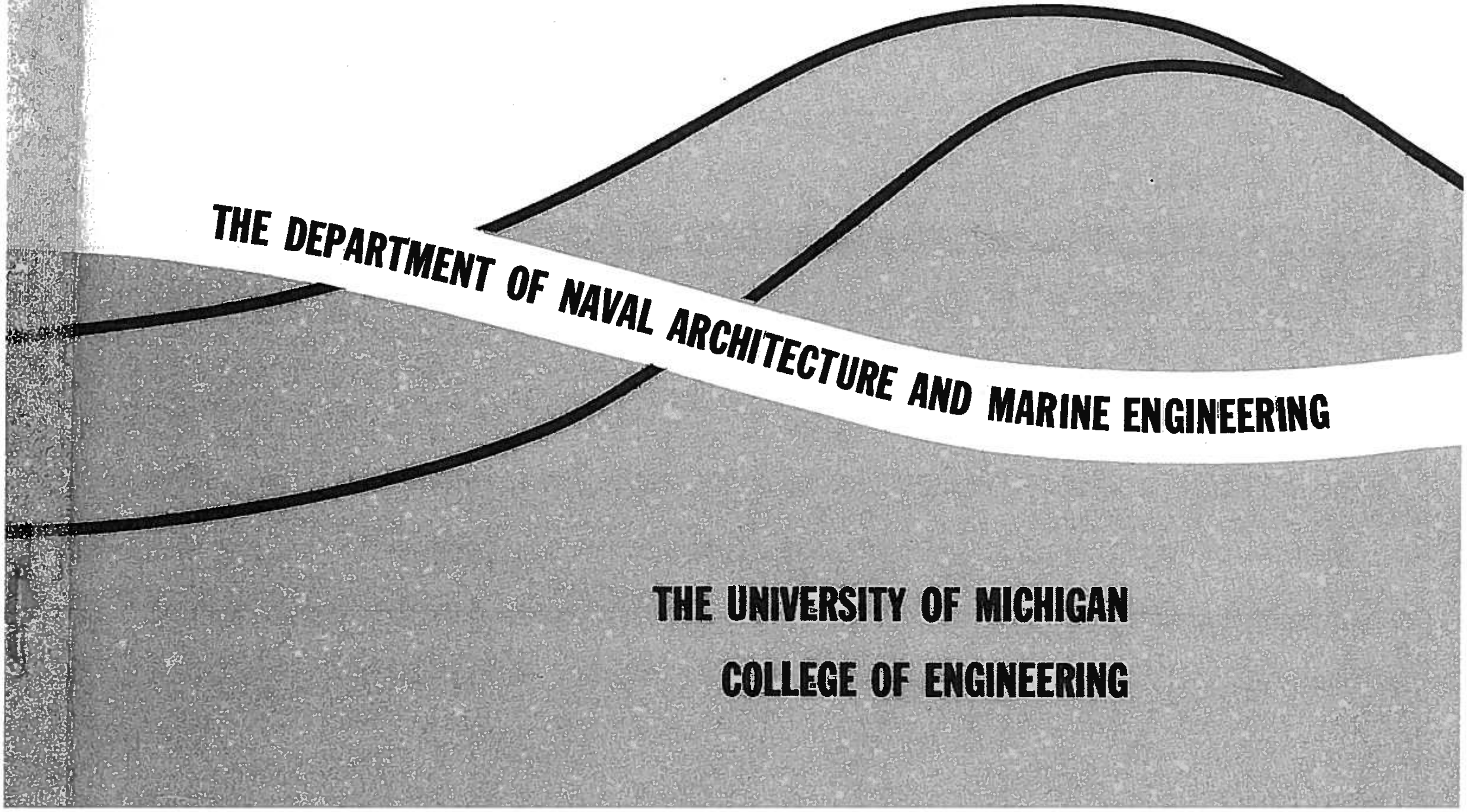
Prepared for
United States Department
of Commerce
Maritime Administration
Contract No. 4-37110



THE DEPARTMENT OF NAVAL ARCHITECTURE AND MARINE ENGINEERING

THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING

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MARITIME ADMINISTRATION
Contract 4 - 37110

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CONTENTS

I. INTRODUCTION

The University of Michigan Department of Naval Architecture and Marine Engineering has studied the possible use of sailing cargo ships in the contemporary American merchant marine. The study, sponsored by the United States Maritime Administration, was prompted by recent world developments in energy supply and environmental concern. Sailing ships are powered, of course, by an energy source that is free of direct cost, free of political control, free of polluting side effects, and in effectively unlimited supply.

It is now on the order of 50 years since sail-borne international trade died out in the merchant fleets of the industrial nations. The reasons for this demise require no analysis, but meanwhile several developments have occurred that give incentive for a re-evaluation of sail for the present and near future. The most significant is the sharp rise in cost of energy required to drive a powered ship. A second is a complex set of changes that can be generally classified as technological advances, such as the improvements in materials that can be used for sails and rigging, and the immense advances in communication and control technology. A third development is the change in standards for seagoing, which includes improvements in safety standards, in habitability standards, and major changes in wage structures. This study is therefore an evaluation of sea commerce by sail -- specifically, U.S.-flag ships trading via U.S. ports -- under contemporary conditions brought about by these changes. The objectives are to determine if such ships would be economically viable, and if so, what the most favorable service would be. In more particular terms, the objective is to furnish guidance to the Maritime Administration for possible continuation of research into commercial sail technology.

The study is an economic comparison of the performances of several sizes of sailing ships vs those of comparable powered ships, all on several long trade routes from North American ports.

The ships, both sail and powered, are of 15,000, 30,000, and 45,000 tons cargo deadweight. The routes studied are East Coast - Liberia, East Coast - North Europe, West Coast - Australia, and West Coast - East Asia. Particular cargoes are not specified, but in general are intended to be bulk cargoes in trades that require the ship sizes listed.

A large uncertainty in this work is the particulars of the ships being examined. Many alternatives are found in existing technology, and more come from technology that has matured since the passing of traditional sail commerce. To cite a single example, selection of sail plan involves choices among conventional square rig, for-and-aft rig, Flettner rotors, rigid airfoil sails, rotating airfoil sails, and perhaps others. The scope of the study was by no means broad enough to permit thorough analysis of all possibilities. Since the objective was one of illuminating economic viability, and <u>not</u> one of establishing what the "best" sailing ship would be, the prototype designs were configured by the engineering judgement of persons familiar with both traditional and modern (i.e. yacht) sailing aided by the limited technical data available in recent literature.

Important assumptions that underlie the study are these:

1. Ships to be built in U.S. shipyards and to operate under U.S. flag.
2. Ships to operate in trades that are best suited to sail (e.g. not to operate in services where scheduled arrival is important).
3. Contemporary standards of manning, habitability, wages, and safety, to be met.
4. Auxiliary engine propulsive power to be installed for use in maneuvering and in calms, but only at a minimum level (i.e. ships are not to be "motorsailers").
5. Study to take no advantage of speculative technology in determining ship performances. Thus, though it be assumed that modern sailing ships would take advantage of the best available weather information, strategies

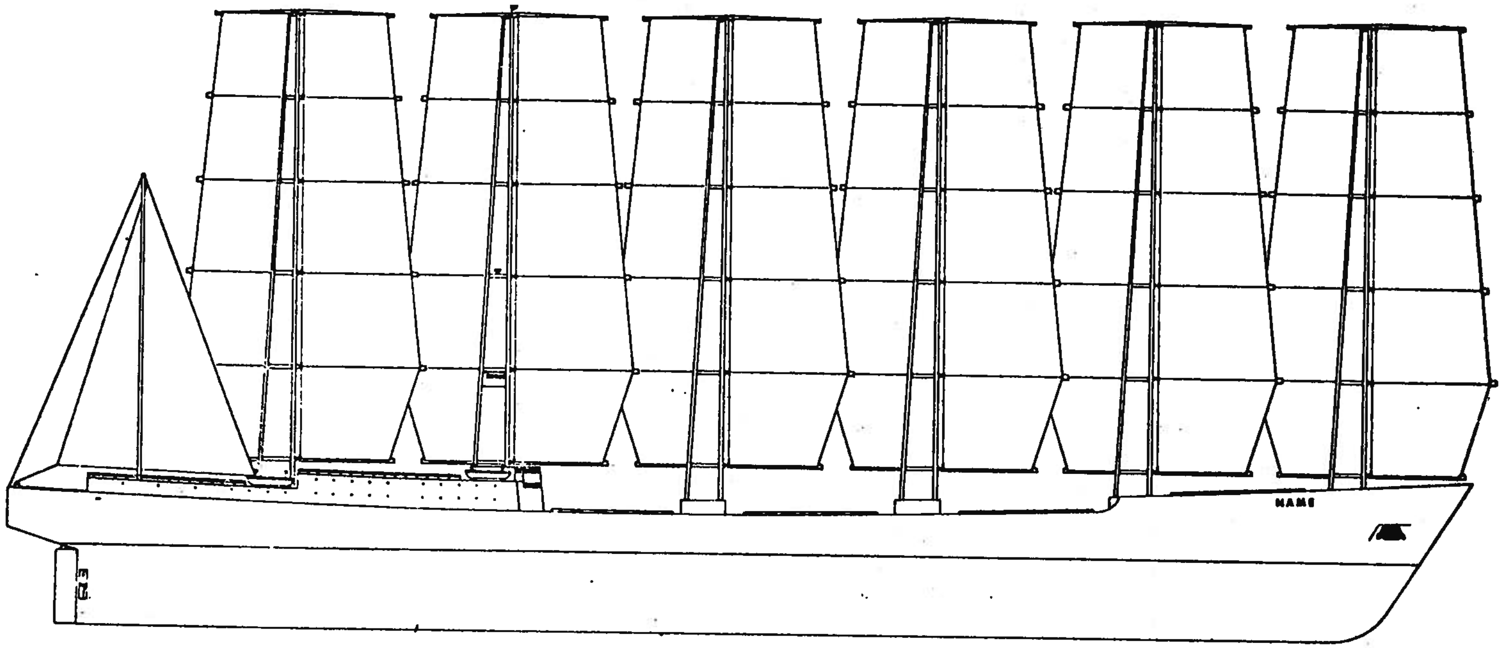


FIGURE 1

45000-DWT BULK CARGO SHIP

B. SCHER
30 OCT 1976

for doing so have not been developed, and benefits of such strategies therefore cannot be included in analyses. The possible benefits thereby ignored are assumed to be covered by the subsequent sensitivity analyses.

As a result of these assumptions, and of the other points mentioned above, the prototype ships that are the basis of the studies are of conservative design, being square-rigged, multi-masted barques and ships (Figure 1) much like the last deep-sea sailing ships (PREUSSEN, POTOSI, et al), but with modernized rig featuring tripod masts without standing rigging. Running rigging is essentially all internal and is manipulated by powered winches at the base of each mast. Sail handling is either "automated" or "pushbutton" from the ship control station. The rig design is inspired by the work of Wilhelm Prölss and B. Wagner in Germany; their publications (1,2) from the Institut fur Schiffbau of the University of Hamburg have provided data on sail forces that are an essential ingredient of this work. The ships are fully modern in their communications, engineering, and accommodation features. Auxiliary diesel propulsion is provided, with the powering criterion being a speed of six knots in calm air and sea.

II. CONCLUSIONS

A. Technical Feasibility

Deep sea commercial sailing ships are quite obviously technically feasible. This conclusion just as obviously comes not from work reported here, but from the historical fact of such feasibility, and from continuing demonstrations by modern sail training ships and ocean-going yachts.

The updated configurations used in this study are likewise safely concluded to be technically feasible, save perhaps for doubts about a few details. Auxiliary propulsion, accommodations, communications, are all conventional items borrowed from powered-ship technology. Structure is conventional. Freeboard and stability standards of modern ships need not be compromised, though the latter of the several rules may have to be modified to suit a large sailing ship. The details about which some doubt is reasonable are mainly in the sail-handling arrangements. Our work does depend on remote powered setting, furling, and trimming of sails, since this precludes the necessity of a large sail-handling crew. While the remote powered techniques have not been demonstrated at sea, they depend on assembly of conventional components. We therefore believe that these techniques, too, are feasible, though minor development work might be needed, especially on such items as de-icing arrangements for sail tracks.

Advanced technology which might benefit a sailing ship, but which has not been demonstrated, has not been an essential part of this study, and therefore no conclusions can be firmly offered. The most promising (seemingly) untested application of technology is the use of complete weather knowledge, coupled with rapid communication of it, in strategies for selecting the fastest routing. Since these strategies appear to be highly complex, they could not be applied in this study, hence no conclusions can be offered on their efficacy. However, our feeling is that the improvement in passage times would be small, especially when averaged over many voyages.

A significant technical point is the apparent upper size limit on commercial sailing ships, a limit that is far below that of powered ships. The limit is a consequence of the need for deep draft to develop side force in on-wind sailing, and of the need for reasonable aspect ratio (which requires height) of the sail plan. Channel depths dictate the limit in the former instance; considerations of reasonable spar structure in the latter. Our conclusion is that the limiting size is about 50,000 tons cargo deadweight, though bigger ships are possible if poorer performance is to be accepted. An important consequence is that a sailing VLCC appears to be impractical. The deep draft consideration also means that a sailing ship must have more ballast capacity for good performance without cargo.

B. Operational Feasibility

The most significant operational difference between a sailing ship and a powered ship is the random nature of the former's arrival time at any designated point, due, of course, to the random nature of the propulsive force. Its use in any service requiring scheduled arrivals is therefore not likely to be feasible.

The sailing ship is obviously best suited for operation where the wind blows hard and steadily. It is therefore better suited to routes that avoid the light and variable wind belts of low latitudes, and to routes that do not require working through narrow waters. However, the effect of these unfavorable factors is mitigated by auxiliary powered propulsion, so that operational feasibility appears to be adequate on the four routes investigated here. Faster average passage times are nonetheless evident on those that do not cross the equator.

Channel depths are more limiting to the sailing ship than to its powered counterpart, since the need for hull side force demands a greater draft for a given displacement. Since our study assumes use of U.S. East Coast ports, the draft is limited to 45 feet, producing a maximum cargo deadweight (in a hull of good sailing performance) of 45,000 tons, which is considerably less than the

70,000 to 80,000 ton deadweight usually assumed to be maximum for this draft. An alternative to deep draft is the use of movable lifting surfaces (e.g. centerboards), but this alternative has not been studied here.

Similarly, the height above water is greater for the sailing ship, since good aspect ratio of sail plan requires tall masts. As noted previously, this is a second major factor in limiting ship size. In the operational sense, mast height may limit the harbors suitable for large sailing ships. For example, the ships studied here cannot pass beneath the Chesapeake Bay bridge just downstream of Baltimore, and only the smallest can squeeze under the Verrazano Narrows or Golden Gate bridges. Telescoping or folding masts perhaps are possible, though the implementation of these concepts is complicated by the running rigging. No investigation was made of such measures.

In geometrically similar ships, wind heeling moments increase as the cube of size ratio, while righting moments increase as the fourth power. Therefore, ships of the size studied here are not limited by wind heeling moments, and operational feasibility is not degraded by the wind heeling phenomenon.

It appears to be quite feasible in the technical sense to handle sails by deck-mounted machinery, resulting in the operational situation of crew duties being comparable to those on a powered ship. Maintenance (e.g. replacing damaged sails) will require some work aloft, and hence require a certain number of persons on board to do this work. We have therefore concluded that operational feasibility is not restricted by availability of suitable crew, but on the other hand, we cannot foresee any significant reductions in crew size compared to powered ships.

The handling of sailing ships in ports and the approaches to ports is a matter for concern, unless they be provided with power equivalent to that used by powered ships in the same situations. The six-knot-calm-water standard used in this study is seemingly the minimum that might be acceptable, but is based on at-sea needs rather than on maneuvering needs. The tacit assumption followed here is that the ships would not attempt to enter or leave port during times of high winds. However, it is easy to imagine emergency situations (e.g. sudden squalls) endangering a ship of very low power and high windage in a narrow channel. The maneuvering question therefore requires further investigation, especially with reference to particular ports. On the other hand, the question is not so much one of feasibility, but of how much economic penalty (cost of larger engine, side thrusters, etc.) may be required.

Cargo handling should present no unique problems for the dry bulk service envisioned here. The absence of standing rigging precludes major interference with shore-side loading and unloading gear of the type found in the bulk trades.

C. Economic Feasibility

This is indeed the vital question, and the one that this study has concentrated on. The judgement resulting is based on the required freight rate (RFR) criterion, this being the rate (typically dollars per ton) that must be charged in order to obtain a specified rate of return on the capital invested in the ship. If the RFR for a sailing ship could be demonstrated to be lower than that of a powered equivalent, then the sailing alternative would presumably be the better choice for the service in question.

The findings of this study with respect to economic feasibility are summarized in Table 1. The basic comparison is between the "best estimate" and the "steamer" columns. With one exception, all entries favor the powered ship. The exception occurs with the smallest ship on the longest voyage, and is a reflection of the unsuitability of small ships in such service, rather than a valid sail vs power comparison. The principal conclusion must therefore be that commercial sailing ships are not competitively superior to powered ships. The conclusion is subject to some qualifications, however.

The RFR figures are subject to a large uncertainty, particularly for the sailing ships. For example, the building costs of such a ship, which are a major ingredient of RFR, are estimates based on the outline designs prepared for this study, and are not based on recent experience with the building of similar ships. There is doubtless a significant measure of uncertainty here. Likewise, uncertainties from lack of immediate precedent and directly applicable data enter the RFR figures from other facets of the analyses. For that reason, both optimistic and pessimistic columns are included, and it can be seen that on the two longest voyages, optimistic estimates do show slight advantages to the sailing ship. Further uncertainty arises from the lack of optimization work to show what the best design of a sailing ship might be; it is possible that tradeoffs among the parameters we have used might produce some improvement in the sail economics.

It may be argued that energy costs will continue to rise, and hence tip the comparisons toward the optimistic column, and perhaps beyond. This may be, but we have no usable trend predictions -- especially no predictions on how other important costs (e.g. cost of sail material) will react to energy costs -- upon which to base conclusion for far horizons, and so attempt none.

In view of the above paragraphs, we conclude that the commercial sailing vessel is not an economically feasible alternative for the American merchant marine in the near future. This conclusion must be tempered by the fact that our estimates do show the sailing ship position to be close to equal footing with powered ships, so that the resolution of uncertainties, and moderate changes in the energy-cost situation might make it more favorable to sail. The picture is therefore such that an immediate move to build sailing ships is not justified, but such that additional study and research to reduce its uncertainties is justified.

Table 1

SUMMARY OF RFR RESULTS

Voyage/Distance	Ship (CDWT)	Optimistic RFR ($/ton)	Best Estimate RFR ($/ton)	Pessimistic RFR ($/ton)	Steamer RFR ($/ton)
New York-Liverpool 6200 naut mile	45000	8.34	8.74	9.15	7.99
	30000	10.10	10.55	11.00	9.59
	15000	14.31	14.84	15.37	13.37
Baltimore-Monrovia 8200 naut mile	45000	10.94	11.47	12.00	10.24
	30000	13.10	13.68	14.27	12.40
	15000	18.38	19.14	19.83	17.44
Cape Flattery, WA. -Shanghai 10500 naut mile	45000	12.75	13.36	13.98	12.87
	30000	15.56	16.26	16.95	15.67
	15000	22.45	23.29	24.12	22.45
San Francisco-Sydney 12800 naut mile	45000	15.48	16.23	16.98	15.54
	30000	18.61	19.44	20.27	19.04
	15000	26.21	27.19	28.16	27.43

III. RECOMMENDATIONS

The Maritime Administration should not contemplate hardware development or production at this time, but should continue a modest effort to develop information showing how and where commercial sail may be used advantageously in the American merchant marine. Its basic objective should be to enhance its ability to continually make rational judgements on alternatives for active development. In the case of sailing ships, this ability requires reduction in the uncertainties that this study has illuminated. Consideration of the following is recommended:

1. Model testing should be undertaken to form a basis for better predictions of performance. Tests of both hull and rig are recommended, but the need is greater for hull tests, since acceptable data on resistance under yaw and heel conditions is not available for commercial ship hulls. In particular, hull model tests should cover a range of hull parameters (i.e. not just good sailing ship forms) to assist subsequent optimization work in sailing ship design.
2. The design of prototype sailing ships should be optimized through parametric study. Alternative values of length/beam ratio, beam/draft ratio, and block coefficient, especially trending toward more conventional bulk-carrier hulls, may produce payload and building cost benefits that offset losses in sailing performance. The work recommended will be most effective if it follows or accompanies the model tests recommended in 1.
3. Sail plan optimization should also accompany hull optimization, since alternatives to square rig may have merits that have not previously been illuminated.
4. The potential benefit of optimal routing, based on instantaneous weather data, reliable weather prediction, and computer-aided decision on subsequent choice of route, should be investigated. This effort might be

based on earlier work in weather routing of powered ships, or even on dynamic programming methods of piping and wiring layout. However, we have found that the sailing ship routing problem has its unique features that preclude an a priori prediction of the approach to take. Further research should therefore be a broad-scope effort to explore a multiplicity of approaches, but with the ultimate aim of producing a usable strategy.

5. Building costs should be examined further to reduce the uncertainty in them, and possibly to find lower values. This effort should be part of the optimization studies.
6. Operation under power in one or more typical ports should be studied in detail to determine how the need for safe operation in crowded waters may set the level of propulsive power and the possible requirement for side thrusters.
7. Economics of at least one particular route and service should be examined in more detail. These would be chosen from those potentially favorable to sail, with the comparisons made between optimum sailing ships, and the powered ships actually used (or contemplated) for the route and service.

IV DESIGN BACKGROUND FOR THE STUDY

Our studies here reported are necessarily based on evaluations of performance and problems of particular ships. For example, characteristics of rig and sailplan which directly affect the aerodynamic force coefficients, and those characteristics of the hull form bearing on resistance, transverse stability, and hull hydrodynamic force coefficients must be established *a priori*. A preliminary effort therefore prepared outline designs for several sailing ships upon which the subsequent studies were based. This chapter describes the ships, and gives brief discussion of some of the choices that were made.

The ships are three commercial sailing bulk carriers of 15,000, 30,000, and 45,000 tons cargo deadweight. Their principal dimensions and significant characteristics are given in Table 2. It should be emphasized that these do not represent optimal designs, since no parametric studies were made to find the best values. Optimization was impractical in absence of the performance and economic results subsequently found, i.e., the whole study is analogous to the first loop of a "design spiral," and is the basis for subsequent optimization (yet to be done), rather than its result.

HULL FORM

In very general terms, the hull form of a modern deep-water sailing cargo ship would bear a greater resemblance to conventionally powered ships than to the relatively yacht-like clippers. The great steel sailing ships of the turn of the century were quite full-bodied by earlier standards, very flat in the floors, and obviously designed at least as much for carrying capacity as for sailing speed.

The principal difference between the hull forms of large commercial sailing vessels and their mechanically driven counterparts lay in the importance of draft as a determinant of sailing performance. While beam/draft ratios for steamers approached or exceeded 3.0, the corresponding ratio for large sailing ships

Table 2

SAILING SHIP PARTICULARS

CDWT	15000	30000	45000
LOA (FT)	575	722	820
LBP (L)	525	660	750
Beam (B)	66	83.4	95
Depth (D)	45	56.5	67
$Draft_{FL}$ (T)	32	39.5	45
Freeboard	13	17	22
L/B	7.955	7.914	7.895
L/T	16.406	16.709	16.667
L/D	11.667	11.681	11.194
B/T	2.063	2.111	2.111
Δ_{FL} (ton)	20000	39750	59250
C_B	0.634	0.640	0.647
C_M	0.890	0.890	0.890
C_P	0.709	0.719	0.727
$C_\nabla x10^3$	4.837	4.889	4.916
$CDWT/\Delta_{FL}$	0.750	0.755	0.760
CN = LBD/100	15593	31099	47738
Total Sail Area (SA) $(FT)^2$	88000	139000	179000
$SA^{1/2}/\Delta_{FL}{}^{1/3}$	10.929	10.924	10.853
Water Ballast (ton)	9200	18086	26633
Δ_{BAL}/Δ_{FL}	0.710	0.700	0.690
Auxiliary Speed (knot)	6	6	6
Approx. SHP	350	550	700
Installed BHP	600	1000	1200
Fuel Tankage (ton)	200	250	275
Complement (est.)	28	28	30

remained quite close to 2.0 and rarely exceeded 2.12 in the deep load condition.

The effect of the aspect ratio of the underwater profile is of primary importance in determining the lift-drag relationship on the hull, and this automatically forces the sailing ship to adopt a maximum draft hull form. A movable lateral-plane appendage is an alternative. Our objections to this are discussed in Chapter V.

Secondly, the block coefficient of the sailing ship hull must reflect the fact that in order to realize a certain "average" speed in service, the sailing ship is compelled to operate for considerable periods of time at speeds far in excess of the average. In fact, the amount of fullness which must be sacrificed in the interest of acceptable performance under sail is related to the operating conditions for which the particular ship is designed: ships operating primarily in regions of relatively light winds may carry extra fullness, while those which must face areas such as the winter North Atlantic must be relatively fine. Inspection of the ship characteristics reveals block coefficients in the vicinity of 0.65, as opposed to a typical value around 0.75 or higher in the case of conventional ocean bulk carriers.

VOLUMETRIC REQUIREMENTS

Due to the need for deep draft as a criterion for acceptable sailing performance, and sizable righting moments to allow sail-carrying power, the ballast requirement for commercial sailing ships is considerably higher than for powered vessels. Typically, the ships under consideration ballast down to about 70% of full load displacement, and about 75% of full load draft. Operating in the ballast condition, the sailing ship tends to be slightly faster off wind due to reduced displacement and wetted surface as compared to full load, but somewhat slower to windward, due to the reduced righting moment and lateral plane.

While required cubic for bunkers is reduced 90% or more compared with competitive steamships, the ballast spaces required result in a ship of approximately the same cubic as a conventional steamer of equivalent deadweight, or even slightly greater.

ARRANGEMENTS

Internal arrangements of spaces are quite similar to modern bulk cargo ship practice, with a few exceptions. Firstly, the total length of cargo holds can be increased due to the drastic decrease of engine room size. The engine room itself can be squeezed as far aft as possible, integrated vertically if electric drive is used, since the diesel-electric generator sets are of such size as to allow this configuration.

Crew accommodation is arranged all aft in a long, low superstructure comprising a connected bridge and poop. The height of superstructures will necessarily be limited by considerations of the sailplan distribution, while the actual accommodation spaces will have to be distributed around one or more of the large cargo hatches passing through the center of the superstructure. Visibility for ship control is enhanced by a "crow's nest" supplementary bridge (on mast 5 in Figure 2). General arrangements of the 45,000 CDWT sailing vessel are shown in Figure 2; the smaller ships are generally similar in layout.

HULL CONSTRUCTION

Conventional practice has been assumed throughout, with longitudinal framing and transverse webs. An unusually deep double bottom is required by ballast considerations, with the usually self-trimming cargo hold design including a hipped tank top and topside ballast/cargo tanks.

Structures in way of masts are not expected to present great problems, with reinforced deck beams and longitudinals taking most of the mast load at deck level, while the heel of the mast may be located directly on the center girder and tied into transverse floors to accept the side loads. Stiffness of the encastrè portion of the mast is quite important if the mast is to be an effective cantilever, but this consideration is greatly enhanced

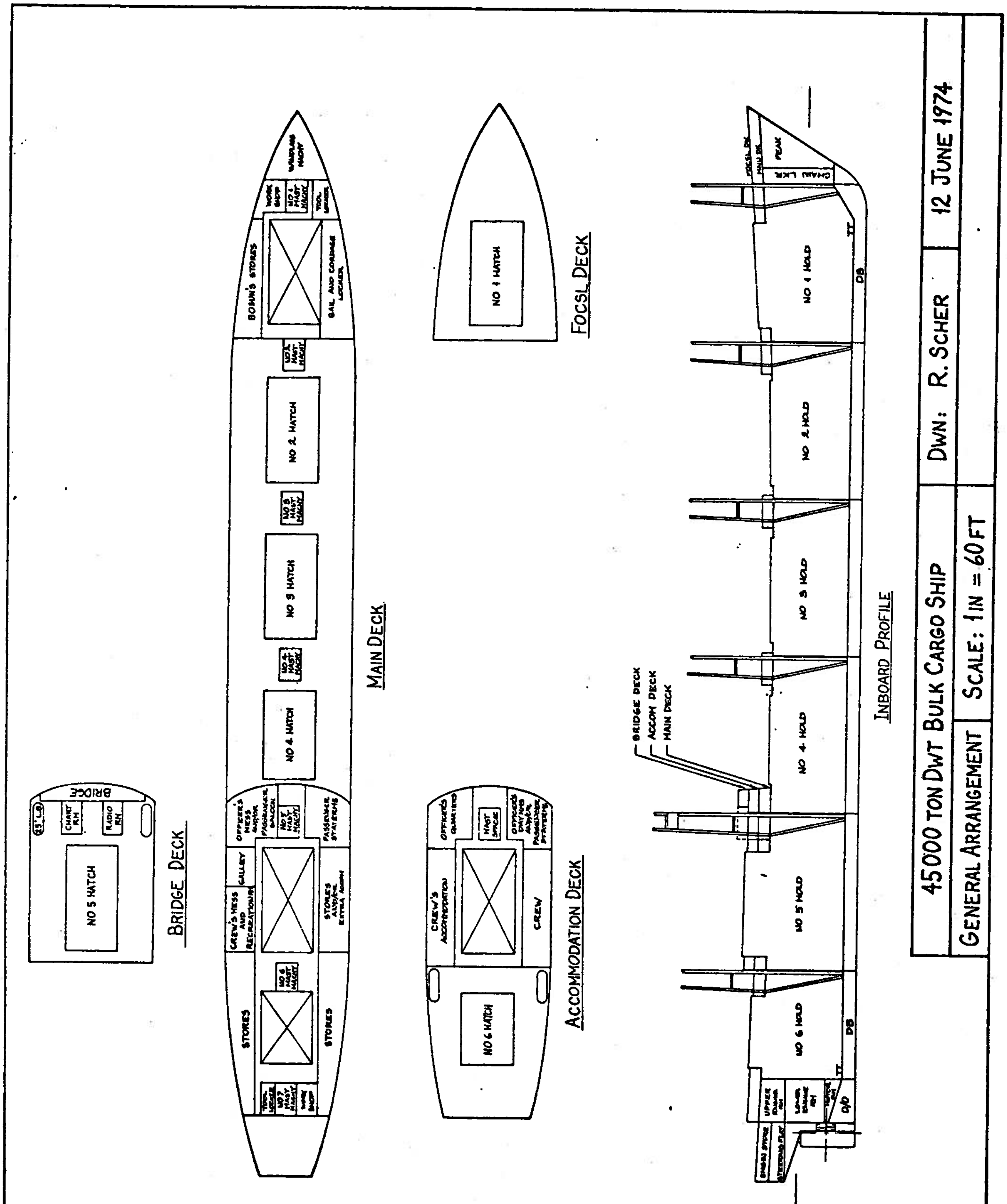


FIGURE 2 Arrangement of 45,000 Ton Bulk Cargo Ship

by tieing each mast into a transverse bulkhead.

RIG

In choosing a starting point for the design of rig and sailplan, consideration was given to a large number of alternative systems including various types of rigid and semi-rigid wingsails, Flettner rotors, mechanical and electrical power conversion systems involving windmill-driven generators and motor-driven screw propellers, as well as conventional sails, both fore-and-aft and square rigged. Each system has its own distinctive advantages and disadvantages, some of which are summarized in Appendix II.

For the purposes of large, relatively low-speed cargo-ship applications, the aerodynamic sophistication of wingsails is misapplied, largely due to the inability of the cargo ship hull form to generate large side forces at reasonable leeway angles. The choices were finally narrowed to the field of conventional sail systems, and in particular, the square rig.

The reasons for this choice were many. First, the available aerodynamic data on multi-masted rigs is principally in the square rig configuration. Second, the square rig offers advantages in engineering simplicity, straightforward application of mechanical, automated sail-handling systems, and control of sail configuration, trim, and twist. Third, the square rig allows an arrangement that minimizes the interference of rig components with loading and unloading gear and other ship-handling operations. Fourth, and most important, the square rig is well matched with the hydrodynamic qualities of the cargo-ship hull, and provides excellent off-wind performance, which must be the strong suit of the deep-water commercial sailing vessel.

The actual design of the square-rigged sailplan is largely a matter of fitting the required sail area onto a given length ship, while satisfying the geometric constraints of aspect ratio, mast spacing, and maximum yard length in relation to the beam of the vessel. In the case of the three study designs, no vertical clearance constraints on masthead height were considered, the final height thus being a product of the other considerations.

It should be mentioned at this point that the 45000-DWT and 15000-DWT vessels are barque rigged, with seven and six masts, respectively, the after mast in both vessels being a transverse bipod structure supporting a roller-furling fore-and-aft staysail. The 30000-ton vessel, on the other hand, is fully square-rigged on all six masts, as shown in Figure 3. This dissimilarity should not be interpreted as indicating any inherent superiority of one rig over the other, but in fact is a result of the requirement for getting a certain total sail area within the constraints of ship length and individual mast aspect ratio. Thus, for example, the 30000-tonner required substantially more sail area than the 15000-ton vessel, and yet its length did not permit the jump from six to seven masts without either crowding the masts too close together or necessitating an excessive aspect ratio for each mast.

The sole advantage of the barque rig, and the reason for its adoption where dimensional and sail area limitations permitted, is that an after sail which can be trimmed quite close to the centerline of the vessel is of value in tacking, and in balancing the rig and helm. In any case, the effect of the choice between barque and full-rig on speed-polar values is expected to be slight, and has not been considered in the determination of the speed-polar curves for the three study vessels.

MASTS AND RIGGING

The selection of a square-rigged sailplan gave rise to a number of alternative systems of masting, each with its own set of advantages and disadvantages. Among the systems that were given serious consideration were the Prölss (1) rotating mast, in which all yards are fixed rigidly to a bipod mast stepped on a rotating turntable, trim of the sails then being accomplished by swinging the entire mast as a single unit. In particular, this system offers the advantage of allowing the sails to be trimmed as nearly parallel to the ship's centerline as desired. However, evaluation of the hull side-force coefficients indicated

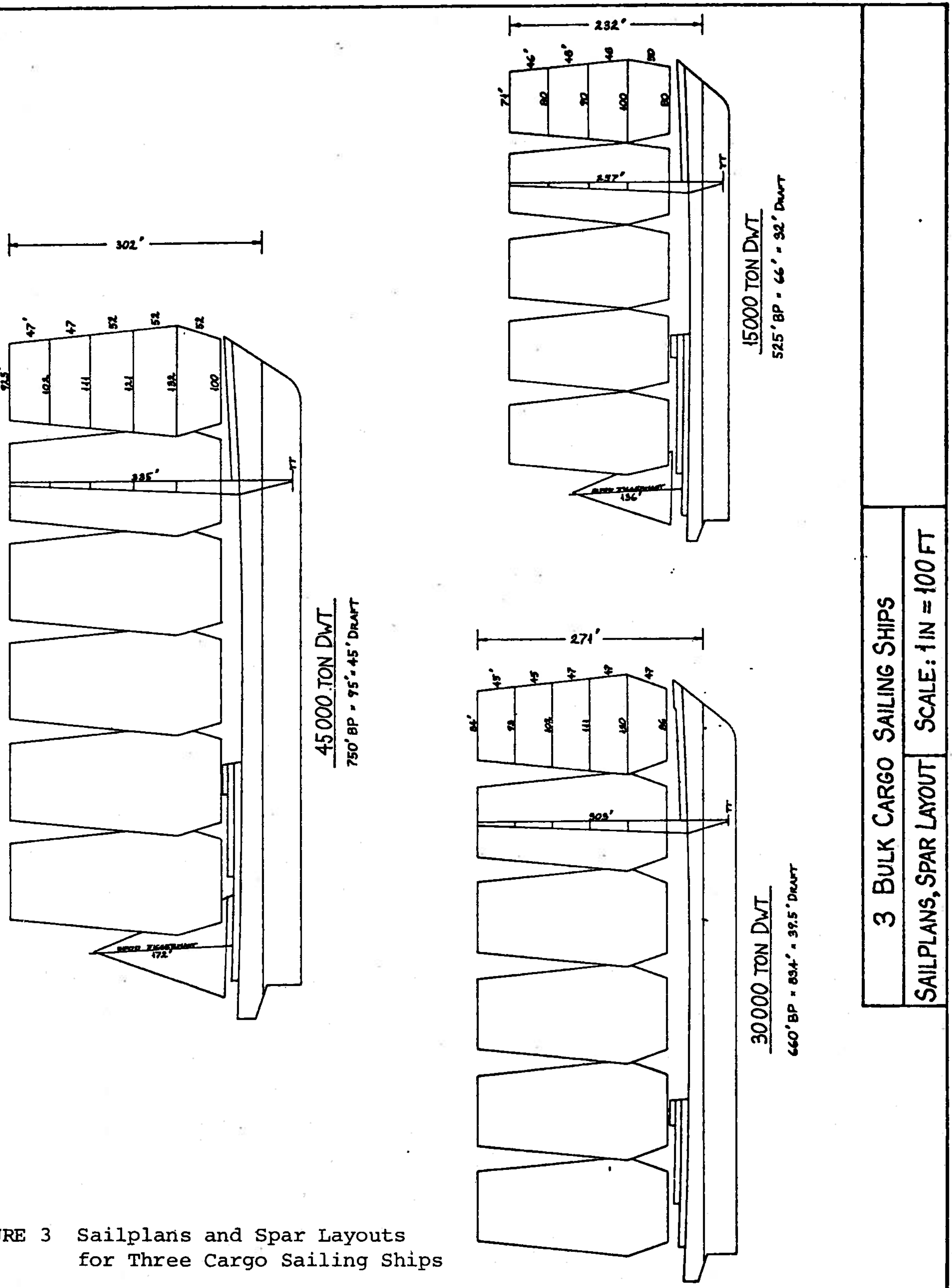


FIGURE 3 Sailplans and Spar Layouts for Three Cargo Sailing Ships

that the value of trimming the sails closer to centerline than 15° - 20° was negligible, the hull form being fundamentally unsuitable for the large side forces generated by trimming the sails too close. In addition, there was some doubt regarding the feasibility of mounting very large masts on turntables.

The mast configuration finally selected was that of an open tripod, with a single leading spar, and two trailing spars, of tubular construction in high tensile steel. The yards are individually actuated for sail trim, being articulated on the forward spar of the mast. The configuration of the tripod permits a range of travel of 75° to either side of square, or 15° off the centerline, which is felt to be adequate for acceptable windward ability in a vessel of this type.

The independent actuation of the yards allows for a limited amount of twist in the sail from masthead to foot, a favorable effect since the apparent wind vector varies with height. By trimming the sails differentially, each yard trimmed a little bit farther from centerline than the one below it, the angle of attack on each sail can be kept close to the optimum value.

Although the actuation system is more complicated in terms of the number of components involved, as compared with rotating masts, the individual components are smaller, simpler, and subject to more reasonable loads. The tripod configuration has been analyzed under simple beam theory - including the effects of torsional stresses due to the offset of the sail center of force from the neutral axis of the tripod, under a designed load of all sail set, wind speed of 50 knots and total force coefficient 1.5. Results of the analysis show that the critical mode of failure as currently designed is buckling of the leeward member. A typical mast-hull tie-in for the 45000 CDWT vessel is shown in Figure 4.

SAILS AND SAIL HANDLING SYSTEMS

In an attempt to keep experimental technologies to a minimum, sail materials and construction were assumed to be conventional. Dacron with steel wire head, foot, and luff reinforcement appears to be a feasible material, although sails of the dimensions now envisioned (say 135 ft wide by 50 ft deep in the case of the 45000-ton vessel) may require further reinforcement since they will have to withstand higher wind velocities than is usually the case.

Required sail area has been arrived at by inspection of past designs, scaled up as $\Delta^{2/3}$ approximately.

Sail-handling systems must provide for the two distinct functions called for in operating the square rig, namely, sail trimming and sail furling. Sail trim is accomplished by swinging (bracing) the yards about a pivot on the leading side of the mast. Actuation may be accomplished by hydraulic cylinders, motor-driven screw rods, or wire braces led to winches on deck. The latter system has been chosen in order to minimize weight aloft, and because it allows the mechanical components (winches) to be placed on the main deck, protected from weather, and in a position for easy maintenance. The lead of each brace is as follows: from the spool of the winch, through a fairlead, up one of the after spars of the tripod mast, through an exit block, and finally, forward to the yard. Each yard is, of course, controlled by two braces, spooled over the winch drum so that one is shortened in as the other is paid out.

The second sail-handling function is furling and resetting. As presently conceived, this would be accomplished by furling the sail on a rotating vertical rod jackstay set between the yards just forward of the mast. When furled, the sail would thus form a slender cylinder against the leading spar of the mast. To set the sail, outhauls leading from the yardarm to the luffs of the sail would be winched in, drawing the sail off the furling stay and out along the yard. Schematic layouts of sail control machinery are shown in Figures 5 and 6.

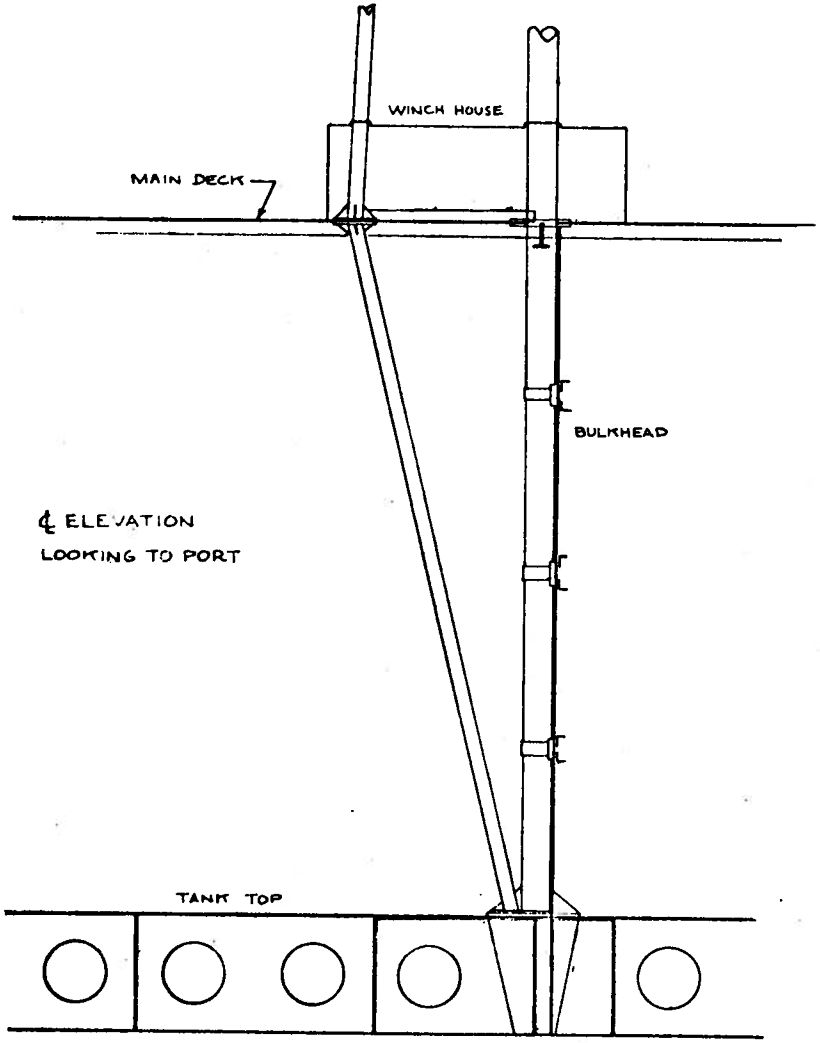
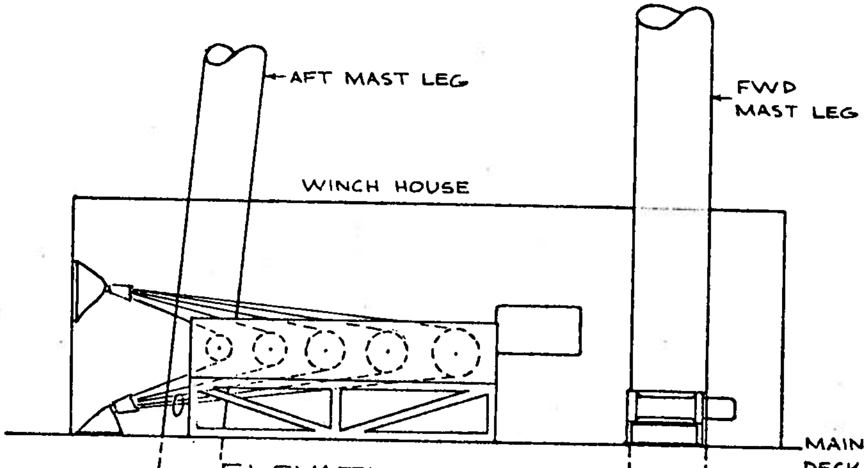
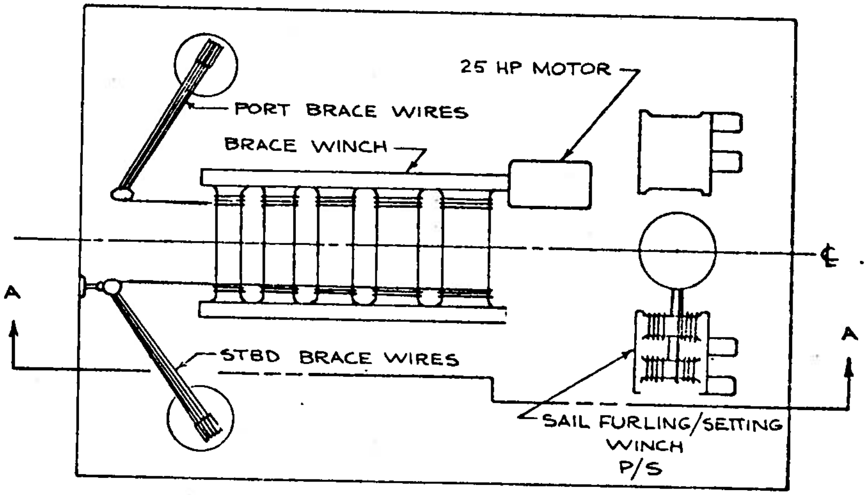


FIGURE 4 Typical Mast-to-Hull Tie-in



ELEVATION A - A



PLAN OF MAST MACHINERY FOR
15,000-TON SHIP OTHERS SIMILAR

FIGURE 5 Sketches of Mast Machinery

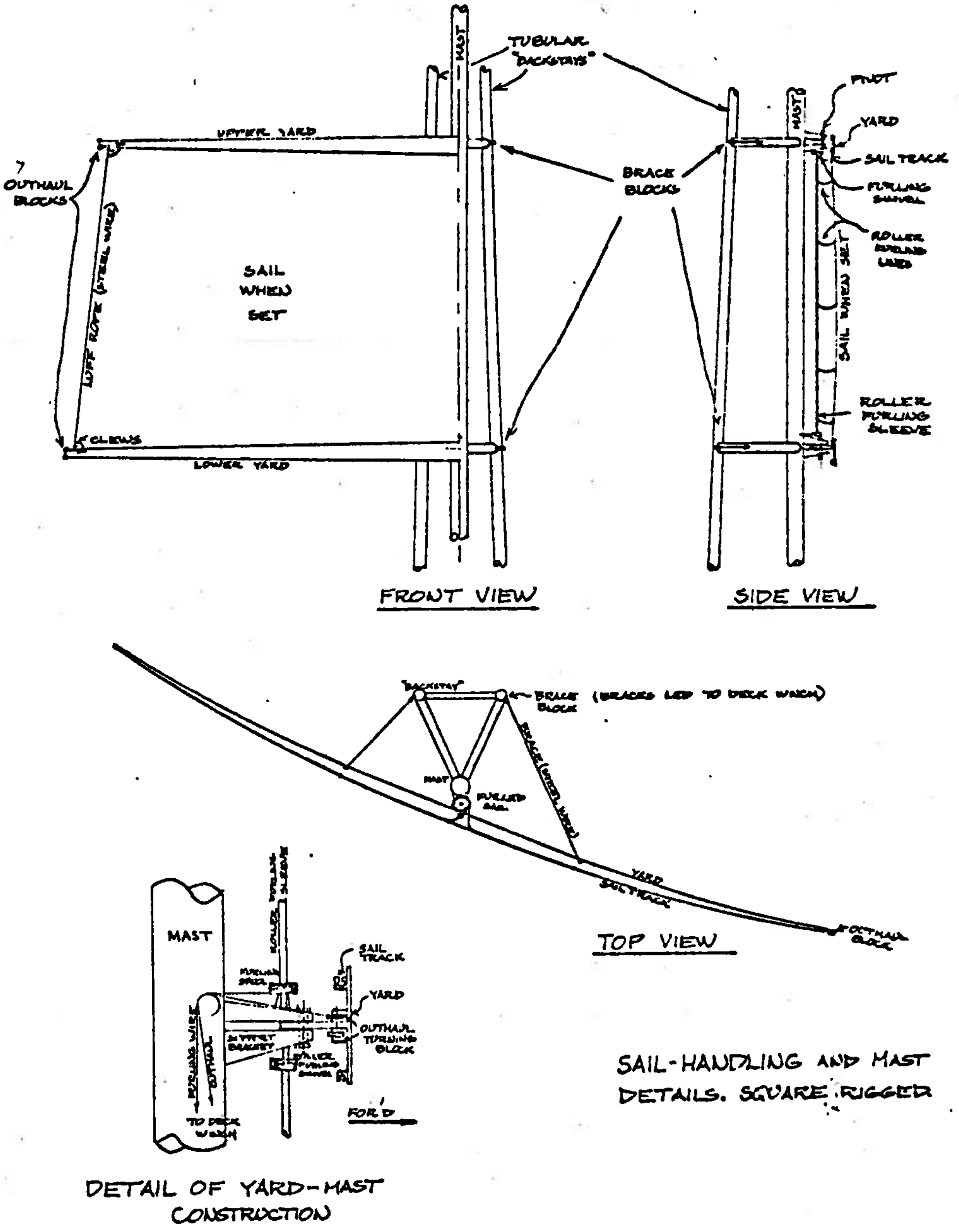


FIGURE 6 Details of Masts and Sail Handling

V. TECHNICAL AND OPERATIONAL PROBLEMS

The technical and operational problems of a sailing ship clearly must be different in at least some respects from those of powered ships. Presumably the problems of traditional sailing are widely known, and hence need not be reiterated. This chapter discusses those problems that seemingly would result from particular features of the designs studied here, from operation in the contemporary marine world, and from the possible application of modern technology.

SAIL PROBLEMS

One of the most difficult problems anticipated with automated sail-handling systems is the accumulation of ice on sail tracks, blocks, fairleads and other vital moving parts. While this problem has not been dealt with explicitly or in detail in the preliminary design of the sail-handling gear, it has been assumed that a solution is possible using some variant of aircraft deicing equipment.

Maintenance and repair of sails requires personnel aloft; however, the design of the rig allows all normal replacement of sails to be accomplished without leaving the mast. Sails would be sent up or down in their furled configuration, and bolted into position on the roller furling gear. It is anticipated that such work would normally be performed in port together with most mast-maintenance operations.

Complete automation of sail-handling functions, that is, fully automatic control of sail trim, furling and setting without direct operator feedback is not a difficult problem. The input variables are relatively few and simple: desired course, apparent wind angle, wind speed, angle of heel, etc. The systems required for automated control exist, and the mechanical equipment involved consists of little more than a collection of low-powered electric deck winches with suitable leads.

TRANSVERSE STABILITY

As a sailing ship's size is increase, certain gains in stability are realized. This effect is largely due to the fact with geometrically similar designs, heeling moment increases as the third power of the scale ratio, while the righting moment increases as the fourth power of the scale ratio. In addition, however, the larger ship actually carries a proportionately lower rig rather than a geometrically similar one, and can, in general, use a proportionately smaller sail area without sacrifice of speed except in very light air. Thus the operational angles of heel for the ships under study are quite small compared with past sailing vessels. A heel of 10° - 12° may be regarded as an upper bound for normal operations.

In fact, the principal problem involving transverse stability appears to be excessive metacentric height and consequent quick rolling. Under some loading conditions, the period is short enough to produce synchronous rolling, although the large damping effect of sails should limit the problem, provided there is enough wind to keep the sails drawing. Therefore, it seems that operational difficulties may be encountered during periods of calm, with heavy beam swell running, perhaps requiring a course alteration to reduce rolling.

More will be said of transverse stability as it affects sailing performance in a later section.

STRUCTURE

The only significant structural problem that can be envisioned is one of excess torsion being produced by unusual combinations of sail setting. An extreme case would be the foremast with full sail in a beam wind, with all other masts bare. However, there is no operational need for such a combination, nor for anything approaching it. The designers would doubtless furnish a booklet of permissable sail arrays, and this has been assumed here, rather than the assumption of any unique torsional strengthening. The problem is thus analogous to that of permissable tank or hold loadings for any bulk carrier.

REGULATORY BODIES

As long as the sailing ship conforms to conventional merchant ship design and construction standards -- hull structure, subdivision, closures, fittings, machinery design, etc -- there should be very little conflict with present regulatory requirements. We note here the few areas where some accomodation with the present rules may be required.

Structure

The possibility of the unusual torsional load has been discussed, and our assumption that this will not be reflected in scantling rules. The submittal for approval of the booklet of permissable sail arrays (also mentioned above), with the supporting torsional analysis, may be a reasonable requirement.

Scantling rules for spars, and for the sails themselves, may reasonably be expected as part of the regulatory picture for these ships.

Freeboard

Present freeboard rules do not cover sailing ships of the size envisioned here. But this appears to be solely an understandable omission by the rule makers. The rules doubtless can be extended, though the makers may not allow the powered ship rules to apply because of the likelihood of greater heel angles. A major difference is not to be expected, however, because this heel angle is small, as noted previously.

Stability

We have noted above that transverse stability does not appear to be a problem. However, a sailing ship with all sail set can suffer a much greater wind heel moment than a powered ship of comparable hull dimensions. The saving factor is the involuntary reduction of that moment by the blowing out of sails long before angle of heel becomes dangerous. Such, at least, is the expectation with traditional canvas, and it must also be the case with the wire-reinforced dacron assumed here. Stability criteria for sailing ships will have to include sail construction standards to ensure that they will indeed fail. The problem of ice forming aloft is also of some concern, and stability criteria will have to be chosen with due regard for it.

CHOOSING A ROUTE FOR MINIMAL PASSAGE TIME

Passage Planning

In a strategic sense, the selection of suitable routes for deep-water commercial sailing vessels is largely a matter of qualitative inspection of synoptic weather data. Obviously, a more quantitative index of suitability is the expected "service" speed for the particular route and track, a quantity given much attention in the computer study described later.

In general terms, however, a "good" route is one which allows the sailing ship to remain in zones of reliable wind, whether contrary or favorable, with high gale frequencies and very low calm frequencies, and which stays as close as possible to the "direct" route.

Synoptic weather and surface current data has been compiled in a number of marine meteorological atlases, (3), including monthly wind charts for most important ocean areas. It must be remembered, however, that the data extracted from wind charts is not dynamic, in the sense that it contains no direct information on the way in which wind conditions vary with time. Nevertheless, since in initially choosing a route we are principally interested in the expectation value of ship's average speed, the monthly wind roses are the primary statistical key to the problem.

Dynamic Routing

While passage planning is a fundamentally static situation, using data compiled from real-time weather measurements, passage making is a dynamic routing problem. Namely, given the state of the wind at present, and in some high-probability future, determine the course of action that takes the ship to its destination in the shortest time.

Information is the critical aspect of the problem. In the past, sailing ship masters had no outside sources of dynamic weather data, and thus had to depend on observation and some obscure "sense" of what conditions might reasonably be expected at some later time.

With existing technology, however, detailed weather data is available for the decision making process in passage making. The most significant item from the point of view of a commercial sailing ship is the ability to track the centers of depressions, and thereby to keep the sailing ship in the more favorable semi-circle of an approaching low-pressure system. The process is akin to the "pressure-pattern" flying practiced by aircraft, a matter of picking up tailwinds and avoiding headwinds.

This analogy breaks down in the sense that the aircraft moves so much faster than the weather patterns that the weather can be considered almost static. In the sailing vessel's case, there is much more time for contingencies to develop, since the ship is generally not moving much faster than the pressure system.

As reflected in the decisions that can be made on board, information on the position and anticipated relative motion of low-pressure centers can assume some importance. Particularly in going to windward, knowledge of the presence of a low-pressure circulation pattern can lead to favoring one tack over the other. Similarly, when reaching off, alterations in course are often possible so as to bring the ship into a more favorable position relative to an approaching low pressure center.

The potential effects of decision making on mean passage times and variances are discussed subsequently. Suffice it to say for the present that the dynamic routing problem as it applies to sailing ships is extremely complex if an approach is made to optimization. However, the possession of such weather information as radar, satellite photographs, and on-board facsimile equipment can provide will be of some value in making critical decisions, whether or not optimum routing is applied continuously.

AUXILIARY PROPULSION

The question of auxiliary propulsion of sailing vessels is essentially two-fold, in that it is not sufficient merely to establish a rational value of installed horsepower requirements, but also to specify a rational engine-use strategy.

The presence of auxiliary propulsion on a sailing vessel immediately places the ship on a continuum with steamers. Obviously, in the search for higher average speeds, one approach would be to install high-powered auxiliaries and depend on them for greater fractions of the total time per voyage. At some point, however, the ship ceases to be a sailing vessel with auxiliary engines and becomes a powered vessel with a large and rather superfluous rig. In fact, ships of this type were operated in the early part of this century, most notably the France II of 1912, and some of the large Rickmers liners. All were disastrous failures, and some ended their days as pure sailing vessels, with engines removed.

The economic reason for this is clear enough: a sailing ship derives whatever advantages it has from its elimination of large engine rooms, and engineering staff; such hybrids as the France II, in combining huge rigs with large engines, actually combined the worst features of both sail and steam, without realizing the full advantages of either.

The principal needs for an auxiliary engine aboard a sailing vessel are to provide maneuvering power in and around ports, and to traverse areas of high-frequency calm. The effect of added auxiliary power on economic performance is detailed later, but it has been a general finding that increased auxiliary power does not significantly affect voyage mean times until the extent of the increase is such as to make the vessel an inefficient sailing cargo carrier. However, the effect of auxiliary power on the variance of voyage times is quite strong, and a very low value of auxiliary power can reduce the variance of voyage times significantly, even when a very conservative engine-use strategy is employed.

This brings us to the second part of the auxiliary-power issue, namely, specifying an efficient strategy for using the installed power plant. A number of reasonable strategies are possible:

(1) Minimum use. The auxiliary engine is used only for in-port maneuvering and in flat calms (wind insufficient for steerage way).

(2) Conservative use. Auxiliary power used when ship speed is below a fixed limit. This is the use applied in the present study.

(3) Maximum use. Auxiliary power used whenever it effectively increases ship speed.

Note that the use of auxiliary power does not imply that sail is not set at the same time. In fact, mixed mode operation (under both power and sail) is the normal practice except in flat calms, which are very low-frequency states.

As in the case of installed horsepower, the voyage mean times are relatively insensitive to engine use strategy, while variances are more strongly affected. The general result, in terms of economic performance, is that strong, reliable winds favor a minimum use strategy, small engines and small bunkers, while light, variable winds favor conservative or nearly maximum use strategies, somewhat more installed power, and larger fuel tanks.

The three study ships were designed for the smallest reasonable power plants, in effect, built-in tugboats to give in-port maneuvering and mobility through unavoidable areas of calm. The starting point requirement was 6 knot speed in still water and air. This means that the engines will not have sufficient power to move the ship against head winds of 50 knots, but these conditions are sufficiently rare when making landfall that the extra installed power is not worthwhile. In such cases, the ship would either wait offshore for better conditions, or sail in as close as practicable and pick up a tow.

PORT OPERATION

Cargo handling apparently will present no major problems to the type of ship studied here, i.e. the dry bulk carrier. The mast structure is well in-board, is (of course) located between hatches, and is not fitted with the maze of standing rigging that might be expected to foul shore-side loading and unloading gear. The yards are the only item of concern. If braced athwartships, upper yards may foul structures such as overhanging ore docks; if braced fore and aft, lower yards may foul gear such as Hulett unloaders. The reply is to manipulate the yards to suit the situation, so that the problem should be no more than a nuisance. It would nonetheless be advisable to examine clearances at expected loading/unloading facilities as part of the ship design process.

Draft for a given deadweight tends to be somewhat deeper for the sailing hull. This may be classed as an economic problem rather than operational or technical, since any ship will presumably be designed to meet the constraints imposed by its areas of service. On the other hand, this brings up the question of movable lateral-plane appendages -- centerboards or leeboards to the small boat sailor -- which could develop the side forces for a relatively beamy, shallow hull. Our belief is that the added complexity required of structure and machinery from massive movable surfaces outweighs their advantages, though there is certainly technical precedent in fin stabilizers, submarine diving planes, and even in conventional rudders. The major objection is more operational, stemming from the likelihood that such surfaces would project well below the hull when in service. A grounding, for example, might well result in a "stuck down" centerboard; repair could be exceedingly difficult.

Perhaps the biggest concern with respect to ports is the handling of the ship under power. The low propulsion power, and a rather large windage, indicate that it could not be handled safely in narrow channels during periods of high wind. Our assumption has been that high winds would require a ship to remain offshore, or in port, until the condition abated. But there is the possibility of high winds, such as from a thunderstorm, arising suddenly while the ship is making the passage between sea and berth. A simple remedy exists in the form of more power on the propeller, and/or side thrusters, but with the obvious economic penalty. Also, it is difficult to predict just how much power in each category should be provided. In an actual design, this can be determined by wind tunnel tests, coupled with analysis of conditions at the ports the ship will serve.

Vertical bridge clearance will present an operational problem at several ports, as illustrated by two simple tables following. First, mast heights are

15,000 ton ship	232 feet
30,000 ton ship	271 feet
45,000 ton ship	302 feet

Vertical bridge clearances at mean high water for harbor-mouth bridges at the U.S. ports specifically mentioned previously are

New York (Verrazano Narrows)	232 feet
Baltimore (Chesapeake Bay)	187 feet
San Francisco (Golden Gate)	232 feet

(data from Corps of Engineers "Port Series")

From this comparison, it is apparent that sailing ships may be limited in the ports they can serve, although we have not considered this to be a serious handicap because of the availability of alternative ports (e.g. Hampton Roads in lieu of Baltimore). A second alternative is folding or telescoping masts. Although such devices doubtless can be constructed, they would add considerable technical complication, especially in view of the internal running rigging here assumed.

In view of the several points discussed in this section, it is apparent that port operations entail difficulties of greater magnitude than those of powered ships. Even though feasibility of operation is by no means spoiled by these difficulties, it is also apparent that they would have to be examined in greater detail before actual sail service could be put into effect.

MANNING REQUIREMENTS

Under ideal conditions (very optimistically) it might prove possible to operate the 45000 deadweight ton vessel with the following minimum crew:

16	Deck department
4	Engine department
4	Stewards department
24	Total

This complement assumes not only full automation of sail handling functions, but also bare minimum maintenance and repair to be performed at sea. The deck department is in three watches of five men each, the master being off watches. Similarly, there are three watchstanding members of the engine room staff, while the chief engineer idles.

It should be remembered that the complement of 24 is a minimum. We do not anticipate operating with this complement, but it represents the optimistic limit, and has been used as such in the economic analysis. A more probable figure is 30, and a pessimistic limit has been set rather arbitrarily at 36. The wide spread between limits is, of course, due to the uncertainties involved in a new and untried type of ship.

The smaller study ships have been assigned identical optimistic crew sizes in the absence of any areas for further reduction.

HOTEL LOAD AND AUXILIARY POWER

Electric power for hotel services, hull engineering, communications, and sail handling, can conveniently be met by a conventional diesel ship service generator and power distribution system, with the usual emergency generator. An electric load analysis shows that the largest of our ships (45,000 tons) would require a maximum of about 430 kw, to be met by a 600 kw machine.

VI SAILING SHIP PERFORMANCE

If a ship without engines could equal the performance of a ship with engines, then the superiority of the former would be difficult to deny. The heart of our study is therefore the prediction -- via computer simulation -- of the performance of the three modern sailing ships under investigation. This chapter summarizes the predicted performances, these being found in Tables 3 through 16. The voyages studied are New York - Liverpool, Baltimore - Monrovia, Cape Flattery - Shanghai, and San Francisco - Sydney. These may be taken as representative of East Coast to North Europe, East Coast to West Africa, West Coast to East Asia, and West Coast to Australia, since passages to other ports in the vicinity of those named would require only minor adjustments; a major portion of total passage time would be spent on a common transoceanic track.

Performance as here used is measured by the time required to make a specified passage. It depends on an instantaneous speed, which is a function of wind strength and bearing relative to the ship's heading, and on the distribution of wind strengths and directions over the track followed in making the passage. Calculation of performance is therefore a process of many steps, and is practicable only through the use of the digital computer. The process used here is fully outlined in an appendix.

Because of the uncertainty in sail passage times, our results consist of two statistics obtained from a large sample of computer runs; the expected (mean) passage time, and the variance of passage time. The former is also converted to a mean speed in the tables.

The results tabulated in this chapter are voluminous because passage times vary with the season, with the direction, and with the size of ship. The best round trip average sea speed is 12.24 knots, Cape Flattery to Shanghai in winter (Table 7), and the worst is 8.22 knots on the same voyage in the summer (Table 15). As is to be expected, the best speed is shown by the biggest ship, and the worst by the smallest. (Table 5 figures excluded here; to be discussed below).

The data of the other tables is summarized in Table 3, which shows only the annual means and variances. The annual mean speeds vary between 9.2 and 10.99 knots. Whether these speeds are "good" depends on the economic comparison between the sail and power alternatives to be discussed in the next chapter, but clearly the performance does not equal that expected of modern powered bulk carriers.

The tabulated data also includes fuel consumption per round trip, this comprising consumption for both propulsion and auxiliary power. The propulsion usage results from using the engine to keep speed from dropping below six knots.

The question of auxiliary propulsion use is an important one. An investigation of one of its aspects produces Table 5, which gives results for the 45,000 ton ship on the North Atlantic without auxiliary propulsion. These results should be compared to those of Table 4. The engine is shown to make a noticeable difference; e.g. the worst round-trip average sea speed is 7.17 knots, compared to 9.30 for ship, season, voyage, otherwise the same. This comparison takes place in the summer when winds are at their poorest; the difference is much less in the winter months. The general picture is this: when and where winds are strong, the engine use reduces variance much more significantly than mean speed; in lighter winds, the mean is also significantly improved.

The principal reason for the relative insensitivity of voyage mean times to auxiliary power is the engine use strategy. Any reasonable strategy, aimed at reducing the sailing ship's dependency on its auxiliary engine and fuel supply, calls for the use of auxiliary propulsion only a fraction of the time at sea, ranging from 0.1 if conditions favor sailing, to 0.22 as a characteristic figure, and as high as 0.50 at certain times of year when wind is in short supply. To go further, and attempt a significant increase in annual mean speed by more power than we have provided, will require a major jump in power and fuel consumption. For example, we estimate that a gain of one knot above the annual mean figures reported in this chapter would require a 4.5 knot increase in rated speed under power (i.e. 6 knots to 10.5 knots), with an increase of engine power in consequence by a factor of about five. This would turn the ship into a low-powered "steamer" with auxiliary sails, a concept which is not under study here.

Table 3

SUMMARY OF RESULTS - Voyage Mean Times, Variances, Equivalent Speeds, and Round Trip Fuel Consumption.

Voyage/Distance	Ship (CDWT)	E[T] (Days)	Var (Days)	D/E[T] (Knots)	RT Fuel (tons)
New York - Liverpool 6200 Naut Mile	45000	24.59	2.33	10.51	85
	30000	26.40	2.44	9.79	82
	15000	28.08	2.54	9.20	65
Baltimore - Monrovia 8200 Naut Mile	45000	33.47	2.33	10.21	127
	30000	35.16	2.50	9.72	117
	15000	36.99	2.58	9.24	91
Flattery - Shanghai 10500 Naut Mile	45000	39.82	3.12	10.99	134
	30000	42.63	3.24	10.26	124
	15000	45.77	3.40	9.56	102
'Frisco - Sydney 12800 Naut Mile	45000	49.11	3.87	10.86	181
	30000	51.48	4.07	10.36	167
	15000	53.85	4.32	9.90	128

Table 4

Voyage Mean Time and Variance

Voyage: New York - Liverpool. Nominal Round Trip = 6200 Naut Mile.

Ship: 45000 CDWT. 750 x 95 x 45' Draft. Auxiliary: 6 kt on 1200 BHP

	Mean and $\sqrt{Var}$ Sea Time (Days)								
	Eastbound		Westbound		Round Trip		Avg. RT Sea Speed (Knots)	Avg. RT Aux. Prop. (Hours)	Total RT Fuel Consump. (Tons)
Quarter	$E[T]$	$\sqrt{Var}$	$E[T]$	$\sqrt{Var}$	$E[T]$	$\sqrt{Var}$			
Dec-Feb	9.11	1.34	12.91	2.11	22.02	2.50	11.73	123	61
Mar-May	10.72	1.65	14.29	1.58	25.01	2.29	10.34	185	81
Jun-Aug	12.50	1.28	15.28	1.59	27.78	2.04	9.30	353	129
Sep-Nov	11.04	1.41	13.74	1.96	24.78	2.41	10.43	202	85
EQUAL WEIGHT ANNUAL AVG.					24.75	2.31	10.44	210	87
SUMMER LAYUP ANNUAL AVG.					24.59	2.33	10.51	203	85

NOTES:

Table 5

Voyage Mean Time and Variance

Voyage: New York -Liverpool. Nominal Round Trip = 6200 Naut Mile.

Ship: 45000 CDWT. 750 x 95 x 45' Draft. Auxiliary: "Pure" sailing ship.

	Mean and $\sqrt{Var}$ Sea Time (Days)								
	Eastbound		Westbound		Round Trip		Avg. RT Sea Speed (Knots)	Avg. RT Aux. Prop. (Hours)	Total RT Fuel Consump. (Tons)
Quarter	E[T]	$\sqrt{Var}$	E[T]	$\sqrt{Var}$	E[T]	$\sqrt{Var}$			
Dec-Feb	9.65	2.01	14.03	3.30	23.68	3.86	10.91	0	30
Mar-May	11.88	3.01	16.34	3.04	28.22	4.28	9.15	0	34
Jun-Aug	15.48	3.44	20.53	7.94	36.01	8.65	7.17	0	43
Sep-Nov	12.45	2.97	15.77	3.91	28.22	4.91	9.15	0	34
	EQUAL WEIGHT ANNUAL AVG.				28.46	5.43	8.98	0	35
	SUMMER LAYUP ANNUAL AVG.				28.11	5.23	9.19	0	34

NOTES:

Table 6

Voyage Mean Time and Variance

Voyage: Baltimore - Monrovia, Liberia. Nominal Round Trip = 8200 Naut Mile.

Ship: 45000 CDWT. 750 x 95 x 45' Draft. Auxiliary: 6 kt on 1200 BHP.

	Mean and $\sqrt{Var}$ Sea Time (Days)								
	Eastbound		Westbound		Round Trip		Avg. RT Sea Speed (Knots)	Avg. RT Aux. Prop. (Hours)	Total RT Fuel Consump. (Tons)
Quarter	E[T]	$\sqrt{Var}$	E[T]	$\sqrt{Var}$	E[T]	$\sqrt{Var}$			
Dec-Feb	16.38	1.50	16.65	1.88	33.03	2.41	10.34	317	125
Mar-May	16.42	1.48	16.28	1.72	32.70	2.27	10.45	298	119
Jun-Aug	18.45	1.45	16.20	1.67	34.65	2.21	9.86	349	135
Sep-Nov	16.91	1.56	16.90	1.82	33.81	2.40	10.11	341	132
EQUAL WEIGHT ANNUAL AVG.					33.53	2.32	10.20	326	127
SUMMER LAYUP ANNUAL AVG.					33.47	2.33	10.21	325	127

NOTES:

Table 7

Voyage Mean Time and Variance

Voyage: Cape Flattery, Wash. - Shanghai. Nominal Round Trip = 10500 Naut Mile.

Ship: 45000 CDWT. 750 x 95 x 45' Draft. Auxiliary: 6 kt on 1200 BHP.

	Mean and $\sqrt{Var}$ Sea Time (Days)								
	Eastbound		Westbound		Round Trip		Avg. RT Sea Speed (Knots)	Avg. RT Aux. Prop. (Hours)	Total RT Fuel Consump. (Tons)
Quarter	E[T]	$\sqrt{Var}$	E[T]	$\sqrt{Var}$	E[T]	$\sqrt{Var}$			
Dec-Feb	16.21	2.11	19.54	2.64	35.75	3.38	12.24	193	94
Mar-May	18.04	2.20	21.42	2.72	39.46	3.50	11.09	322	133
Jun-Aug	22.54	1.40	26.18	2.32	48.72	2.71	8.98	572	210
Sep-Nov	17.67	1.78	21.25	2.k3	38.92	2.78	11.24	317	131
	EQUAL WEIGHT ANNUAL AVG.				40.23	3.09	10.87	337	138
	SUMMER LAYUP ANNUAL AVG.				39.82	3.12	10.99	326	134

NOTES:

Table 8

Voyage Mean Time and Variance

Voyage: San Francisco - Sydney, Australia. Nominal Round Trip = 12800 Naut Mile.
Ship: 45000 CDWT. 750 x 95 x 45' Draft. Auxiliary: 6 kt on 1200 BHP

Mean and $\sqrt{Var}$ Sea Time (Days)

Quarter	Eastbound		Westbound		Round Trip		Avg. RT Sea Speed (Knots)	Avg. RT Aux. Prop. (Hours)	Total RT Fuel Consump. (Tons)
	E[T]	$\sqrt{Var}$	E[T]	$\sqrt{Var}$	E[T]	$\sqrt{Var}$			
Dec-Feb	23.39	2.69	25.99	2.85	49.38	3.92	10.80	450	178
Mar-May	23.93	2.65	24.81	2.82	48.74	3.87	10.94	491	185
Jun-Aug	23.60	2.60	24.69	2.74	48.29	3.78	11.04	406	165
Sep-Nov	24.33	2.66	25.75	2.84	50.08	3.89	10.65	504	193
	ANNUAL AVERAGE				49.11	3.87	10.86	462	181

NOTES:

Table 9

Voyage Mean Time and Variance

Voyage: New York - Liverpool. Nominal Round Trip = 6200 Naut Mile.

Ship: 30000 CDWT. 660 x 834 x 395 ft draft. Auxiliary: 6 kt on 1000 BHP.

	Mean and $\sqrt{Var}$ Sea Time (Days)								
Quarter	Eastbound		Westbound		Round Trip		Avg. RT Sea Speed (Knots)	Avg. RT Aux. Prop. (Hours)	Total RT Fuel Consump. (Tons)
	E[T]	$\sqrt{Var}$	E[T]	$\sqrt{Var}$	E[T]	$\sqrt{Var}$			
Dec-Feb	10.03	1.45	14.00	2.28	24.03	2.70	10.75	167	66
Mar-May	11.84	1.73	15.01	1.63	26.85	2.38	9.62	198	76
Jun-Aug	12.87	1.33	15.77	1.61	28.64	2.09	9.02	363	115
Sep-Nov	12.04	1.48	14.87	2.02	26.91	2.50	9.60	219	81
	EQUAL WEIGHT ANNUAL AVG.				26.51	2.42	9.74	233	84
	SUMMER LAYUP ANNUAL AVG.				26.40	2.44	9.79	226	82

NOTES:

Table 10

Voyage Mean Time and Variance

Voyage: Baltimore - Monrovia, Liberia. Nominal Round Trip = 8200 Naut Mile.

Ship: 30000 CDWT. 660 x 834 x 39.5' Draft. Auxiliary: 6 kt on 1000 BHP.

	Mean and $\sqrt{\mathrm{Var}}$ Sea Time (Days)								
Quarter	Eastbound		Westbound		Round Trip		Avg. RT Sea Speed (Knots)	Avg. RT Aux. Prop. (Hours)	Total RT Fuel Consump. (Tons)
	E[T]	$\sqrt{\mathrm{Var}}$	E[T]	$\sqrt{\mathrm{Var}}$	E[T]	$\sqrt{\mathrm{Var}}$			
Dec-Feb	17.32	1.58	17.94	2.03	35.26	2.57	9.69	338	117
Mar-May	17.29	1.56	17.15	1.86	34.44	2.43	9.92	313	110
Jun-Aug	18.99	1.55	16.67	1.80	35.66	2.38	9.58	359	122
Sep-Nov	17.71	1.65	17.69	1.98	35.41	2.58	9.65	357	121
	EQUAL WEIGHT ANNUAL AVG.				35.18	2.49	9.71	341	117
	SUMMER LAYUP ANNUAL AVG.				35.16	2.50	9.72	340	117

NOTES:

Table 11

Voyage Mean Time and Variance

Voyage: Cape Flattery, Washington - Shanghai. Nominal Round Trip = 10500 Naut Mile.

Ship: 30000 CDWT. 660 x 834 x 39.5' Draft. Auxiliary: 6 kt on 1000 BHP.

	Mean and $\sqrt{Var}$ Sea Time (Days)								
	Eastbound		Westbound		Round Trip		Avg. RT Sea Speed (Knots)	Avg. RT Aux. Prop. (Hours)	Total RT Fuel Consump. (Tons)
Quarter	E[T]	$\sqrt{Var}$	E[T]	$\sqrt{Var}$	E[T]	$\sqrt{Var}$			
Dec-Feb	16.98	2.16	21.87	2.77	38.85	3.51	11.26	210	92
Mar-May	19.23	2.25	22.84	2.87	42.07	3.65	10.40	343	125
Jun-Aug	23.79	1.45	27.62	2.43	51.41	2.83	8.51	603	193
Sep-Nov	18.86	1.84	22.73	2.19	41.59	2.86	10.52	338	124
EQUAL WEIGHT ANNUAL AVG.					43.04	3.21	10.16	360	130
SUMMER LAYUP ANNUAL AVG.					42.63	3.24	10.26	348	124

NOTES:

Table 12

Voyage Mean Time and Variance

Voyage: San Francisco - Sydney, Australia. Nominal Round Trip = 12800 Naut Mile.

Ship: 30000 CDWT. 660 x 834 x 395 ft Draft. Auxiliary: 6 kt on 1000 BHP.

	Mean and $\sqrt{Var}$ Sea Time (Days)						Avg. RT Sea Speed (Knots)	Avg. RT Aux. Prop. (Hours)	Total RT Fuel Consump. (Tons)
	Eastbound		Westbound		Round Trip				
Quarter	E[T]	$\sqrt{Var}$	E[T]	$\sqrt{Var}$	E[T]	$\sqrt{Var}$			
Dec-Feb	24.90	2.84	27.65	3.00	52.55	4.13	10.15	480	167
Mar-May	25.15	2.78	26.08	2.99	51.23	4.08	10.41	516	174
Jun-Aug	24.21	2.73	25.36	2.87	49.57	3.96	10.76	417	150
Sep-Nov	25.57	2.80	27.13	2.99	52.70	4.09	10.12	530	178
	ANNUAL AVG.				51.48	4.07	10.36	485	167

NOTES:

Table 13

Voyage Mean Time and Variance

Voyage: New York - Liverpool. Nominal Round Trip = 6200 Naut Mile.

Ship: 15000 CDWT. 525 x 66 x 32 ft Draft. Auxiliary: 6 kt 600 BHP

	Mean and $\sqrt{Var}$ Sea Time (Days)								
	Eastbound		Westbound		Round Trip		Avg. RT Sea Speed (Knots)	Avg. RT Aux. Prop. (Hours)	Total RT Fuel Consump. (Tons)
Quarter	E[T]	$\sqrt{Var}$	E[T]	$\sqrt{Var}$	E[T]	$\sqrt{Var}$			
Dec-Feb	10.32	1.48	15.99	2.52	26.31	2.92	9.82	183	56
Mar-May	12.55	1.78	16.03	1.68	28.58	2.44	9.04	211	62
Jun-Aug	13.07	1.36	16.02	1.63	29.09	2.12	8.88	369	83
Sep-Nov	12.84	1.52	15.86	2.08	28.70	2.58	9.00	234	65
EQUAL WEIGHT ANNUAL AVG.					28.13	2.52	9.18	252	66
SUMMER LAYUP ANNUAL AVG.					28.08	2.54	9.20	241	65

NOTES:

Table 14

Voyage Mean Time and Variance

Voyage: Baltimore - Monrovia, Liberia. Nominal Round Trip = 8200 Naut Mile.
Ship: 15000 CDWT. 525 x 66 x 32' Draft. Auxiliary: 6 kt 600 BHP.

	Mean and $\sqrt{\text{Var}}$ Sea Time (Days)								
	Eastbound		Westbound		Round Trip		Avg. RT Sea Speed (Knots)	Avg. RT Aux. Prop. (Hours)	Total RT Fuel Consump. (Tons)
Quarter	E[T]	$\sqrt{\text{Var}}$	E[T]	$\sqrt{\text{Var}}$	E[T]	$\sqrt{\text{Var}}$			
Dec-Feb	18.60	1.69	19.28	2.09	37.88	2.69	9.02	363	92
Mar-May	18.29	1.65	18.08	1.90	36.37	2.52	9.39	330	86
Jun-Aug	19.57	1.65	17.17	1.84	36.74	2.47	9.30	370	92
Sep-Nov	18.60	1.72	18.58	2.03	37.18	2.66	9.19	375	93
	EQUAL WEIGHT ANNUAL AVG.				37.03	2.59	9.23	359	91
	WINTER LAYUP ANNUAL AVG.				36.99	2.58	9.24	359	91

NOTES:

Table 15

Voyage Mean Time and Variance

Voyage: Cape Flattery, Wash. to Shanghai. Nominal Round Trip = 10500 Naut Mile.

Ship: 15000 CDWT. 525 x 66 x 32' Draft Auxiliary: 6 kt on 600 BHP

	Mean and $\sqrt{Var}$ Sea Time (Days)								
	Eastbound		Westbound		Round Trip		Avg. RT Sea Speed (Knots)	Avg. RT Aux. Prop. (Hours)	Total RT Fuel Consump. (Tons)
Quarter	E[T]	$\sqrt{Var}$	E[T]	$\sqrt{Var}$	E[T]	$\sqrt{Var}$			
Dec-Feb	18.55	2.28	23.97	3.02	42.52	3.78	10.29	230	79
Mar-May	20.70	2.34	24.59	2.97	45.29	3.78	9.66	369	101
Jun-Aug	24.63	1.53	28.59	2.97	53.22	2.93	8.22	624	143
Sep-Nov	20.28	1.94	24.45	2.28	44.73	2.99	9.78	363	99
EQUAL WEIGHT ANNUAL AVG.					46.13	3.37	9.48	386	104
SUMMER LAYUP ANNUAL AVG.					45.77	3.40	9.56	373	102

NOTES:

Table 16

Voyage Mean Time and Variance

Voyage: San Francisco - Sydney, Australia. Nominal Round Trip = 12800 Naut Mile

Ship: 15000 CDWT. 525 x 66 x 32' Draft. Auxiliary: 6 kt on 600 BHP.

	Mean and $\sqrt{Var}$ Sea Time (Days)								
	Eastbound		Westbound		Round Trip		Avg. RT Sea Speed (Knots)	Avg. RT Aux. Prop. (Hours)	Total RT Fuel Consump. (Tons)
Quarter	E[T]	$\sqrt{Var}$	E[T]	$\sqrt{Var}$	E[T]	$\sqrt{Var}$			
Dec-Feb	26.37	3.01	29.30	3.20	55.67	4.39	9.58	508	130
Mar-May	26.45	2.94	27.42	3.18	53.87	4.33	9.90	543	133
Jun-Aug	24.86	2.90	26.03	3.06	50.89	4.22	10.48	428	115
Sep-Nov	26.79	2.96	28.42	3.16	55.21	4.33	9.66	555	136
	ANNUAL AVERAGE				53.85	4.32	9.90	507	128

NOTES:

VII ECONOMIC ANALYSIS

MODES OF ECONOMIC COMPARISON

In comparing two extremely dissimilar types of ships, it is advantageous to revert to the simplest measure of merit, at least in the first approximation. Therefore, it was decided quite early that the economic comparison would be on the basis of required freight rate, before taxes.

There remains the problem of selecting particular conventional ships to serve as measuring sticks for the economic value of the sailing vessel. Clearly, there are a number of reasonable ways to choose the competitive ships, and the choice is critical to the outcome of the comparison.

(1) Comparison on the basis of ships optimized for near unlimited annual cargo. This basis is quite unfavorable for the sailing ship, since it at once places the emphasis on extremely large vessels. Since the size of the sailing vessel is more stringently limited both by considerations of rig design and deeper draft, this type of comparison places the sailing vessel in competition with a much larger steamship, with the result a foregone conclusion.

(2) Comparison on the basis of ships optimized for a given annual transport capacity. Here, the nature of the sailing ship's performance is an obstacle to the comparison, since the expected voyage time fluctuates widely on an annual basis, and is further subject to the vagaries of the random process. A fair comparison could, in fact, be made on this basis, but it is doubtful that the sailing ship would be employed in a constant-throughput service. On the basis of the straight average performance, neglecting the economic costs of variance, it is perhaps possible for the sailing ship to show to advantage, however, a complete analysis would have to include penalties for deviations from schedule, deviations which a sailing ship is ill-equipped to avoid.

(3) Comparison on the basis of equal deadweight. This form of comparison yields results which are as favorable to the

sailing ship as any that can be reasonably devised. In fact, it might be argued that this comparison is slightly biased in favor of the sailing vessel, since the steamer would presumably be of much shallower draft than the sailing ship, and thereby a more versatile cargo carrier.

However, comparison according to scheme (3) has the added advantage of presenting two ships that are roughly comparable in initial costs and operating costs (other than fuel). Particulars of three competitive steamers, chosen under criterion (3), are given in Table 17. Although we did not attempt to optimize these designs, they are believed to be near optima for the specified payloads, this belief being based on work (unpublished) done by other University of Michigan research groups.

BUILDING COSTS

The estimates of construction costs for the three sailing vessels are included in Appendix III (bound separately).

In general, the estimates show construction costs in the neighborhood of 10% higher than the comparable deadweight steamer, largely due to the increased volumetric requirements of ballast tanks, resulting in a larger ship for the deadweight. Further, the relative fineness of the sailing ship, together with a somewhat higher length/beam ratio, tend to increase construction costs.

The only substantial disagreement with the R.A. Stearn report involves the cost of sails, which, at this point, is virtually anyone's guess, since sails of this type and size have never been lofted. The Stearn estimate is based on $\$4/ft^2$, chosen from estimates supplied by sailmakers, ranging from a low of $\$3/ft^2$ to as high as \$6. We tend to favor the low estimate, although with series production of sails it could conceivably be slightly lower, say $\$2.50/ft^2$. The effect of this uncertainty on the initial cost of the ship is slight, but its effect on annual maintenance and repair costs may be decisive, as will be seen.

Table 17

PARTICULARS OF COMPETITIVE STEAMERS

DWT		15,000	30,000	45,000
LOA	(ft)	525	650	740
LBP (L)		485	600	683
BEAM (B)		80	100	113
DEPTH (D)		40.4	48	54.1
DRAFT$_{FL}$ (T)		26.4	32.7	37.7
FREEBOARD		14	15.3	16.4
L/B		6.063	6.000	6.044
L/T		18.371	18.349	18.117
L/D		12.005	12.500	12.625
B/T		3.030	3.058	3.000
$_{FL}$(ton)		21,400	41,400	60,800
C_B		0.731	0.739	0.731
C_M		0.990	0.990	0.990
C_P		0.738	0.746	0.738
$C \times 10^3$		6.565	6.708	6.679
DWT/ $_{FL}$		0.701	0.725	0.740
CN = LBD/100		15,675	28,800	41,754
V_S (knot)		14	14.5	15
V_S/ L		0.636	0.592	0.574
SHP		8,650	11,500	14,000
COMPLEMENT		24	27	30

Table 18

Economic Analysis and RFR

Voyage: New York - Liverpool

Ship: 45000 CDWT

	Sailing Ship Optimistic	Operating Estimate	Costs Pessimistic	15-KT Steamer
Operating cycle (days/yr)	340	340	340	340
Sea Days/RT	24.59	24.59	24.59	17.22
Port Days/RT	4.00	4.00	4.00	4.00
Total Days/RT	28.59	28.59	28.59	21.22
RT/Year	11.89	11.89	11.89	16.02
Complement	24	30	36	30
Total Fuel/RT (tons)	85	85	85	1312
Invested Cost ($1000)	24397	24397	24397	22262
Annual Costs ($1000)				
Wages & Subsistence	438	548	657	548
Maintenance & Repair	261	351	441	185
Insurance	214	230	246	195
Port Expenses	37	37	37	50
Overhead & Misc.	150	150	150	150
Subtotal AOC ($1000)	1100	1316	1531	1128
Fuel ($1000)	93	93	93	1543
Annual Operating Cost	1193	1409	1624	2671
Annual Capital Cost	3269	3269	3269	2983
Average Annual Cost	4462	4678	4893	5654
Annual Transport (tons)	535000	535000	535000	707800
Required Freight Rate($/ton)	8.34	8.74	9.15	7.99

Table 19

Economic Analysis and RFR

Voyage: Baltimore - Monrovia

Ship: 45000 CDWT

	Sailing Ship Optimistic	Operating Estimate	Costs Pessimistic	Steamer
Operating cycle (days/yr)	340	340	340	340
Sea Days/RT	33.47	33.47	33.47	22.78
Port Days/RT	4.00	4.00	4.00	4.00
Total Days/RT	37.47	37.47	37.47	26.78
RT/Year	9.07	9.07	9.07	12.70
Complement	24	30	36	30
Total Fuel/RT (tons)	127	127	127	1729
Invested Cost ($1000)	24397	24397	24397	22262
Annual Costs ($1000)				
Wages & Subsistence	438	548	657	548
Maintenance & Repair	261	351	441	185
Insurance	214	230	246	195
Port Expenses	28	28	28	40
Overhead & Misc.	150	150	150	150
Subtotal AOC ($1000)	1091	1307	1522	1118
Fuel ($1000)	106	106	106	1612
Annual Operating Cost	1197	1413	1628	2730
Annual Capital Cost	3269	3269	3269	2983
Average Annual Cost	4466	4682	4897	5713
Annual Transport (tons)	408200	408200	408200	557800
Required Freight Rate($/ton)	10.94	11.47	12.00	10.24

Table 20

Economic Analysis and RFR

Voyage: Cape Flattery, Wash. - Shanghai

Ship: 45000 CDWT

	Sailing Ship Optimistic	Operating Estimate	Costs Pessimistic	Steamer
Operating cycle (dyas/yr)	340	340	340	340
Sea Days/RT	39.82	39.82	39.82	29.17
Port Days/RT	4.00	4.00	4.00	4.00
Total Days/RT	43.82	43.82	43.82	33.17
RT/Year	7.76	7.76	7.76	10.25
Complement	24	30	36	30
Total Fuel/RT(tons)	134	134	134	2208
Invested Cost ($1000)	24397	24397	24397	22262
Annual Costs ($1000)				
Wages & Subsistence	438	548	657	548
Maintenance & Repair	261	351	441	185
Insurance	214	230	246	195
Port Expenses	24	24	24	32
Overhead & misc.	150	150	150	150
Subtotal AOC ($1000)	1087	1303	1518	1110
Fuel ($1000)	95	95	95	1661
Annual Operating Cost	1182	1398	1613	2771
Annual Capital Cost	3269	3269	3269	2983
Average Annual Cost	4451	4667	4882	5754
Annual Transport (tons)	349200	349200	349200	447100
Required Freight Rate($/ton)	12.75	13.36	13.98	12.87

Table 21

Economic Analysis and RFR

Voyage: San Francisco - Sydney, Australia

Ship: 45000 CDWT

	Sailing Ship Optimistic	Operating Estimate	Costs Pessimistic	Steamer
Operating cycle (days/yr)	340	340	340	340
Sea Days/RT	49.11	49.11	49.11	35.56
Port Days/RT	4.00	4.00	4.00	4.00
Total Days/RT	53.11	53.11	53.11	39.56
RT/Year	6.40	6.40	6.40	8.59
Complement	24	30	36	30
Total Fuel/RT (tons)	181	181	181	2687
Invested Cost ($1000)	24397	24397	24397	22262
Annual Costs ($1000)				
Wages & Subsistence	438	548	657	548
Maintenance & Repair	261	351	441	185
Insurance	214	230	246	195
Port Expenses	20	20	20	27
Overhead & Misc.	150	150	150	150
Subtotal AOC ($1000)	1083	1299	1514	1105
Fuel ($1000)	106	106	106	1694
Annual Operating Cost	1189	1405	1620	2799
Annual Capital Cost	3269	3269	3269	2983
Average Annual Cost	4458	4674	4889	5782
Annual Transport (tons)	288000	288000	288000	372100
Required Freight Rate ($/ton)	15.48	16.23	16.98	15.54

Table 22

Economic Analysis and RFR

Voyage: New York - Liverpool

Ship: 30000 CDWT

	Sailing Ship Optimistic	Operating Estimate	Costs Pessimistic	14½KT Steamer
Operating cycle (days/yr)	340	340	340	340
Sea Days/RT	26.40	26.40	26.40	17.82
Port Days/RT	3.33	3.33	3.33	3.33
Total Days/RT	29.73	29.73	29.73	21.15
RT/Year	11.44	11.44	11.44	16.08
Complement	24	28	32	27
Total Fuel/RT (tons)	82	82	82	1138
Invested Cost ($1000)	18286	18286	18286	16720
Annual Costs ($1000)				
Wages & Subsistence	438	511	584	493
Maintenance & Repair	200	270	340	149
Insurance	161	173	185	147
Port Expenses	32	32	32	45
Overhead & Misc.	100	100	100	100
Subtotal AOC ($1000)	931	1086	1241	934
Fuel ($1000)	86	86	86	1343
Annual Operating Cost	1017	1172	1327	2277
Annual Capital Cost	2450	2450	2450	2240
Average Annual Cost	3467	3622	3777	4517
Annual Transport (tons)	343200	343200	343200	471000
Required Freight Rate ($/ton)	10.10	10.55	11.00	9.59

Table 23

Economic Analysis and RFR

Voyage: Baltimore - Monrovia

Ship: 30000 CDWT

	Sailing Ship Optimistic	Operating Estimate	Costs Pessimistic	Steamer
Operating cycle (days/yr)	340	340	340	340
Sea Days/RT	35.16	35.16	35.16	23.56
Port Days/RT	3.33	3.33	3.33	3.33
Total Days/RT	38.49	38.49	38.49	26.89
RT/Year	8.83	8.83	8.83	12.64
Complement	24	28	32	27
Total Fuel/RT (tons)	117	117	117	1499
Invested Cost ($1000)	18286	18286	18286	16720
Annual Costs ($1000)				
Wages & Subsistence	438	511	584	493
Maintenance & Repair	200	270	340	149
Insurance	161	173	185	147
Port Expenses	25	25	25	35
Overhead & Misc.	100	100	100	100
Subtotal AOC($1000)	924	1079	1234	924
Fuel ($1000)	95	95	95	1391
Annual Operating Cost	1019	1174	1329	2315
Annual Capital Cost	2450	2450	2450	2240
Average Annual Cost	3469	3624	3779	4555
Annual Transport (tons)	264900	264900	264900	367400
Required Freight Rate ($/ton)	13.10	13.68	14.27	12.40

Table 24

Economic Analysis and RFR

Voyage: Cape Flattery - Shanghai

Ship: 30000 CDWT

	Sailing Ship Optimistic	Operating Estimate	Costs Pessimistic	Steamer
Operating cycle (days/yr)	340	340	340	340
Sea Days/RT	42.63	42.63	42.63	30.17
Port Days/RT	3.33	3.33	3.33	3.33
Total Days/RT	45.96	45.96	45.96	33.50
RT/Year	7.40	7.40	7.40	10.15
Complement	24	28	32	27
Total Fuel/RT (tons)	124	124	124	1913
Invested Cost ($1000)	18286	18286	18286	16720
Annual Costs ($1000)				
Wages & Subsistence	438	511	584	493
Maintenance & Repair	200	270	340	149
Insurance	161	173	185	147
Port Expenses	21	21	21	28
Overhead & Misc.	100	100	100	100
Subtotal AOC ($1000)	920	1075	1230	917
Fuel ($1000)	84	84	84	1425
Annual Operating Cost	1004	1159	1314	2342
Annual Capital Cost	2450	2450	2450	2240
Average Annual Cost	3454	3609	3764	4582
Annual Transport (tons)	222000	222000	222000	292400
Required Freight Rate ($/ton)	15.56	16.26	16.95	15.67

Table 25

Economic Analysis and RFR

Voyage: San Francisco - Sydney

Ship: 30000 CDWT

	Sailing Ship Optimistic	Operating Estimate	Costs Pessimistic	Steamer
Operating cycle (days/yr)	340	340	340	340
Sea Days/RT	51.48	51.48	51.48	36.78
Port Days/RT	3.33	3.33	3.33	3.33
Total Days/RT	54.81	54.81	54.81	40.11
RT/Year	6.20	6.20	6.20	8.47
Complement	24	26	32	27
Total Fuel/RT (tons)	167	167	167	2332
Invested Cost ($1000)	18286	18286	18286	16720
Annual Costs ($1000)				
Wages & Subsistence	438	511	584	493
Maintenance & Repair	200	270	340	149
Insurance	161	173	185	147
Port Expenses	17	17	17	24
Overhead & Misc.	100	100	100	100
Subtotal AOC ($1000)	916	1074	1226	913
Fuel ($1000)	95	95	95	1450
Annual Operating Cost	1011	1166	1321	2363
Annual Capital Cost	2450	2450	2450	2240
Average Annual Cost	3461	3616	3771	4603
Annual Transport (tons)	186000	186000	186000	241800
Required Freight Rate ($/ton)	18.61	19.44	20.27	19.04

Table 26

Economic Analysis and RFR

Voyage: New York - Liverpool

Ship: 15000 CDWT

	Sailing Ship Optimistic	Operating Estimate	Costs Pessimistic	Steamer
Operating Cycle (days/yr)	340	340	340	340
Sea Days/RT	28.08	28.08	28.08	18.45
Port Days/RT	2.67	2.67	2.67	2.67
Total Days/RT	30.75	30.75	30.75	21.12
RT/Year	11.06	11.06	11.06	16.10
Complement	24	26	28	24
Total Fuel/RT (tons)	65	65	65	822
Invested Cost ($1000)	11656	11656	11656	10620
Annual Costs ($1000)				
Wages & Subsistence	438	475	511	438
Maintenance & Repair	128	172	216	103
Insurance	103	110	118	94
Port Expenses	27	27	27	40
Overhead & Misc.	50	50	50	50
Subtotal AOC ($1000)	746	834	922	725
Fuel ($1000)	66	66	66	971
Annual Operating Cost	812	900	988	1696
Annual Capital Cost	1562	1562	1562	1423
Average Annual Cost	2374	2462	2550	3119
Annual Transport (tons)	165900	165900	165900	233200
Required Freight Rate ($/ton)	14.31	14.84	15.37	13.37

Table 27

Economic Analysis and RFR

Voyage: Baltimore - Monrovia

Ship: 15000 CDWT

	Sailing Ship Optimistic	Operating Estimate	Costs Pessimistic	Steamer
Operating Cycle (days/yr)	340	340	340	340
Sea Days/RT	36.99	36.99	36.99	24.40
Port Days/RT	2.67	2.67	2.67	2.67
Total Days/RT	39.66	39.66	39.66	27.07
RT/Year	8.57	8.57	8.57	12.56
Complement	24	26	28	24
Total Fuel/RT (tons)	91	91	91	1084
Invested Cost ($1000)	11565	11656	11656	10620
Annual Costs ($1000)				
Wages & Subsistence	438	475	511	438
Maintenance & Repair	128	172	216	103
Insurance	103	110	118	94
Port Expenses	22	22	22	31
Overhead & Misc.	50	50	50	50
Subtotal AOC ($1000)	731	829	917	716
Fuel ($1000)	71	71	71	999
Annual Operating Cost	802	900	988	1715
Annual Capital Cost	1562	1562	1562	1423
Average Annual Cost	2364	2462	2550	3138
Annual Transport (tons)	128600	128600	128600	179900
Required Freight Rate ($/ton)	18.38	19.14	19.83	17.44

Table 28

Economic Analysis and RFR

Voyage: Cape Flattery - Shanghai

Ship: 1500 CDWT

	Sailing Ship Optimistic	Operating Estimate	Costs Pessimistic	Steamer
Operating Cycle (days/yr)	340	340	340	340
Sea Days/RT	45.77	45.77	45.77	31.25
Port Days/RT	2.67	2.67	2.67	2.67
Total Days/RT	48.44	48.44	48.44	33.92
RT/Year	7.02	7.02	7.02	10.02
Complement	24	26	28	24
Total Fuel/RT (tons)	102	102	102	1416
Invested Cost ($1000)	11656	11656	11656	10620
Annual Costs ($1000)				
Wages & Subsistence	438	475	511	438
Maintenance & Repair	128	172	216	103
Insurance	103	110	118	94
Port Expenses	17	17	17	25
Overhead & Misc.	50	50	50	50
Subtotal AOC ($1000)	736	824	912	710
Fuel ($1000)	66	66	66	1041
Annual Operating Cost	802	890	978	1751
Annual Capital Cost	1562	1562	1562	1423
Average Annual Cost	2364	2452	2540	3174
Annual Transport (tons)	105300	105300	105300	141400
Required Freight Rate ($/ton)	22.45	23.29	24.12	22.45

Table 29

Economic Analysis and RFR

Voyage: San Francisco - Sydney

Ship: 15000 CDWT.

	Sailing Ship Optimistic	Operating Estimate	Costs Pessimistic	Steamer
Operating Cycle (Days/yr)	340	340	340	340
Sea Days/RT	53.85	53.85	53.85	38.10
Port Days/RT	2.67	2.67	2.67	2.67
Total Days/RT	56.52	56.52	56.52	40.77
RT/Year	6.02	6.02	6.02	8.34
Complement	24	26	28	24
Total Fuel/RT(tons)	128	128	128	1725
Invested Cost ($1000)	11656	11656	11656	10620
Annual Costs ($1000)				
Wages & Subsistence	438	475	511	438
Maintenance & Repair	128	172	216	103
Insurance	103	110	118	94
Port Expenses	15	15	15	21
Overhead & Misc.	50	50	50	50
Subtotal AOC($1000)	734	822	910	706
Fuel ($1000)	71	71	71	1056
Annual Operating Cost	805	893	981	1762
Annual Capital Cost	1562	1562	1562	1423
Average Annual Cost	2367	2456	2543	3185
Annual Transport (tons)	90300	90300	90300	116100
Required Freight Rate ($/ton)	26.21	27.19	28.16	27.43

CAPITAL RECOVERY

For all ships, an interest rate of 12% has been assumed over a life of 20 years, resulting in a capital recovery factor of 0.134. The assumption is implicit that the sailing ships will be able to secure financing at the same interest rate as the steamers.

OPERATING COSTS

The assumptions outlined in following paragraphs have been made to provide starting points for the economic analysis. While the costs are in some cases the result of oversimplified expressions, they are generally in line with recent values (4, 5). In computing the operating costs of the ship, some of the numbers could only be roughly estimated. In these cases optimistic, best estimate, and pessimistic values are presented. In the final economic analysis all three different values are considered.

Wages: An average of \$17,000 per man is assumed for all ships, and on all routes. Possibly, this results in a distortion favorable to the sailing ship, at least in its early stages of development, since the gear on board will be largely experimental, and therefore requiring more highly paid hands. Also, it is possible that the sailing ship, spending longer periods at sea and encountering (deliberately) more severe weather, might be compelled to pay on a higher scale.

Subsistence: A figure of \$1080/man·year is assumed, for all ships.

Maintenance and Repair: For the conventional ships, annual M & R costs were computed on the following basis:

$$\text{Hull M \& R} = \$12500\ (\text{CN}/1000)^{2/3}$$

$$\text{Machinery M \& R} = \$\ 6000\ (\text{SHP}/1000)^{2/3}$$

For the sailing vessels, the following cost breakdown was employed:

Hull M & R = $\$12500\ (CN/1000)^{2/3}$
Machinery M & R = \$ 6000, flat
Rig M & R = \$0.50 × SA (Sail Area, ft^2) (optimistic)
= \$1.00 × SA (best estimate)
= \$1.50 × SA (pessimistic)

The life expectancy of sails is considered to be 4 years, so the figures quoted correspond to \$2, \$4, and \$6 per square foot, respectively, including maintenance costs on masts, yards and sail handling equipment.

Insurance: Total annual insurance costs for the conventional ships was figured at 0.88% of the investment. Optimistically, insurance for the sailing ship was figured at the same rate, while the intermediate and pessimistic values included surcharges of 7½% and 15% of the annual cost, respectively.

Port Expenses: Total port expenses, including per diem expenses for an average port time of 2+(DWT/22,500) days per round trip were approximated by the following:

$$\text{Port expenses per round trip} = \$2160 + \$21.40\left(\frac{DWT}{1000}\right)$$

Overhead: Overhead and miscellaneous costs were arbitrarily set at \$3.33 x DWT.

Fuel: Bunker fuel price was placed at \$11.25/barrel, with diesel fuel at \$14.06/barrel.

In performing the economic comparison, it was assumed that no costs were incurred by failures to hold to a schedule. In any real application, it is almost certain that some extra cost would attach itself to delays, either directly or indirectly, as in the form of additional inventory space required to deal with the slack or surplus created by irregular arrivals and departures.

The economic results are summarized in Table 1, and itemized for each particular route, and for each of the three study ships, in Tables 18-29 optimistic, pessimistic, and best estimated operating costs are tabulated, based on the cost approximations given above, and compared with the selected steamship's performance.

Sensitivities of the RFR to the variables annual average speed, as defined in Section III, building cost, and fuel price are shown graphically in Figures 7 - 18. In each case, the RFR of the competitive steamer is also graphed for purposes of comparison.

The vertical bars on the sailing ship average speed sensitivity curves indicate the speed results from the computer model discussed previously, and should be considered the best estimated value.

SENSITIVITIES

A few general observations on the nature of the sensitivities displayed in the previous figures should be pointed out.

(1) The sensitivities represent only partial derivatives of RFR with respect to the variables considered. Thus, no higher order coupling of sensitivities (e.g., the effect of fuel price on building costs, wages, etc.) is indicated.

(2) For this reason, the effects of changes in fuel price about the assumed values are nearly linear.

(3) The vertical spacing of the RFR curves for optimistic, best estimate, and pessimistic operating curves are approximately centered on the best estimate values.

(4) The sensitivities of the RFR of the smaller ships are generally greater, due to the lower investment involved.

(5) The smallest ship (15000-ton DWT) appears more favorable *vis-a-vis* its nominal competitor, particularly on the longer voyages. This, however, is a false conclusion, since it merely reflects the inherent unsuitability of the small steamship for the long voyage, and in fact, such a competitive situation is not likely to arise in reality.

(6) The form of the sensitivity curves is quite similar from route to route.

(7) The cross-over points for all sensitivity variables

are well outside anticipated values for the Atlantic routes, while the cross-over points for the Pacific routes lie athwart the steamer RFR, indicating a just marginal economic comparison based on the best estimate operating costs. The exception to this is the 15000-tonner, which, as mentioned in (5) above, is a paper comparison only, reflecting an unsuitability of the small steamer.

(8) Other considerations being equal, long routes favor the sailing ship, as expected intuitively. In fact, however, actual routes with round trip distances exceeding that of the North Pacific route involve both hemispheres, necessitating the crossing of three zones of light variables, namely, the north and south Horse Latitudes, and the equatorial calm. Thus, in reality, much of the advantage accruing to very long voyages is evaporated in the lower average speeds generated in crossing these zones.

(9) The sensitivities to fuel price for all routes show that almost any rollback of fuel price levels results in an overwhelming inferiority for the sailing ship in terms of RFR.

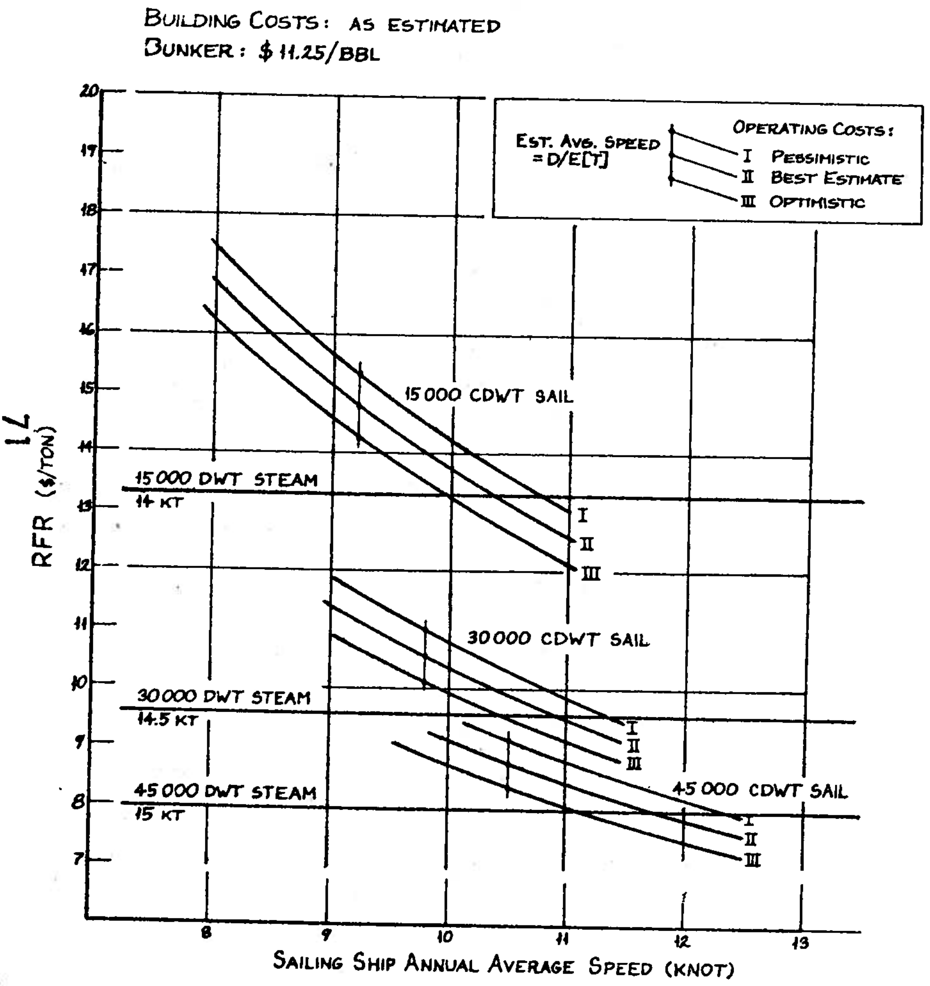


FIGURE 7 Sensitivity of Required Freight Rate to Average Speed -- New York to Liverpool

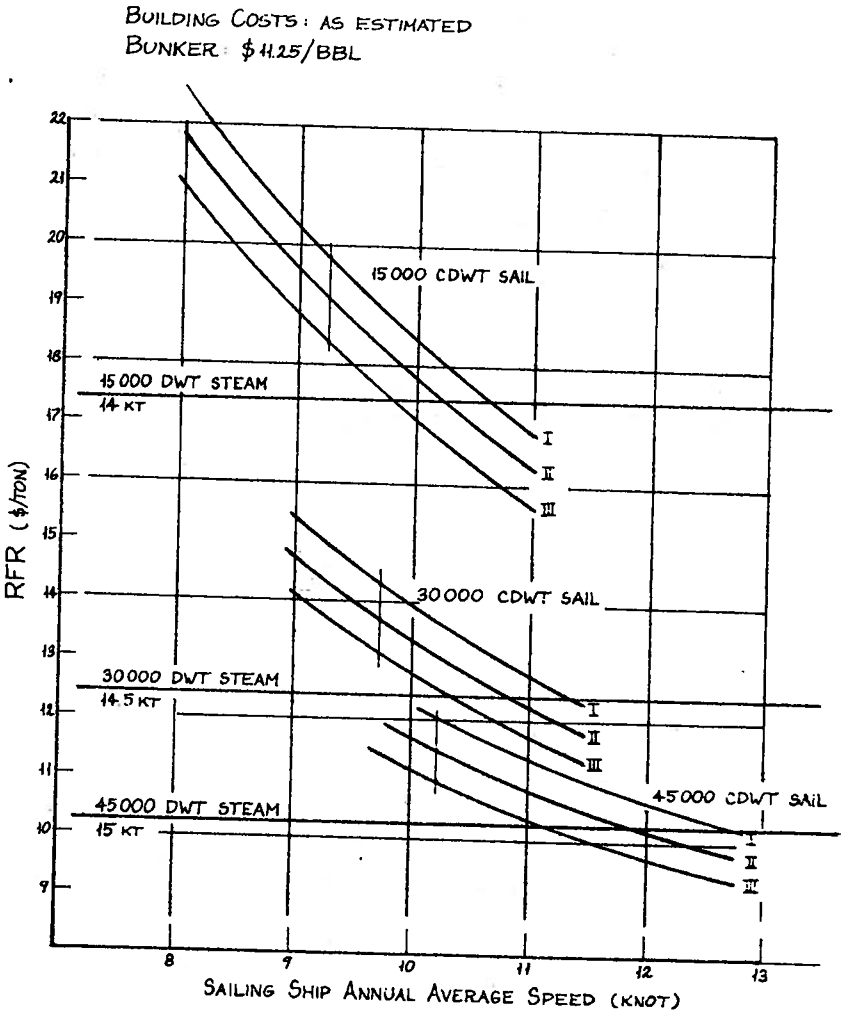


FIGURE 8 Sensitivity of Required Freight Rate to Average Speed -- Baltimore to Monrovia

Building Costs: as estimated
Bunker: $ 11.25/BBL

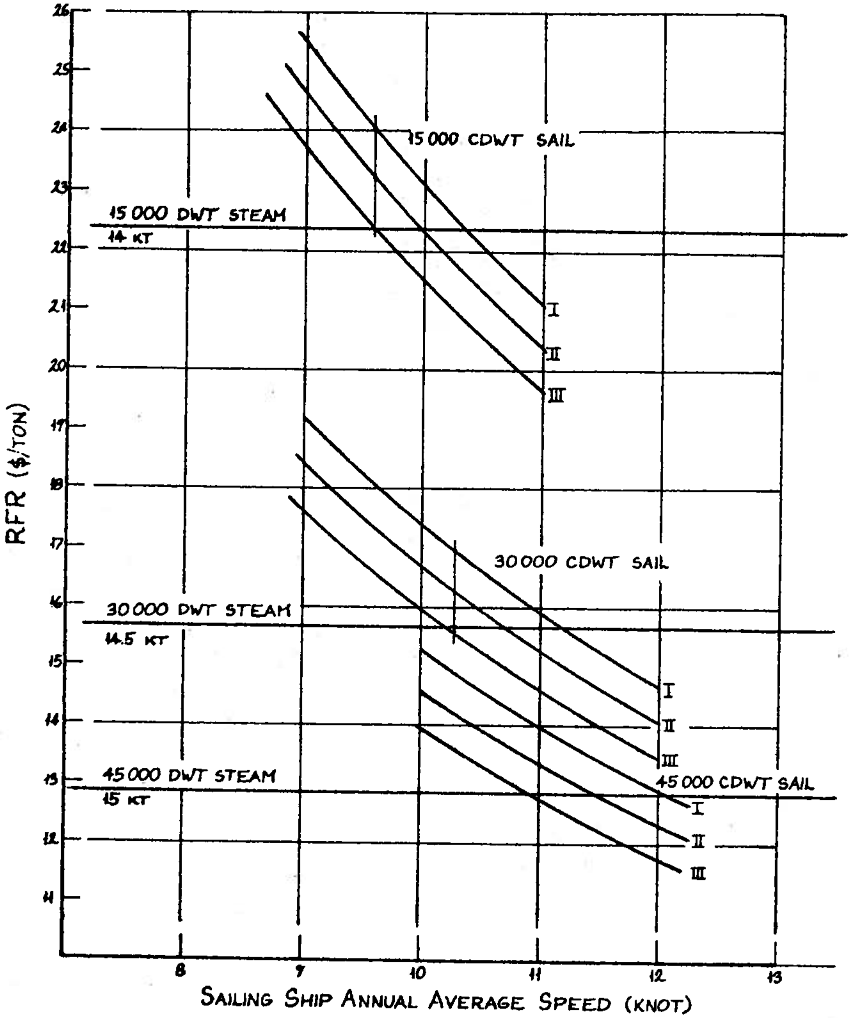


FIGURE 9 Sensitivity of Required Freight Rate to Average Speed -- Cape Flattery to Shanghai

Building Costs: as estimated
Bunker: $ 11.25/BBL

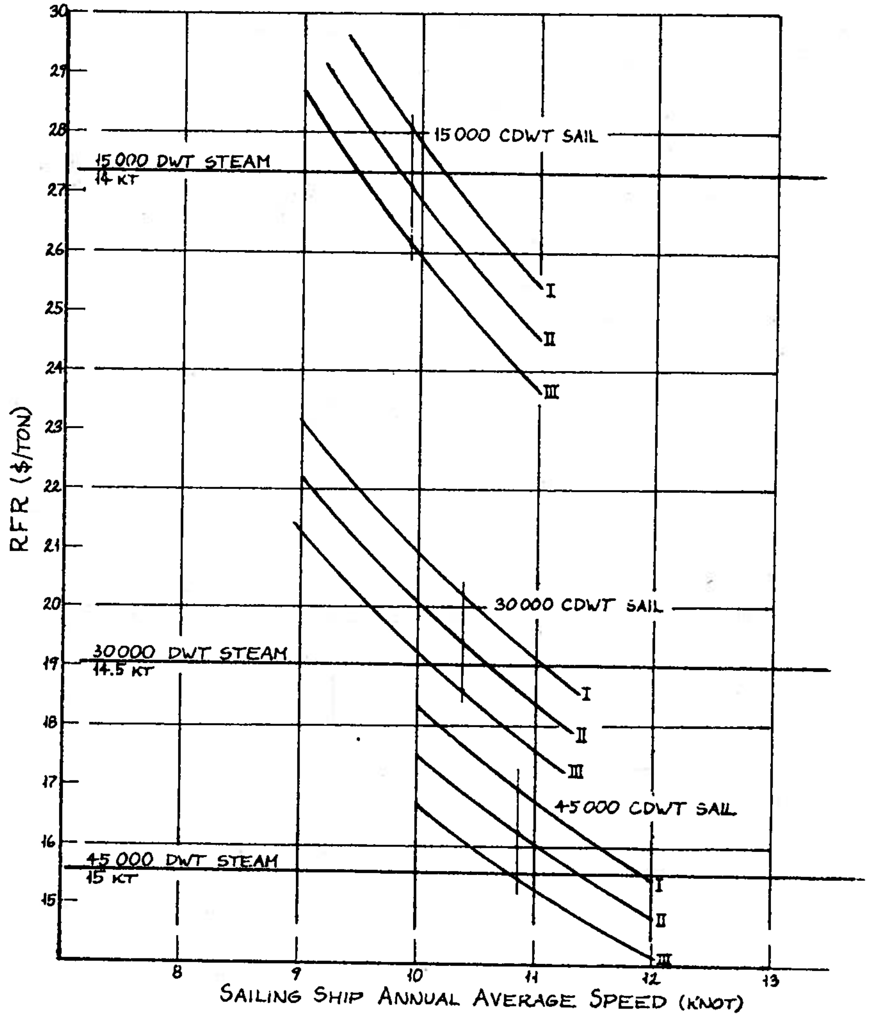


FIGURE 10 Sensitivity of Required Freight Rate to Average Speed -- San Francisco to Sydney

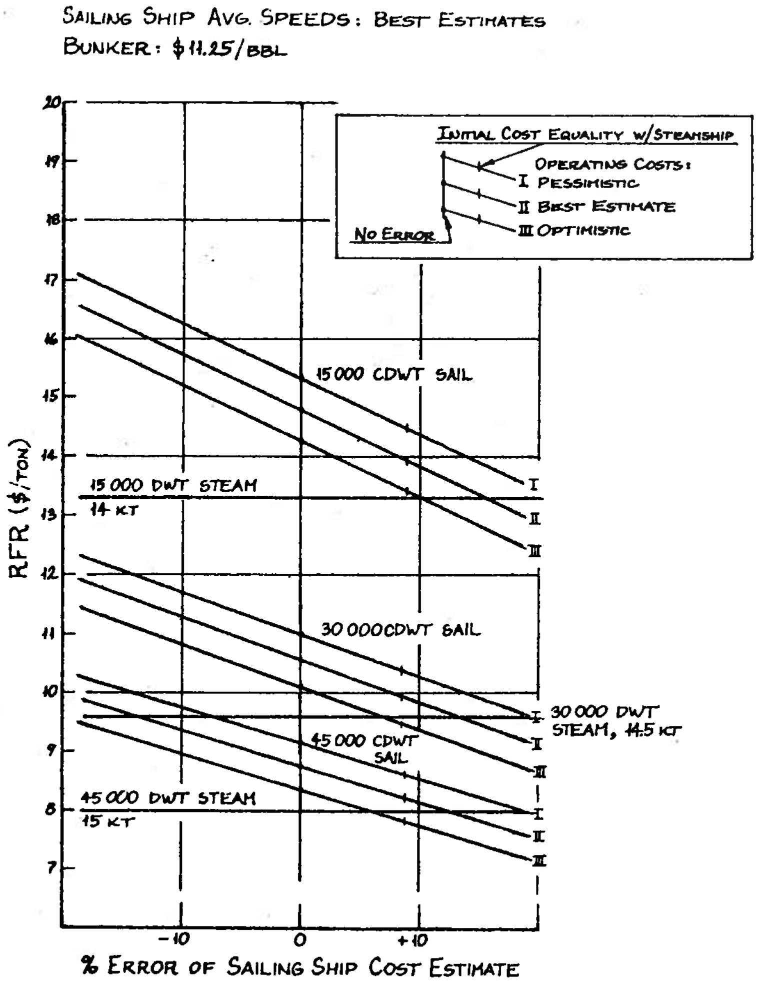


FIGURE 11 Sensitivity of Required Freight Rate to Uncertainty in Building Cost -- New York to Liverpool

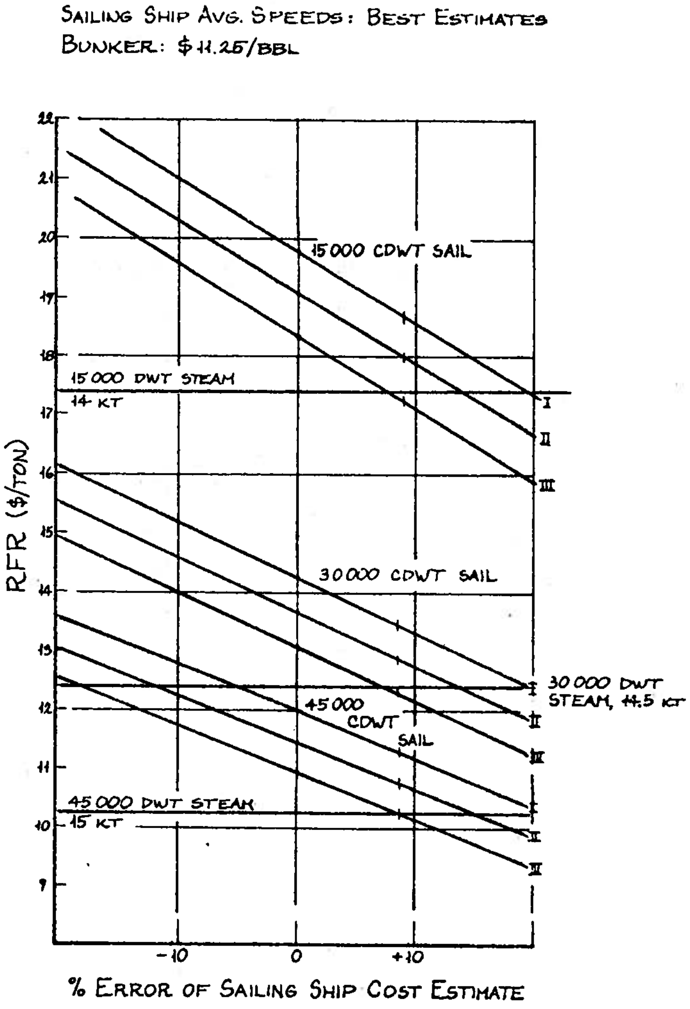


FIGURE 12 Sensitivity of Required Freight Rate to Uncertainty in Building Cost -- Baltimore to Monrovia

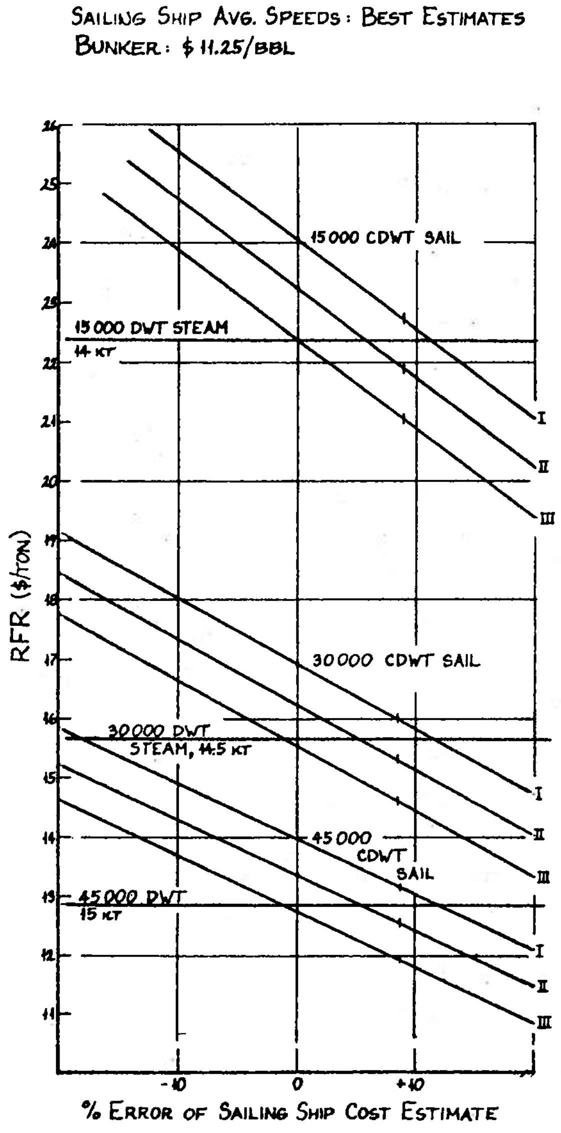


FIGURE 13 Sensitivity of Required Freight Rate to Uncertainty in Building Cost -- Cape Flattery to Shanghai

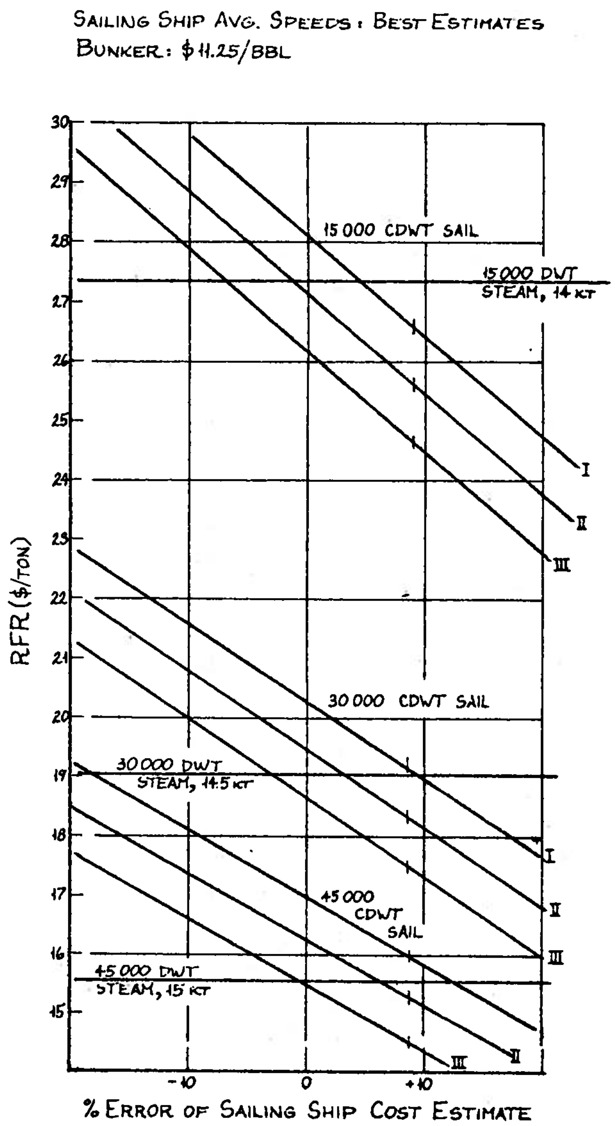


FIGURE 14 Sensitivity of Required Freight Rate to Uncertainty in Building Cost -- San Francisco to Sydney

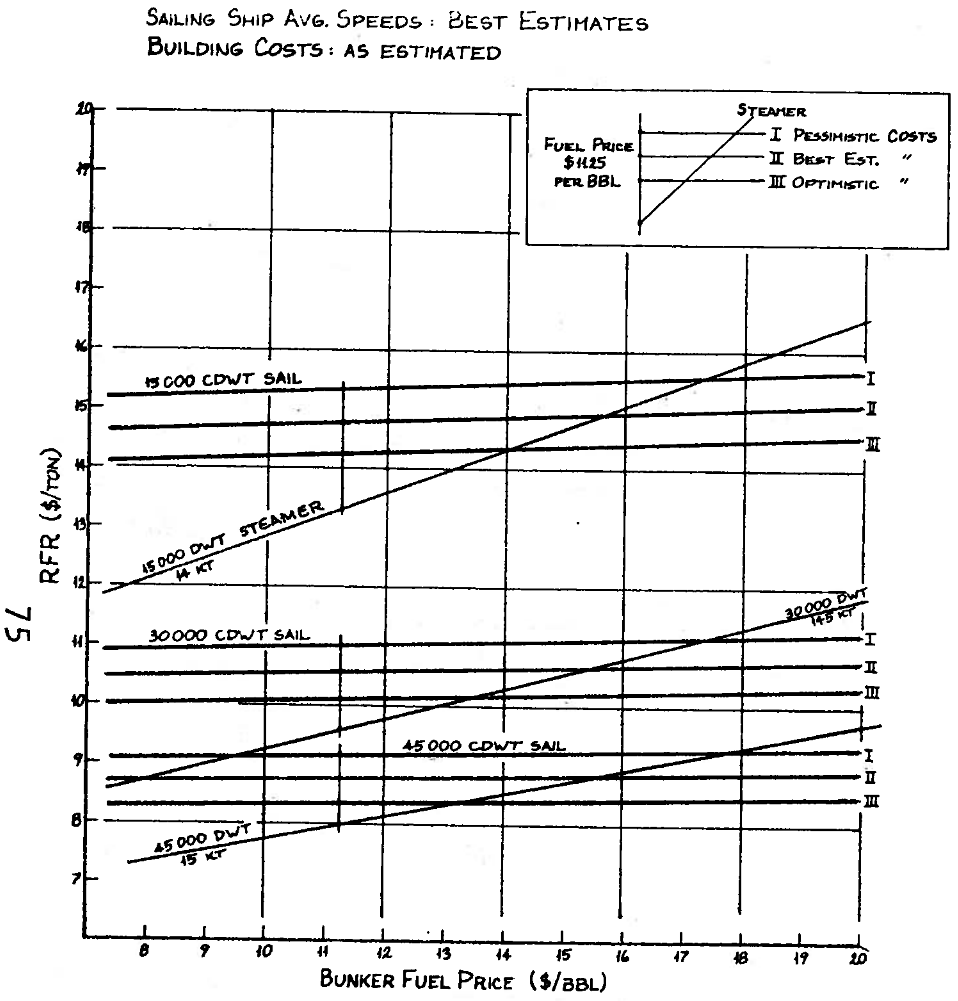


FIGURE 15 Sensitivity of Required Freight Rate to Fuel Price -- New York to Liverpool

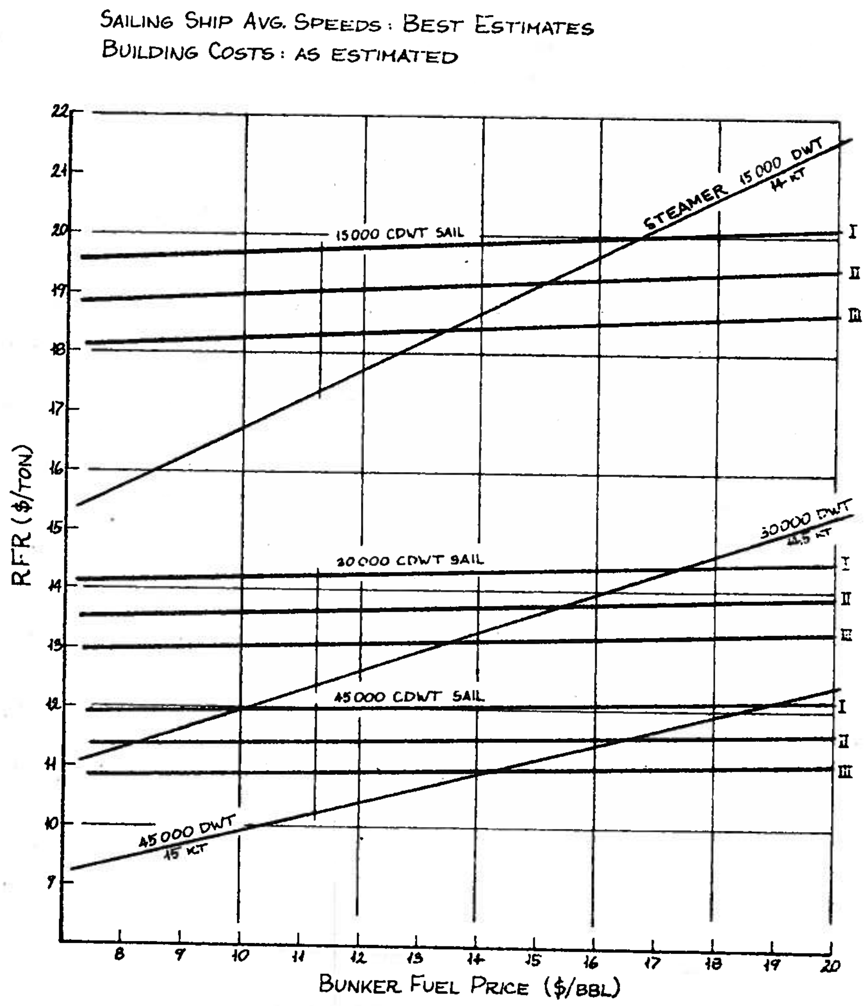


FIGURE 16 Sensitivity of Required Freight Rate to Fuel Price -- Baltimore to Monrovia

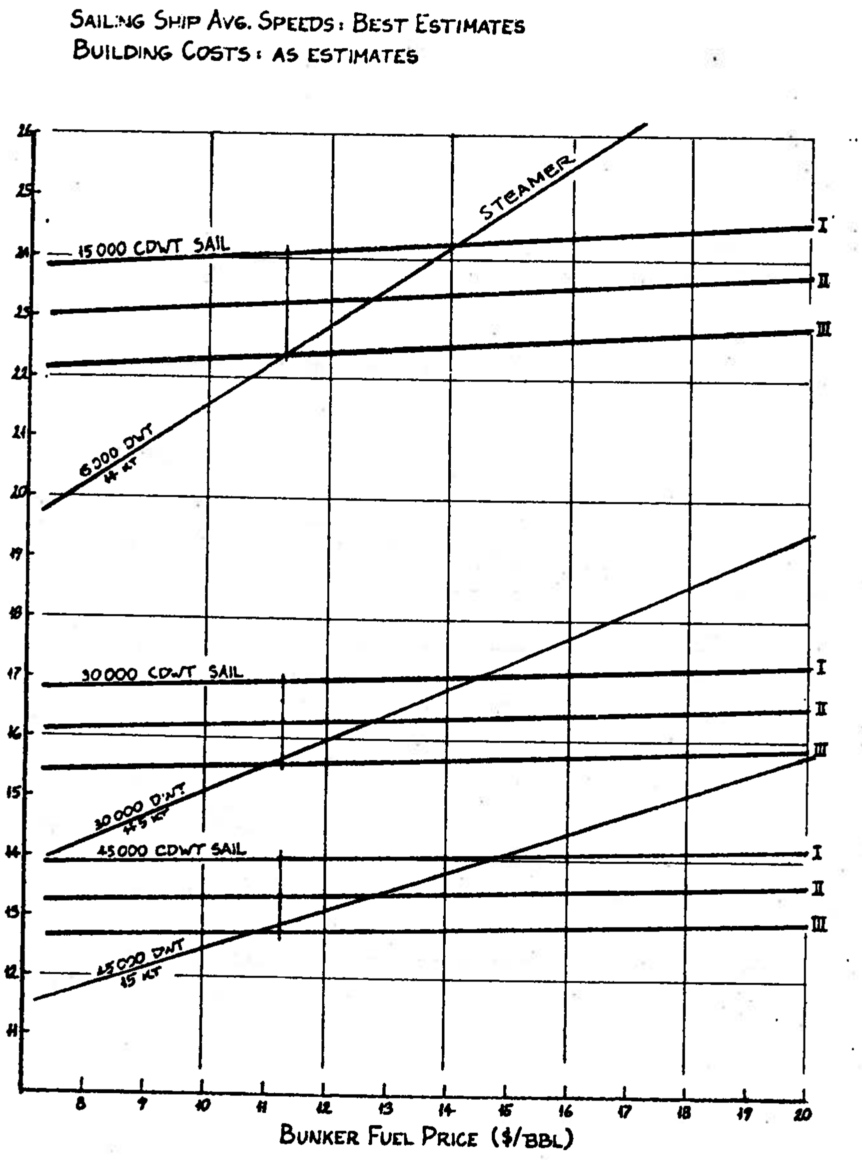


FIGURE 17 Sensitivity of Required Freight Rate to Fuel Price -- Cape Flattery to Shanghai

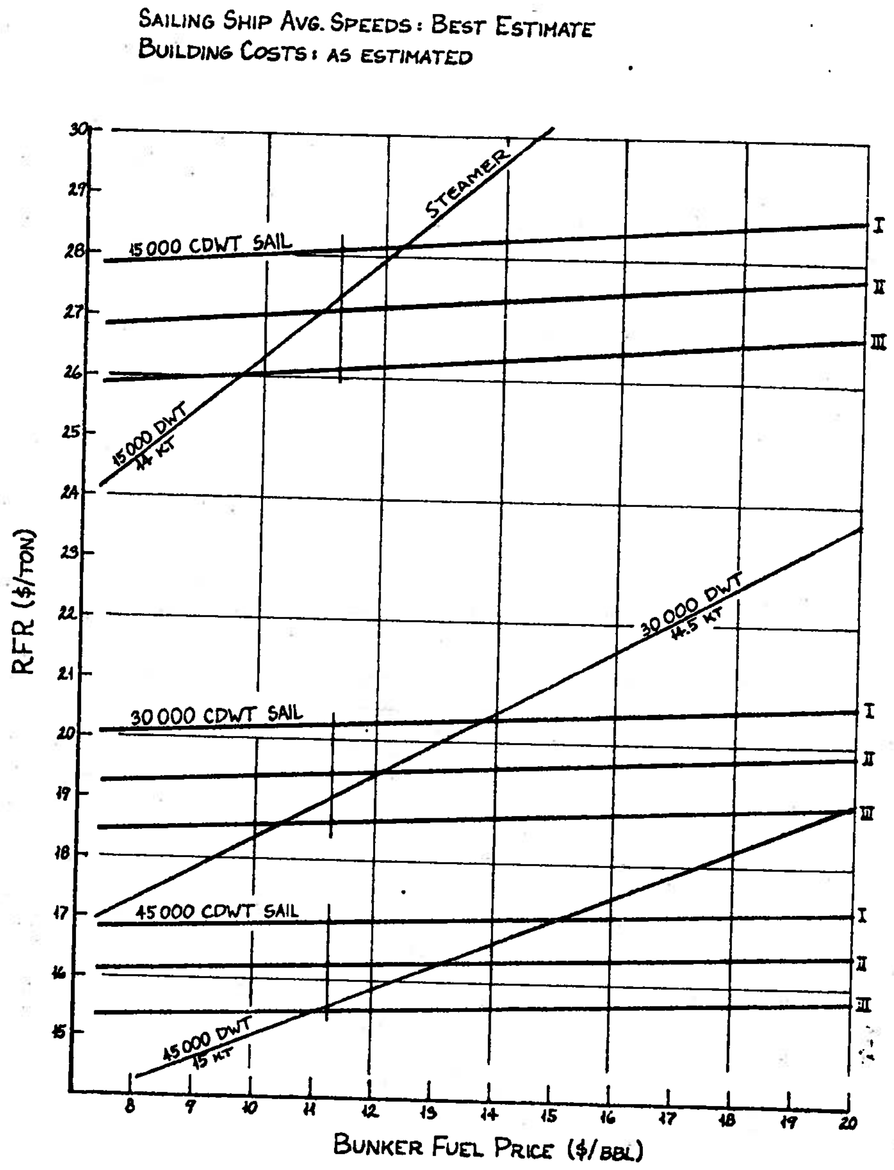


FIGURE 18 Sensitivity of Required Freight Rate to Fuel Price -- San Francisco to Sydney

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APPENDIX I

CALCULATION OF SAILING SHIP PERFORMANCE

In the economic analysis of conventional merchant ships, it is a fairly straightforward matter to find an optimal service speed. Within the limits set by hull form requirements, dimensional restrictions, stability, and available power plants, the designer can select a speed which maximizes some measure of economic merit. Once established, this speed remains sensibly constant over the life of the ship.

By contrast, a sailing vessel has no uniquely defined service speed. The sailing ship's power is not generated aboard, but derived from a velocity field whose instantaneous magnitude and direction at a given point are random variables. The joint probability density function of these two variables changes both with position and time of year. Furthermore, the efficiency with which the sailing ship transforms wind forces into thrust depends on the wind speed and direction, relative to the ship's heading.

For these reasons, a sailing ship's "service" speed can have only a statistical definition, with different values for each route, sailing track, and time of year. This fact is the underlying problem in any analysis of sailing-ship economics.

In particular, the problem can be stated as follows: for a given sailing vessel, operating on one certain route over the entire year, find the expected value of the voyage time, and thus the number of voyages per year. If a definition of operating speed is required, it can be defined as some nominal round trip distance divided by the expected value of voyage time.

A second facet of the sailing ship problem also arises from the random nature of its propulsion. Since the total time required for a single round trip is a random variable, its distribution will be characterized not only by its mean, E(T), but also by its variance, σ_T^2.

In any real economic application of the sailing vessel, the number of voyages per year is simply related to E(T), but certain economic penalties may also accrue to excessive values of σ_T^2. Thus, in general, the two quantities E(T) and σ_T^2 are related to revenues and costs. In the present economic analysis, no costs of variance are included, so the economic results will depend solely upon E(T).

SIMULATION

Early in the project a full simulation method was considered, incorporating modelling of low-pressure systems, their central motions and circulations, together with some decision-making functions on the part of the "captain". The complexities involved in such a treatment were found to be impractical for this study, and a simplified approach was therefore chosen.

Instead of allowing the sailing ship to alter its route as weather conditions change, the ship's track was prespecified, yielding a so-called one-dimensional model. Under this model, the distance along the track is sufficient to specify the ship's position at any instant of time. For any given origin and destination, different tracks can be specified in order to examine variations in the passage statistics.

Simplified weather data based on the monthly surface wind charts in the U.S. Navy Marine Climatic Atlas of the World (3) was employed in this study. The use of a "full-scale" weather model including pressure systems was rejected, since it is far more complex and of only limited value when combined with the one-dimensional co-ordinate system used to define the track.

A more detailed discussion of the information to be gained by using a full simulation system will be presented in subsequent sections. For the present feasibility study the use of a simplified model to determine the economic performance of the sailing ship is felt to be justified, especially in view of the cost and complexity of the full simulation method. As more sophisticated weather data becomes available a complete simulation could be used to refine and verify the one-dimensional model results.

THE ONE-DIMENSIONAL MODEL

The purpose of the one-dimensional model is to provide a simple computational method for arriving at the mean passage time and variance, E(T) and σ_T^2, for a specified track between two ports and a given time of year. Note that the track length, D, need not be the shortest distance between the two ports, nor will it necessarily correspond to the usual steamer distance.

Basically, the model combines wind data along the track with ship performance curves to determine ship speed along the track, runs the ship along the track over an ensemble of trips, and computes the voyage mean times and variances. To accomplish this, the track is subdivided into sufficiently small intervals, such that within each interval the following conditions are satisfied:

(1) A single joint probability density function is sufficient to define the frequency distribution of the wind speed and direction for all points in the interval.

(2) A single value of the vector mean current is sufficient to take account of the drift experienced by the ship in crossing the interval.

(3) The track may be approximated by a straight line segment within the interval.

With these three conditions satisfied, the one-dimensional model can be applied to the problem of simulating the sailing ship's performance. The details of the required input data and the methods used in the model are discussed below.

CLIMATOLOGICAL DATA

In marine meteorological atlases such as the U.S. Navy Marine Climatic Atlas of the World, (3), synoptic data on wind and current have been compiled in the form of monthly wind rose charts and quarterly current charts showing prevailing or vector-mean current.

The wind rose is a simple graphical representation of the probability density function of the vector wind, or more particularly, a joint probability density function of the two quantities wind direction and speed, the latter normally defined on the

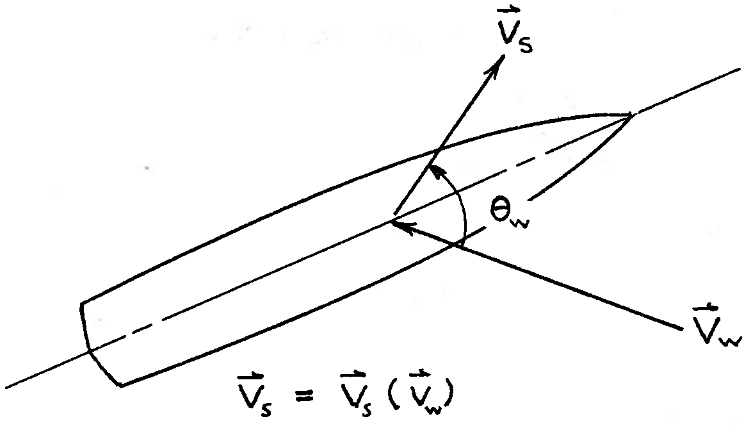
Beaufort scale.

The wind rose necessarily represents the wind data in discrete form, giving probabilities for a finite number of intervals of wind direction and speed. In particular, the wind roses used in this study were 8-point roses, that is, 45° wind-direction intervals, and four speed intervals on each direction point. In addition, the probability of calm is carried by each wind rose, naturally independent of direction. Thus the wind probabilities given by any wind rose can be placed in the form of a 4 x 8 matrix, plus the probability of calm. In the computer program, the probabilities are arranged so that comparison with a random number, uniformly distributed between 0 and 1, yields values of wind direction and speed according to the probabilities given by the wind rose.

The prevailing or vector-mean current is also of considerable importance in the determination of sailing ship performance. No probability matrix is necessary, since the vector-mean current can be simply superimposed on the response of the ship to the wind probability matrix.

SPEED POLAR CURVES

The speed polar is the functional relationship between ship speed, wind speed, and wind angle, illustrated below.

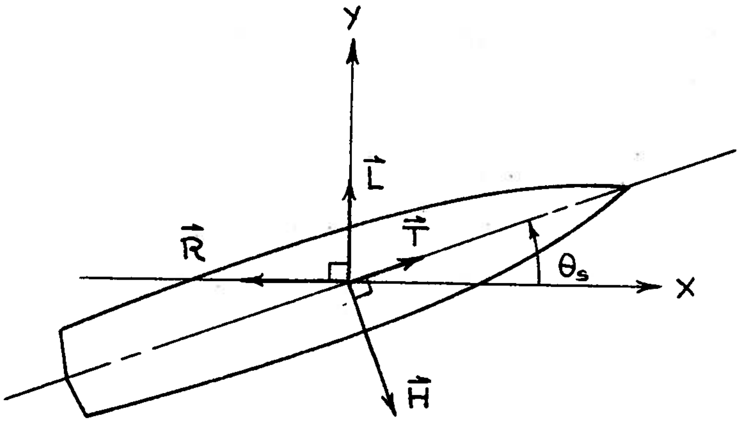


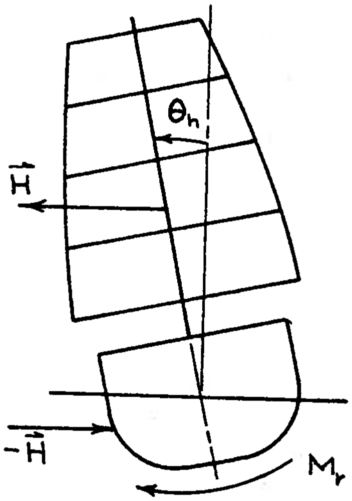
where $\vec{V}_s$ = ship velocity along track

$\vec{V}_w$ = wind velocity

θ_w = angle between true wind and track

The solution technique employed to find the speed polar was to vary two of the four independent variables - V_{ap}, θ_{sp}, V_s, θ_s - until an equilibrium of the forces applied to the sailing ship was attained. The force diagrams are shown below.





where $\vec{L} = \vec{L}\ (V_s,\ \theta_s)$ = hydrodynamic lift of hull

$\vec{R} = \vec{R}\ (V_s,\ \theta_s)$ = hydrodynamic resistance of hull

$\vec{T} = \vec{T}\ (V_{ap},\ \theta_{ap})$ = aerodynamic thrust of sails

$\vec{H} = \vec{H}\ (V_{ap},\ \theta ap)$ = aerodynamic lateral force of sails

V_s = ship speed, knots

θ_s = ship leeway angle

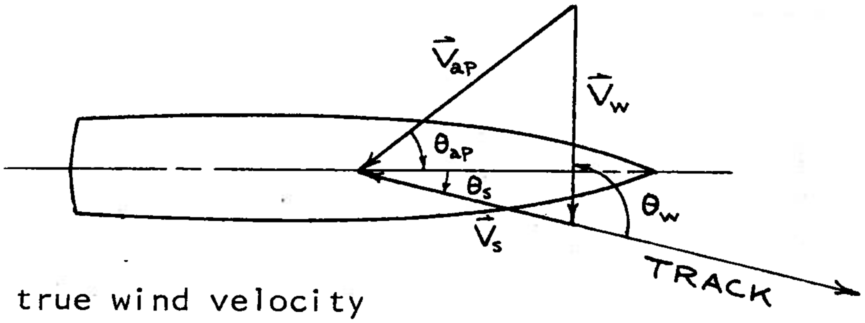
V_{ap} = apparent wind speed, knots

θ_{ap} = apparent wind angle

θ_h = heeling angle

M_r = righting moment

True and apparent wind are related as shown below.



$\vec{V}_w$ = true wind velocity

θ_w = true wind angle

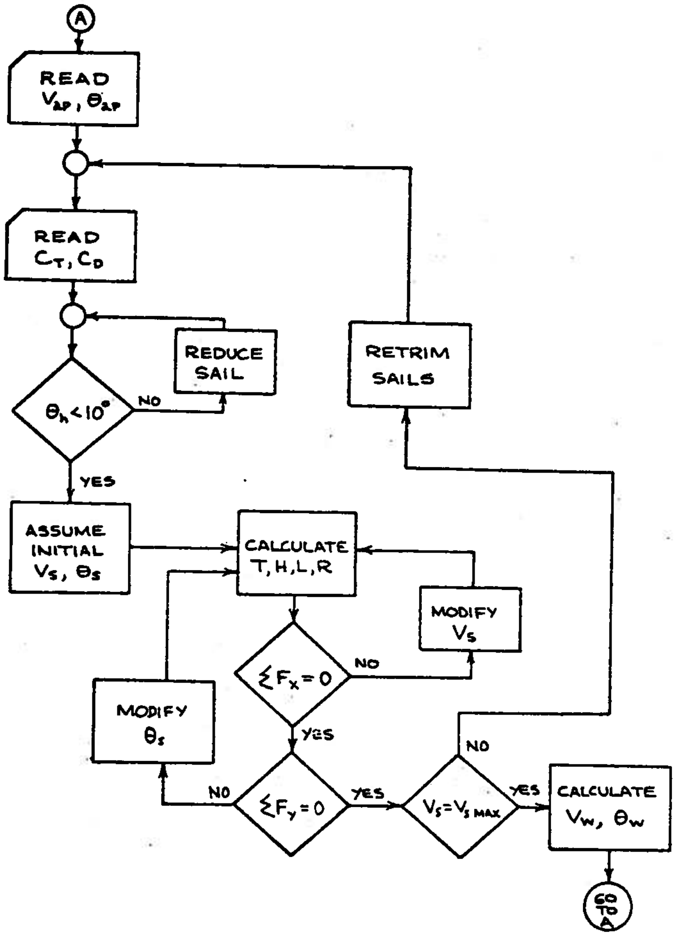
$$V_w^2 = V_{ap}^2 + V_s^2 - 2V_{ap}V_s \cos(\theta_{ap} + \theta_s)$$

$$\theta_w = \text{arc cos } [(V_{ap}^2 - V_w^2 - V_s^2)/2V_sV_w]$$

Since the sail lift and drag data base was derived from wind tunnel tests, it was presented in terms of apparent wind by necessity. The solution to the sailing ship speed polar problem was therefore carried out in terms of apparent wind speed and direction:

$$\vec{V}_s = (V_s, \theta_s) = \vec{V}_s \ [(\vec{V}_w \ (\vec{V}_{ap}, \vec{V}_s)]$$

A simplified flow chart of the solution process is given below:



Numerical values of θ_{ap} ranged from 30° to 180° in steps of 10° to 100°, and in steps of 20° thereafter. V_{ap} varied from 0 to approximately 60 knots in steps of 2 knots. Therefore, about 360 solutions were determined for each sailing ship, enabling precise interpolation for the specific wind speeds called for by the wind rose data.

The sail force coefficients, C_T and C_H, are plotted in Figure 19. The initial values of C_T and C_H, chosen in all iterations on apparent wind speed and direction were those furthest from the origin. Subsequent values, prior to determination of maximum V_S, represent improvements in lift-drag ratios.

The heeling angle was limited to 10° or less, using the minimum full load GM, by a proportionate reduction of sail force coefficients. It would be realistic to reduce the heeling arm at the same time, since upper sails would be struck first, but this was not done, resulting in a small measure of conservatism.

The calculation of hydrodynamic forces on the hull is repeated many times until forces balance both along and perpendicular to the track. Hull resistance is the sum of calm water resistance without leeway, induced drag due to leeway, and added resistance due to waves. The first part was estimated from Series 60 test data, the results of which are presented in Figure 20 which is augmented by a factor of 1.10 to allow for appendages and fouling. To approximate added resistance in waves, the calm water resistance was multiplied by the factor

$$1 + \left(\frac{Vap}{100}\right)^2 \cdot \frac{750}{LWL} \cdot \exp\left[1 - \left(\frac{\theta ap}{40}\right)^4\right]$$

for the largest ship some representative values of the factor are given below. (The values of θ_w that are the basis for estimating θap are also included.)

Beaufort	θw	Vap	θap	Factor
8 - 12	60	59	40	1.350
6 - 7	60	41	38	1.205
6 - 7	90	39	53	1.018
6 - 7	130	25	85	1.000
4 - 5	60	24	36	1.086
4 - 5	90	23	50	1.001

It is seen that when beating in strong winds, added resistance is as much as 35% of the base. Added resistance becomes negligibly small for beam winds. Increases in ship speed due to following seas have been ignored.

The final component of hull resistance is induced drag due to angle of attack. The induced drag coefficient is presented in

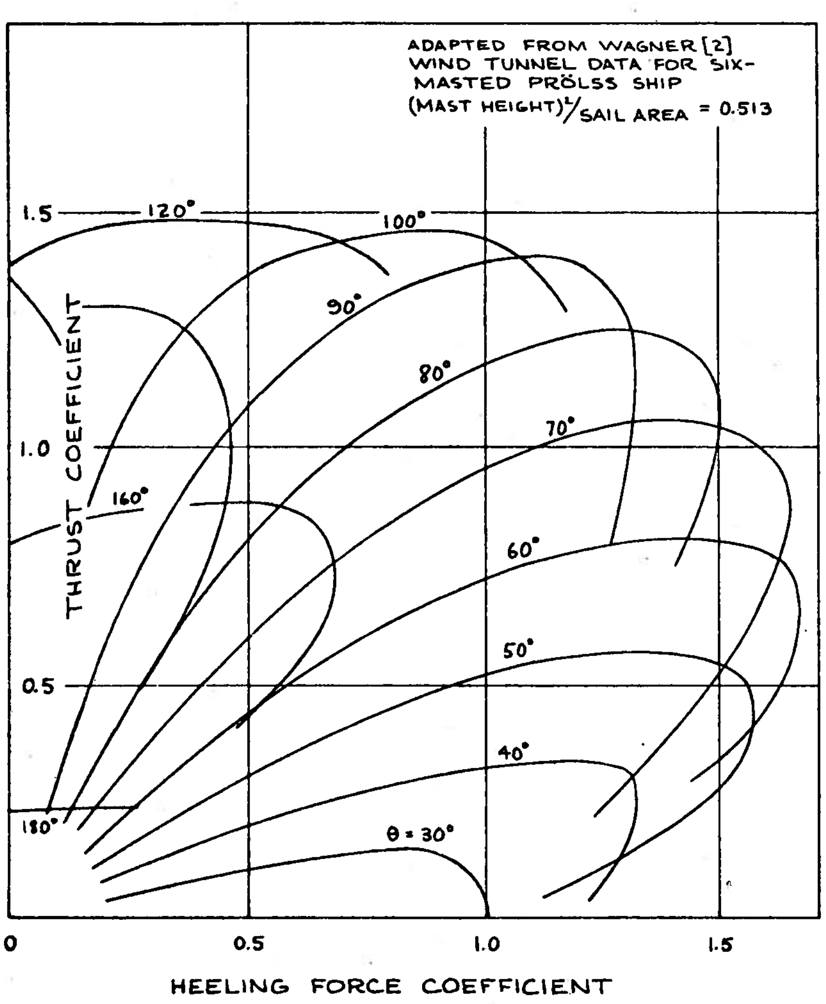


FIGURE 19 Sail Thrust Force Coefficient vs Sail Heeling Force Coefficient

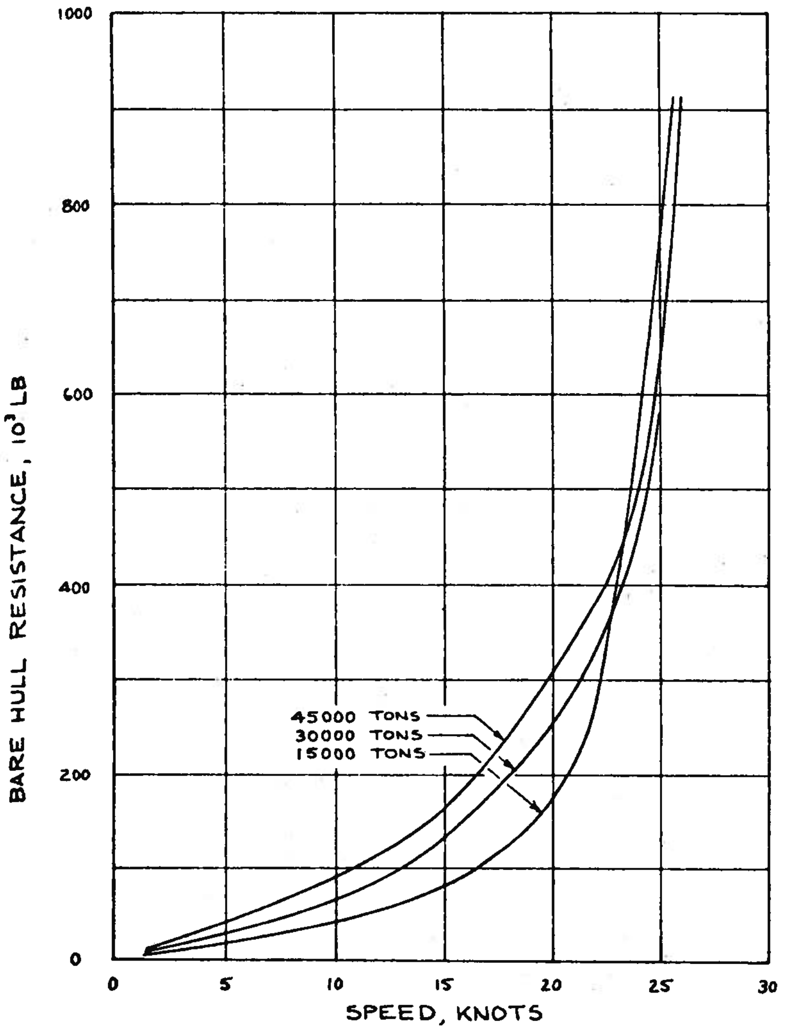


FIGURE 20 Resistance vs Speed from Series 60 Data

Figure 23 and is reportedly based on tank tests of a Mariner model. Hull lift is based on the lift coefficient, also plotted in Figure 23.

No speed dependency is considered here, but since the Froude number when beating is at most 0.20 (speed length ratio at most of 0.60) the omission is probably not significant. However, the sailing ship draft to length ratio is somewhat greater than that of the Mariner, indicating that the predictions of beating performance may be conservative.

The sail thrust and heel forces are calculated using the force coefficients plotted in Figure 19. Based upon wind tunnel tests of an essentially similar sailing ship design, the data are considered reliable.

V_S and θ_S are varied systematically until a solution is found. Then new values of C_T and C_H are taken from the data of Figure 19 and the process is repeated, until maximum ship speeds have been determined for all 360 of the (V_{ap}, θ_{op}) pairs.

The final results, after interpolating for the Beaufort levels for which climatological data was given, are plotted in Figures 24, 25 and 26. Beaufort wind speeds at an elevation of 10 meters are given in Figure 21, while Figure 22 illustrates the variation of speed with height above the sea surface. The Beaufort levels in the speed polars, Figures 24, 25, and 26 correspond to wind velocities at the sail centroid. It is interesting to note that the tacking angle when beating remains close to 120° for most wind conditions. This value is adequate from the standpoint of ship safety, but offers considerable room for improvement. The potential benefit depends on the proportion of time spent beating. Also, the necessity for tacking downwind is obvious. Finally, the three ships cannot sail up to the 6 knot auxiliary speed in winds of less than Beaufort 3.

COMPUTATIONAL METHOD FOR THE ONE-DIMENSIONAL MODEL

As previously mentioned, the one-dimensional model computes the passage time statistics by running an ensemble of trips over a predefined track. Basically, each trip consists of a number

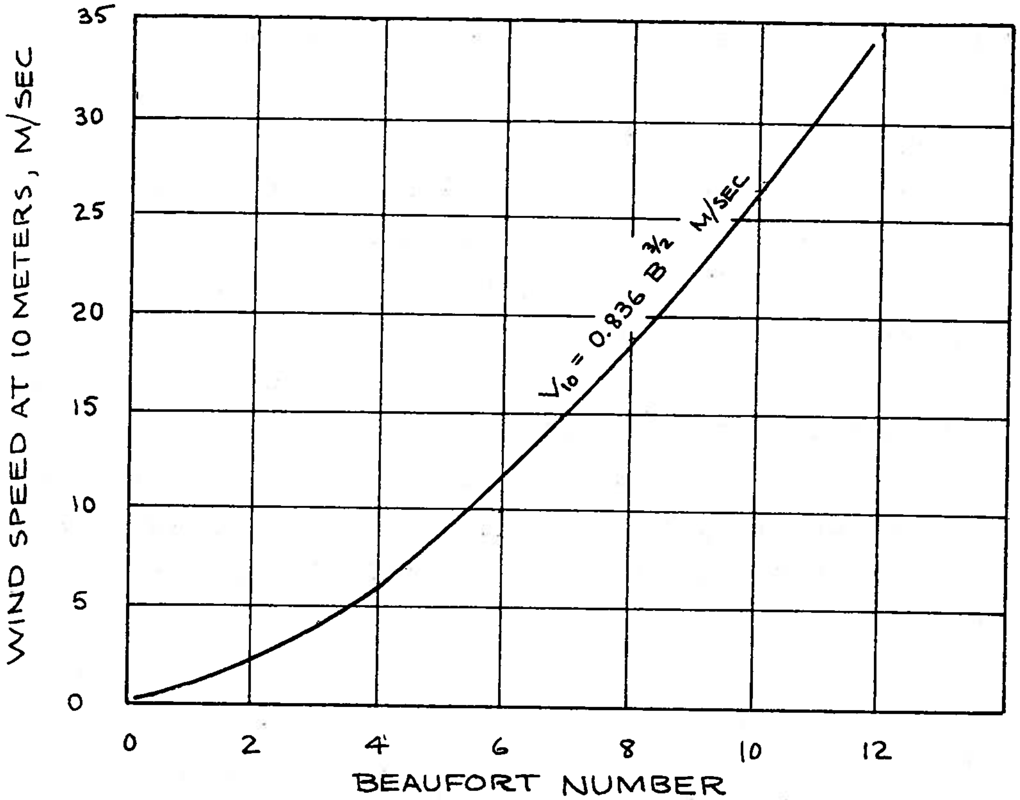


FIGURE 21 Beaufort Wind Scale (from International Shipbuilding Progress, 1964)

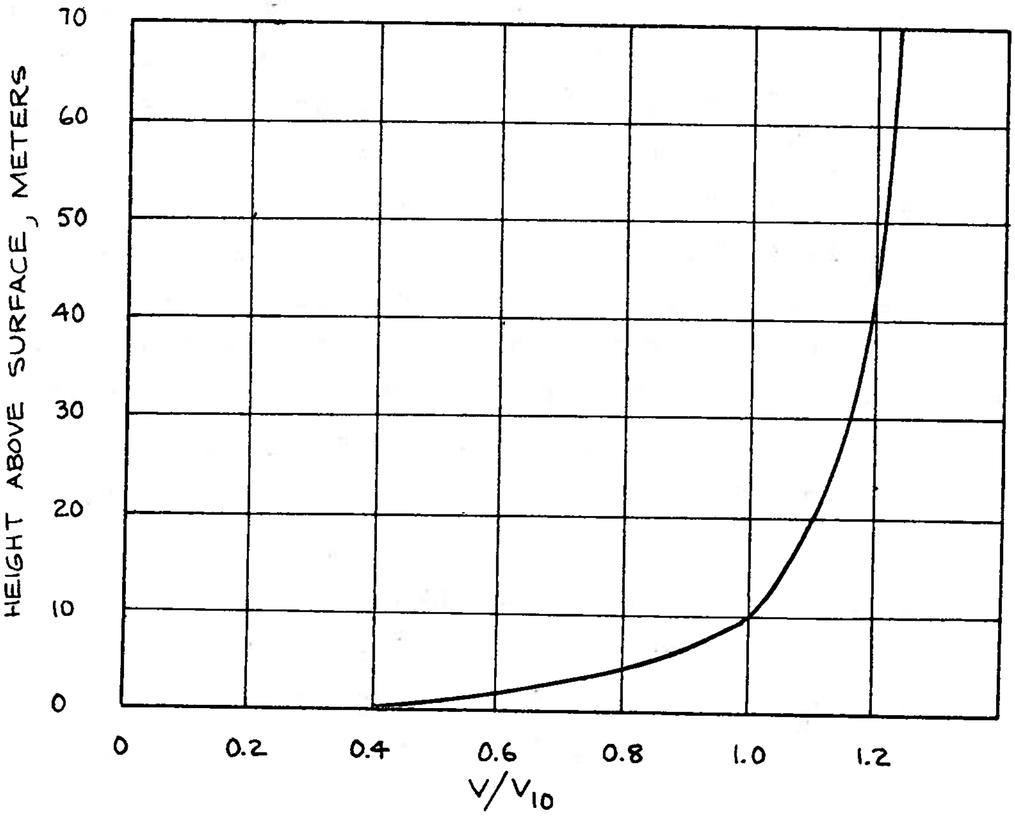


FIGURE 22 Wind Velocity Gradient according to Schoeneich (from International Shipbuilding Progress, 1964)

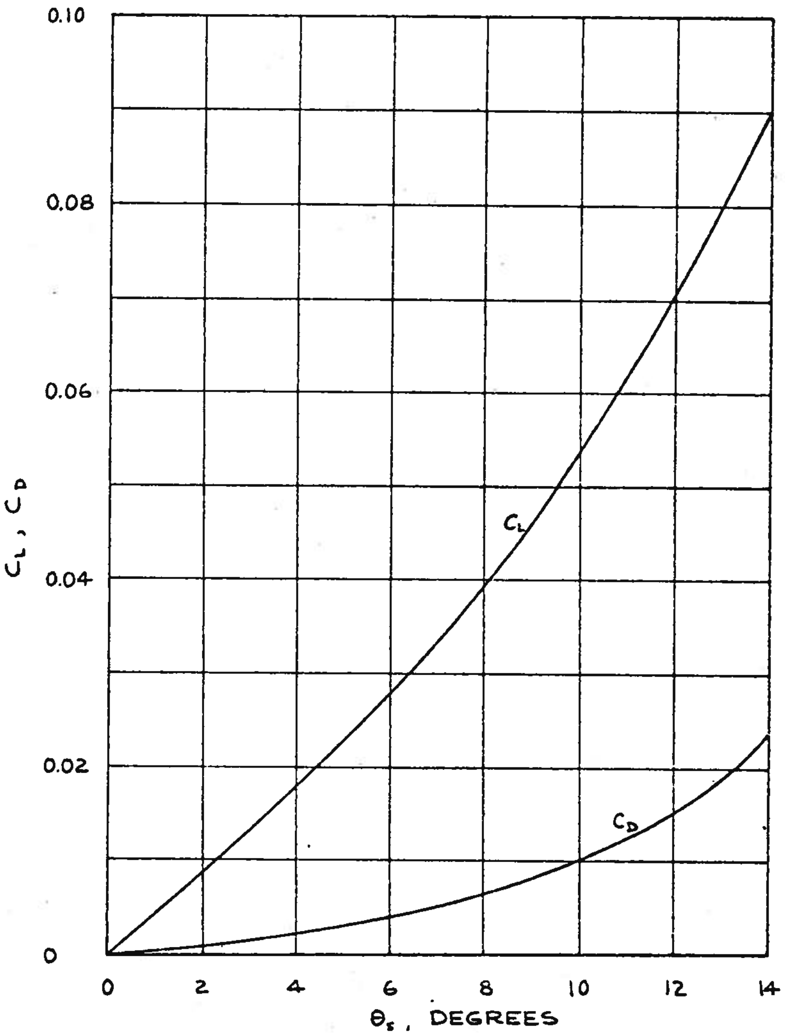


FIGURE 23 Lift and Induced Drag Coefficients vs Leeway Angle for Mariner Ship [2]

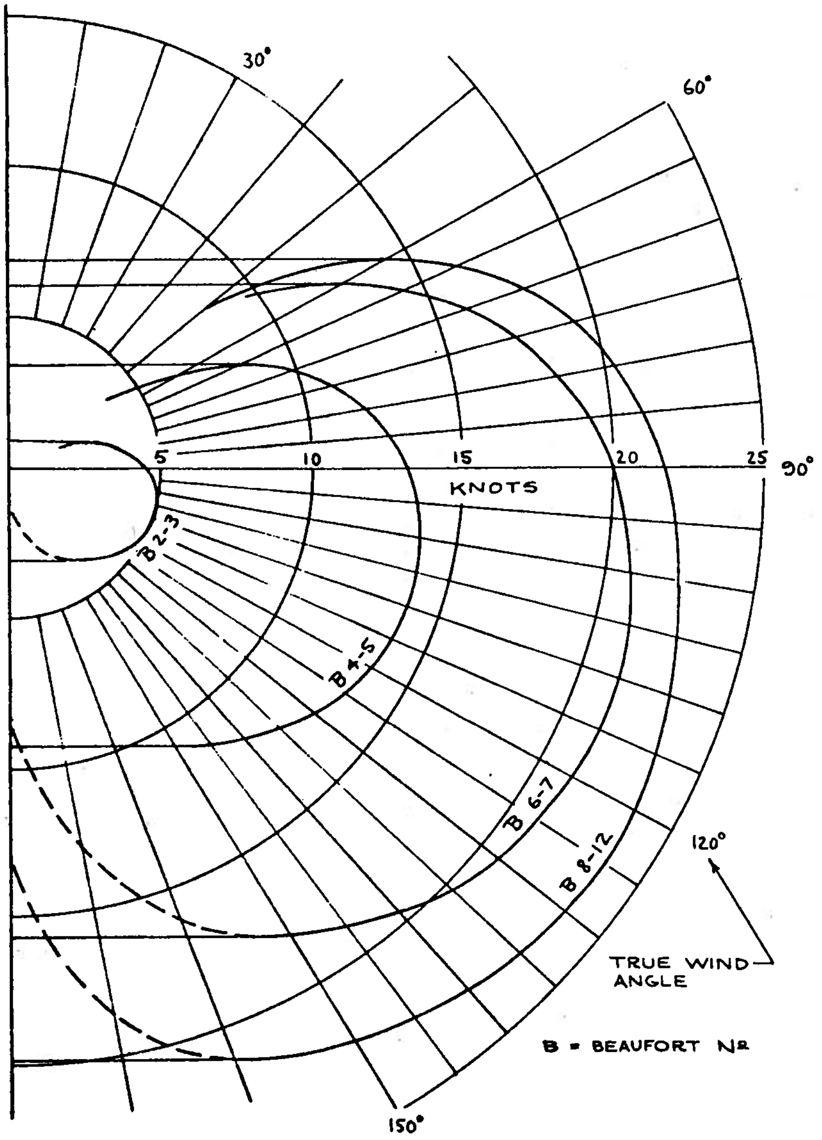


FIGURE 24 Speed Polar for 15,000 ton Sailing Ship, Full Load, $\overline{GM}$ = 6.3 ft

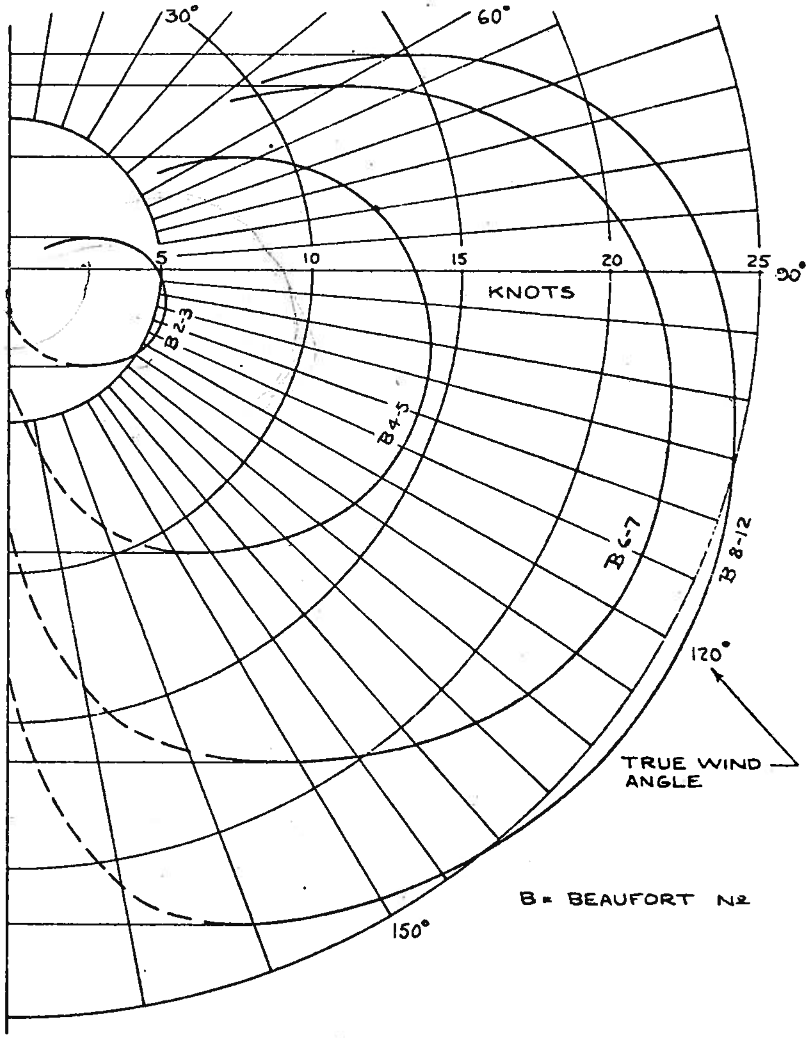


FIGURE 25 Speed Polar for 30,000 ton Sailing Ship, Full Load, $\overline{GM}$ = 6.3 ft

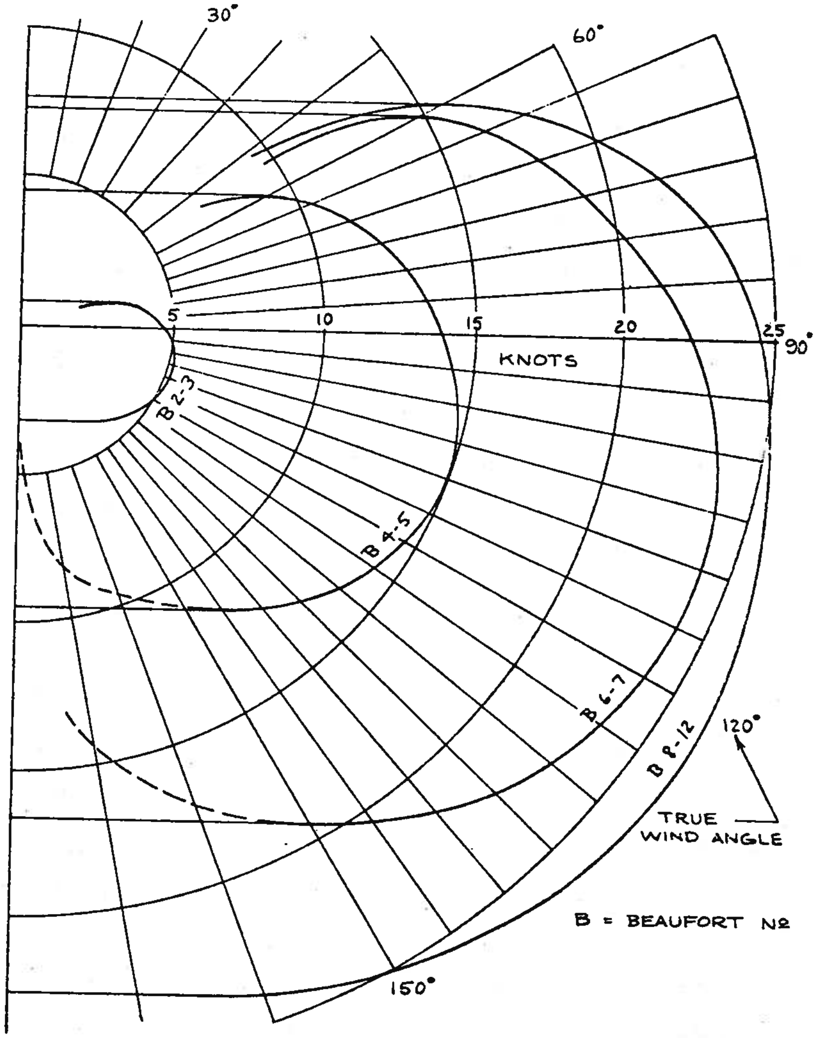


FIGURE 26 Speed Polar for 45,000 ton Sailing Ship, Full Load, $\overline{GM}$ = 6.3 ft

of time steps. At each time step a wind velocity and direction are found subject to the probabilities described by the appropriate wind rose. Knowing the wind velocity and direction, the distance traveled along the track in the given time interval is easily computed. The ship is then moved that distance and the process repeated.

The random variable representing the different instantaneous combinations of wind speed and direction is computed using the wind probability array for the appropriate wind rose and a random number generator. The random number generator produces a number between 0 and 1 which is evenly distributed. By subdividing the interval 0 to 1 into subintervals of widths proportional to the probability of a certain wind speed and direction combination, the probability that the generated random number falls into any subinterval is equal to the probability of that wind speed and direction. Thus, for each time step a random number is generated which gives a corresponding wind speed and direction.

Once the wind speed and direction are established, the known course and wind direction yield wind angle with respect to the ship's course. With this angle and the known wind speed, the program determines ship speed from the speed-polar data, then corrects for the effect of current.

At this point, the program advances the ship's position by an amount equal to the ship speed multiplied by a prespecified time step, and advances the clock by one time step. Subject to a termination check that ends the voyage when the objective is reached, the program then returns to the random number generator, obtaining a new random value, and applies it to the wind probability matrix corresponding to the ship's new position.

At the end of 10 trips, mean time and variance are computed, and the program begins again, repeating sets of 10 trips each until the statistics, $E(T)$ and σ_T^2, converge to within some prespecified tolerance.

In addition to the values of $E(T)$ and σ_T^2, the program also generates statistical information on auxiliary engine use, needed in appraising the sailing ship's fuel costs.

It should be noted here that the size of the time step is related to the autocorrelation time of the wind, being a typical value of the time between significant changes in wind conditions. Since this value is not generally known with any accuracy, the time step has been arbitrarily set at 24 hours. The size of the time step has been found to exert no influence on the resulting value of E(T), however, its effect on the variance σ_T^2, is quite important. It has been found that in the limit as time step $\rightarrow 0, \sigma_T^2 \rightarrow 0$; while in the limit of long time step, σ_T^2 will tend to approach some relatively large but finite value, a fact guaranteed by the finite variance of the random variable ship speed.

Since the present economic analysis depends solely upon E(T), the effect of time step on σ_T^2 is of no economic significance in this study. However, in a more complete economic model, involving costs of variance, the accurate assessment of the autocorrelation time, or time step, associated with each particular wind rose would become necessary.

The convergence of the statistics is fairly rapid, typically requiring three or four sets, that is, 30-40 trips for the mean to converge within 1% of a steady value. The convergence of σ_T^2 is much slower, requiring 10-12 sets for convergence to the 1% criterion.

Convergence is somewhat faster on the long routes, and at low values of the time step, while at higher values of time step the statistics take substantially longer time to converge. This effect is due solely to the number of random samplings of the wind data required to complete a voyage.

ANNUAL CORRECTED MEANS AND VARIANCES

Thus far, we have dealt with voyage statistics (means and variances) corresponding to a given track, ship, and month.

By averaging the statistics over the entire year, either monthly or quarterly, since the wind data varies sufficiently smoothly over the year to allow quarterly averaging, an annual corrected voyage expectation time and variance can be calculated.

This is done as follows:

(1) For each quarter of the operating year of 340 days (85 days), the seasonal average port-to-port time is added for the two legs of the voyage to obtain mean sea days per round trip.

(2) A preset number of port days per round trip, with no variance, is added to the result obtained in step (1), to obtain mean total days per round trip (seasonal).

(3) The number of round trips per quarter is then computed for each quarter.

(4) Summing these results yields total voyages per year, based on equal weighting for all seasons. The total annual average days per trip, sea days per trip and annual average port-to-port speed can then be computed.

In many parts of the world, seasonal average speeds fall off markedly in the summer months. Thus, an economic advantage can be gained by concentrating the lay-up days in the summer, rather than distributing them evenly over the four quarters. The procedure used is the same as outlined above, but instead of dividing the 340 day operating cycle into four equal periods of 85 days, the summer operating season is reduced to 70 days, while the three remaining seasons are increased to 90 days each. The resulting "summer lay-up" annual averaged statistics are slightly better, and this operating scheme is employed in the economic analysis.

Results generated by the one-dimensional model are considered reliable to the extent that the following approximations hold:

(1) The partitioning of the track is sufficiently fine that a single joint probability density function of wind applies to all points in a particular interval.

(2) A single value of the vector-mean current applies to the entire interval.

(3) The track can be represented as a straight line segment within any one interval.

(4) Departures of the ship from the track are negligible.

The limitations on conditions (1) and (2) arise essentially from the nature of the available meteorological data. Condition (4) prohibits large departures, say 50-100 nautical miles, from the track. The distance actually covered when tacking is taken account of in the speed-polar data, and thus tacking is not necessarily in violation of condition (4); the restriction is imposed to control in some sense variations of total track length, and to prevent ambiguities arising when the ship strays outside the region governed by the prespecified set of wind roses.

Statistical limitations of the method arise primarily from the discrete nature of the wind data, and from the lack of explicit correlation in time. Implicitly, however, there is a certain degree of temporal correlation of the wind implied in the choice of time step.

APPENDIX II
SOME COMMENTS ON WIND-PROPULSION DEVICES OTHER THAN SAILS

As was mentioned earlier, there are numerous alternatives to conventional sails for application to commercial vessels. Without prejudice to their possible usefulness in certain situations we can enumerate some of their advantages, together with the adverse considerations that dictated the adoption of a more conventional rig.

Flettner Rotors - Vertical axis rotating cylinders are very efficient thrust generating devices, allowing sizable resultant forces to be generated at low wind speeds, and at relatively small angles to the true wind. Cylinder projected areas would only have to be between 15% - 25% of conventional sail area for a given force, and in light to moderate conditions some advantage might be gained in beating or close reaching. Downwind, however, the drag acting on the much smaller cylinders would not provide as much thrust as the larger conventional sails.

More critically, however, the Flettner rotor depends on variation in the ratio of angular velocity to free stream wind velocity in order to change the orientation of the resultant force with respect to the free stream direction. In particular, in the limit of high wind speeds, the rotor must be driven at a very high rpm to realize any useful lift component. Structural and dynamic considerations limit the maximum rotor speed attainable, and thus the performance of rotor ships in moderate to heavy wind conditions is inferior to conventional sail-propelled vessels.

In addition, the problems of "reefing" the rotor surfaces are considerable, and the cost of constant power input to the rotors is large compared with the occasional power requirements of changing sail trim on a conventional vessel.

In conclusion, Flettner rotors could be a viable alternative in ships where light air and windward performance are the dominating conditions, however, in deepwater trades more of a premium is placed on moderate-heavy air sailing and on reaching and downwind speed. Thus, for the purposes of the routes and services discussed, it is doubtful that any advantages would be gained of sufficient magnitude to outweigh the structural, practical, and operational drawbacks of the rotor ship.

"Windmill-Electric Propulsion with Screw Propeller" - The primary drawback of this form of drive lies in the relative inefficiencies of the energy transformations involved. Losses occur in the windmills themselves, both aerodynamically and through bearing friction, transmission losses in the electric generators, lines, and motor might amount to another 20%, and finally, another 25% energy loss is typical even of a good screw propeller.

Then, too, the total area of windmill blade discs would have to be at least on the order of conventional sail area, requiring large banks of trainable windmills, and masthead heights perhaps even higher than in conventional sailing vessels of similar size.

The most obvious practical advantage of windmill drive lies in its theoretical ability to go dead to windward. However, in order to make good on this theoretical ability, the drag of supporting structures must be minimized, the reactive thrust of the windmills themselves must be small in relation to their torque output, and the screw must be kept in good hydrodynamic conditions, i.e., well submerged - with no emmersions under severe pitching, etc.

When reaching, the windmill ship is not free of the requirements for hull side forces to balance the reactive thrust of the generating devices and the drag of supporting structures. While the side forces would naturally be smaller in magnitude than those required for a conventional sailing vessel, allowing a shallower draft to be adopted, the effect of the flow into the propeller of a yawed ship would be negative on efficiency, and would have to be examined carefully, in addition to the added resistance due to yaw angle.

In summary, the advantages of windmill drive are somewhat problematic, the efficiencies are low due to the energy transformations required, and the engineering problems are at least as acute as for a sail-powered vessel.

<u>Wing-Sails</u> - The aerodynamic advantages of a properly designed rigid airfoil over a sail of equivalent area are well known. However, several factors militate against their employment on the type of vessel under consideration.

First, the aerodynamic superiority only exists at small angles of attack, important only when close hauled or close reaching, or on very fast-sailing craft such as catamarans, hydrofoil-borne vessels, or iceboats, clearly outside the scope of feasible ocean bulk carriers. Second, many of the wing-sail systems currently envisaged employ symmetric foil sections, whose advantage over a "soft", but cambered, thin wing section is rather small. Third, the rigid foil presents difficulties in reefing and control, although some systems are designed so that the wing automatically luffs into the wind when overloaded, thus relieving the forces to an extent. True, a well streamlined symmetrical foil section offers little drag when its chord is turned parallel to the flow, however, the inertia of a large wing-sail structure about its pivot is certainly not negligible, so the transient forces encountered in shifting winds might not be reduced sufficiently to eliminate the need for some means of actually reefing or reducing the wing area.

Since the windward and high-speed aerodynamic advantages of rigid foils are of little importance in a slow, deepwater cargo vessel, it is not felt that any advantage commensurate with the difficulties involved would be realized.