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A CASE STUDY OF THE EFFECT OF REDUCED SHIP SPEED AND OFF DESIGN OPERATION OF THE POWER PLANT ON THE NET EARNING RATE OF A STEAM TURBINE POWERED VLCC

Harald Rein*

The combination of greatly increased bunker fuel prices and low charter rates has resulted in increased interest in the means available for reducing the fuel bill of the VLCC. Many of these ships are operating at reduced speeds today for the purpose of fuel savings and cost reductions. A relatively detailed case study of a VLCC has been made in order to provide some guidelines as to when reduced speed operation of such a ship may result in lower costs and greater net annual returns. The problem is looked at both from the point of view of an oil company with its own fleet of tankers and that of a shipowner operating on the spot market.

It is shown that relatively significant savings can be made by slow steaming under certain economic conditions. The possible impact that the increased bunker prices may have on future marine power plant design, with respect to possible demands for better off design performance, is also briefly discussed.

NOMENCLATURE

B	—bunker price (bunker C oil)	\$/tonne
R	—daily running expenses of own ships, or rate of hire of chartered ships	\$/day
F	—cost of transportation per ton cargo	\$//tonne
D	—voyage distance, one leg	nm.
Dwt	—summer deadweight of ship	tonnes
C_S	—cargo capacity of ship	tonnes
K_W	—water and stores allowance	tonnes
S	—No. of ships in the oil company's fleet	
n	—No, of R/T per ship per year at the given ship speed	
V_L	—average ship speed, laden voyage	kn
V_B	—average ship speed, ballast voyage	kn
∇_L	—loss of ship speed, laden voyage, due to fouling of underwater hull	kn
∇_B	—loss of ship speed, ballast voyage, due to fouling of underwater hull	kn
SFC	—specific fuel consumption	kg/kWh
FC_L	—average fuel consumption, laden voyage	tonne/h
FC_B	—average fuel consumption, ballast voyage	tonne/h
FCP_L	—average fuel consumption, loading port	tonne/h
FCP_D	—average fuel consumption, discharge port	tonne/h
FC_W	—average fuel consumption, waiting for higher rates	tonne/h
P_L	—port charges loading port	\$
P_D	—port charges, discharge port	\$
Y_P	—total port time per round trip	days
Y_{OFF}	—average number of off-hire days per ship per year.	days
Y_V	—No. of days per round trip	days
Y_E	—No. of days in excess of normal for which surplus fuel must be provided (based on full service speed)	days
Y_X	—total number of days per year in which the oil company's own ships are chartered out	days
Y_W	—average number of waiting days per R/T holding out for higher rates	days
Z_T	—total amount of oil required to be transported	tonne/year
Z_O	—amount of oil carried by the oil company's own fleet at a given ship speed	tonne/year
Z_{OD}	—amount of oil which can be carried by the oil company's own fleet at full service speed	tonne/year
Q	—net annual return for a ship (interest and depreciation not deducted)	\$/year
ΔQ	—loss of net annual return	\$/year
SFC^{*}_{TI}	—specific fuel consumption of tanker T1 at full service speed	kg/kW
T_{INF}	—temperature at inlet to the main turbine control valve	°C
P_{INF}	—pressure at inlet to the main turbine control valve	bar
P_{CON}	—pressure in main condenser	mbar
λ	—boiler excess air ratio	

INTRODUCTION

General

With the trebling of bunker fuel prices at the end of 1973 the percentage of the total costs representing fuel costs between ports for a VLCC rose very significantly. Consequently the variations in bunker prices and fuel rates now have a much greater influence than before on the costs of operating the ship and on the net annual return. Before December 1973 fuel costs were at a level where variations in charter rates would hardly ever have an effect on the optimum ship speed which would always be the full service speed of the ship. The situation today is different. In the past three years many shipowners and oil company controlled tanker companies have resorted to reducing the speed of their large crude oil carriers in order to reduce costs. What has characterized the situation in this period is a high fuel price level and charter rates generally equal to or below the break even point of the operating costs.

The objective of the study described in this paper was to examine in more detail the economic conditions which must prevail for reduced speed operation of existing VLCC to

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* Det Norske Veritas

become of interest. It is clear that even if optimum ship speeds below the normal fuel service speed may be seen to exist under certain economic conditions it is equally important to determine the magnitude of the savings to be made by reducing ship speed, i.e. the degree of significance must be established. For this reason results are presented which show how costs and net annual return vary with ship speed under various economic conditions rather than simply what the optimum speeds are under the same conditions.

THE POWER PLANT

Performance characteristics

Every VLCC has its own performance characteristic both with respect to hull and propeller and with respect to machinery. There are important differences between the fuel-speed characteristics of diesel ships and steam-turbine ships, between turbine ships with reheat and non-reheat power plants, and there are even significant differences between ships in the latter category (non-reheat) due to variations in system configurations and component efficiencies. Therefore, it would not be possible to employ in a study such as this, a set of hull and machinery characteristics which are generally representative of all VLCC. Instead the study is based on the use of the performance characteristics of a particular VLCC with a conventional turbine power plant. This has the advantage that the characteristics refer back to a real ship which is important because it brings out interesting points that are either missed or ignored when more generalized smooth characteristics or averages are used.

The ship selected to serve as a basis for this case study has a power plant which is not necessarily typical of VLCC with conventional steam turbine plants. However, the plant is interesting because it serves to illustrate the consequences of a fairly common plant design philosophy with respect to part load operation of the plant. Although the results obtained are truly representative of this particular ship only it is fairly easy to extend the results also to other VLCC including those with diesel machinery. Most of the conclusions that can be drawn apply equally well to all such ships and the methods used are of course generally applicable to virtually all types of tankers.

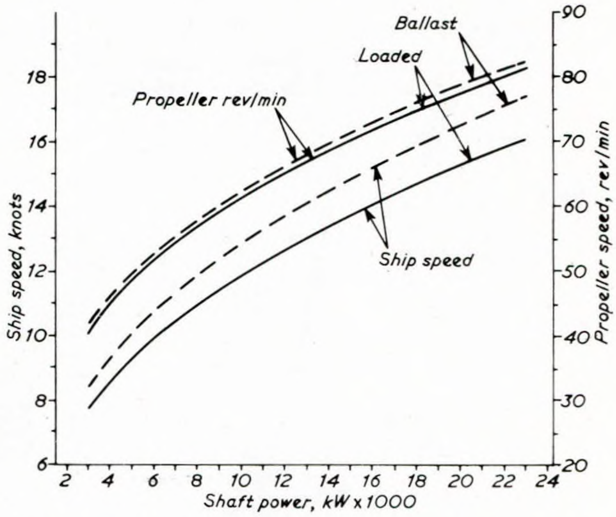


Fig 2—*Hull and propeller performance characteristics*

MACHINERY AND HULL PERFORMANCE CHARACTERISTICS

Hull and propeller performance

In the analysis it has been found convenient to separate the machinery performance characteristic from the performance characteristics of the hull and propeller. The latter characteristics are represented by the ship speed versus shaft power curves seen in Fig. 2. There are two such curves, one for the laden condition of the ship and one for the ballast condition.

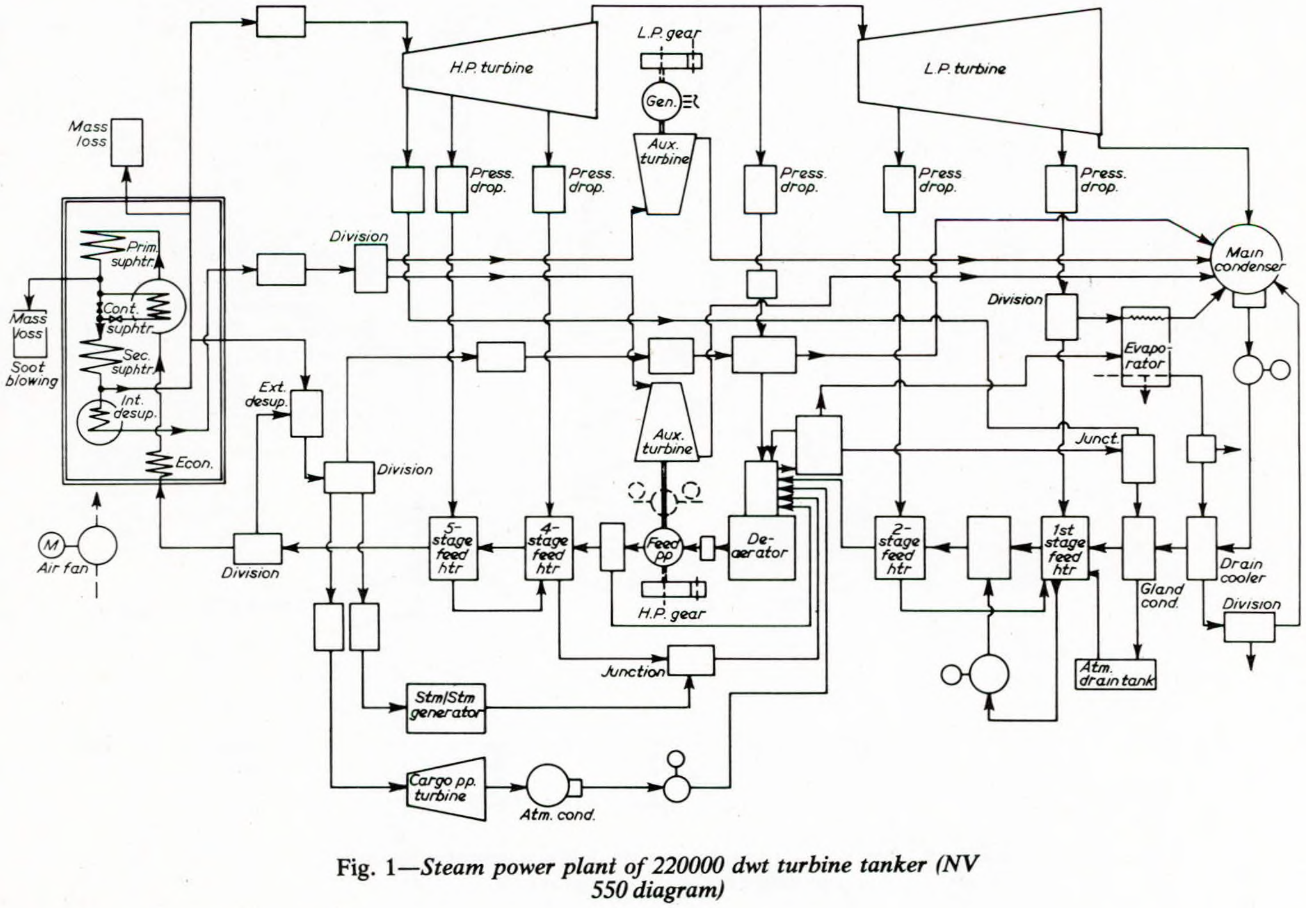


Fig. 1—*Steam power plant of 220000 dwt turbine tanker (NV 550 diagram)*

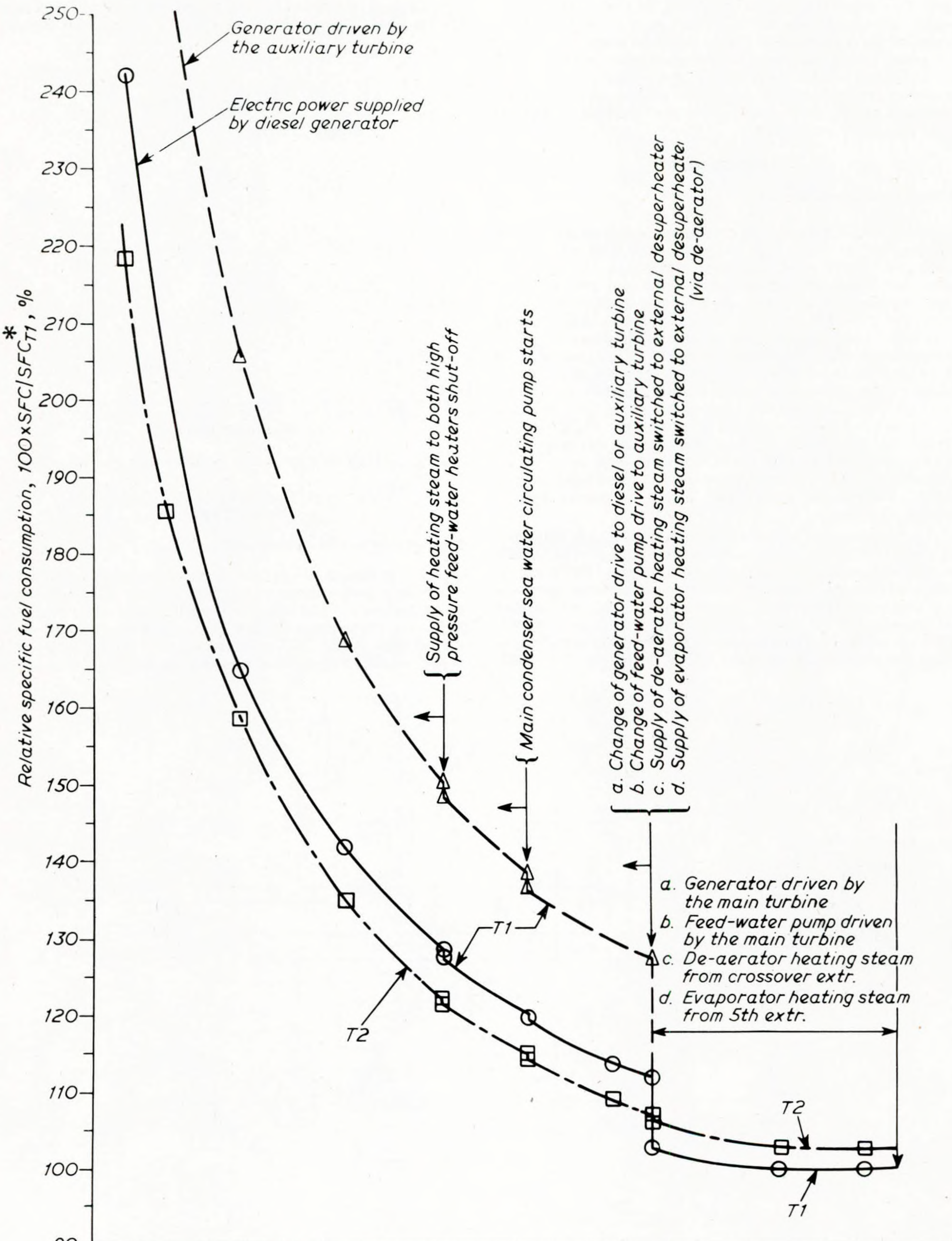


Fig. 3—*Percentage change in specific fuel consumption relative to design value of power plant T1*

Corresponding curves for propeller speed versus shaft power are shown in the same figure since revs/min are occasionally referred to in the paper, but these characteristics are not required for the execution of the economic analysis.

The ship speed versus horsepower characteristics were first obtained from model test data and were later modified to agree with speed trial data. These curves therefore represent the "as new" condition of the ship.

Machinery performance

The specific fuel consumption curves was calculated by means of a DnV computer program used for heat balance calculations of marine steam power plants. The program, called NV550, has a flexible, modular structure which makes it well suited for studies of various system arrangements in order to determine their relative merits in terms of specific fuel consumption.

The various component performance data used as input to the program is believed to be relatively accurate at high and medium powers but is possibly much less accurate at the very low powers. Fortunately, any inaccuracy at the low power end of the fuel consumption curve is of minor consequence for the conclusions that can be drawn from the analysis.

The same specific fuel consumption characteristic has been applied both for the loaded and the ballast condition of the ship. In reality there are slight differences between the characteristics under these two conditions, but these differences have been ignored rather than complicate the analysis by using separate curves. Under conditions of the same power output fuel consumption is virtually identical for the two conditions, but there are slight differences in propeller rev/min which will move the occurrence of the changeover of modes of operation for some components to fractionally lower shaft powers.

Under full power conditions the specific fuel consumption is of the order of 270 g/kWh which means that in terms of design speed fuel consumption the machinery rates among the very best steam turbine power plants of the non-reheat type. It is emphasized that this number is based on the various manufacturers' performance curves rather than actual measurements. Some ship data is given below referring to design conditions and full service speed.

Ship deadweight	220 000 dwt
Shaft power	22 900 kW
Propeller speed	81 rev/min
Full service speed, laden	16 kn
Full service speed, ballast	17·1 kn
Main turbine inlet temperature	510 °C
Main turbine inlet pressure	59·6 bar
Condenser pressure	50·7 mbar
Inlet temperature, auxiliary turbines	288 °C
Inlet pressure, auxiliary turbines	42·4 bar
Boiler excess air	5 per cent
De-aerator pressure	5·7 bar
Specific fuel consumption	270 g/kW h

Changes in modes of operation

We observe in the specific fuel consumption curve that as ship speed is reduced there are sudden increases in the fuel consumption at certain points in the curve due to changes in the mode of operation of some components. The curves marked T1 refer to the power plant shown in Fig. 1. The curve marked T2 refers to an assumed, modified version of the same power plant.

The most dramatic change in specific fuel consumption of power plant T1 occurs at the point where power drive of the generator and the feedwater pump is shifted from the main turbine to the auxiliary turbines. The changes in modes of operation at this point is governed by the following effects:

a) generator drive is shifted to the generator's auxiliary turbine due to the fact that the lower speed limit (73·6 rev/min) has been reached at this point;

b) feed pump drive is shifted to the feed pump's auxiliary turbine due to the fact that the necessary pressure difference between the boiler drum and the pump discharge can no longer be maintained at the reduced speed of the high pressure turbine;

c) supply of heating steam to the de-aerator is switched from the primary to the secondary supply due to the fact that the pressure in the crossover extraction has fallen below the lower pressure limit (4·4 bar) set for the de-aerator; the crossover extraction here represents the primary supply and the external desuperheater the secondary supply;

d) supply of heating steam to the evaporator, which has a condensate cooled distillate cooler, is switched from the primary supply to the secondary supply due to the fact that the pressure in the fifth extraction of the main turbine has fallen to a level where it is unlikely that it will be able to develop enough heating steam to sustain the average necessary fresh water requirements. The fifth turbine extraction represents here the primary supply and the external desuperheater the secondary supply.

All the above mentioned changes in modes of operation may not necessarily occur at exactly the same point, but the propeller speeds at which they are likely to occur were so close that it was found convenient to show them taking place simultaneously.

Most of the increase in specific fuel consumption at this point is due to the very low thermodynamic efficiencies of the auxiliary turbines compared to the thermodynamic efficiency of the main turbine. Also, the steam temperatures and pressures at inlet to the auxiliary turbines are much lower than they are at inlet to the main turbine which has a negative effect on overall plant efficiency.

Both auxiliary turbines are single stage Curtis turbines and both exhaust directly to the condenser. They are thus operating under much larger pressure drops than they are primarily designed for, and consequently have very low efficiencies. Clearly these turbines are intended for use under manoeuvring operation of the ship only, in which case the specific fuel consumption is relatively unimportant since the time spent by the ship manoeuvring constitutes only a small fraction of the total operating time of the machinery.

However, in this case we are concerned with the specific fuel consumption of the machinery under continuous operation of the ship at reduced ship speeds. It is seen then from the curves in Fig. 3 that using the diesel generator rather than the turbogenerator represents a better alternative for power plant T1 under continuous operation at ship speeds below 14·3 kn. In the economic analysis this is therefore the characteristic that has been used as representing the machinery performance of the ship. It will be noted that the fuel consumption of the diesel generator is included in the total for the curve after first scaling up the diesel generators fuel consumption by a factor of approximately 1·5 to take into account the difference in price between heavy fuel oil and diesel oil.

Power plant T2

Power plant *T2* is identical to T1 with the exception that both single stage auxiliary turbines have been replaced by more efficient multistage turbines. The thermodynamic efficiencies of these turbines are assumed to be of the order of 60 per cent to 68 per cent under design condition. This is still well below the efficiency of the main turbine but several times better than the efficiencies of the auxiliary turbines in power plant *T1*.

Both auxiliary turbines take steam from the boiler at the same steam conditions as exists at inlet to the main turbine. The generator turbine still exhausts to the main condenser while the feed pump turbine exhaust to the medium pressure system delivering steam to the de-aerator. The fuel consumption curve of this system has been included in Fig. 3 to demonstrate that there are quite significant differences in the fuel consumption of various plants at off design conditions depending on the type of arrangement and selection of components. It has been assumed here that in this plant there is no facility for coupling the generator and feed pump to the main turbine under full power conditions. This results in somewhat higher specific fuel consumption at full load than for T1. However, in principle there is no reason why even this plant could not run with the generator and feed pump coupled to the main turbine in the 70 per cent to 100 per cent power range except that the capital investment costs would be rather high.

ECONOMIC ANALYSIS

General

Two principal cases are looked at in this analysis which is aimed at establishing the economic conditions under which reduced speed operation of VLCC may result in reduced costs or increased earnings. The two cases are as follows:

a) an oil company with its own fleet of ships requires to transport a given amount of oil annually between the port of Mena Al Ahmadi in the Arabian Gulf and the port of Rotterdam, Europe;

b) a shipowner operating on the spot market with a VLCC between the same two ports and on a regular basis, who is able to obtained a given charter rate that the market holds.

Fig. 4 shows the rate of fuel consumption per nautical mile for the ship used in this analysis (i.e. *T1* with diesel generator). Below ship speeds of 10 kn the component data available is generally too inaccurate to permit a correct determination of the minimum point on the curve. However, it is likely that this minimum point will occur somewhere between 6 and 8 kn. For ships of this size a speed of about 8 kn is normally considered the minimum for maintaining adequate manoeuvring control. If the objective of this exercise was to minimize total oil consumption per tonne cargo carried by existing VLCC this would then be the optimum speed. It would also be the optimum speed of a VLCC returning to the Arabian Gulf from Europe with little or no prospects of obtaining a charter until some time after it had arrived.

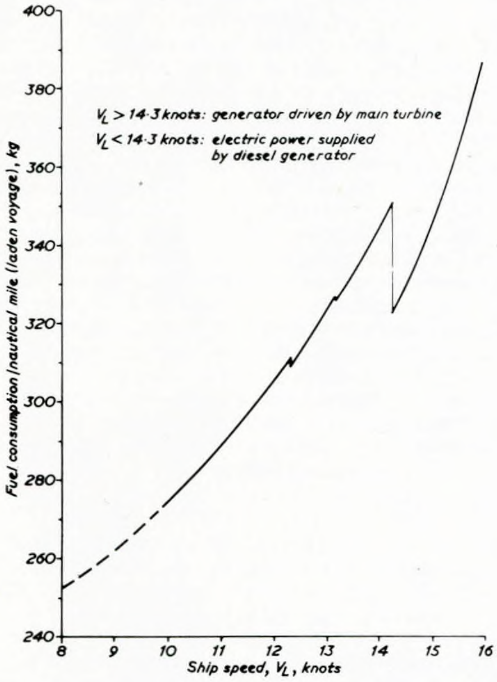


Fig. 4—*Fuel consumption per nautical mile versus ship speed*

However, in a normal situation this speed is far too low to represent the optimum in terms of costs per ton cargo or in terms of net annual return. To evaluate costs per tonne cargo on a per trip basis the following equation is used:

$$F = \frac{(P_L + P_D + B \cdot K_1 + Y_P \cdot R) + D \cdot \frac{R}{24} \cdot \left(\frac{1}{V_L} + \frac{1}{V_B}\right) + D \cdot B \cdot \left(\frac{FC_L}{V_L + \nabla_L} + \frac{FC_B}{V_B + \nabla_B}\right)}{Dwt - \left[FC_L\left(\frac{D}{V_L} + 24 Y_E\right) + 24 \cdot FCP_L \cdot \frac{Y_P}{2} + Kw\right]} \tag{1}$$

where $K_1 = \frac{Y_P}{2} \cdot 24\left(FCP_L + FCP_D\right)$

(Note: F represents only operating costs, not capital costs, interests and depreciation)

Each ship is assumed to spend an equal number of days in discharge and loading ports and the rate of fuel consumption in the loading port equals approximately 25 per cent of the fuel consumption rate at full service speed; the corresponding rate for the discharge port has been set at 50 per cent;

The effect of hull fouling is not studied in this analysis and ∇_L and ∇_L have therefore been set to zero throughout when the cost function F is being calculated;

The total trip costs can be divided into three fractions each represented by one of the three terms in the numerator of equation (1). There the first term represents total port costs including the cost of consumed fuel and daily running expenses. These costs are constant on a single trip basis but changes in ship speed will influence the frequency of port calls which means that these costs will vary on an annual basis.

The second term represents the total running expenses per trip between ports. These costs will vary with ship speed on a per trip basis but on an annual basis will remain constant as long as the ship is not laid up. Thus, on an annual basis these costs cannot be influenced by varying ship speed.

The third term represent the total fuel costs between ports and these costs will vary considerably with ship speed as can be deduced from Fig. 4. The distribution between these costs as ship speed is varied is shown in Fig. 5. The curves are based on current nominal values of bunker fuel prices and daily running expenses. The curves have been extended to show the influence on the cost distribution of increases in the price of bunker oil.

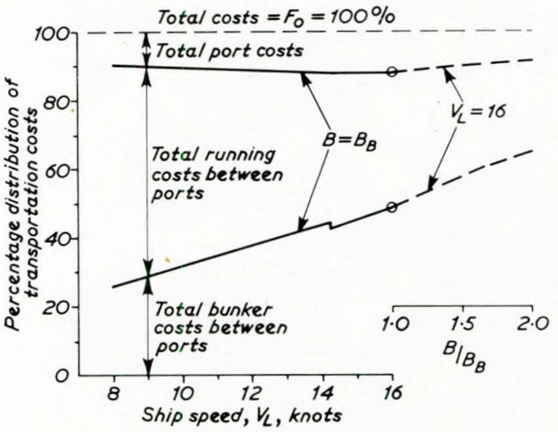


Fig. 5—*Percentage distribution of transportation costs.*

Fig. 6 shows how the cost function, *F*, varies with ship speed for various bunker prices. The curves show that minimum costs to occur at a ship speed of 14·3 kn. However, one should not be mislead to accept this as an optimum speed. Costs as well as net annual return must be optimized on an annual basis rather than on a per trip basis. Let us now therefore consider the two cases separately.

Case a): Oil company with own fleet of ships

The oil company requires a fixed annual amount of oil, Z_T to be transported from AG to Europe. The oil will in part be transported by the company's own fleet of ships and in part by ships available for charter on the tanker market. The latter ships are available at a rate F_H ($/ton cargo) while cost of transportation by own ships is calculated according to equation (1). By reducing the ship speed of the own ships less cargo is carried by the own fleet and this reduction in capacity must then be balanced by letting a greater share of the total requirement be carried by chartered ships.

The parameters which will have the greatest effect on the optimum speed of existing ships under these circumstances are bunker prices and charter rates. Both these parameters have been varied systematically in the analysis. The annual oil requirement Z_T relative to the transportation capacity of the own fleet of ships operating at full service speed has also been varied in order to determine the influence of that parameter too.

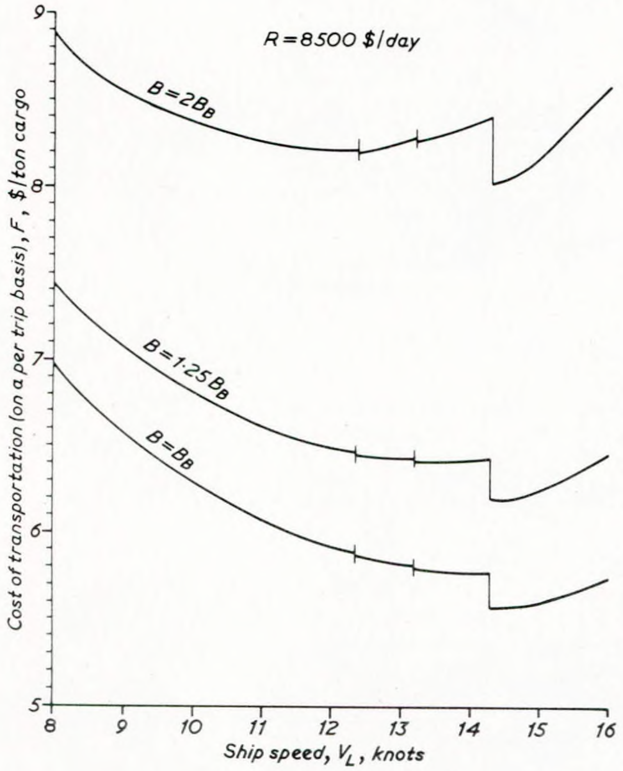


Fig. 6—*Costs of transportation per tonne cargo on a per trip basis.*

For calculation of transportation costs of own ships, by substitution of values into equation (1), the following values have been used:

$R = R_O$ = 8500 $/day
D = 11293 n.m.
K_W = 300 tonnes
Y_E = 4 days
S = 8 ships
Y_P = 4 days
P_L = 30000 $
P_D = 70000 $
Dwt = 220 000
Y_{OFF} = 15 days

Most of the data has been taken from Ref. 1 but only nominally correct values have been used. R_O is here the daily running expenses of the own ships. All eight ships in the fleet are assumed to be identical sister ships. Total transportation capacity of this fleet per year operating at full service speed between the Arabian Gulf and Europe is approximately 10 x 106 tonnes, i.e. $Z_{OD} \simeq 10 \times 10^6$ tonnes. The average bunker price is varied in terms of a basic bunker price, B_B, which nominally represent the current price. It has been set equal to 72 $/tonne fuel. For convenience a fixed relationship has been assumed to exist between V_L and V_B which is such that both speeds corresponds to very nearly the same shaft power.

i.e. $V_B = 1.08 \cdot V_L$ (2)

except when $V_L > 15{\cdot}83$ kn when the maximum speed in ballast of 17·1 kn is retained.

When, at a given ship speed, own ships have a greater transportation capacity than that required to carry the amount Z_T, it is assumed that for the remaining time of the year they are chartered out at the same rate as when the oil company is itself hiring ships.

Let F_T = total costs of transportation per tonne cargo (Z_T) required annually, $/tonne cargo
F_O = costs per tonne cargo carried by the own ships, $/tonne cargo
F_H = costs per tonne cargo carried by ships available for chartering, i.e. the replacement costs of the own ships, $/tonne cargo
Y_X = total number of days per year that the own ships will be chartered out, due to surplus transportation capacity at the given ship speed

In calculating total transportation costs one has to distinguish between two cases:

i) $\underline{Z_O < Z_T}$

(insufficient transportation capacity in own fleet)

then $Z_T \cdot F_T = Z_O \cdot F_O + (Z_T - Z_O) \cdot F_H + S \cdot R_O \cdot Y_{OFF}$

$$\text{i.e. } F_T = \frac{Z_O}{Z_T} \cdot F_O + \left(1 - \frac{Z_O}{Z_T}\right) \cdot F_H + Y_{OFF} \cdot \frac{S \cdot R_O}{Z_T} \quad (3)$$

where $Z_O = S \cdot n \cdot C_S$

ii) $\underline{Z_O > Z_T}$

(surplus transportation capacity available in own fleet)

then $Z_T \cdot F_T = F_O \cdot Z_T - Y_X \cdot (R_H - R_O) + S \cdot R_O \cdot Y_{OFF}$

$$\text{i.e. } F_T = F_O - Y_X \left(\frac{R_H - R_O}{Z_T}\right) + Y_{OFF} \cdot \frac{S \cdot R_O}{Z_T} \quad (4)$$

It is clear that this latter case can only occur when Z_T is less than Z_{OD}

R_H represent here the daily rate of hire charges ($/day) and it can easily be converted to either an equivalent Worldscale rate (W) or a time charter rate.

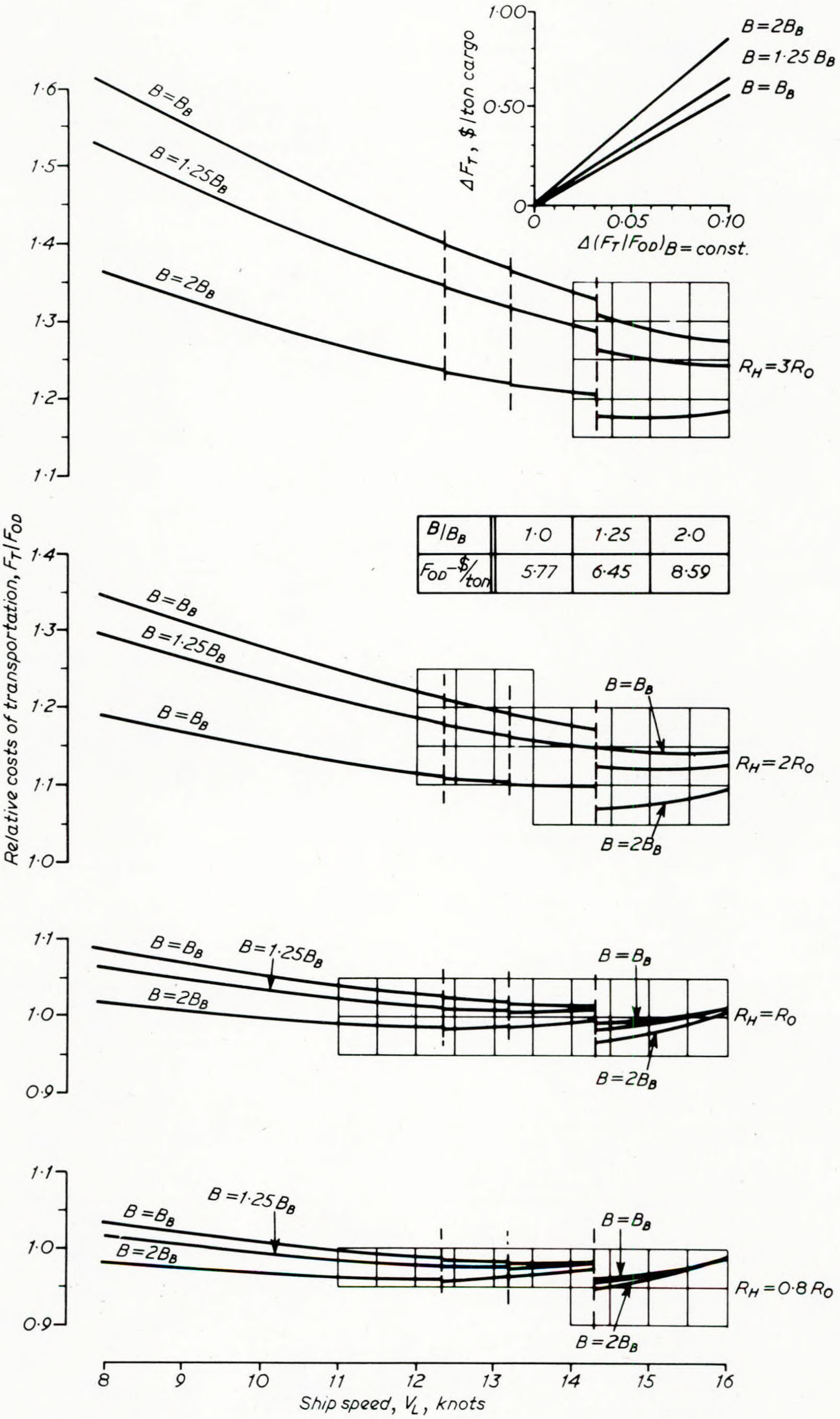
The variables R_H and F_H both represent charter rates but define these rates in different terms. However, when R_H increases or decreases so will F_H increase or decrease. It is therefore logical to define a relationship between these terms which can be used to evaluate one variable when the other is known. The following definition of F_H in terms of R_H has thus been used.

$F_H = F$ when R_H is substituted into equation (1) and otherwise using data for the own ships at full service speed.

In reality F_H will vary with the size of ship chartered which means that a more arbitrary relationship could have been used between F_H and R_H.

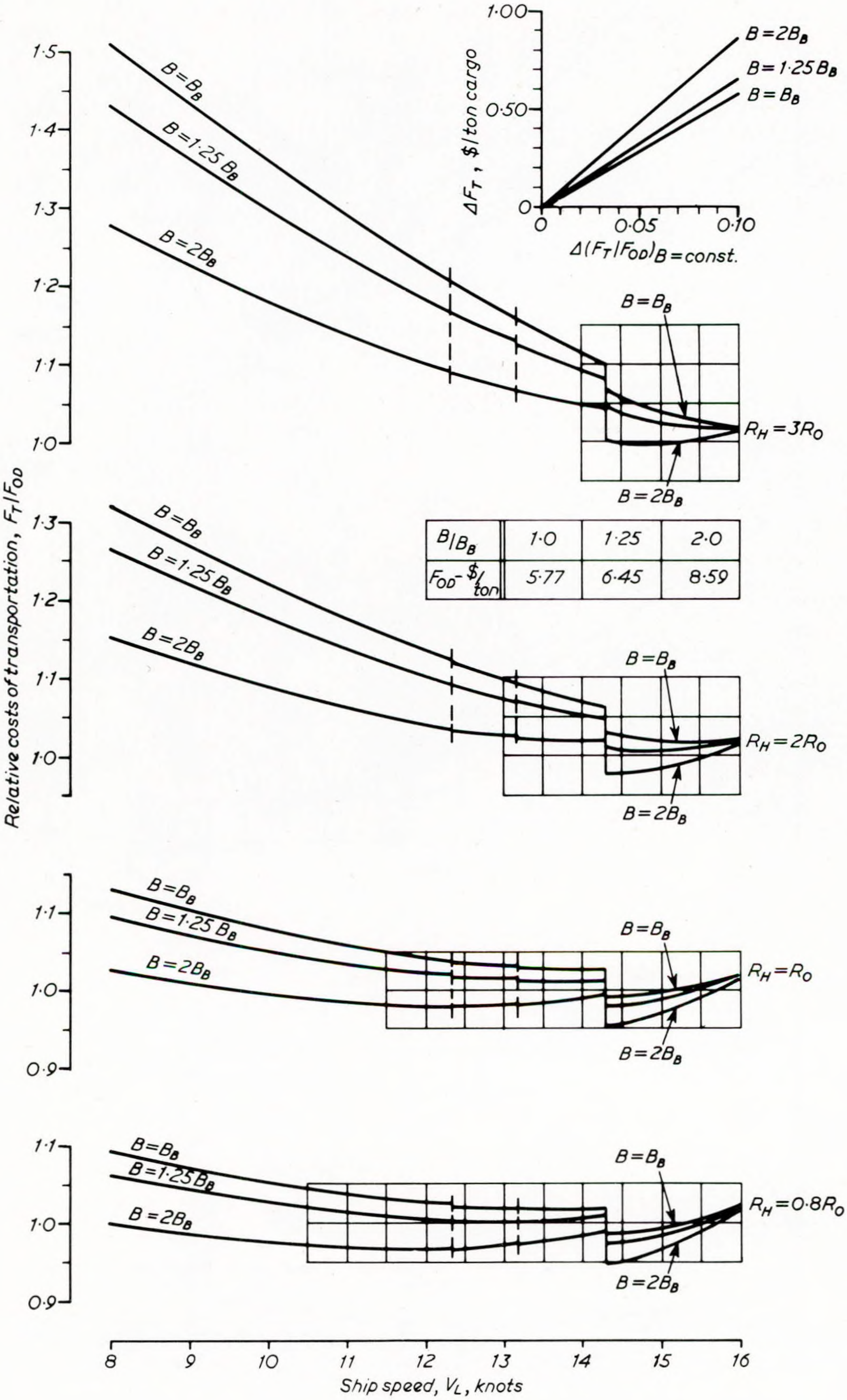
In the analysis charter rates have thus been varied in terms of R_H rather than F_H but it is evident from the definition of F_H that a change in R_H will result in a corresponding change in F_H. However, while R_H is not influenced directly by changes in bunker prices F_H will increase as bunker prices go up. Permitting F_H to vary in this manner in the analysis is only natural since one can hardly expect to get the cargo transported at the same costs per tonne if bunker prices do go up.

Corresponding values of R_H and F_H are shown in Table I below. For convenience R_H has been varied in terms of R_O which is constant. It should be noted that the actual value of R_O has no significance with respect to what the optimum ship speed will be since on an annual basis the total running costs of the own ships is not influenced by ship speed. The curves obtained are thus, in principle, equally applicable to ships with higher or lower daily running expenses.



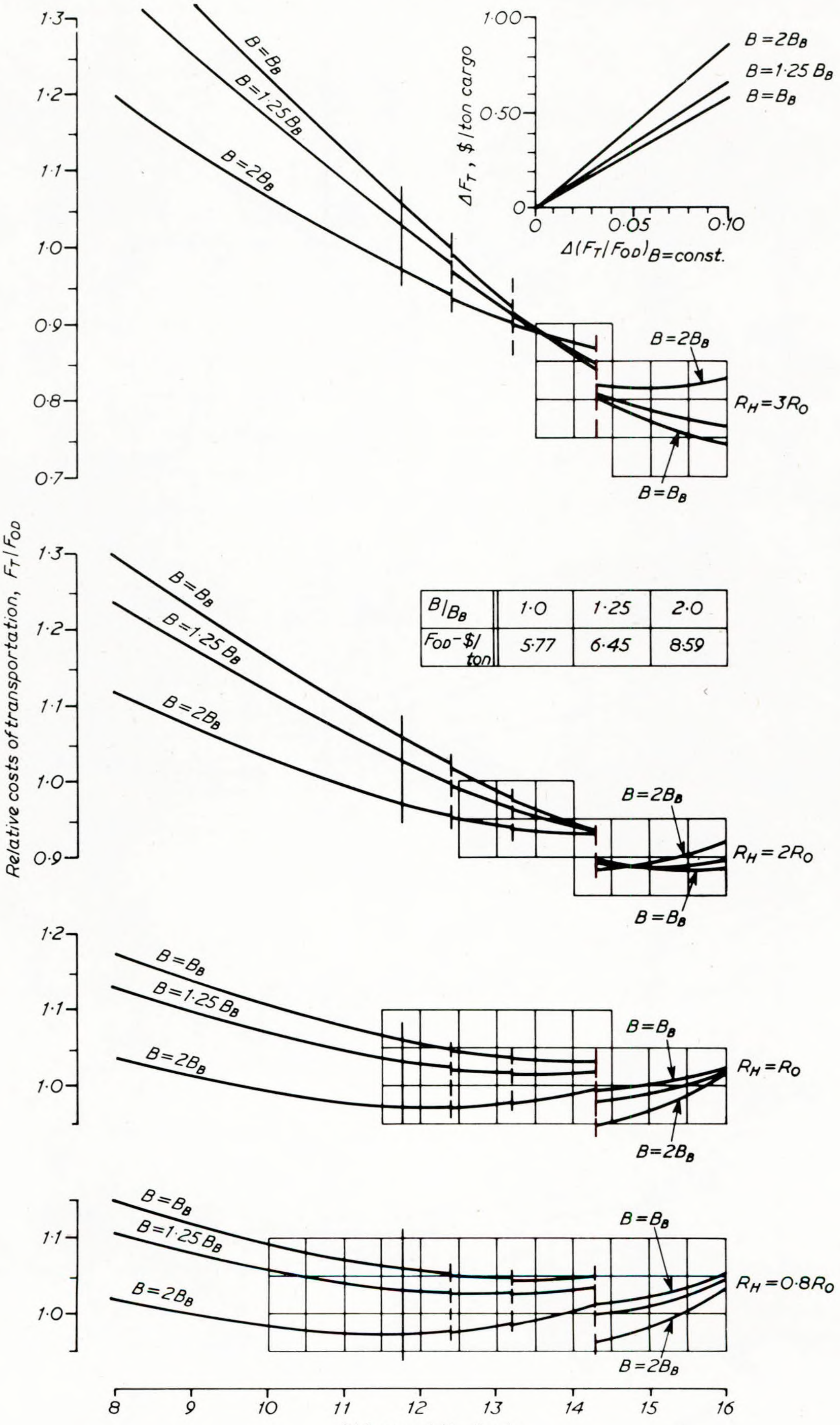
B/B_B	1·0	1·25	2·0
F_{OD}–\$/ton	5·77	6·45	8·59

Fig. 7—Z_T—$1.5Z_{OD}$: *Case of insufficient transportation capacity of oil company's own fleet.*



B/B_B	1·0	1·25	2·0
F_{OD}-\$/ton	5·77	6·45	8·59

Fig. 8—$Z_T = Z_{OD}$: *Transportation capacity of the oil company's own fleet balances demand.*



B/B_B	1·0	1·25	2·0
F_{OD}–$/ton	5·77	6·45	8·59

Fig. 9—$Z_T = 0{\cdot}75\ Z_{OD}$: *Case of surplus transportation capacity in oil company's own fleet.*

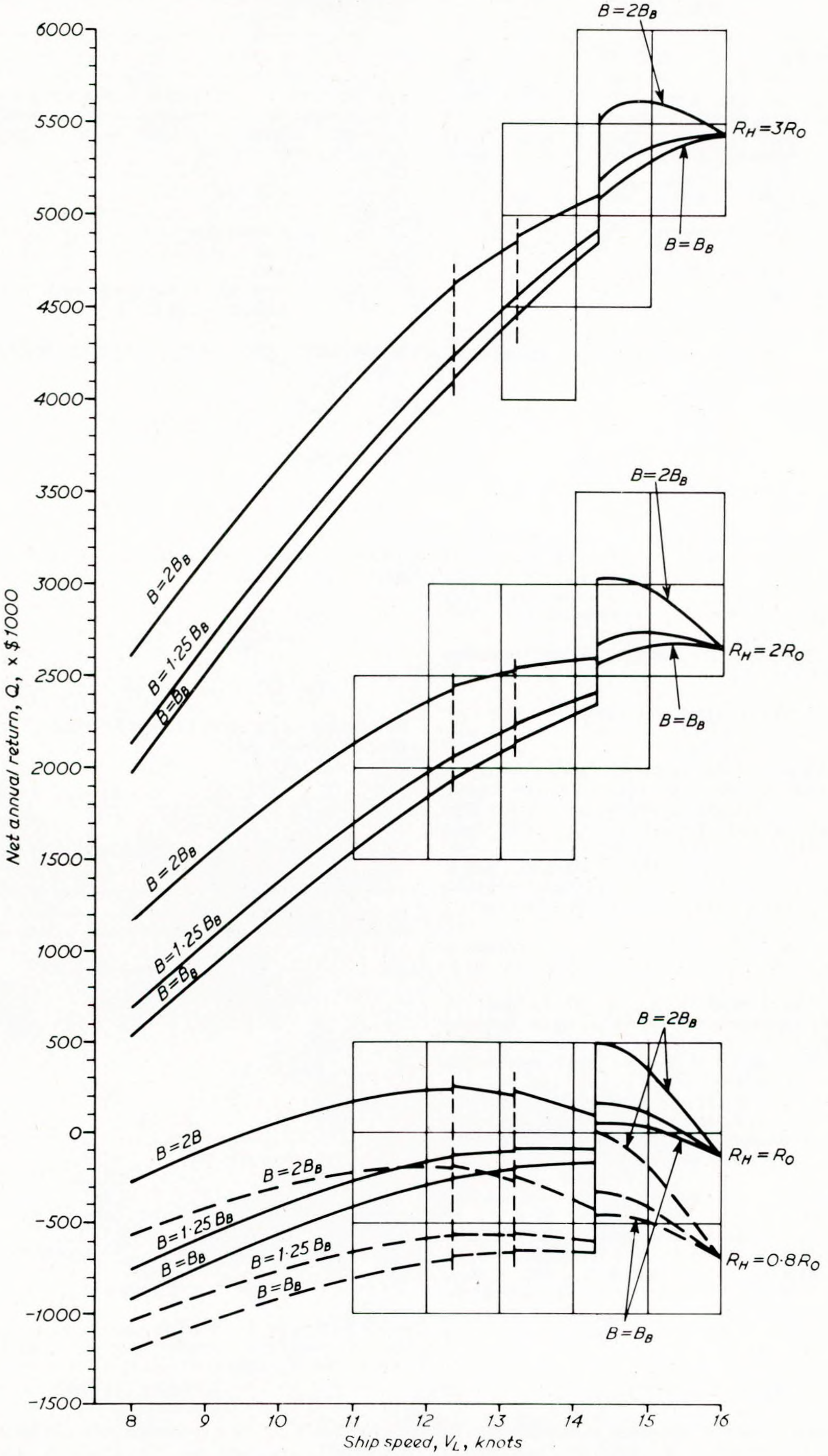


Fig. 10—*Variations in net annual return for shipowner operating on-the-spot market.*

TABLE I

R_H/R_O	$B = B_B$		$B = 1{\cdot}25\ B_B$		$B = 2\ B_B$	
	F_H – $/ton	W	F_H–$/ton	W	F_H–$/ton	W
0·8	5·28	32·1	6·00	36·4	8·14	49·5
1·0	5·73	34·8	6·45	39·2	8·59	52·2
2·0	7·99	48·6	8·70	52·9	10·84	65·9
3·0	10·24	62·2	10·95	66·5	13·10	79·6
4·0	12·49	76·0	13.21	80·3	15·35	93·3

Wsc. flat = 16·45 $/ton Mena—Rotterdam
W = Worldscale points

For a given ship speed the number of days per round trip and the number of round trips per ship per year are given by the following equations:

$$Y_V = Y_P + \frac{D}{24}\left(\frac{1}{V_L} + \frac{1}{V_B}\right) \tag{5}$$

$$n = \frac{365 - Y_{OFF}}{Y_V} \tag{6}$$

Let V_{LT} = average speed that own ships must maintain on laden voyages to carry exactly the required amount of cargo Z_T (relevant only when $Z_T > Z_{OD}$)
V_{BT} = ship speed in ballast condition corresponding to V_{LT}
Y_{VT} = No. of days per round trip corresponding to speed V_{LT}
n_T = No. of round trips per ship per year corresponding to speed V_{LT}

The variable Y_X in equation (4) can then be obtained from the following equation:

$$Y_X = S(365 - Y_{OFF} - Y_{VT} \cdot n_T) \tag{7}$$

In order to collect all cost curves in families of related curves and show their individual variation on the same scale it was necessary to present results as relative costs rather than actual costs. Relative costs is here meant by the ratio F_T/F_{OD} where F_{OD} is defined as follows:

F_{OD} = magnitude of cost function F when R_O and B are substituted into equation (1) and otherwise using full service speed data for the ship.

Like F_H this cost function will increase with increases in bunker price, but unlike F_H it is not affected by changes in R_H.

Results from the calculations are presented in Figs. 7, 8, and 9 for the three principal cases in which an oil company might find itself:

i) transportation capacity of the own fleet is significantly below the requirement (Fig. 7).,
ii) transportation capacity of the own fleet is relatively well balanced to the requirement (Fig. 8),
iii) transportation capacity of the own fleet significantly exceeds the requirement (Fig. 9).

Case b): Shipowner operating a VLCC on the spot market

The shipowner is assumed to be operating in the same trade with a VLCC identical to the one represented by the performance curves in Figs, 1, 2, 3, and 4. It is also assumed that the market offers a chartering rate F_H which the shipowner can obtain for his ship on a regular basis. Using the same notation as previously, the net annual return can be computed from the relation

$$Q = n \cdot C_S \cdot (F_H - F_O) - Y_{OFF} \cdot R_O \tag{8}$$

Obviously the shipowner is interested in maximizing this return. The effect of reducing ship's speed on this return is shown plotted in Fig. 10. The effects of variation in charter rates and increases in bunker prices are also shown. As in case a. charter rates are varied by varying R_H and calculating corresponding values of F_H according to the given definition, rather than varying F_H directly.

In a more real situation it is clear that rates may vary quite considerably and in many cases the shipowner will hold out for better rates and let his ship remain anchored in a stand-by position in the Arabian Gulf. It is then relevant to look at what rate increases he must obtain to come out even on an annual basis after waiting in the Gulf for rate improvements for a certain number of days.

Let F_H = charter rate available if shipowner does not wait for a rate improvement
Q_O = net annual return corresponding to the rate F_H
Y_W = average number of waiting days per round trip
FC_W = fuel consumption rate when ship lies waiting (ton/h)
F_H = rate improvement required to give same net annual return for a given Y_W value

Let the number of round trips per year be redefined as follows:

$$n = \frac{365 - Y_{OFF}}{Y_V + Y_W} \tag{9}$$

We then have,

$$Q_O = \frac{365 - Y_{OFF}}{Y_V} \cdot C_S \cdot (F_H - F_O) - Y_{OFF} \cdot R_O \tag{10}$$

To retain the same net annual return when $Y_W > 0$ we must have,

$$Q_O = \frac{365 - Y_{OFF}}{Y_V + Y_W} \cdot [C_S \cdot (F_H + \Delta F_H - F_O) - Y_W \cdot (24 \cdot FC_W \cdot B + R_O)] - Y_{OFF} \cdot R_O \tag{11}$$

By subtracting equation 10 from equation 11 and rearranging the variables we get,

$$\Delta F_H = Y_W \left[\frac{24 \cdot FC_W \cdot B + R_O}{C_S} + \frac{F_H - F_O}{Y_V}\right] \tag{12}$$

i.e. we see that a linear relationship exists between ΔF_H and Y_W. Curves showing how ΔF_H varies with Y_W at various given market rates for the reference ship of this analysis are shown in Fig. 11. It is evident that relatively significant rate improvements are necessary to justify a long waiting period.

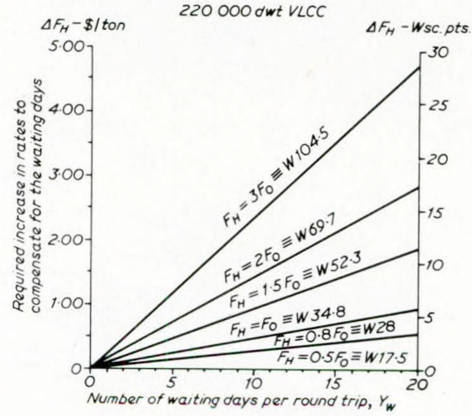


Fig. 11—*Required increase in charter rate to obtain same net annual return for a given number of waiting days per round trip (B=72 $/t, R_O=8500 $/day, F_O=5·73 $/t, Y_V=61 days, FC_W= 21t/day).*

As far as Fig. 10 is concerned it should be understood that the simplified approach on which it is based may not give valid results in periods where there is a significant, predictable movement in the charter rates. Short term considerations will then determine the optimum speed.

INTERPRETATION OF RESULTS

Under what conditions should ship speed be reduced

The curves of Figs. 7, 8, 9, and 10 all show the same general trends. At very low charter rates costs can be decreased and the net annual return increased by reducing ship speed even with bunker prices at their present level. As bunker prices increase the benefit of operating at reduced ship speed increases also.

However, as rates are increased there is greater incentive for the ship to carry more cargo per year and even at very moderate rates the point is relatively quickly reached where the full service speed of the ship is again the most profitable speed to be operating at. Where this point occurs depends, of course, on the bunker prices and, also, in the case of an oil company, on the total annual oil requirement relative to the transportation capacity of its own fleet.

At current bunker prices slow steaming this type of ship will generally cease to be an attractive proposition at rates of hire (R_H) in the range 17 000 \$/day to 25,000 \$/day ($2R_O < R_H < 3R_O$) which in Worldscale points represent roughly the range *W50* to *W60*. At substantially higher bunker prices, such as twice the current one, rates might have to go as high as 34 000 \$/day ($4R_O$, *W76*) before the full service speed of the ship will become the optimum speed. It should be understood that it is the actual value of R_H relative to bunker prices that counts in this respect, not the magnitude of R_H relative to the daily running expenses of own ships, R_O.

One should keep in mind the fact that even the highest value of R_H considered in this analysis represent a relatively moderate Worldscale rate. The Worldscale rate corresponding to $R_H = 3R_O$ is *W62·2* and for many VLCC of the size of the ship used in this case study this is still below what is occasionally referred to as the minimum necessary rate. The minimum necessary rate, which include allowances for capital investment costs, interest, depreciation, etc. may easily go as high as *W65* depending on the initial investment in the ship. It is evident, therefore, that at more normal charter rates slow steaming of the VLCC will rarely represent an optimum speed condition.

Consequences for marine power plant design

At the very lowest rates the optimum speed of this ship falls to about 14·3 knots. The sudden rise in specific fuel consumption at this point represents in reality an economic barrier to further speed reductions. Ships with a more smooth specific fuel consumption characteristic may have optimum speeds as low as about 12 to 13 kn if the rate falls to near the break even point for lay-up of the ship or if there is a dramatic increase in the bunker price.

It is clear from the curves that at low rates there may be quite significant cost differences between operation at full service speed and the optimum reduced speed. More specifically if we look at Fig. 8 ($Z_T = Z_{OD}$) and take the case when the bunker price is equal to the basic bunker price of 72 \$/ton ($B = B_B$) and the rate of hire is equal to 6800 \$/day ($R = \cdot 8R_O$) the difference in costs between these two ship speeds comes to ·19 \$/ton cargo which on an annual basis represent a total cost difference of about \$ 235 000 per ship in favour of the lower speed. For practical reasons the optimum ship speed would have to be a little higher than 14·3 kn to avoid the unstable conditions at that point, which means that the actual cost difference would be a little less than the figure just quoted.

It is apparent from the same curve that without the sudden jump in specific fuel consumption at 14·3 kn even further quite significant savings in costs could have been realized. If the future trend is going to be that bunker prices rise faster than other costs the further savings could come to several hundred thousand dollars per ship per year when the charter rates are low. Awareness of this situation invites certain reflections on both existing tankers and tankers which will be built in the future:

i) shipowners will be encouraged to look at what modifications, if any, can be made in the machinery of their ships to improve part load performance;

ii) it provides incentive for shipowners and designers of marine power plants to take a keen interest in the specific fuel consumption of any future tanker that is going to be built, not only at full speed, but also at reduced speeds.

The amount of investment to be made in the ship machinery to improve specific fuel consumption at reduced speeds depends, of course, on the estimated amount of time the tanker is likely to operate at low charter rates as well as an estimate of bunker fuel prices over the 15 to 20 year life of the ship.

If prospects are such that this will be a relatively long period, say more than 2 years, the decision will probably be not to order a new ship. Such considerations will therefore limit the investment to be made in the existent ship to improve the performance at reduced speed.

To be competitive at normal to high charter rates the design speed of tankers will still have to be in the 14 to 16 kn range (Ref. 2 and Ref. 3). For the greater part of the life of the tanker this will also be the optimum operating speed of the ship. Therefore, the emphasis will still have to be on achieving the lowest possible specific fuel consumption at this speed, without ignoring the importance of a good fuel characteristic at reduced speed in order to give the ship necessary speed flexibility in periods of low charter rates.

Condition of power plant and hull

With bunker prices at their present level and fuel costs accounting for the greater share of the daily operating costs of a VLCC it is clear that it is of the greatest importance to keep the machinery in good condition. The curves in Figs. 12, 13, 14, and 15 provide ample proof of this. The effect on specific fuel consumption of deviations from design conditions of four of the more important variables in the power plant is shown. Corresponding losses in net annual return have also been plotted and show that, each of the following conditions result in a loss of net annual return of \$40 000:

- a drop in boiler superheater steam temperature of 16·5°C
- a drop in boiler superheater steam pressure of 2·75 bar
- a rise in main condenser pressure from 50·7 mbar to 54·7 mbar (same sea water inlet temp.)
- an increase in boiler excess air from 5 per cent to 15·5 per cent.

The \$40 000 is an approximate figure only, and does not include secondary effects such as reductions in shaft power and ship speed. The effect of condenser pressure variations are also difficult to predict and in many plants reductions in condenser pressure below design may have a much less pronounced effect than shown here.

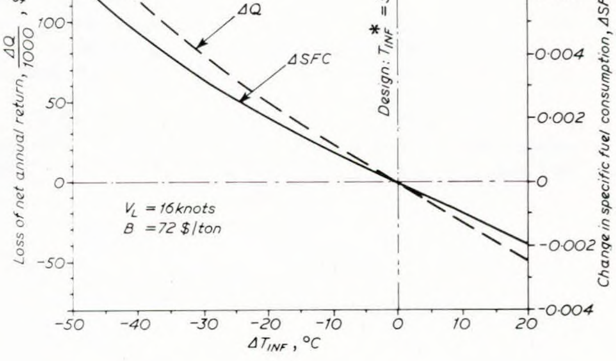


Fig. 12—*Effect of change in steam temperature at inlet to main turbine control valve.*

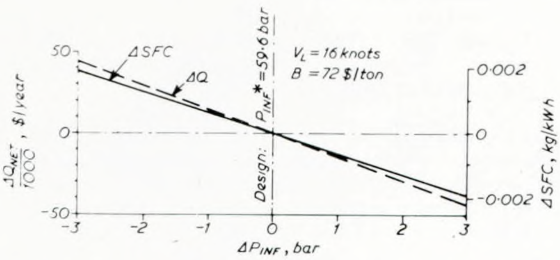


Fig. 13—*Effect of change in steam pressure at inlet to main turbine control valve.*

The symbols used in those figures are defined as follows:

$$\Delta SFC = SFC - SFC^{*}$$
$$\Delta T_{INF} = T_{INF} - T^{*}_{INF}$$
$$\Delta P_{INF} = P_{INF} - P^{*}_{INF}$$
$$\Delta Q = Q^{*} - Q$$

superscript $* =$ design or full service speed conditions
All curves represent the case $V_L = 16$ kn, $B = 72$. $/tonne

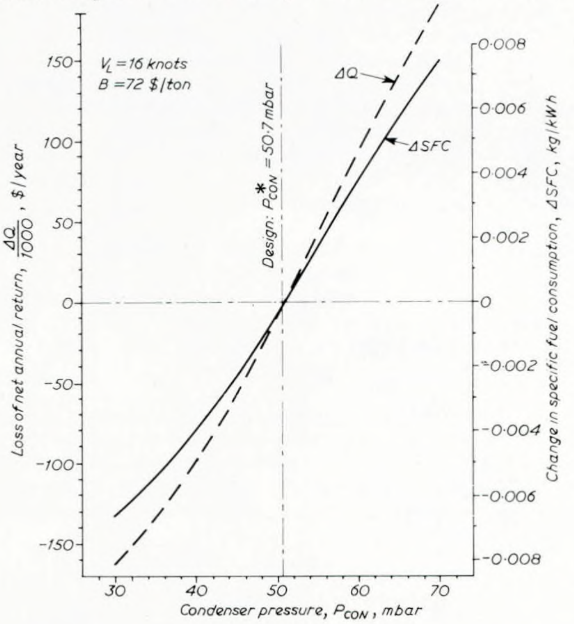


Fig. 14—*Effect of changes in condenser pressure.*

Equally important is the condition of the underwater hull (Ref. 6). Facilities exist in equation (1) for investigating the effect of speed reductions due to fouling and a gradual increase in the roughness of the underwater hull but this was not part of this analysis.

An important point to consider when slow steaming VLCC is whether reduced speed operation of the plant over an extended period of time would have a detrimental effect on some of the plant components. At the present time there is insufficient data available to tell whether or not it has had negative effects in the past. However, the author is familiar with at least one case where it was suspected that an accelerated build up of deposits of solid matter on the surface of the superheater tubes on the flue gas side could have been attributed to slow steaming. If it is found that slow steaming does have some adverse effects on the conditions of the power plant components, then the corresponding increases in maintenance and off-hire costs must naturally also be taken into account and be balanced against possible savings.

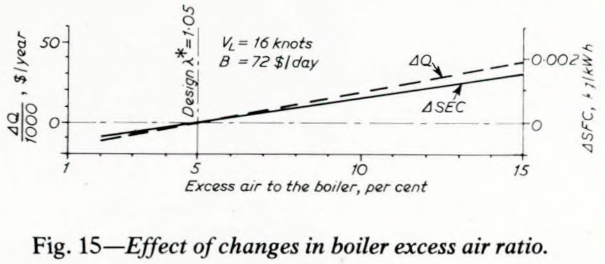


Fig. 15—*Effect of changes in boiler excess air ratio.*

CONCLUSION

The analysis carried out shows that since the large increase in bunker prices in December 1973 the optimum speed of existing VLCC has become very sensitive to changes in charter rates and fuel prices. At very low rates slow steaming will generally result in very definite economic gains while at medium and high rates the full service speed of the ship will again represent the optimum speed. A doubling of the present bunker price may cause VLCC to operate with reduced speeds even at moderate to fair charter rates.

Although new VLCC may be designed with lower top speeds they may still require improved off design performance characteristics to allow them to operate with minimal costs and minimal loss of earnings in periods with low charter rates. This will present a new challenge to designers of marine power plants who must be prepared to offer greater flexibility than before with respect to variations in the continuous operating speed of a ship.

The present level of charter rates and bunker prices may also justify additional capital expenditure on better equipment and components in order to reduce fuel consumption under reduced speed operation. Tanker companies and shipowners may thus find it to be in their interest to make modifications in the power plant of their ships in order to eliminate or reduce the kind of sudden increases in specific fuel consumption that occurs in the fuel consumption characteristic of some of the existing ships.

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Discussion

MR. R. F. THOMAS, F.I.Mar.E., said that the market for large crude carriers in the form of VLCC and ULCC was international, and the open competition for business gave a good example of the laws of supply and demand, in the short term the supply and demand was matched by the market rate, and in the longer term by new building and disposal of ships.

If the supply requirement for the transportation of oil exceeded the tonnage available, the market rate rose. Conversely, if the supply requirement was less than the capacity of ships available, the market rate fell. These statements were fundamental and it must be remembered that the quantity of oil to be moved in any given period of time on a global basis, was a finite quantity.

The reasons why people chose to be shipowners was a complex issue. Major oil companies tended to own a certain quantity of tonnage in order to meet, to an extent, their own transportation requirements. The difference between the owned capacity and required capacity to be moved was met in various ways. Often extensive use was made of time chartered vessels to make up the majority of the difference. The final balancing operation, due to the continuous peaks and troughs in the required capacity to be moved, was met, amongst other ways, by chartering in or out, on a spot rate which was determined by the laws of supply and demand.

There was another rate which needed to be considered, namely the Required Freight Rate. This could be calculated on a costs/annum basis:

Determination of Required Freight Rate (RFR)

	Costs/Annum	*Basic Headings*
Capital		Capital
Fuel		Fuel
Maintenance Crew Fixed		Operating
Port		Port
	Total	

$$\text{RFR} = \frac{\text{Total Annual Costs}}{\text{Annual potential}}$$

$$(\text{Annual Potential} \simeq \text{No. of Voyages x Payload})$$

Examination showed that this method was similar to that used by the author in equation (1) but made allowance for capital charges.

Of the four basic headings—capital charge, fuel, operating costs and port cost—capital charges were by far the most significant part of the RFR before the increase in bunker prices in 1973.

The capital charge calculation contained several factors, including first cost and the method by which the money was raised for purchase. At the time of the large crude carrier building boom owners, were internationally competing for building berths for what, in many instances, were yard standard ships. The standard form of machinery arrangement for non-reheat steam plants ranged from simple systems with two stages of feed heating to five-stage feed heated cycles with attached auxiliaries as shown in Fig. 1.

In general, these vessels were designed about a full power condition and extensive consideration was not given to the part power condition because it was not requested.

The large crude carriers building boom was, for the present, over, and they were faced with an international over tonnage situation which was reflected in a depressed market rate.

This over-tonnage situation on a global basis had been met in numerous ways. These included speed reduction, accelerated disposal programmes, and lay-up, the considerations to be taken into account being both at a micro-and macro-level.

Figs. 7, 8 and 9 of the paper were technically interesting as they showed what would happen under a series of variable conditions. Especially so with the condition $RH = 0{\cdot}8\ Ro$ in Fig. 9. Here one saw two minima for the relative cost of transportation $F_T\ F_{DD}$ when $B = 2B_B$. This indicated a degree of flexibility in operation of this particular type of plant under the stated conditions.

The interpretation of the results with reference to the consequences for marine power plant design were, he thought, significant, especially so the concept of interest of the specific fuel consumption, not only at full speed, but also at reduced speed, of any future tanker.

This provided a challenge to the designer, who must, for effective results, work with and not against the natural laws of thermodynamics. Since large crude carriers in the main spent over 90 per cent of their time at sea, in conditions which might be considered as a series of steady states, there appeared no technical reason why the internal temperatures and pressures with the cycle could not be varied to suit particular conditions with advantage to the fuel rate. Maybe there were possibilities in the adoption of passing steam back into the L.P. cylinder at a late stage. Reheat steam plants had, in the past, been considered inflexible, but was this true for current designs? He suggested not.

Attached auxiliaries had an effect on the specific fuel consumption as shown in Fig. 3. By the use of a variable speed epicyclic drive, attached auxiliaries could still be used even with significant (25 per cent) reduction of shaft speed.

The permutations and combinations were many, each needing to be explored.

It should be remembered that the present over-tonnage situation in the tanker market had occurred before. For different reasons, over-tonnage existed in the thirties and also part of the fifties. On this evidence it was possibly shortsighted to say that it could not happen again. Any additional flexibility incorporated in future marine power plants must be cost effective and it was for each owner to make his own decision rules.

MR. J. N. MACKENZIE, F.I.Mar.E., said that, although the paper referred specifically to VLCC, many of the fundamentals mentioned applied to a large range of ships and it was on these that he wished to comment.

In non-technical ship management, the term "economic ship's speed" was frequently misused as it was not related to other factors; this paper assisted in viewing this term in its correct perspective.

As the author had pointed out, fuel cost contributed a very high proportion of operating cost although, after inclusion of capital depreciation and interest charges, a rather lower proportion than shown in Fig. 5.

Regarding Fig. 5, could the author comment on the proportion of the section marked B, attributable to total maintenance cost and also machinery maintenance cost.

He was particularly interested in Figs. 12,13,14 and 15, as some 14 years ago, in a paper to this Institute, he had produced a composite diagram showing the increase in annual fuel costs for steamships in the 40 000 to 50 000 shp range, related to deviation from various design parameters. With a steam plant there were many variables under the control of the operating staff which would produce a significant effect on fuel consumption.

If the effect of all those deviations were added together, and there had been steam plants in which they were added together, the total effect would produce quite an alarming annual cost when, compared with the cost of machinery repairs; hence his remarks on Fig. 5.

As shown in diagrams 12,13,14 and 15, quite small percentage deviations from design would increase fuel cost, but how was the plant to be controlled unless all these deviations could be measured with accuracy. In some steam plants, the lack of attention to original installation and periodic calibration of thermometers, pressure gauges etc, precluded accurate control. He had come across flue gas analysing equipment which had fallen into disuse because, in the words of the operating engineer, the mysterious "they" had said it cost too much to repair and yet the annual fuel cost resulting from excess air could more than balance the cost of new equipment every year.

Had he interpreted the author's remarks in the paper correctly to indicate that the specific fuel consumption was not measured by shipboard trials. Accurate service measurement of specific fuel consumption, over relatively short periods, was notoriously difficult and this could be further complicated if accurate measurements were not made under ideal conditions when the plant was new. In order to identify changes in fuel consumption, could the author comment on the method of monitoring service performance with accuracy of the instruments involved and normal standards of human error.

Obtaining optimum performance from a steam plant could be a challenge to the Engineer Officer, but this was only effective with appropriate guidance on the financial effects and the balance between fuel and repair cost.

Referring to the consequences for plant design, there was no doubt that it was a difficult task to keep steam plants operating at maximum efficiency. The solution might be to replace the beautiful purring turbine with a noisy, dirty, smelly but very much more efficient diesel engine.

MR. L. SINCLAIR, F.I.Mar.E., said that the author was to be congratulated on a thought-provoking paper, very appropriate at this time of high fuel costs. A number of the points made would be studied very carefully by those interested in the subject.

Normally a classification society was concerned with factors affecting the strength and serviceability of the ship and in the setting of acceptable minimum standards of construction. It would be of interest, therefore, to know if this paper represented a new excusion into the science of ship operations and that, in future, DnV would be offering a consultative service to shipowners in a field in which they would not hitherto have seemed expert.

The information on turbine efficiency was of interest and the enormous reduction in power for a relatively small speed drop was emphasized. For example, if this 16-knot ship was reduced in speed to 14 knots, the power was reduced from 22 900kW to 15 340kW and the rev/min from 81 to 70 (constant Admiralty coefficient and slip). From diagram 3, Curve T2, this involved an increase in specific fuel consumption of about 6 per cent, which was extremely important and could amount to an annual saving of well over £100 000 for a 30 000 horsepower installation.

The question that should be asked was, why the diminution in fuel economy? Was it due to thermal losses because of the relatively light loading at reduced power, or was it due to turbine blade efficiency changes? In other words, with a c.p. propeller, in attempting to restore the situation, would the pitch be reduced to give the designed rev/min or would it be increased to give the same torque?

In the case of the diesel engine (a constant torque machine), running at reduced power with a fixed pitch propeller would involve some loss of thermal efficiency. By increasing the pitch of a controllable pitch propeller to give constant torque, i.e. 54 rather than 70 rev/min, the thermal situation and the designed fuel economy would be assumed to be restored. The author's comments as to how the situation could be redressed in the case of a steam turbine would be valued, as 6 per cent of the fuel bills could, in certain case justify an annual renewal of the propeller.

MR. J. N. EDGAR, M.I.Mar.E., said that he would be grateful to have the author's opinion on the following two suggestions.

The first was in connexion with the lower limit of speed given as 14·3 knots in Fig. 2. This would appear to be at a power of 16 500 kW at 73·6 rev/min see Fig. 3 and the text on the following page.

A rough estimate had been made of the open water efficiency of the propeller, designed for 22 900 kW at 81 rev/min and 16 knots, but operating at the aforementioned 14·3-knot condition. A comparable estimate had been made on the assumption that a controllable pitch propeller, if fitted to the ship, could be made to run at rev/min well above the limiting value of 73·6 rev/min without too great a penalty in efficiency loss. For example, if allowed to run at 81 rev/min with 16 500 kW, the loss in efficiency would probably be about 2 to 3 per cent.

In terms of the fuel index shown in Fig. 4, at 14·3 knots at 81 rev/min with the c.p. propeller, and the generator driven by the main turbine, the index would rise from about 322 to about 330 which was considerably less than the value of about 350 which applied at the limiting rev/min with the fixed pitch configuration, i.e. a gain of about 6 per cent. Also, of course, 14·3 knots would no longer be the lower limit of speed.

It might be that consideration of the operational characteristics of the main engine itself might invalidate some of this argument, but he would be glad to have the author's views. In this context, the secondary benefits of the c.p. propeller would be the elimination of the astern turbine and better stopping ability.

Secondly, there was the ever-present possibility of examining the advantage of fitting a ducted propeller. This would give a fundamental gain in efficiency and, hence, fuel consumption, especially if rated rev/min lower than 81 could be utilized, which could be a possibility with the ducted propeller configuration.

Would the author care to comment on the second suggestion and, of course, to the logical step of fitting a ducted controllable pitch propeller in order to have the best of both worlds.

Correspondence

DR. I. L. BUXTON, B.Sc., said that Mr. Rein had made a most useful contribution to the literature of ship operating economics, discussing an important current problem. He showed the important conclusions under "Interpretation of Results" which were helpful for operators to obtain an indication as to when slow steaming was likely to be economic (or rather, less uneconomic) than full speed operation. For such a preliminary screening, before detailed investigations were put in hand, it might be worth recalling the old approximation that slow steaming of existing ships was only economic when daily fuel costs at sea exceeded half the daily hire for the ship. This could be demonstrated for a time-chartered ship by making some simplifying assumptions, e.g. no step functions in the speed/fuel consumption curve, assuming fuel consumption proportional to the cube of the speed and ignoring port time and cost. Then:

$$\text{Optimal speed} = \text{Designed speed} \times \sqrt[3]{\frac{\text{Daily time-charter hire}}{(2 \times \text{Daily fuel cost at sea})}}$$

In normal freight markets the cube root term was above unity, indicating that optimal speed should be the designed speed. Of course this formula was not a substitute for Mr. Rein's analysis, but a "first shot" to indicate whether to do more detailed studies.

Quite probably many operators already had drawn up, for each of their ships, a generalized diagram showing the optimal speed under varying conditions of the two principal variables—freight rate and fuel price—which might look similar to Fig. 8, but probably with an ordinate expressed in dollars for a typical trade route.

The step introduced in the fuel consumption curve, when switching from main engine driven auxiliaries, was very marked—most of the author's curves indicated that either this corresponding speed or the full speed was likely to be the optimum. Perhaps the author could indicate from DnV records how prevalent this feature was compared with other forms of auxiliary power generation and, in the latter cases, if there were any other corresponding large steps in the curves.

The author had mentioned that new VLCC—and some would eventually be ordered—might have lower speeds than hitherto (because fuel prices had risen since current new ships were designed). This could indeed be proved analytically, but the process was likely to be a fairly gradual one as charterers were initially less likely to accept new vessels with markedly lower speeds than the existing fleet available.

Author's Reply

The comments made in the contributions to the discussion of the paper had given the author much food for thought. He greatly appreciated these comments, and wished to address himself to the many specific questions raised and to clarify some of the points made in the paper.

Mr. Thomas had stressed the fact that capital costs represented a very large fraction of the overall costs on which the calculation of the Required Freight Rate (RFR) was based. This, of course, was true although, as he had pointed out, the capital cost fraction was a less dominant factor than before due to the increase in bunker fuel prices in 1973. The RFR was an important parameter in studies of ship life cycle costs and consequently was of considerable interest to shipowners comparing various ship investment alternatives involving secondhand tonnage or new ships, different propulsion machineries and different cargo handling equipment.

The analysis of this paper did not concern itself with economic alternatives involving procurement or sale of ships. Inclusion of such alternatives would easily result in a much more complicated analysis than the very simple one presented, without adding much to the understanding of when and how much ship speed should be reduced.

For an existing ship, operated by a tanker company or an independent shipowner, the capital investment cost was a foregone conclusion, and these costs could not in any way be influenced by variations in the applied operating speed of the ship. If a more purely mathematical approach was used and the overall cost function on equations (3) and (4) was made to include a representative capital cost item for the whole fleet, then partial differentiation with respect to the ship speeds VL and VB, to determine maxima and minima points on the cost curve, would give the optimum ship speed for a given set of cost data. The capital cost item would then drop out of the differential equations, which served to demonstrate the fact that capital costs had no influence on the optimum speed of existing ships.

The analysis presented here was concerned with how control and proper selection of ship operating speed might be used to obtain the best economic result for ships that already existed. Since capital investment costs had no influence on the optimum operating speed of these ships, it was not included in the cost function F defined by equation (1). The cost function took into account only the overall ship operating costs, because these were the only costs which could be influenced by changes in ship speed. If one compared the cost items included in the author's cost function with the cost items in Mr. Thomas' table for calculation of RFR it would be seen that the only difference between the two was the capital cost which, for the reasons stated above, had been excluded from the author's cost function. It was seen, from equation (1), that B took account of the fuel costs, R_O represented maintenance, crew, stationaries and other fixed costs, P_L and P_D represented port costs.

The author agreed with Mr. Thomas that epicyclic gearing re-presented an interesting possibility for solving the problem of retaining a low specific fuel consumption at reduced ship speed. It could be used to keep the auxiliaries attached to the main turbine over a greater speed range, as well as to maintain a high rotating speed for the main turbines in order to preserve the higher turbine efficiencies obtainable close to the design speed. Whether the savings potentially obtainable were sufficient to compensate for its greater complexity and capital costs was another matter. It must be kept in mind that substantial savings in costs could be obtained only when charter rates were at a very low level.

Whatever the outcome of a more thorough evaluation of the epicyclic gear alternative, it was clear that the system designer of ship machinery should not content himself simply with designs that yielded a low specific fuel consumption at the design speed. He should also make it his objective to provide design solutions which resulted in low specific fuel consumption over a range of ship speeds. How great the range of possible continuous operating speeds should be depended on the range of charter rates that the ship might have to operate under. In general, shipowners would be prepared to operate their ships at rates as low as the break-even level for lay-up of the ship, if this was the best that the market had to offer.

For VLCC, of the size employed in this case study, the break-even lay-up rate might be as low as W27-W28. The daily running expenses would then be somewhat lower than the nominal figure of 8500 \$/day used here. If the ship had a relatively smooth specific fuel consumption curve, such as the T2 curve in Fig. 3, the corresponding speed reduction to operate at the optimum ship speed, would be of the order of 4 knots. This corresponded to a 25 per cent reduction from the full speed of 16 knots. This was an indication of the speed range over which a low specific fuel consumption was particularly important. For other ships, other applications and other trades the corresponding speed range might be smaller or larger.

Mr. McKenzie had asked about the proportion of the operating expenses attributable to maintenance costs. Maintenance costs were part of the daily running expenses which, in the analysis, were represented by the symbol R_O. The nominal figure used for R_O was taken from reference (1). The figures in reference (1) were averages of data received from a great number of shipowners. Unfortunately, the various factors contributing to the total daily maintenance costs were not specified separately and it was, therefore, not possible to quote any specific figure for the maintenance cost. Other sources of information indicated that these costs varied a great deal from ship to ship, but for simple cost analysis purposes one could probably assume that roughly some 30 per cent of the total daily running expenses were attributable to maintenance costs.

In the analysis presented it was assumed that maintenance costs were not influenced by ship operating speed, i.e. R_O was assumed to be the same whatever the ship speed. For most ships this was probably a fair assumption to make. However, some shipowners might have experiences with their own ships which allowed them to make predictions about how ship speed reductions would affect their maintenance costs. In that case this effect should, of course, be included in the cost analysis and R_O should be made a function of ship speed.

On the the other hand, it was clear that no universal relationship existed between these two parameters. Depending on type of propulsion machinery, system arrangement and maintenance strategy, maintenance costs might increase as well as decrease with reductions in ship operating speed.

It was interesting to note that as long as the total daily running expenses, R_O, were considered to be independent of ship speed, the actual magnitude of R_O had no influence on what the optimum ship operating speed would be or on the savings to be made per ship per year. This point was, perhaps, not too readily observed from the equations presented, but substitution of the expression for F_O and Z_O into equations (3) and (4) and F_O into equation (8), and subtraction of reduced speed costs from full speed costs, would demonstrate that this was so. Basic logic led to the same conclusion, since it was clear that, as long as all ships in their own fleet were in active operation, the total annual running expenses would remain the same, regardless of what operating speed was being used.

The lack of influence of the magnitude of the fixed daily running expenses, R_O, on the savings in costs applied even to equation (12). Substitution of the expression for F into that equation would show R_O to disappear from the equation which meant that the variable ΔF_h is independent of the value of R_O.

Mr. McKenzie's remarks on Figs. 12, 13, 14 and 15 were quite pertinent. These figures were included in the paper to show how important it was to keep the machinery in good condition and using sensors and instrumentation which permitted accurate measurement and control of the more significant performance parameters.

Equally important was the condition of the underwater hull. Now that prices of bunker fuel were much higher than before, it was clear that increased attention must be paid to the problem of fouling of the underwater hull and the ship speed reductions resulting from it. Use of better fouling prevention paints and more frequent scrubbing of the hull were in order.

Further to Mr. McKenzie, it was correct that the fuel consumption curves for the ship of this case study were based on calculations rather than measurements. Measurements were made during the trials of a similiar ship and these checked the calculated results reasonably well, but only a few data points were obtained, insufficient to make the complete curve required for this analysis.

A certain degree of inaccuracy could probably be tolerated in the absolute values of the observed readings for a fuel/speed curve. More important was good repeatability and relative accuracy, i.e. the percentage error should be approximately the same in magnitude and direction over the whole range of measurements.

In the last few years VLCC and ULCC had been equipped with increasingly better instruments, sensors and data-recording equipment for machinery diagnostic and condition monitoring purposes. For these ships it should not be too difficult to obtain fuel/speed curves of sufficient accuracy. Control of ship speed could later be aided by also measuring propeller speed and shaft power, and comparing the readings with corresponding data sets already obtained.

In the less well-equipped ships, one would have to be content with fuel/speed curves of less accuracy. These might have to be based on averages of recorded amounts of fuel consumed and time taken on voyages of known length. Through the scatter of points thus obtained the most likely fuel/speed curve could be drawn. Even a curve of such comparative roughness should provide a fair basis for calculation of optimum ship speed. If reduced speed data was not available, a third order curve ($FC \propto V^3$) could be assumed as a first approximation until more data had been collected.

Which type of propulsion machinery was more difficult to operate at maximum efficiency, diesel or steam turbine, was an open question. More important, as far as this paper was concerned, was the fact that the method of analysis used applied equally well to all tankers, regardless of type of propulsion machinery with which the tanker was equipped. In the case of diesel ships, one must take care to include also the costs of cylinder oil, lubricating oil and the diesel oil consumption of any auxiliary machinery. For better accuracy, a separate term should be included to account for the fuel consumption due to tank cleaning. This applied to steam turbine ships as well as diesel ships.

Mr. Sinclair had been surprised that someone attached to a classification society should present an analysis in an area which was apparently far removed from the more conventional areas of classification activity. A point to note in this respect was that classification rules today, in setting acceptable minimum standards of construction, were concerned with performance and operation (availability) of essential machinery and instrumentation systems, in addition to the factors affecting strength and serviceability of the ship.

DnV had, in the past and on a consultancy basis, carried out a number of projects involving techno-economical evaluations and solutions of problems in the maritime field. These activities evolved mainly from their extensive research programmes on ships, machinery and marine environment. What was new today was that those activities had been made the specific responsibility of a recently formed department for Maritime Advisory Services (MAS).

The second question raised by Mr. Sinclair concerned the 6 per cent increase in specific fuel consumption, observed in the T2 curve in Fig. 3, as ship speed was reduced from 16 knots to 14 knots. It must be remembered here that the specific fuel consumption was the total fuel oil flow per hour to the burners divided by the shaft power available to the propeller. A not insignificant fraction of the fuel oil flow represented a supply of energy that was used for purposes other than propulsion. Moreover, the load on some of the components in the power plant was relatively insensitive to changes in propulsive power and would decrease proportionally much less than the corresponding reduction in shaft power. Examples of this were the turbo-generator load, the fresh water production by the evaporator, the steam/steam generator load and, to a lesser extent, the power requirement on the turbine driven feed water pump.

As a consequence of this, the relative effect of the almost constant generator load, and other similiar loads, on specific fuel consumption, increased as shaft power was reduced. The specific fuel consumption would, therefore, go up, even if thermal efficiencies in the plant should remain the same. In the case mentioned by Mr. Sinclair, the effect of the generator load alone accounted for about 1·5 per cent of the increase. Another 1 per cent was due to the step increase in the curve at the speed of 14·3 knots. Some 0·5 per cent was caused by a 9°C drop in superheater steam exit temperature. The proportion attributable to the main turbine was probably no more than 1 per cent to 2 per cent. This was the only portion that could be influenced by use of a c.p. propeller.

If a c.p. propeller was used in a ship with steam turbine machinery, the objective would have to be the restoration of design rev/min in order to maintain a high thermal efficiency for the main turbine. Turbine efficiency was primarily a function of what was normally referred to as velocity ratio, or some equivalent variable in the case of a multi-stage turbine. The velocity ratio would remain at its optimum value if the design rev/min was restored, provided throttling losses through the control valve were minimized. Provided some means of nozzle group control was available, the latter condition could generally always be met for continuous operation at reduced ship speed.

At the higher rev/min values, the change in turbine efficiency with changes in propeller speed was relatively small. In the case of the T2 machinery it was doubtful whether a c.p. propeller could be used to produce enough of a saving in fuel consumption, at reduced ship speed, to make it an interesting alternative to the simpler and less expensive fixed pitch propeller.

In the author's opinion, the c.p. propeller alternative was more interesting for machineries similar to that applicable to the T1 curve in Fig. 3. The c.p. propeller could then be used to retain a sufficiently high propeller speed to allow the generator and the feed pump to be driven by the main turbine over a greater range of ship speeds. This would increase the potential range of optimum ship speeds and, thus, also the savings to be made when charter rates were low. The same observation had been made by Mr. Edgar. The author did not see anything in the characteristics of the power plant that would invalidate this argument.

It was probably true to say that, whatever innovation was being used to improve the fuel/speed characteristic of a ship, it tended to involve higher capital costs and greater complexity. Due to the latter, there might also be a risk of reduced availability. A more thorough analysis, that took into account capital costs, maintenance costs and the reliability aspect, would be required to determine the merit of each innovation. This, of course, applied also to the c.p. propeller and the ducted propeller alternative suggested by Mr. Edgar. What was certain was that, with the greatly increased bunker fuel prices, the shipowner now got a much better return on investments that resulted in lower specific fuel consumption for a ship. Greater expenditures for this purpose could, therefore, also be justified.

Dr. Buxton had pointed out the fact that, for ships with machinery of the type to which the T1 fuel consumption curve applied, the optimum ship speed tended to be either the full speed or the speed at which a switch was made in auxiliary power generation from main turbine drive to auxiliary turbine drive. This, of course, was due to the large step increase in specific fuel consumption at the point where the switch in auxiliary power generation occurred. Step changes of this magnitude, associated with auxiliary power generation phenomena, were likely to be found only in ships with generator and feed pump drive arrangements similar to those for the T1 machinery, at least as far as steam turbine propulsion was concerned.

Generator drive by the main turbine at the higher propeller speeds was not unusual, but the same arrangement for the feed water pump was less common. From thermodynamic efficiency considerations, main turbine drive of these machines at the higher propeller speeds was rather attractive. The designer then took advantage of the high efficiency available in the main turbine. Even the best designed and most suitably selected auxiliary turbines did not have a thermodynamic efficiency comparable to that of the main turbine. The improvement in specific fuel consumption that could be obtained through the T1 arrangement was quite well demonstrated by the T1 and T2 curves in Fig. 3 in the higher shaft power range.

Thus, the step increase in the specific fuel consumption curve of the T1 machinery was not, in itself, an argument for refraining from application of main turbine drive to the generator and the feedwater pump at the higher propeller speeds. Rather, it was a question of what quality of auxiliary turbines one should select for driving these components at the lower propeller speeds, or perhaps what alternative solution to use for improved low speed efficiency.

Step changes in the specific fuel consumption curve of a steam turbine ship might occur for a variety of reasons. Even a change of no more than 2 per cent might be significant if it occurred close to the full service speed of the ship. Any such step change would have the effect that it eliminated a range of ship speeds in its immediate neighbourhood from the range of potential optimum ships speeds that could be used for continuous operation under conditions of low charter rates. The higher the ship speed at which the step change occurred, the more severe the effect.

A slightly modified version of the T2 machinery might serve to illustrate a typical cause of a step change in the specific fuel consumption curve. If, in the T2 system the feed-water system was exhausting to the condenser rather than to the de-aerator a much greater flow of live steam would be required when steam from the cross-over could no longer be used. The result would have been a more significant step change in the specific fuel consumption curve at the speed of 14·3 knots.

Step changes in the opposite direction would occur in machinery with throttle control of the steam flow to the main turbine and one or more nozzle groups controlled by separate valves. At reduced ship speeds, the nozzle groups might be shut off which resulted in a stepwise improvement in power plant efficiency. The main turbines of the T1 and T2 machinery had direct nozzle group control of the steam flow, which was why no step changes of that kind were seen in their specific fuel consumption curves.

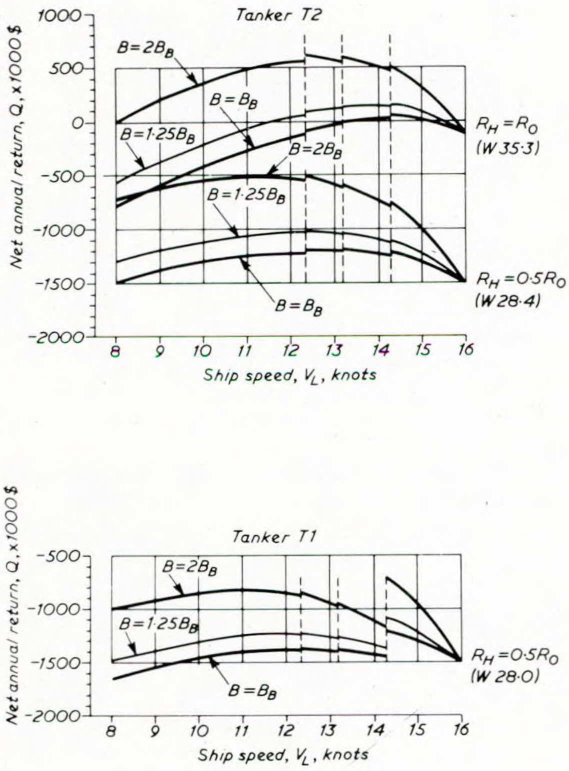

Fig. 16—*Ship owner operating on the spot market*

In the case of diesel machinery, step changes in specific fuel consumption might occur when a switch was made from an exhaust boiler to an oil-fired auxiliary boiler for steam production. An increase in specific fuel consumption, based on equivalent costs, would also take place in a diesel ship when a switch had to be made from a steam turbine driven generator to a diesel generator.

The author did have some notes of caution regarding the formula presented by Dr. Buxton for a "first shot" indication of the optimum speed of time-chartered ship.

In the case of time-chartered ships, the fuel oil expenses were paid by the charterer, not by the shipowner. For the time-period covered by the charter, the shipowner received the same net return regardless of what ship speed was being used. The charterer on the other hand might save money through reductions of ship speed and it was to the charterer that the formula would then have to apply.

Once a ship had become time-chartered, the hiring expenses were fixed for the period of time covered by the charter and the charterer should then, for analysis purposes, look at the ship as being part of his own fleet of ships. The daily rate of hire to be used in Dr. Buxton's formula would, therefore, have to be the one available in the market for the same ship at the time the analysis was made, rather than the actual rate of hire paid for the ship.

TABLE II—SAVINGS OBTAINED BY REDUCING SHIP SPEED

$Z_T = Z_{OD}$
$(V_L)_{max}$ = 16 knots

Tanker T1							
R_H/R_O	W	B/B_B	V_{OPT}	ΔV	ΔF_T	Savings	ΔQ
			Knots	Knots	$/ton	$/ship/year	$/year
1	34·8	1·0	14·5	1·5	0·15	181 000	181 000
		1·25	14·5	1·5	0·23	288 000	288 000
		2·0	14·5	1·5	0·50	611 000	611 000
0·5	28·0	1·0	14·5	1·5	0·24	297 000	297 000
		1·25	14·5	1·5	0·33	405 000	405 000
		2·0	14·5	1·5	0·59	727 000	727 000
Tanker T2							
1	35·3	1·0	14·5	1·5	0·14	168 000	168 000
		1·25	14·5	1·5	0·22	272 000	272 000
		2·0	12·5	3·5	0·58	721 000	721 000
0·5	28·4	1·0	12·5	3·5	0·28	340 000	340 000 ←
		1·25	12·5	3·5	0·41	506 000	506 000
		2·0	11·5	4·5	0·83	1022 000	1022 000

*Savings $= \Delta F_T \cdot Z_T / S$

Although ship speed was reduced for the purpose of reducing fuel expenses when charter rates were low, it should be realized that a significant proportion of the savings might be attributable to reductions in some of the other cost items. One should therefore be careful about making the kind of simplifications made in the development of the optimum speed expression presented by Dr. Buxton. This could be illustrated by the following example.

A VLCC, identical to the one used in this case study, equipped with the T2 machinery and operating on the spot market between the Arabian Gulf and Europe would have an optimum speed of 12·5 knots at the low market rate of W28·4. The corresponding total savings in costs, would be approximately 340 000 $/year out of which 136 000 $/year were savings in port associated expenses. Thus more than one-third of the savings came from the fact that the ship made fewer port calls per year at the reduced ship speed and thus paid less in port charges and in port fuel expenses.

TABLE III—COST EXAMPLE 2, IMPROVEMENT IN NET ANNUAL RETURN

$$Q = n \cdot C_S \cdot (F_H - F_O) - Y_{OFF} \cdot R_O$$

$$= n\Big[\underbrace{C_S \cdot F_H}_{Q_H} - \underbrace{(P_L + P_D + B \cdot K_1)}_{Q_P} \underbrace{- D \cdot B \cdot \Big(\frac{FC_L}{V_L + \nabla_L} + \frac{FC_B}{V_B + \nabla_B}\Big)\Big]}_{Q_B} \underbrace{- R_O \cdot 365}_{Q_R}$$

i.e. $Q = Q_H + Q_P + Q_B + Q_R$

$\Delta Q = Q_2 - Q_1 = \Delta Q_H + \Delta Q_P + \Delta Q_B + \Delta Q_R$

Data: Tanker T2

$R_H = 0{\cdot}5 R_O = 4250$ \$/day (W 28·4)

$B = B_B = 72$ \$/day

Ship speed, V_L, is reduced from 16·0 knots to 12·5 knots, (Optimum speed)

1. $V_{L1} = 16{\cdot}0$ knots, $Y_{V1} = 60{\cdot}9$ days/trip, $n_1 = 5{\cdot}74$ trips/year
2. $V_{L2} = 12{\cdot}5$ knots, $Y_{V2} = 76{\cdot}5$ days/trip, $n_2 = 4{\cdot}56$ trips/year

$$\Delta Q = \Delta Q_H + \Delta Q_P + \Delta Q_B + \Delta Q_R$$
$$= -1\,174\,000 + 136\,000 + 1\,378\,000 + 0$$
$$= 340\,000 \text{ \$/year}$$

TABLE IV—ADDED INTEREST COSTS ON CARGO IN TRANSIT AT REDUCED SHIP SPEED

$$I = \frac{i}{100} \times \frac{Y_L}{365} \times Z_T \times J \qquad Y_L = \frac{D}{24 \times V_L}$$

i = Interest rate = %

Y_L = Number of days of sailing on laden leg

J = Price of crude oil – \$/ton

I = Interest costs on cargo in transit – \$

$$Y_{LM} = \frac{D}{24 \times V_{LM}}$$

V_{LM} = Maximum service speed, laden voyage – knots

$$\Delta I = \frac{i}{100} \times \frac{\Delta Y_L}{365} \times Z_O \times J$$

$$\Delta Y_L = Y_L - Y_{LM} = \frac{D}{24} \times \Big(\frac{1}{V_L} - \frac{1}{V_{LM}}\Big)$$

X = Fraction of increase in interest costs to be charged to transportation costs

(1) $\underline{Z_O < Z_T}$

$$F_T' = \frac{Z_O}{Z_T} \times F_O + \Big(1 - \frac{Z_O}{Z_T}\Big) F_H + Y_{OFF} \times \frac{S \times R_O}{Z_T} + X \times \frac{i}{100} \times \frac{\Delta Y_L}{365} \times J \times \frac{Z_O}{Z_T}$$

(2) $\underline{Z_O > Z_T}$

$$F_T' = F_O - Y_X \cdot \Big(\frac{R_H - R_O}{Z_T}\Big) + Y_{OFF} \times \frac{S \times R_O}{Z_T} + X \cdot \frac{i}{100} \cdot \frac{\Delta Y_L}{365} \cdot J$$

A simplification of perhaps greater consequence, as far as the analysis applicable to an oil company was concerned, was the fact that added interest costs on the cargo in transit at reduced ship speed had been omitted from equations (3) and (4). In principle the ship speed in laden condition and in ballast should always be treated as two independent variables, but as long as all factors having a bearing on transportation costs were influenced quite similarly by proportional changes in the two ship speeds, a fixed relationship, such as that used in the analysis in the paper, might be assumed without introducing any significant error. However, if the added interest costs on the cargo in transit were charged to the transportation costs, then it would no longer be correct to apply fixed relationship between the two speeds. The interest costs would have little or no influence on the optimum speed for the ballast leg of the round trip, but a rather significant effect on the optimum speed for the laden leg. In general, it could be said that the inclusion of the interest costs in the transportation cost function equations would tend to limit reductions in ship speed, for optimization purposes, to about 1·5 knots below the design speed as far as the laden leg of the trip was concerned. This was true, even for VLCC with very smooth specific fuel consumption characteristics.

Under what circumstances added interest costs should be charged to the transportation costs, when ship speed was reduced, was another matter. It would depend primarily on the extent to which reductions in ship speed influenced the time between purchase and resale of the transported oil.

In conclusion the author thanked the contributors to the discussion of the paper for the interest that they had taken in it. Their comments and questions, and perhaps also the reply stimulated by them, should provide the basis for a better understanding of the points to consider in selecting the optimum ship operating speed, and the possible design modifications required to give flexibility of operation in new ships.

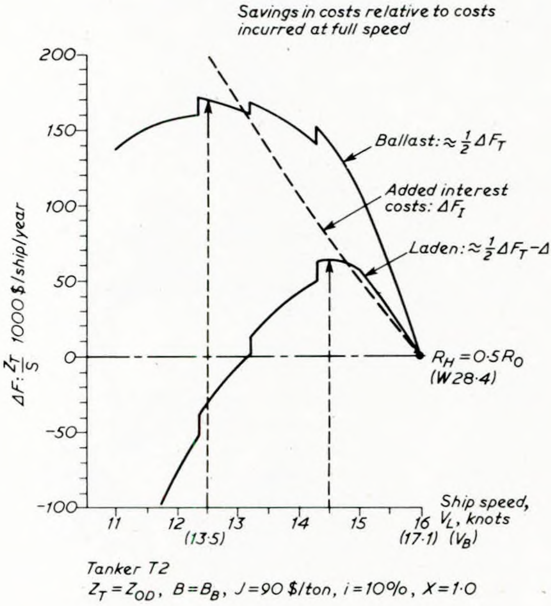

Fig. 17—*Approximate calculation of optimum speeds when added interest charges on cargo are included.*