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STATUS OF RESEARCH INTO ENGINEERING ECONOMY IN THE DESIGN OF GENERAL CARGO SHIPS

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(Interim Report to The University of Michigan's Office of Research Administration for Work Done to Date Under Sponsored Research Account 04465)

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PREFACE

This paper is an interim report of the work done to date under a grant from The University of Michigan's Office of Research Administration. It is issued at this time, not only as a courtesy to the sponsor, but for the benefit of students in the writer's class in preliminary ship design. It is planned that these students will, in turn, extend of the scope of these investigations as part of their class assignments.

Few, if any, sections of this report are intended to be used other than as supplements to classroom lectures. In most cases, conclusions of the studies are presented without explanation, which shortcoming will be corrected in the final report. For these reasons distribution must perforce be limited.

Owing to the pressures of other responsibilities, the writer has not been able to properly check every calculation presented herein. All figures are subject to further checking and reanalysis.

The writer was fortunate to have the earnest and able assistance of two students: Edson Graves and Susan Atkins. He was also lucky enough to receive extensive support from many interested individuals in shipyards, design offices, ship operating companies and government agencies. These gentlemen contributed much confidential factual information and helpful advice. To all of these people, as well as to the Office of Research Administration, the writer wishes to express his thanks.

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ABBREVIATIONS

C: General indication of a coefficient, with or without subscript, which is defined wherever used.

C_B: Block coefficient, based on design draft, design displacement and length between perpendiculars.

C_P: Prismatic coefficient with same basis as C_B.

CN: Cubic number $= \frac{LBD}{100}$.

d: Design draft.

D: Depth to uppermost continuous deck.

D_M: Modified depth which corrects for extent of superstructure.

DWT: Deadweight at design draft.

Δ: Displacement in saltwater at design draft.

EBC: Equivalent bale capacity.

L: Length between perpendiculars

L_S: Length of superstructure within fore and aft perpendiculars

SHP_N: Normal installed shaft horsepower (equals maximum power $\div$ 1.10).

V_K: Nominal sea speed in knots, taken as trial condition speed at 80 percent of normal power, assuming operation at design draft.

W_O: Net weight of outfitting.

W_{HE}: Net weight of hull engineering, wet

W_S: Net weight of steel structure

W_M: Net weight of machinery, wet.

Note: All dimensions are in feet, weights in long tons.

INTRODUCTION

The aim of this study (which is still underway) is to determine, through statistical analysis, the relationship between the various technical and economic factors in general cargo ship design and operation. Such information is generally lacking in the literature and the eventual publication of the present work should prove useful to the profession.

In addition to the large body of information privately supplied by many individuals, extensive use is made of published works which lavish certain areas to excess while grossly neglecting others. Interpretation of the accumulated data presents many difficulties; frequently the information is unusable as submitted and requires guess work in application; some data points represent fleet averages, some, ship class averages and some, individual vessels; as frequently happens, most data points tend to cluster near the middle of the chart with few, if any, points at the extremes. In short, the available statistics are hardly suitable for straightforward mathematical interpretation; rather, considerable common sense and judgment based on past experience with other types of ships have been employed to propose what order may lie in the plotted chaos.

An important part of this effort has been to devise suitable parameters for analysis of the available information. Several of the plotting schemes are new, some are based on the work of other students in the field and some are taken from the writer's earlier studies.

Wherever possible, the conclusions are presented in mathematical rather than curve form. This is done for three reasons: to reduce the cost of this report, to increase accuracy of subsequent work, and to encourage the use of computers. The final report, however, will contain graphical presentation of many of the mathematical expressions.

In order that the results of this study may be applied to radical as well as conventional ship designs, all factors are treated in parametric form. Those relationships, such as hull proportions, which merely reflect human judgment are distinguished from those which come about more or less naturally. Also, the range of ship size, power and speed extends way beyond present concepts of practical ships. See Table I.

TABLE I

RANGE OF FACTORS CONSIDERED

Item	Minimum	Maximum
L	180	800
B	30	110
D	10.5	65
d	8	40
Displacement	1,000	75,000
Deadweight	750	60,000
Cubic Number	500	60,000
V_K	8	38
SHP_N (single screw)	0	40,000
SHP_N (twin screw)	0	70,000
C_B	0.50	0.90

Where propulsion machinery is a factor, single screw geared steam turbines are assumed. In several cases reference is also made to twin screw or diesel drives, both of which merit further research in future years.

All cost factors are based on ships built in U. S. yards and operated under U. S. flag. Subsidy support is already well covered in other references and is not included in this study.

Tramp ships are of little direct interest to U. S. flag shipowners and where it makes a difference, berth line operation is intended. However, most conclusions are equally applicable to either type ship.

DESIGN ANALYSIS

General

This chapter attempts to summarize current U. S. practice in the design of general cargo ships. Since U. S. designs are limited in number, a preliminary analysis of modern European practice has been used to establish trends. It is not intended that the resulting conclusions be accepted as the royal road to the ideal design, but rather as an indication of conventional practice, the development of which is necessary to further studies of weights and costs. Intellectual inbreeding is all too common in the marine profession and the student is advised to respect but not worship the work of his elders. Having developed this healthy skepticism, he should then apply it with equal generosity to his own productions.

It must also be cautioned that the various hull proportions, although discussed individually, are in reality strongly interrelated.

In the preliminary design of an actual ship, the method of attack will depend on the statement of the problem. Frequently, the owner (or government) will be quite arbitrary about such primary factors as size and speed, thus leaving the designer with little challenge except to optimize the proportions and details of design. The more enlightened owner will work with the naval architect to study the functional needs of the trade route along with the interlocking relationship of technological capabilities (such as influence of high speed on attracting cargo). This presupposes market surveys to predict the amount and fluctuations in the various cargos to be carried over the life of the ship. Such surveys should be used to establish suitable stowage factors and capacities.

Designing a ship as a vehicle of commerce rather than as something that looks like the last ship certainly involves more work for both the owner and the naval architect. However, it is the rational way to do it and is the method toward which this study is directed, although the ideas and information generated can be applied to the more restricted design problems as well.

One complicating factor in general cargo ship design is the problem of partial draft. To start with, in actual operation, such ships seldom put to sea loaded down to their marks; either there is not enough cargo or it is too light. This leads to changes in speed and power relationships, fuel consumption, etc. Secondly, since most general cargo is pretty low in density, minimum freeboard is seldom a requirement and drafts are more likely to be set by scantlings than by geometry of the ship. Further complications arise from such factors as the carriage of dense raw materials on the homeward voyage, and availability of commodities suitable for deck cargo. Thus each trade route makes its own particular impact on the design of the ship and the uniformity of purpose found in bulk carriers is missing, particularly in the ships of the liner trade.

Proportions

Figures 1 and 2 show the proportions of recently designed ships of both U. S. and European origin. These figures should be studied along with most of the paragraphs which follow.

Various authorities, including Posdunine and G. S. Baker, have shown that length seems to vary with speed and displacement according to the following empirical relationship:

$$L = C\left(\frac{V_K}{V_K + 2}\right)\Delta^{\frac{1}{3}}$$

Where C = coefficient which ranges from 20.1 to 21.95 in recent U. S. designs. Average value equals 20.7

Pending further research, a preliminary estimate of length can be based on the above, using C = 20.7. Greater lengths will lead to excessive steel weights and construction costs. Smaller lengths will tend towards high resistance, poor seakeeping characteristics and, possibly, cramped cargo handling arrangements.

Design draft is normally chosen as large as possible considering the probable loading conditions at each of the intended ports of call and intermediate canals. European cargo ships average about 25.5 feet design draft while recent U. S. designs average about 29.5 feet. A design draft greater than 30 feet is extremely rare, however. European coasters may have design drafts more like 20 feet and drafts as small as 17.5 feet are not uncommon.

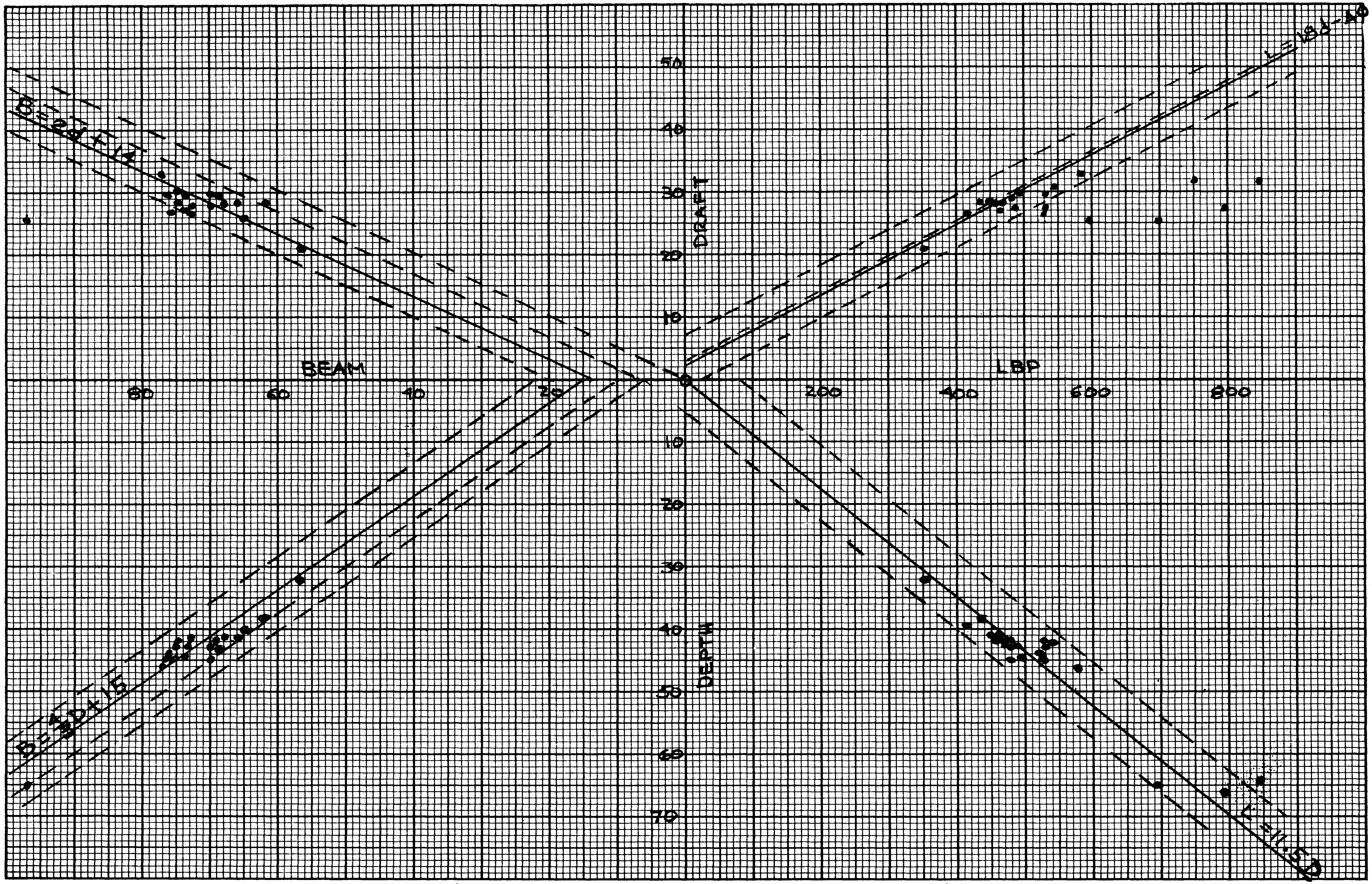


FIG. 2: PROPORTIONS OF RECENT U.S. CARGO SHIP DESIGNS, INCLUDING ROLL-ON & CONTAINER TYPES. (DASHED LINES: EUROPEAN TRENDS)

The length-draft ratio is an important criterion. Excessive values may lead to slamming damage forward and increased danger of propeller emersion. The classification societies maintain certain minimum limits on scantling draft in the case of long bulk cargo ships ( ) and would no doubt impose similar restrictions in the case of abnormally proportioned general cargo ships. Of course, scantling draft can be considerably greater than design draft if conditions warrant.

European cargo ships have an average relationship of:

$$L = 18d - 50 \text{ feet}$$

$$\text{or} \quad d = 0.555L + 3 \text{ feet}$$

Recent U. S. designs indicate a slightly greater length, on the average:

$$L = 18d - 40 \text{ feet}$$

$$\text{or} \quad d = 0.555L + 2.22 \text{ feet}$$

In recently proposed containership and roll-on, roll-off designs, practical draft restrictions, coupled with great length requirements, have resulted in length-draft ratios ranging from 23 to 29!

Beam may be limited by external restrictions such as locks, building ways or dry docks. It can also be influenced by its proportion to other dimensions, principally draft. Increases in beam-draft ratios (for a given length, draft and displacement) allow decreases in block and prismatic coefficients, the net result, frequently, being a reduction in resistance. Stability considerations also set both maximum and minimum limits on the ratio of beam to draft; and stability, in turn, is affected by cargo density (through its influence on freeboard, as discussed later), type of cargo handling gear, extent of deck erections, and other practical considerations.

The beam of the average modern European cargo ship is about 2d + 7 feet, with 2d as a practical minimum and 2d + 20 feet as a practical maximum. In recent U. S. designs, beams range from 2d + 5 feet to 2d + 22 feet, with 2d + 14 feet as an average. In the case of the previously mentioned roll-on, roll-off designs, beams run as high as 2d + 46 feet.

The ratio of length to beam is another useful criterion. Large values suggest long, skinny ships with good rectangular holds but relatively low stability. Perhaps the chief virtue of the ratio lies in the fact that practical values seem to fall within moderately narrow bands; thus any tendency towards non-conformity warns one to proceed with caution. Analysis of large numbers of ships indicates that length and beam can be related as follows:

$$L = 9.25B - C$$

where C has the following values:

	European Practice	U. S. Practice
Average	130	170
Minimum	75	100
Maximum	185	215

In the case of roll-on, roll-off designs, C has been as low as 85.

All of the dimensions discussed up to this point have been concerned with the underwater portion of the hull and provision of proper displacement and deadweight capacity. The final principal dimension, depth, introduces problems of freeboard and the provision of proper volumetric capacity. In some cases, questions of hull girder requirements may also prove critical.

If the intended cargo is relatively dense, say no more than 50 cubic feet per ton, then a full scantling ship will be suitable. With the majority of general cargo, however, greater volume will be required. Obviously, the ideal design results in a vessel which is full and down when carrying the probable available cargo although it is seldom easy to predict what that will be over the life of the ship, nor are requirements likely to be uniform both outbound and inbound. Recourse to shelter deck design is always possible. However, the shelter deck concept has fallen into disrepute in this country and most of our newer ships are of scantling draft design; that is, freeboard is measured from the uppermost continuous deck; but the scantling draft (which is somewhat more than the design draft) increases the freeboard over that required by the geometry of the ship.

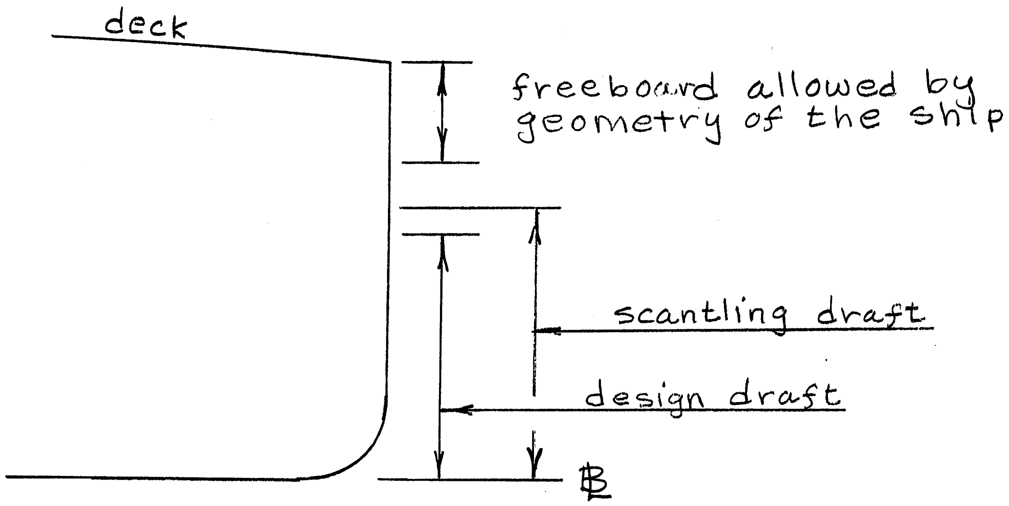


Figure 3
Scantling Draft Ship

Figures 4 and 5 can be used to quickly establish the approximate minimum freeboard requirements. However, the practice of using a scantling draft design makes minimum freeboard of academic interest only. Freeboard and depth, then, are essentially functions of the required volumetric capacity. This is developed further in a subsequent section.

The length-depth ratio must be considered in light of its influence on hull girder strength and consequently on steel weight. The average value is about 11.5 in both U. S. and European practice, with a length distribution ranging from 60 feet less, to 80 feet greater than this value.

The ratio of beam to depth deserves consideration. Low values suggest a possible deficiency in stability; values greater than 2.0 require special consideration in calculation of section modulus (   ) unless longitudinal bulkheads are present.

One of the most convenient measures of overall ship size is the well known cubic number, abbreviated "CN" in many of the charts and formulas of this paper:

$$CN = \frac{LBD}{100}$$

Occasionally situations arise in which the length of a ship is known but depth and/or beam are unknown. In such cases, the cubic number can be estimated as follows:

$$CN \simeq 100\left(\frac{L}{100}\right)^{3.15}$$

It can be easily shown that the cubic number bears the following relationship to the design displacement:

$$CN = \frac{0.35}{C_B} \times \frac{D}{d} \times \Delta$$

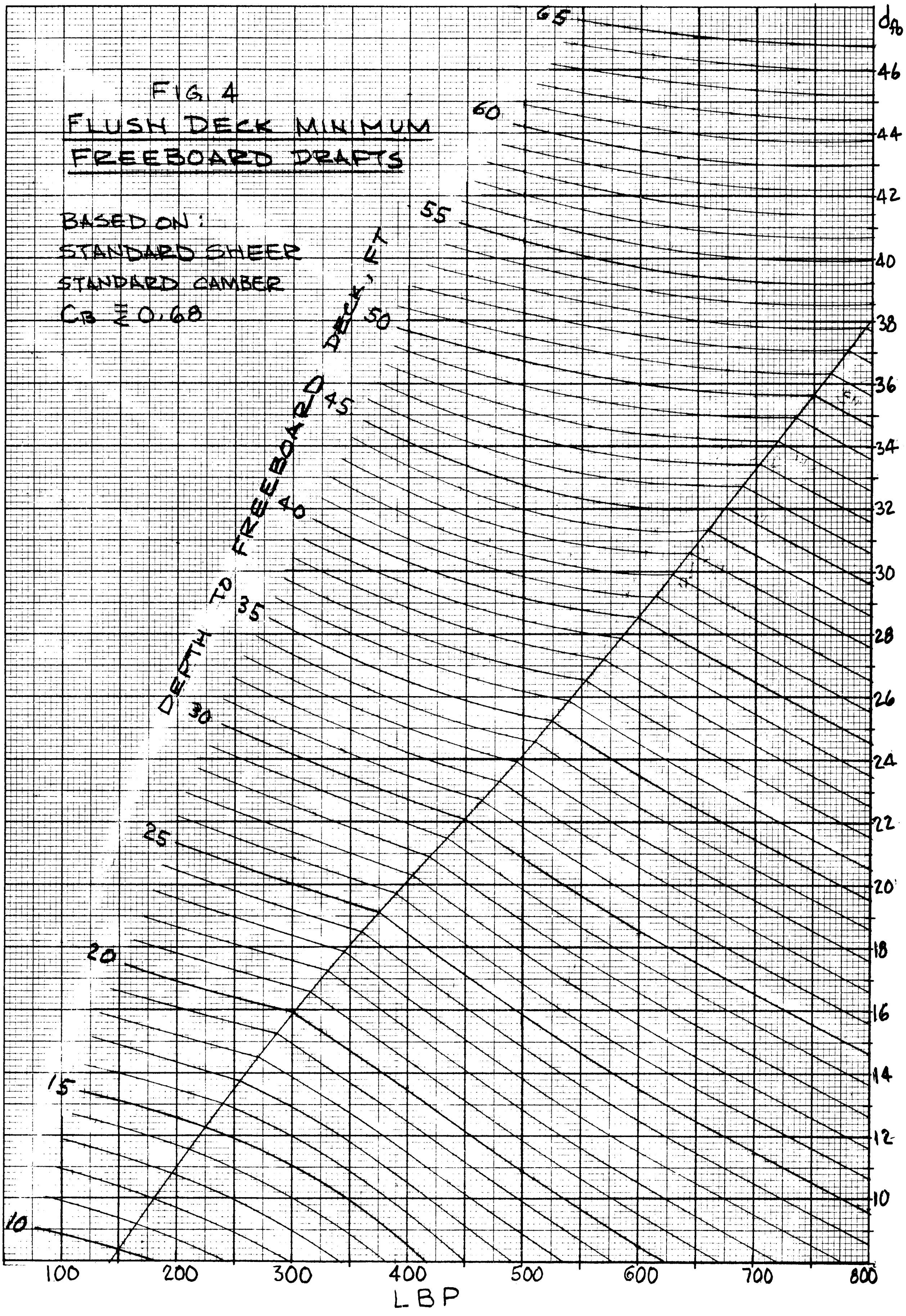
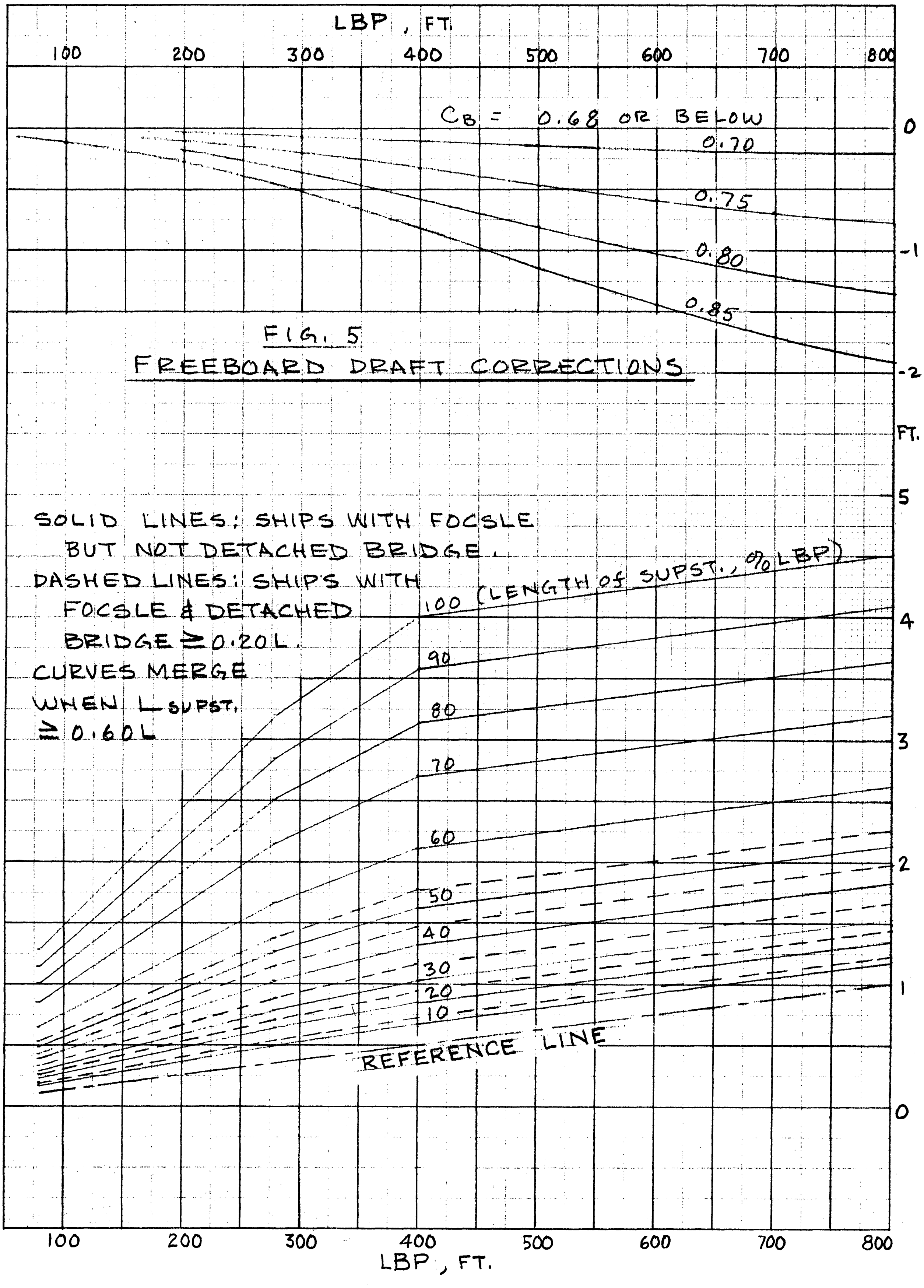


FIG. 4
FLUSH DECK MINIMUM
FREEBOARD DRAFTS
BASED ON:
STANDARD SHEER
STANDARD CAMBER
CB ≥ 0.68
DEPTH TO FREEBOARD DECK, FT
65
60
55
50
45
40
35
30
25
20
15
10
d_{fb}
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
100
200
300
400
500
600
700
800
LBP


LBP, FT.
100
200
300
400
500
600
700
800
CB = 0.68 OR BELOW
0.70
0.75
0.80
0.85
0
-1
-2
FT.
5
4
3
2
1
0
FIG. 5
FREEBOARD DRAFT CORRECTIONS
SOLID LINES: SHIPS WITH FOCSLE BUT NOT DETACHED BRIDGE.
DASHED LINES: SHIPS WITH FOCSLE & DETACHED BRIDGE ≥ 0.20L.
CURVES MERGE WHEN L SUPST. ≥ 0.60L
100 (LENGTH of SUPST., % LBP)
90
80
70
60
50
40
30
20
10
REFERENCE LINE
100
200
300
400
500
600
700
800
LBP, FT.

Substituting average values for C_B and D/d, one obtains the following approximation:

$$CN \approx 0.87 \Delta$$

Values of the constant will approach 0.95 for high-cubic ships and 0.80 for low-cubic ships, based on U. S. practice.

Volumetric Requirements

In designing a cargo ship, the provision of sufficient cargo hold volume is just as important as the provision of sufficient displacement; and the shape and distribution of the cargo holds merit the same attention as does that of the underwater hull form.

The first problem here is to select a freeboard and depth that will give the desired volumetric capacity. After studying the available literature on the subject of volume estimation (   ) a somewhat new approach has been developed, as outlined below.

As a means of including superstructure (but not deckhouse) volume, the depth to the uppermost continuous deck (D) is abandoned in favor of a modified depth (D_M). Assuming a superstructure height of eight feet:

$$D_M = D + \frac{L_S}{L} \times 8$$

where L_S = length of superstructure within fore and aft perpendiculars in feet

($\frac{L_S}{L}$ averages 20.5 percent in recent U. S. designs).

A further sophistication is required to put all kinds of cargo spaces into the common denominator of required volume of enclosing structure. Bale capacity is chosen as the most common measure and special cargo spaces are corrected to the bale capacity they would provide if designed for dry cargo. The corrected sum of all cargo spaces is called "equivalent bale capacity" (EBC) and it is expressed as follows:

EBC = Bale Capacity + C_R x Reefer Cargo Volume + C_L x Liquid Cargo Volume + C_C x Below-Deck Containerized Cargo Volume.

Based on the references previously cited, the following C values are recommended for average conditions:

C_R = 1.21 for 'tween deck reefer cargo spaces

C_L = 0.90 for cargo deep tanks

C_C = 1.15 for cargo containers

Thus, for any required apportionment of reefer, liquid, containerized and regular dry cargo, one can quickly estimate the required equivalent bale capacity. The next step, then, would be to convert this requirement to the necessary modified depth (D_M). A cubic number based on D_M at once suggests itself as a useful parameter. However, fullness of form and size of engine room are two influential factors which must also receive consideration. After some study, the following expression has been found to satisfy the above requirements:

$$\text{EBC} = (C_B - 0.10)\ LBD_M - \text{EBC of Machinery Space.}$$

Thus,

$$D_M = \frac{\text{EBC} + \text{EBC of Machinery Space}}{(C_B - 0.10)\ LB}$$

The equivalent bale capacity of single screw steam turbine machinery spaces may be estimated as follows:

$$\text{EBC of machinery space} = C + 6.75\ \text{SHP}_N.$$

$$\text{For machinery amidships: } C \approx 46{,}000$$

$$\text{For machinery aft : } C \approx 85{,}000$$

The above method is felt to be basically sound and amenable to as much further refinement as one may find desirable. Further research should determine suitable machinery space volumes both for multiple screw plants and for other types of machinery.

Depth may also be determined by an altogether different approach, the thought being that the depth-draft ratio should bear a direct relationship to the cargo stowage factor. That is, a ship designed for light bulky cargos should have relatively great freeboard compared to draft. This method, while using the same refinements as in the previous method, does not appear to match the other in accuracy, at least at this stage of investigation. However, it does offer the advantage of relat [illegible]
plication. Table II summarizes the [illegible] s
U. S. designs:

TABLE II

RATIO OF MODIFIED DEPTH TO DRAFT APPROPRIATE TO VARIOUS CARGO STOWAGE FACTORS EXPRESSED AS EQUIVALENT BALE CAPACITY ÷ DEADWEIGHT

$\frac{EBC}{DWT}$	45	50	55	60	65	70	75	(con't.)
$\frac{D_M}{d}$	1.32	1.41	1.49	1.56	1.63	1.69	1.75	(con't.)

$\frac{EBC}{DWT}$	80	90	100	110	120	130	140
$\frac{D_M}{d}$	1.81	1.91	2.00	2.08	2.15	2.21	2.27

Tonnage

Many minor operating costs are based on gross or net tonnage. Analysis of several actual ships leads to the following expression which may be useful in estimating tonnage:

$$\text{Tonnage Measurement} = C\ (CN \times C_B - 1000)$$

where C has the following values:

gross tonnage	shelter deck design	0.95
" "	normal design	1.25
net tonnage	shelter deck design	0.55
" "	normal design	0.77

Hull Form

Many volumes have been written on the subject of hull form and it is not the purpose of this paper to duplicate such efforts. However, two resistance factors deserve special mention here: fullness of form and fatness ratio. Beam-draft ratio has already been discussed in an earlier section.

Fullness of form can be expressed either as block coefficient (C_B) or prismatic coefficient (C_P). In commercial ships, the maximum section coefficient (C_χ) is so close to unity that C_B and C_P are almost equal.

Fullness of form, by itself, is not a complete criterion of resistance. For example, a tugboat has a very low C_P and yet, obviously, such a form is more resistful per ton of displacement than, say, a racing shell of about equal C_P. The reason is that the tug has its displacement squeezed into a very short length. This relative distribution of displacement can be expressed by the traditional displacement-length ratio:

$$\Delta/(\frac{L}{100})^3$$

or by the newer (and truly dimensionless) fatness ratio:

$$\nabla/(\frac{L}{10})^3$$

Over the years, many experts have attempted to establish the proper relationship between fullness of form (C_P or C_B) and speed as measured by speed-length ratio ($V/\sqrt{L}$). For a given deadweight capacity, a high C_P or C_B requires a relatively small set of dimensions with consequent savings in building and upkeep costs. On the other hand, a low C_P or C_B requires relatively low horsepower with consequent savings in machinery and fuel costs. Within the range of normal speed, as $V/\sqrt{L}$ is increased, resistance becomes more crucial and the optimum C_P or C_B drops. While all of the published curves of C_P or C_B vs $V/\sqrt{L}$ have been drawn with the above thought in mind, as far as is known, none has directly utilized actual dollar studies.

Earlier studies (   ) tentatively conclude that, in general cargo ship design, C_P and C_B may be varied widely with only negligible effect on overall ship profitability. If this can be verified, designers will be given new latitude in choosing hull form coefficients.

Watson (   ) rightfully argues that C_P must not be chosen without concurrent consideration of $\Delta/(\frac{L}{100})^3$. His recommended values are included in Figure 6 along with similar values proposed by Saunders (   ). It is suggested that, upon completion of the current study, a rigorous reanalysis

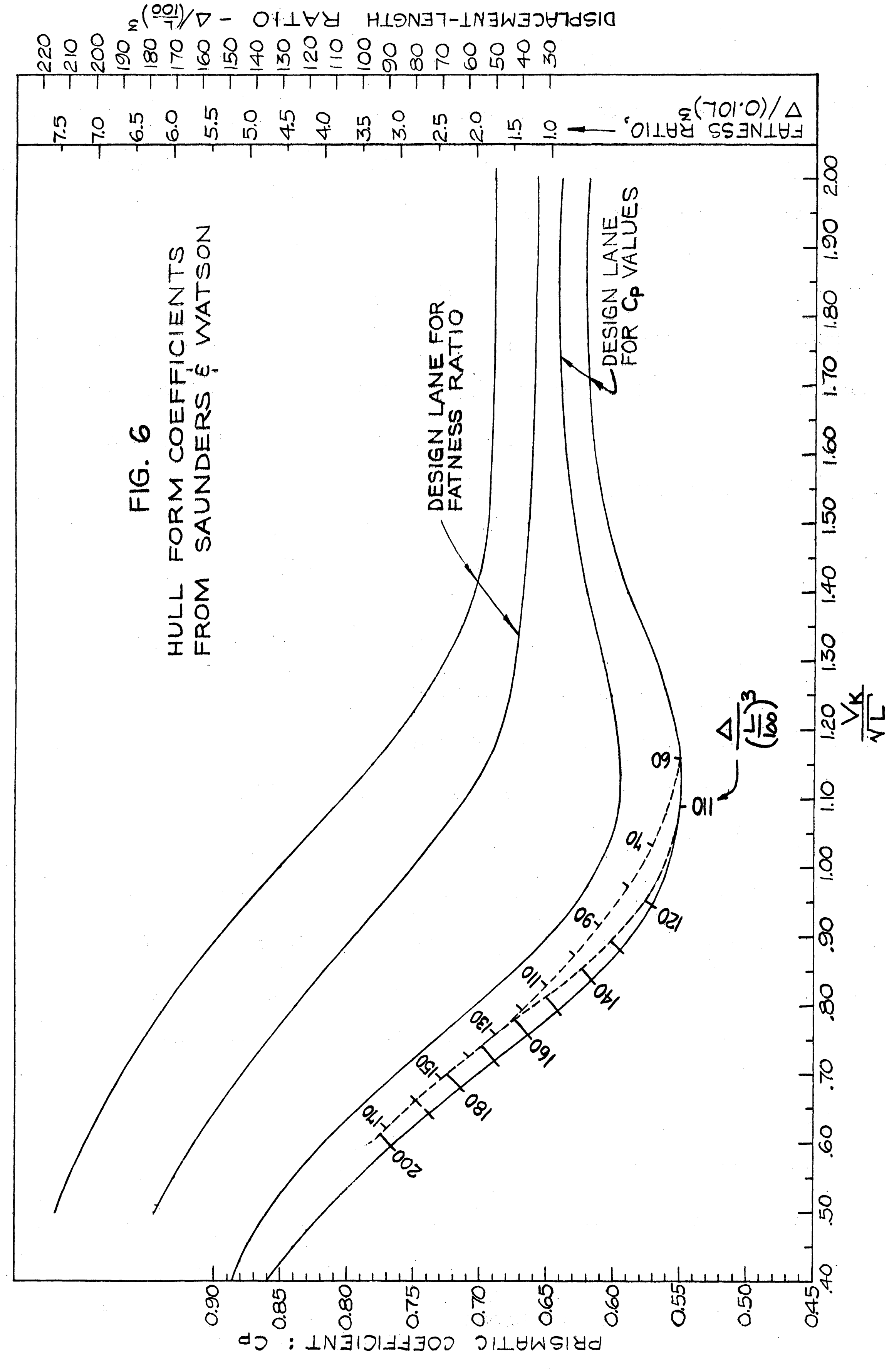


FIG. 6
HULL FORM COEFFICIENTS FROM SAUNDERS & WATSON

be made of the economically optimum C_P and $\Delta / (\frac{L}{100})^3$. It is probable that contours, rather than a single curve, of C_P vs $V/\sqrt{L}$ can be developed, each suitable to a given trade.

Speed and Power

Pending further studies, Figure 7 may be used to estimate speed and power for single screw merchant ships of normal proportions and fullness of form. The figure also contains contours of length based on the already discussed relationship:

$$L = 20.7 \left(\frac{V_K}{V_K + 2}\right) \Delta^{\frac{1}{3}}$$

Figure 8 may be used for speed and power estimation for twin screw merchant ships of normal proportions and fullness of form. Contours are derived from data taken from Reference , with an arbitrary increase of 17 percent to allow for twin rather than single screw propulsion (lower propulsive efficiency, greater appendage resistance).

Further studies are required to develop definite relationships between proportions and powering requirements. Such work, which could be based on the Series 60 results ( ), would allow economic analysis of varying proportions including hulls of rather abnormal design.

Cargo Handling

Cargo gear capacity should bear a direct relationship to the size of the cargo holds. Studies show that the following rough relationship exists:

$$\text{Pairs of cargo booms} \simeq 1 + 1.425 \times \text{Bale Capacity}/1000$$

FIG. 7 SINGLE SCREW SHIPS, APPROXIMATE RELATIONSHIP OF SPEED, LENGTH, DISPLACEMENT & POWER

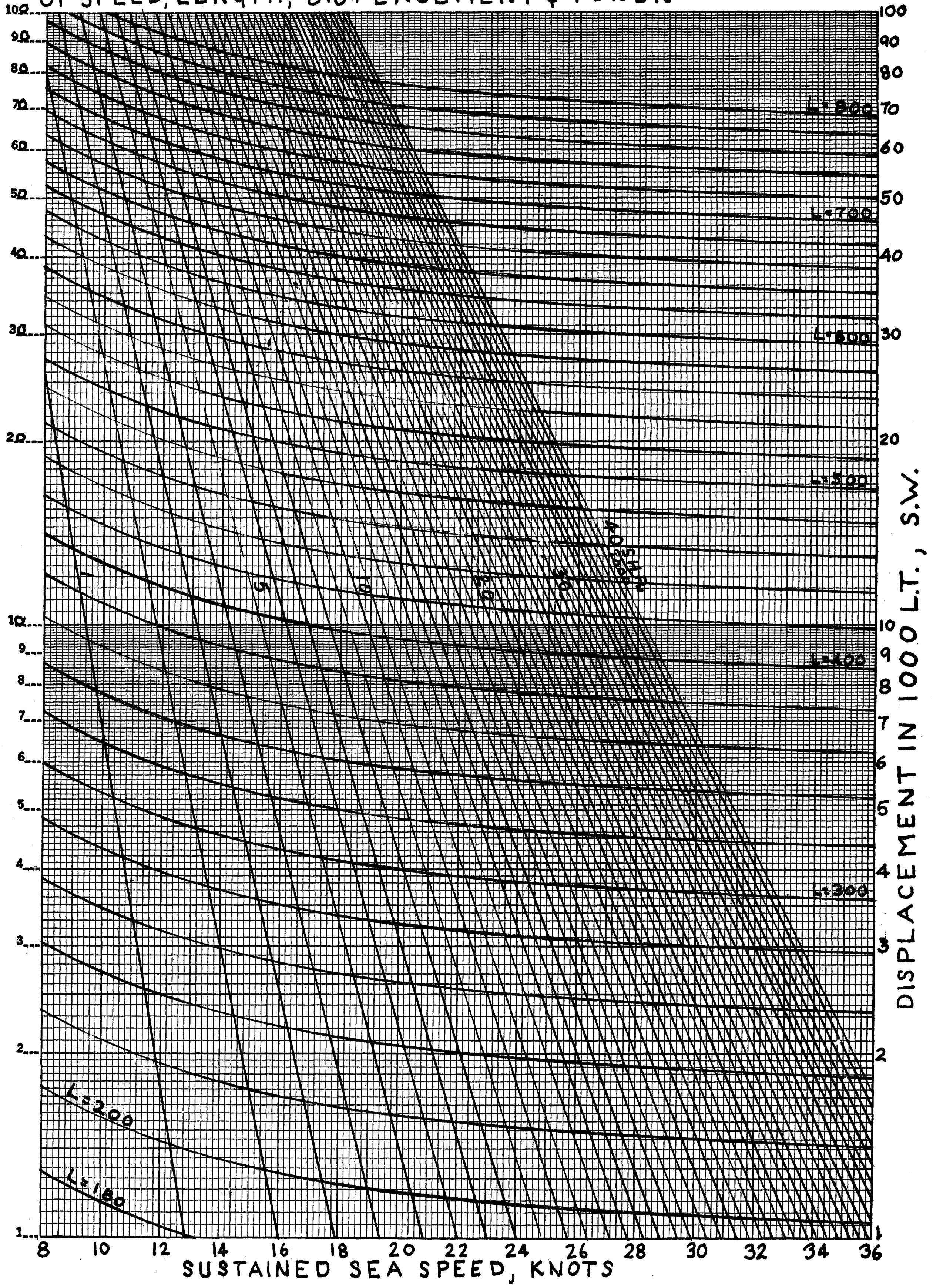
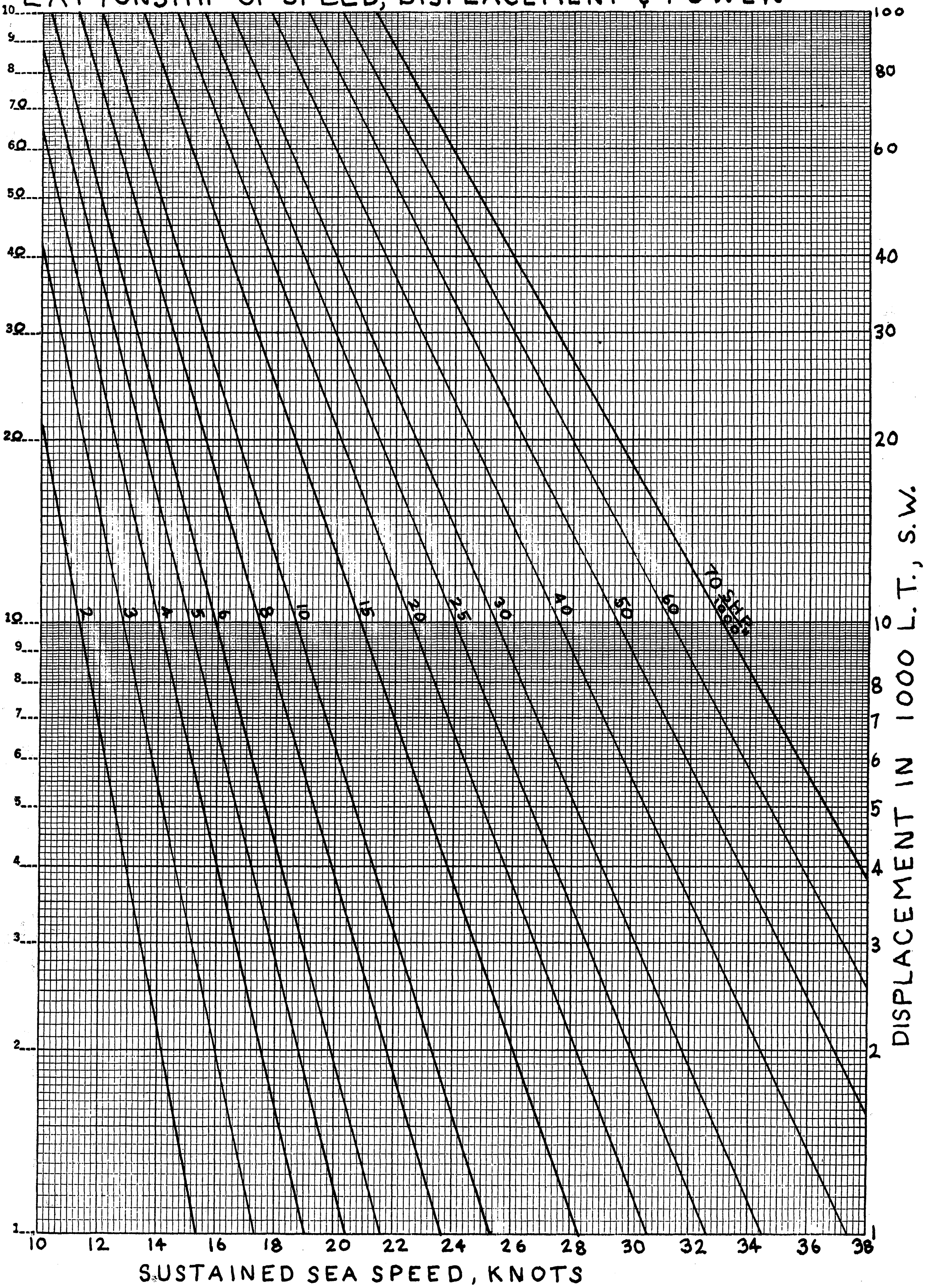


FIG. 8 TWIN SCREW SHIPS, APPROXIMATE RELATIONSHIP OF SPEED, DISPLACEMENT & POWER



WEIGHTS

Categories

For purposes of preliminary design, weights should be subdivided into a reasonably small number of groups. Considerable compromise is required here because of the following considerations:

1. For simplicity, the number of groups should be small; this inevitably leads to inaccuracies.

2. The weight breakdown must bear close relationship to that used by the various shipyards which supply factual data. These breakdowns are tied to history and contain many contradictions.

3. The same breakdown must also be suitable for calculating building costs, most of which are based on weights.

In this study, weights are divided into the four conventional categories: steel hull, outfitting, hull engineering (wet) and propulsion machinery (wet). The exact definition is that detailed by Watson in Chapter II (A)of Reference

Future studies might benefit from a complete reevaluation of the outfitting and hull engineering categories. The breakdown used here leaves much to be desired in its application to either weight or cost estimation.

Steel Hull Weights

Empirical analysis of many actual ships, leads to the following simplified expression for the net weight of the steel hull in long tons:

$$W_S = 340 \left(\frac{CN}{1000}\right)^{0.9} \times C_1 \times C_2 \times C_3$$

where CN = cubic number = $\frac{LBD}{100}$

$C_1 = 0.675 + 1/2\ C_B$

$C_2 = 1 + 0.36\ \frac{L_S}{L}$

$C_3 = 0.00585\left(\frac{L}{D} - 8.3\right)^{1.8} + 0.939$

and L = length between perpendiculars in feet

B = beam in feet

D = depth to uppermost continuous deck in feet

C_B = block coefficient at design draft

L_S = length of superstructure within fore and aft perpendiculars in feet.

A somewhat more rational, but usually less accurate, approach to steel weight estimation is based on freeboard rule requirements ( ) for section modulus of the hull girder. This method has the merit of automatically correcting for differences in scantling draft and is possibly superior in predicting steel weights of very large ships:

$$W_S = \left(12.85 - 0.786\ \frac{N}{1000}\right)N \times C_1 \times C_2$$

where $N = 1.11\ \frac{Bd}{D}\left(\frac{L}{100}\right)^{8/3}$ for $L > 200$

$N = 1.5\ \frac{Bd}{D}\left(\frac{L}{100}\right)^{9/4}$ for $200 > L > 160$

and C_1, C_2, L, L_S, B and D are as just defined and
d = scantling draft in feet.

Outfitting Weights

The weight of outfitting in long tons may be expressed as follows:

$$W_O = C_O \left(\frac{CN}{1000}\right)^{0.825}$$

where CN = cubic number = $\frac{LBD}{100}$

C_O = 170 in elaborate designs

= 125 in average designs

= 110 in austere designs

These relationships are arrived at empirically from data based on modern U. S. practice.

Hull Engineering Weights

The wet weight of hull engineering in long tons may be expressed as follows:

$$W_{HE} = C_{HE} \left(\frac{CN}{1000}\right)^{0.825}$$

where C_{HE} = 82 in elaborate designs

= 62 in average designs

= 53 in austere designs

(See comments under previous section).

Machinery Weights

Modern steam turbine propulsion machinery has weight characteristics which vary with the square root of the horsepower:

$$W_M = C_M \sqrt{\frac{SHP_N}{1000}}$$

where W_M = wet weight of propulsion machinery in long tons

SHP_N = normal installed shaft horsepower

C_M : See Table III for values.

TABLE III

VALUES OF MACHINERY WEIGHT COEFFICIENT, C_M

	Machinery Location	
Arrangement	Amidships	Aft
Single screw, average	247	225
Single screw, minimum	230	213
Twin screw, average	313	301
Twin screw, minimum	301	289

BUILDING COSTS

Categories

As a matter of convenience, building costs are put into the same subdivisions used in the weight analysis. The additional category of miscellaneous costs is appended to account for those direct costs, such as drafting, which involve no weight in the finished ship.

Steel Hull Costs

Material: Averages $220 per long ton of steel, net weight. This includes transportation and covers special shapes, welding rod, castings, forgings and a nominal quantity of aluminum as well as the regular shipbuilding steel.

Labor: Man-hours can be estimated as follows:

$$MH = C\left(\frac{W_S}{1000}\right)^{0.85}$$

C varies from 68 in a well equipped and efficient yard to 140 in an average small and inexperienced yard. In an average large yard, C will run around 90.

W_S = net weight of structural hull.

Outfitting Costs

Material: Costs per ton range from $720 to $1250 with an average of $980.

Labor: Man-hours may be estimated as follows:

$$MH = C\left(\frac{W_O}{100}\right)^{0.9}$$

C ranges from 15,000 to 27,500 with an average of 20,000

W_O = weight of outfit.

The above costs assume little or no subcontracting of joiner work, deck covering, etc.

Hull Engineering Costs

Material: Unit costs vary between \$2000 and \$3400 per ton, with an average of \$2700 per ton.

Labor: Man-hours can be estimated on the following basis:

$$MH = C\left(\frac{W_{HE}}{100}\right)^{0.75}$$

C ranges from 39 to 72 with an average of 51

W_{HE} = weight of hull engineering (wet).

Machinery Costs

Material: Costs can be estimated as follows:

$$\text{Material cost} \approx \$440,000\ \left(\frac{SHP_N}{1000}\right)^{0.6}$$

Labor: Man-hours can be estimated as follows:

$$MH \approx 25,400\ \left(\frac{SHP_N}{1000}\right)^{0.6}$$

Since both labor and material costs vary with the six-tenths power of the shaft horsepower, a simple expression for total cost of installed machinery may be arrived at as follows:

$$\text{Machinery Cost} \approx C\left(\frac{SHP_N}{1000}\right)^{0.6}$$

Assuming 70 percent overhead, 5 percent profit and \$3 per hour labor rate, C will come to \$630,000. If, in addition, miscellaneous costs are included, C will increase to \$690,000

The above figures are based on single screw geared steam turbine machinery located amidships. Certain other conditions can be estimated by application of the following coefficients to both material and labor costs (or total costs, if preferred):

Single screw aft	: 0.91
Twin screw amidships	: 1.27
Twin screw aft	: 1.24

Miscellaneous Costs

Many important costs involve work with which none of the ship's weight categories are concerned. These include drafting, purchasing, blueprints, scheduling, model tests, material handling, cleaning, launching, staging, drydock, tests and trials, insurances, classification, bond, patents and so forth.

On the average, the subtotal of material costs for steel hull, outfitting, hull engineering and machinery should be increased by ten percent for miscellaneous materials. Similarly, labor costs should be increased by 33 percent for miscellaneous direct labor.

Overhead Costs

Indirect costs are usually taken as a percentage of the direct plus miscellaneous labor costs. A good average figure is 70 percent.

Hourly Rates

For the year 1961, an average hourly rate, including a normal amount of overtime and piecework bonus, would be about $2.90. Looking to completion of this project in 1962, a rate of $3.00 will be assumed.

Profit

Profit is generally calculated as a percentage of the summation of all the material and labor costs, including overhead, although this method does not give a meaningful measure of return on stockholders' investment. The average markup is perhaps 7.5 percent in good times. In average times, five percent is more likely and that is the figure used in this study.

Duplicate Ship Savings

All of the above cost figures are based on a single ship contract and include drawings, templates, purchase orders and other non-recurring needs. In the case of multiple ship contracts, the cost per ship will be reduced according to the following relationship:

$$\text{Cost of Nth ship} = \frac{\text{Cost of single ship}}{N^x}$$

where N = number of identical ships

x is an exponent which varies from 0.055 to 0.145, with an average value of about 0.100.

These figures apply to normal merchant ships. Simple craft such as barges would have lower exponents, naval vessels would have higher. Also, an inexperienced yard should have a relatively high exponent because its labor force learns much from the first ship.

Summary of Building Costs

For ease of application, average values of more important costs factors are summarized in Table IV.

Additional Costs

In addition to the predicted shipyard bill, the owner should include about \$200,000 per design for naval architect's fee (on a subsidized vessel) plus his own expenses in connection with the newbuilding.

TABLE IV

SUMMARY OF AVERAGE BUILDING COST FACTORS

	Material		Labor (MH)	
	Direct	Direct + Misc.	Direct	Direct + Misc.
Steel Hull	\$220 W_S	\$242 W_S	$90(\frac{W_S}{1000})^{0.85}$	$120(\frac{W_S}{1000})^{0.85}$
Outfit	\$980 W_O	\$1080 W_O	$20{,}000(\frac{W_O}{100})^{0.90}$	$26{,}600(\frac{W_O}{100})^{0.90}$
Hull Eng.	\$2700 W_{HE}	\$2970 W_{HE}	$51(\frac{W_{HE}}{100})^{0.75}$	$68(\frac{W_{HE}}{100})^{0.75}$
Mach'y (S.S., [illegible])	$\$440{,}000(\frac{SHP_N}{1000})^{0.6}$	$\$484{,}000(\frac{SHP_N}{1000})^{0.6}$	$\$25{,}400(\frac{SHP_N}{1000})^{0.6}$	$\$33{,}800(\frac{SHP_N}{1000})^{0.6}$

W_S = Net weight of steel structure

W_O = Net weight of outfitting

W_{HE} = Net weight of hull engineering

SHP_N = Normal installed shaft horsepower

SCHEDULING AND OTHER OPERATING FACTORS

General

Any careful analysis of general cargo ship operations must face the complication of frequent operation at partial draft. There will also be variations in power utilization resulting from the combined influences of partial loading and maintenance of practical schedules. Changes in power utilization lead further to changes in fuel rate. Matters such as these are dealt with below.

Scheduling Requirements

(To be added)

Power Required for Speeds and Displacements Other Than Designed

Figures 9, 10 and 11 can be used to estimate the power required to maintain speed at displacements either above or below the design condition. They may also be used to estimate the power required at speeds other than the design speed and at displacements which vary from the designed value. Each figure contains a family of contours for each of three block coefficients. Three figures are required: one for over-powered ships, one for normally-powered ships and one for under-powered ships; that is, for ships which are relatively full, normal, or fine-lined, considering their speed-length ratios. These contours are derived from Reference

Fig. 9

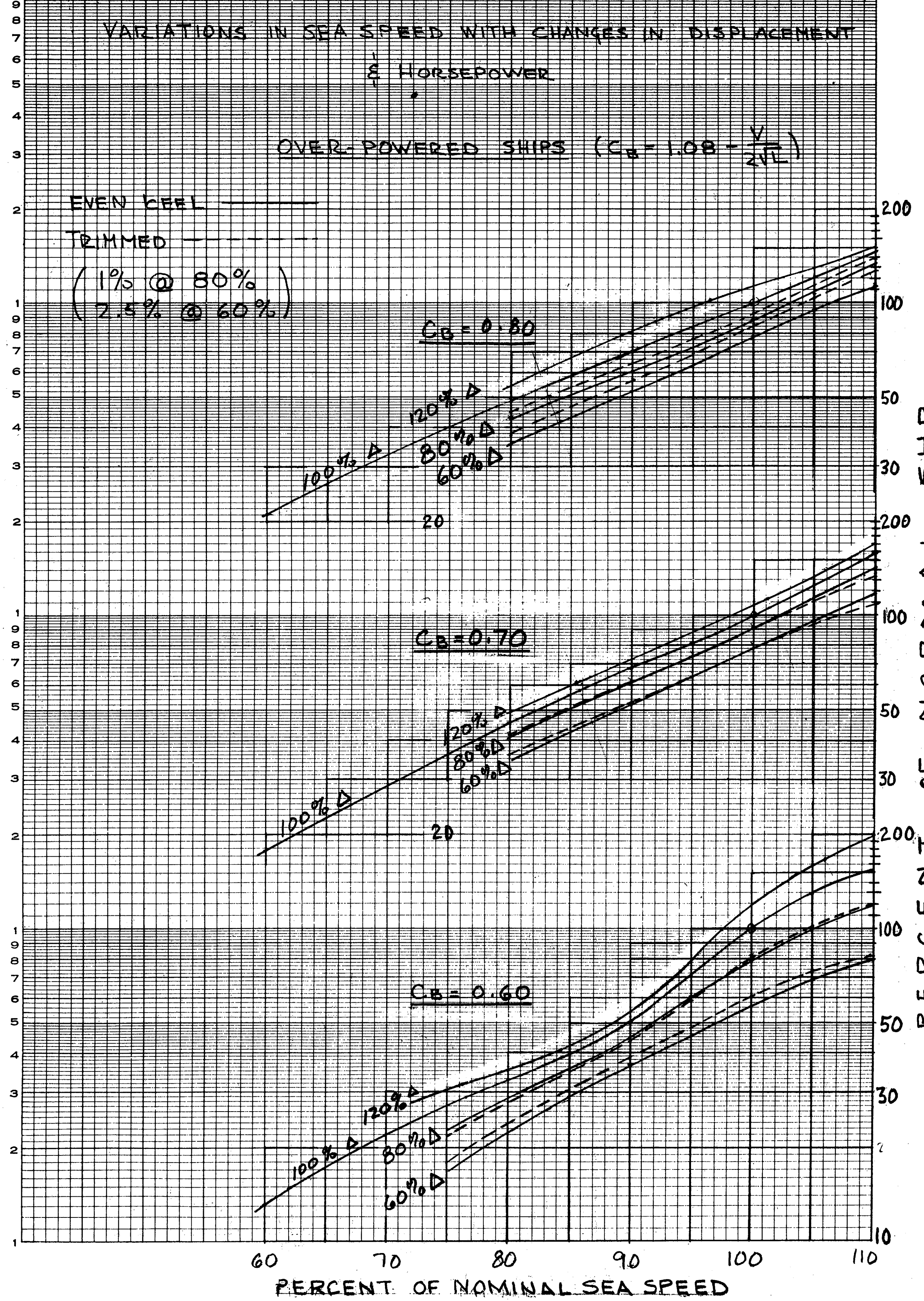

VARIATIONS IN SEA SPEED WITH CHANGES IN DISPLACEMENT
& HORSEPOWER
OVER-POWERED SHIPS ($C_B = 1.08 - \frac{V}{2\sqrt{L}}$)
EVEN KEEL
TRIMMED
(1% @ 80%
2.5% @ 60%)
$C_B = 0.80$
$C_B = 0.70$
$C_B = 0.60$
120% Δ
100% Δ
80% Δ
60% Δ
200
100
50
30
20
10
60
70
80
90
100
110
PERCENT OF NORMAL SHP
PERCENT OF NOMINAL SEA SPEED

FIG. 10

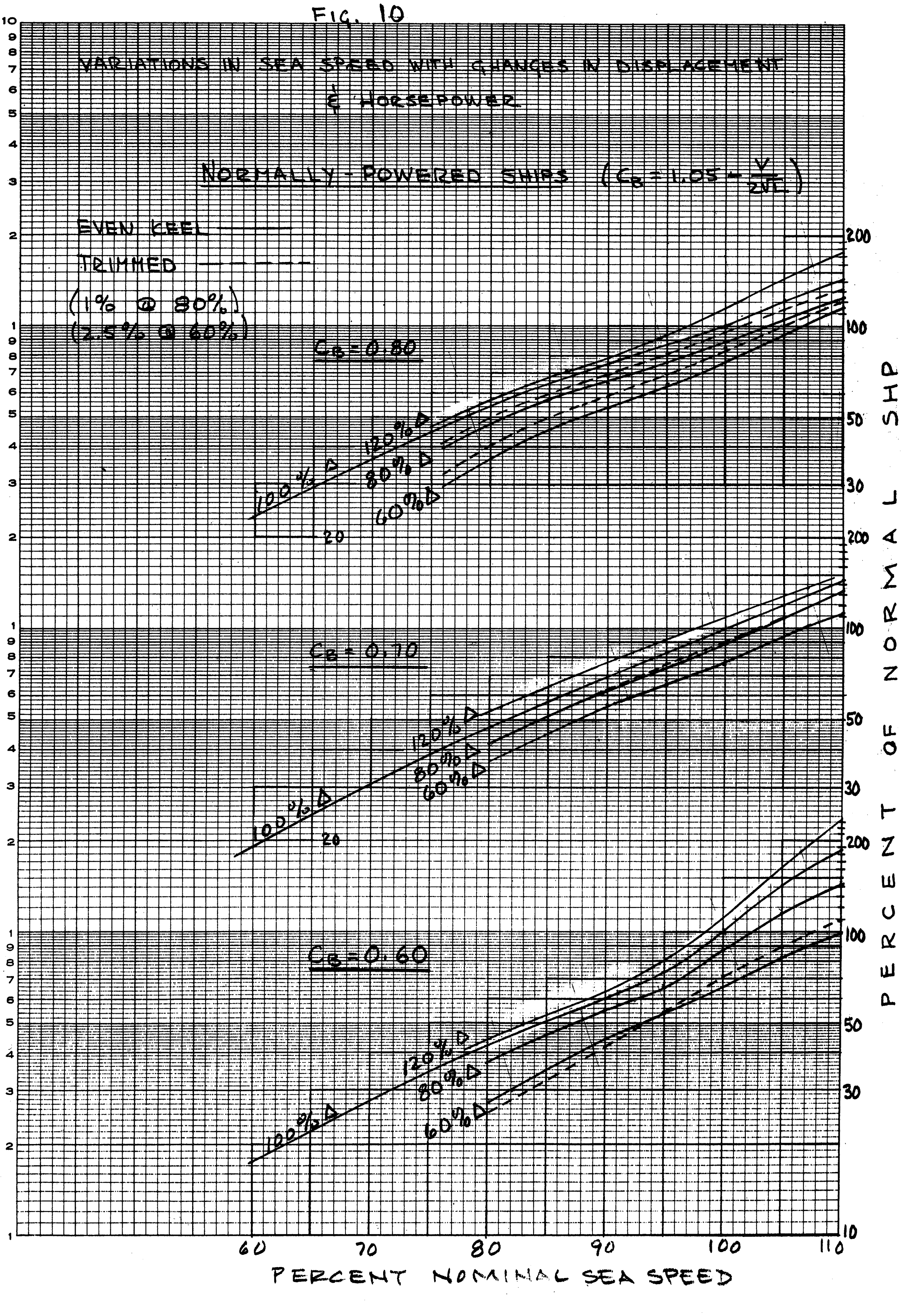
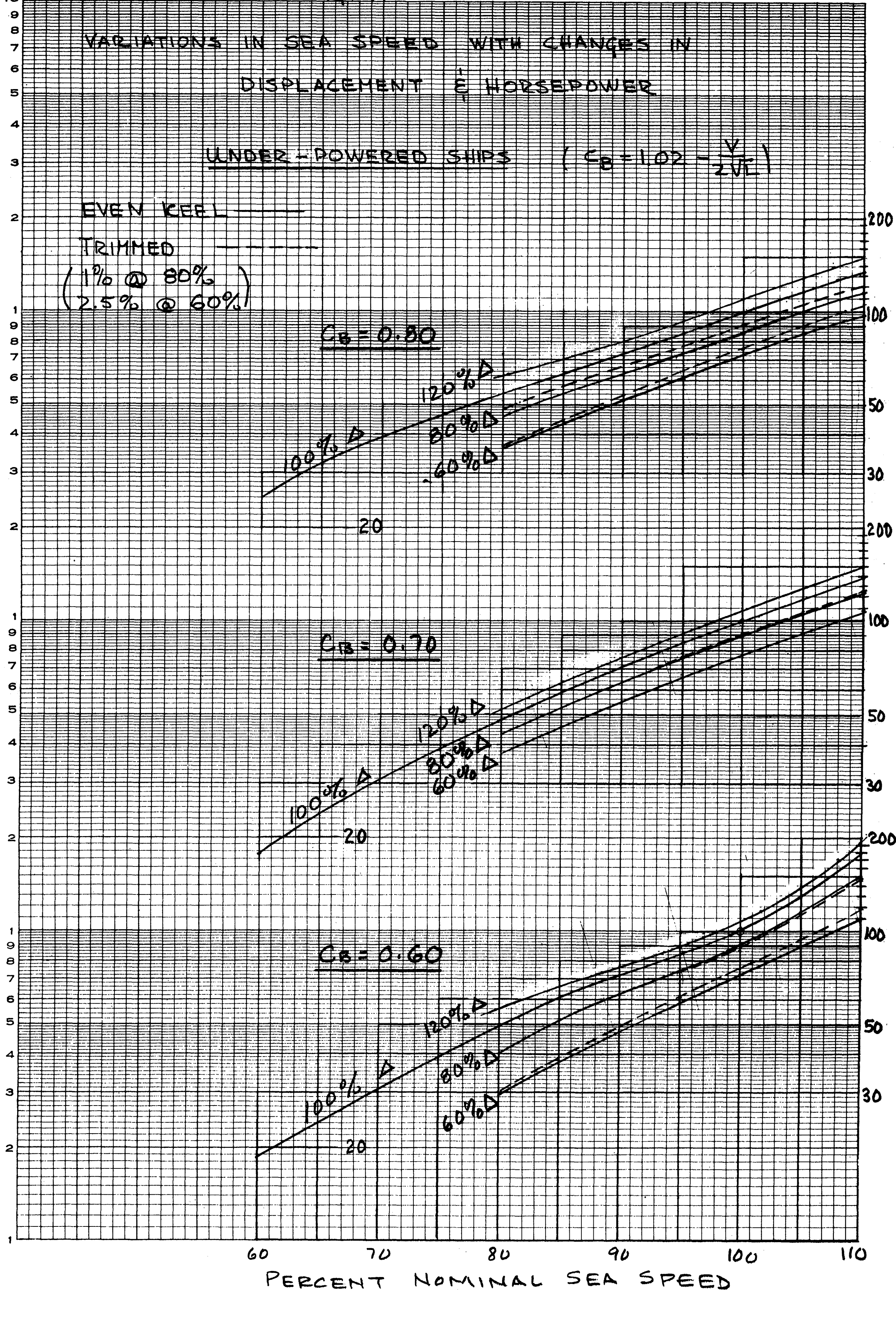

VARIATIONS IN SEA SPEED WITH CHANGES IN DISPLACEMENT & HORSEPOWER
NORMALLY-POWERED SHIPS ($C_B = 1.05 - \frac{V}{2\sqrt{L}}$)
EVEN KEEL
TRIMMED
(1% @ 80%)
(2.5% @ 60%)
$C_B = 0.80$
$C_B = 0.70$
$C_B = 0.60$
100%
120%
80%
60%
PERCENT OF NORMAL SHP
PERCENT NOMINAL SEA SPEED
60
70
80
90
100
110
200
100
50
30
20
10

FIG. 11


VARIATIONS IN SEA SPEED WITH CHANGES IN
DISPLACEMENT & HORSEPOWER
UNDER-POWERED SHIPS ($C_B = 1.02 - \frac{V}{2\sqrt{L}}$)
EVEN KEEL
TRIMMED
(1% @ 80%
2.5% @ 60%)
$C_B = 0.80$
$C_B = 0.70$
$C_B = 0.60$
120% Δ
100% Δ
80% Δ
60% Δ
PERCENT OF NORMAL SHP
PERCENT NOMINAL SEA SPEED
60
70
80
90
100
110
20
30
50
100
200

Fuel Consumption

Average modern marine steam turbine plants, when operated at designed power, should have normal all-purpose fuel rates close to those shown in Reference   for the 600 psi - 850^{o} F cycle, arrangement G. Converted to daily consumption, these are approximately equivalent to:

$$\text{Barrels per day} = 50 + 34.2\left(\frac{SHP_N}{1000}\right)$$

$$\text{Tons per day} = 8 + 5.18\left(\frac{SHP_N}{1000}\right)$$

In addition, for every ten tons of reefer and air conditioning capacity add 1.5 barrels or 0.226 long tons per day. Average large U. S. cargo liners require about 13 barrels or two tons per day for this purpose.

The above fuel rates should be modified when vessels operate at partial horsepower. Figure 12 and Table V may be consulted for correction factors which may be applied.

Port Fuel

(To be added)

Idle Status Fuel

(To be added)

Reserve Fuel

(To be added)

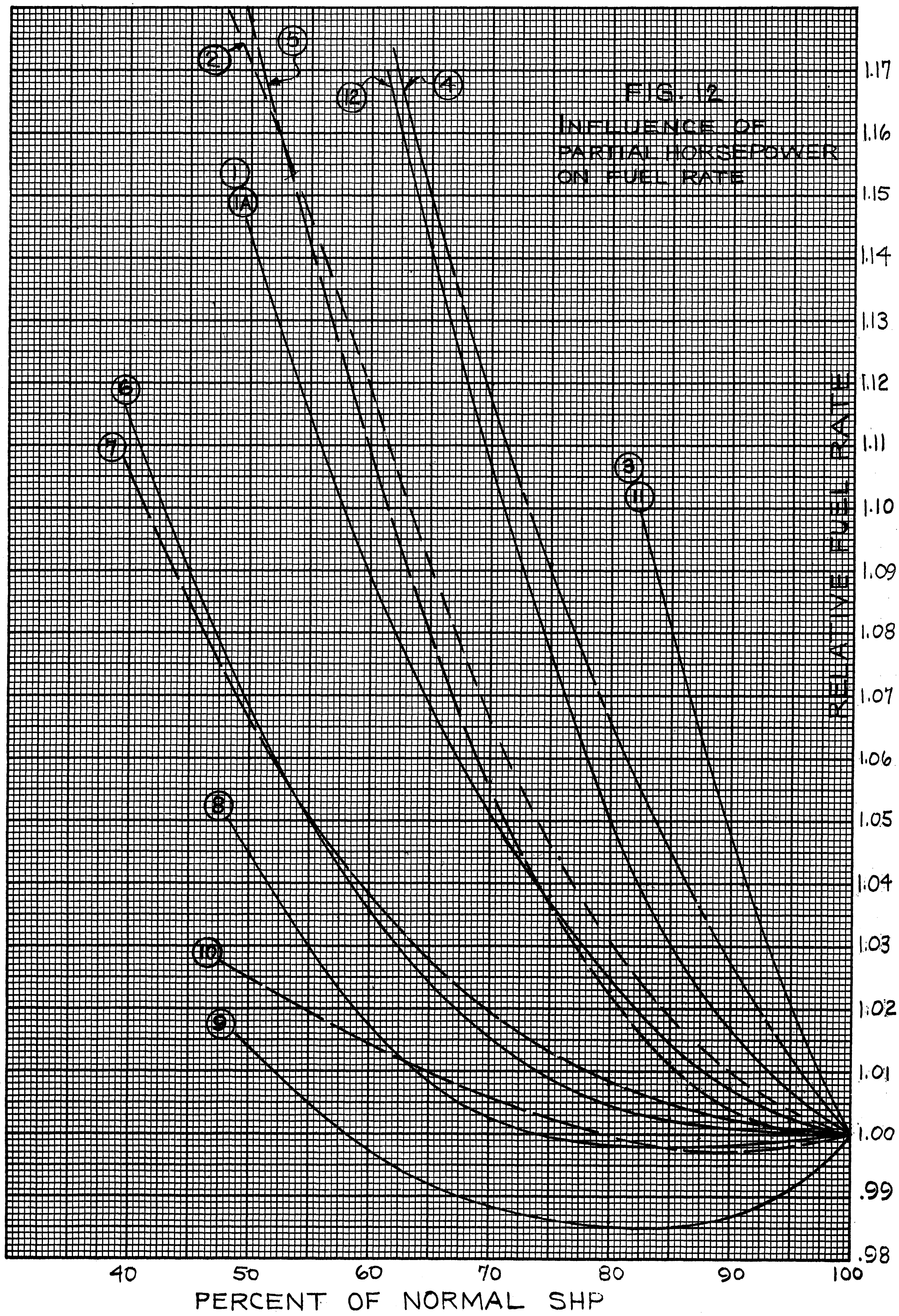


FIG. 12
INFLUENCE OF PARTIAL HORSEPOWER ON FUEL RATE
RELATIVE FUEL RATE
PERCENT OF NORMAL SHP
40
50
60
70
80
90
100
.98
.99
1.00
1.01
1.02
1.03
1.04
1.05
1.06
1.07
1.08
1.09
1.10
1.11
1.12
1.13
1.14
1.15
1.16
1.17
1
1A
2
3
4
5
6
7
8
9
10
11
12

Weight of Fresh Water, Stores and Supplies

(To be added)

TABLE V

EXPLANATION OF CURVES IN FIGURE 12

(1) Steam turbines, average values, Ref.

(1A) Steam turbine, 17,500 SHP, Ref. .

(2) Steam turbine, Ref. .

(3) Gas turbine, 6000 SHP, Ref. .

(4) Gas turbine (all purpose), 6000 SHP, Ref. .

(5) Gas turbine (propulsion only), 6000 SHP, Ref. .

(6) Gas turbine 3340 SHP, Ref. .

(7) Gas turbine 10,500 SHP, Ref. .

(8) Diesel (direct, geared, electric), average values, Ref.

(9) Diesel, 9200 BHP, direct, Ref. .

(10) Diesel, 15,000 BHP, direct, Ref. .

(11) Diesel, 6000 SHP, geared, Ref. .

(12) Free piston gas turbine, 6000 SHP, Ref. .

OPERATING COSTS

Wages

The first step in estimating wages is to figure the crew size. This is best done by department, and for each such division, actual practice varies widely among different operators. After careful study of all the available data, the following relationship is suggested:

$$\text{Total Crew} = C_{ST}\left[C_{DK}\left(\frac{CN}{1000}\right)^{1/6} + C_{ENG}\left(\frac{SHP_N}{1000}\right)^{1/5} + \text{cadets}\right]$$

If 12 passengers are carried, add two to the crew.

For diesel machinery, use:

$$C_{ENG}\left(\frac{BHP_N}{1000}\right)^{1/3}$$

Table VI lists appropriate values for the various coefficients. Use of the above method will usually yield answers involving fractional parts of crew members. This sounds silly but the fractions should be retained for subsequent application of average annual rates.

TABLE VI
CREW SIZE COEFFICIENTS

Item	Notes	Min.	Aver.	Max.
C_{ST}	(Steward's Department)	1.20	1.25	1.33
C_{DK}	(Deck Department)	11.5	13	14.5
C_{ENG}	(Engine Department)			
	Steam turbine, single screw	11	12	15
	Steam turbine, twin screw	13.75	15	16.5
	Diesel, single screw	8.5	10	11

Average wage costs per man have increased rapidly in recent years (while crew size has changed but little). This is the one cost factor which should certainly be projected to the ship's mid-life, say 15 years from the date of study. The probable changes in the other cost factors are so small that they are usually best ignored. Under current levels, the average annual total crew cost including fringe benefits but not subsistence is $10,000 per man. The writer's predicted level for 1976 is $16,000 per man (based on recent trends). This figure will be restudied when current labor negotiations are settled.

Subsistence

An average figure for annual subsistence costs is $770 per man.

Fuel

Fuel utilization has been discussed in a previous section. A good average figure for Bunker C is $2.50 per barrel or $16.575 per long ton.

Maintenance and Repair

Costs of maintenance and repair vary widely. Some trade routes involve more storm damage than others. Some owners assign much maintenance work to the crew, which disguises that cost under the heading of wages. Some owners are satisfied with lower standards of upkeep than others. Some hull forms are more prone to slamming damage, and so forth. This item, then, is one of the most difficult to analyze. For estimating purposes, the following approximations are suggested:

$$\text{Annual cost of Hull M \& R} \approx \$10{,}000 \left(\frac{CN}{1000}\right)^{2/3}$$

$$\text{Annual cost of machinery M \& R} \approx \$4{,}800 \left(\frac{SHP_N}{1000}\right)^{2/3}$$

Stores and Supplies

This category comprises paint, cleaning materials and lubricating oil Most of these items are essentially for maintenance and are applied by the crew. Hence the annual cost should be a function of the crew size (N_C). Analysis of many data points leads to the following approximations

For crews of 50 men or less:

$$\text{Annual cost of stores and supplies} \simeq \$80\left(\frac{N_C}{10}\right)^4$$

For crews numbering over 50:

Annual cost of stores and supplies

$$\$50{,}000 + \$4{,}000\ (N_C - 50)$$

where N_C = Number in crew.

Protection and Indemnity Insurance

Protection and indemnity insurance is carried to protect the owner against law suits, most of which arise from his own crew members. While rates are quoted on a gross tonnage basis, actual levels are more logically related to crew size:

Annual cost of P & I insurance $\simeq$ \$965 per crew member.

Hull and Machinery Insurance

Hull and machinery insurance may be estimated as follows:

Annual cost of H & M insurance $\simeq$ \$50,000 + 0.7% of invested cost.

War Risk Insurance

Annual war risk insurance can be taken as 0.1% of invested cost.

Miscellaneous Costs

(To be added)

Port Charges

(To be added)

Cargo Handling Costs

(To be added)

Port Fees and Commissions

(To be added)

PLANS FOR FURTHER WORK

The reader has probably noticed that many sections of this report consist simply of a title plus note that the subject matter will be developed later. Most such work is well underway but not yet ready for reporting. It is expected that these sections will soon be completed and made available in an addendum.

It is planned that the students will make a parametric study based on arbitrarily assigned combinations of displacement and power. These studies will aim at the production of several curves useful in preliminary design as well as in estimation of shipbuilding costs.

Current interest in shipboard automation is high and the study will deal with the influence of crew size on cost of accommodations and operating factors. Similarly, the impact of containerized cargo will also be studied. Other topics will no doubt suggest themselves as the work develops.

Finally, of course, the entire project will be summarized in a formal report which will be made available to the marine profession.