# Ducted Versus Conventional Propellers: A Comparison Based on Economy

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### Synopsis

This paper discusses the general economies of considering ducted propellers in comparison with conventional propellers and presents two approaches.

Three examples are cited: the first for a 26,000 tonne dwt bulk carrier, the second for a 215,000 tonne dwt tanker and thirdly for a 65,000 tonne dwt OBO vessel. A computer programme has been developed which studies certain parameters, the variations of which are discussed.

### Introduction

Ducted propellers have been in use for over forty years, the main application being on tug boats and trawlers where the benefits to be derived from the point of view of increased thrust are greater, the propeller loading being extremely high. In general propeller loading increases as the speed of advance decreases and this fact led to the early applications to ships used for towing. On these vessels increases in total thrust of between 25 and 40 per cent were found to be possible for a ducted system compared with the conventional open propeller.

In recent years it has been realised that propeller ducts are of interest for large merchant ships, it now being understood that because of the increasing power and comparatively low speed, such vessels now operate under conditions rather similar to those experienced by the towing vessel mentioned above. The increase in total thrust and thus in propulsive efficiency may not be so dramatic as on ships with these towing duties, but nevertheless it will be seen to be sufficient to make a major contribution to the economy of ship operation.

An increase in ship speed or a decrease in power by improving the propulsive efficiency is and has long been a subject worthy of consideration and this is especially the case since the explosive increases in bunker oil prices recently suffered. The paper shows the economy resulting from increased performance achieved by fitting a conventional ship with a fixed ducted propeller and also illustrates the economic importance of relatively small changes in propulsive efficiency for whatever reason.

Model experimental results and full scale examples are used to illustrate the problem which is restricted to the use of fixed rather than steerable ducts. While steerable ducts offer interesting possibilities for the future, they also lead to some difficult technical problems, not the least of which are related to the large forces on the bearings. Perhaps as a result there is as yet little experience of steerable ducts fitted to the large ships with which this paper is concerned.

### General

Around the middle of the 1960's Strømmen Staal became interested in propeller ducts, which were a logical extension of their acknowledged ability in the field of ship stern castings, forgings and fabrications. At the same time SMM were considering, as propeller design specialists, the means of increasing thrust at high propeller loadings and it was perhaps inevitable that the two companies combined their technologies. The investigations of Strømmen Staal bore fruit in December 1970 when the Kawasaki-built T.T. *GOLAR NICHU* was delivered.

The Kawasaki productive capacity and long order book and the Strømmen Staal 'know-how' resulted in considerable sales and a significant development of the ducted propeller system in Japan. This led to the fitting of ducted propellers to some 24 ships and orders for as many more.

SMM meanwhile concentrated on the theoretical aspects of ducted propellers and in particular the design of the propeller in the duct to ensure compatability of loading between duct and propeller.

In early 1975 SMM and Strømmen Staal agreed to collaborate on the design and sales of ducts, primarily for the large merchant ship field. Orders were obtained but it was unfortunate that the collapse of the VLCC market and subsequent ship cancellations has in Europe largely restricted developments to the smaller conventional duct field.

The paper is divided into two parts, the first describing an exercise completed in the U.K. on a 26,000 tonne bulk carrier, covering model tests and an economic evaluation. The second part is concerned with the technical approach and experience gained in Norway on the *GOLAR NICHU* and other subsequent ducted systems fitted in Japan. It will be noted that in the first part consideration is given largely to a reduction in power at the designed speed while in the second part attention is focussed on the influence of increased speed at the same power and gives examples for a 215,000 tonne tanker and a 65,000 tonne OBO ship.

## PART I

### A Bulk Carrier: Economics of a Ducted Propeller System

It was decided to consider the fitting of a ducted propeller system to a vessel which had already been subjected to considerable model testing and for which the model hull was still available. No hull modifications were permitted and it was assumed to be a retro-fit exercise. In the circumstances it will be realised that there are fairly severe inhibitions imposed on the designer and therefore it is unlikely that the solution is the optimum for the prescribed conditions. The basic hull form was a good one and it was generally assumed therefore that there was not a great deal of scope for improvement.

The vessel's basic dimensions were as follows:

| | |
|---|---|
| Hull LBP | 170.7 M |
| Breadth MLD | 22.7 M |
| Draught | 10.43 M |
| Displacement | 32,400 tonnes |

| | |
|---|---|
| Block Coefficient | 0.782 |
| Engine | Sulzer 6RND68 |
| MCR | 9,900 |
| BHP | 8,910 |
| RPM | 150 |

The reduction in shaft horsepower from fitting the duct is based on report 51.2.114 covering model experiments conducted at NPL to a contract jointly financed by British Ship Research Association, Austin & Pickersgill and Stone-Manganese Marine. This report indicates that at constant speed, a power reduction in the loaded condition of 7.3 per cent can be expected. While there are no directly comparable figures for the ballast condition earlier tests on the same model had indicated that about 2 per cent reduction in power could be expected under these conditions.

The maximum service power was taken as 90 per cent MCR of the machinery, i.e. 8,910 BHP or 8,730 horsepower delivered to the propeller. It has been assumed that all the propellers are capable of absorbing the full power, without limitation on RPM, the corresponding ship speeds being taken from the model experimental results. The estimated powers and speeds are shown in the following table:

| | *Loaded* | *Ballast* |
|---|---|---|
| Basic ship | 8,910 BHP=<br>15.10 knots | 8,910 BHP=<br>16.15 knots |
| Ducted ship same speed | 8,260 BHP=<br>15.10 knots | 8,730 BHP=<br>16.15 knots |
| Ducted ship same power | 8,910 BHP=<br>15.32 knots | 8,910 BHP=<br>16.21 knots |

Since bulk carriers of this type spend about 65 per cent of their sea-time loaded, it is possible to estimate a mean reduction in delivered power of about 5.44 per cent for constant speed, i.e. 8,425 BHP, or an increase in speed of about 0.16 knots at constant power, from 15.47 to 15.63 knots.

This study was completed in April 1976 and both the capital costs involved and the fuel savings have since been affected by escalation and devaluation. However, the objective is to give a qualitative rather than a quantitative assessment of the possibilities but it is clear that present day costs would enhance the effect of any fuel savings on the overall economy.

**Cost Estimate**

| | | |
|---|---|---|
| Conventional propeller | | £29,660 |
| Propeller for duct | £25,260 | |
| Duct and connections | £32,000 | |
| Ducted propeller total | | £57,260 |
| Additional cost of ducted installation | | £27,600 |
| Estimated fitting costs | | £3,500 |
| TOTAL EXTRA FIRST COST | | £31,100 |

Although rates of return on ship investments as a whole are of the order of 10-15 per cent before tax, a rather higher rate of return is considered necessary for an additional investment financing a comparative innovation. If 20 per cent is taken as a reasonable figure, this corresponds to a Capital Recovery Factor of 20.5 per cent over a 20-year life, which can also be expressed as a payback period of 4.9 years for an investment with uniform cash flow (Series Present Worth Factor=1/CRF). Thus the ducted ship has to produce each year at least an extra 0.205 × 31,100, equivalent to £6,380 before tax, to prove a worthwhile investment.

Calculations have been made to show whether this minimum rate of return is achieved for a range of assumed fuel prices, freight rates and power reductions (in addition to the assumed 5.44 per cent). Calculations have been

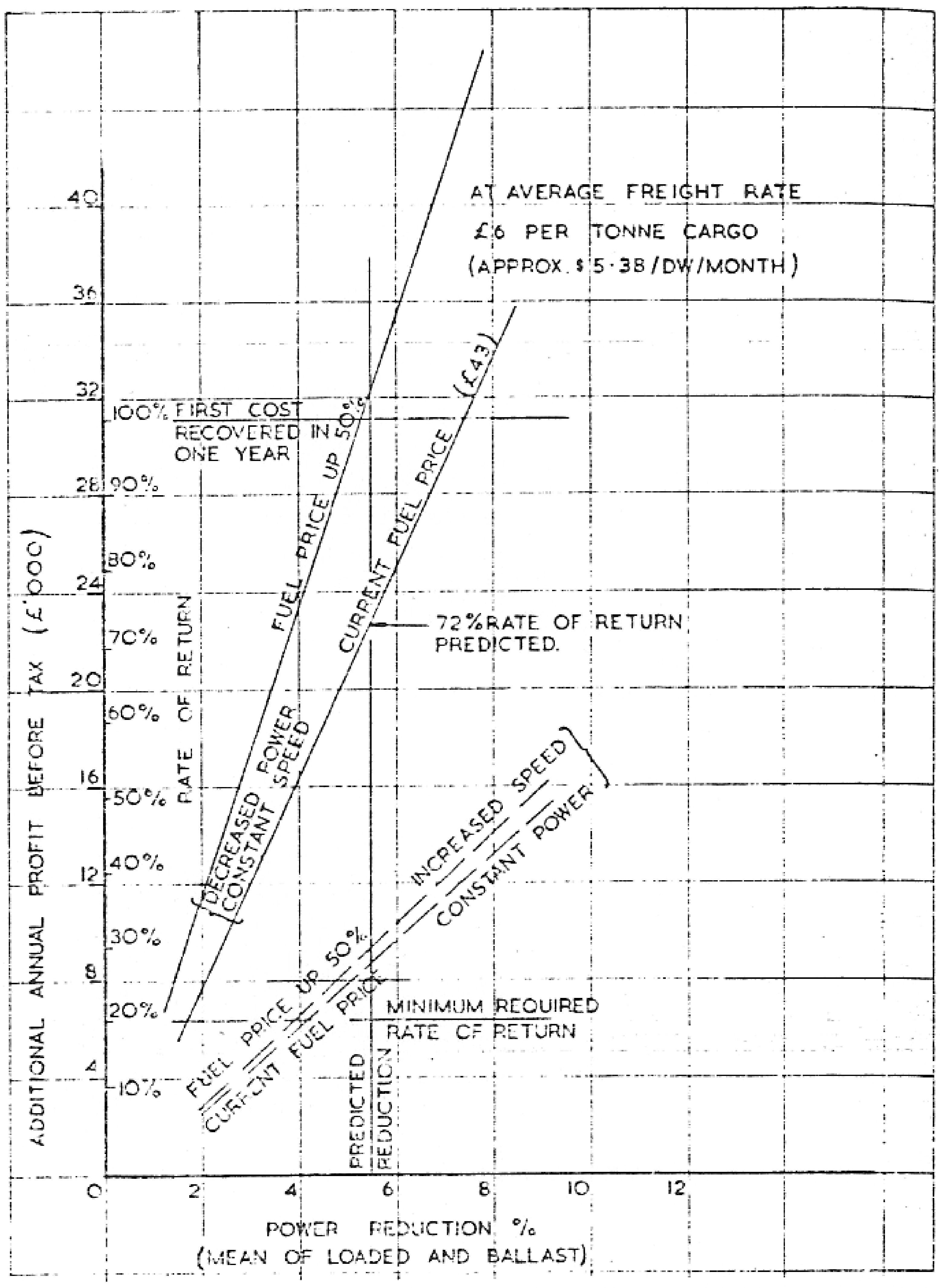

*Fig. 1—Profit vs. power reduction (given F.R.)*

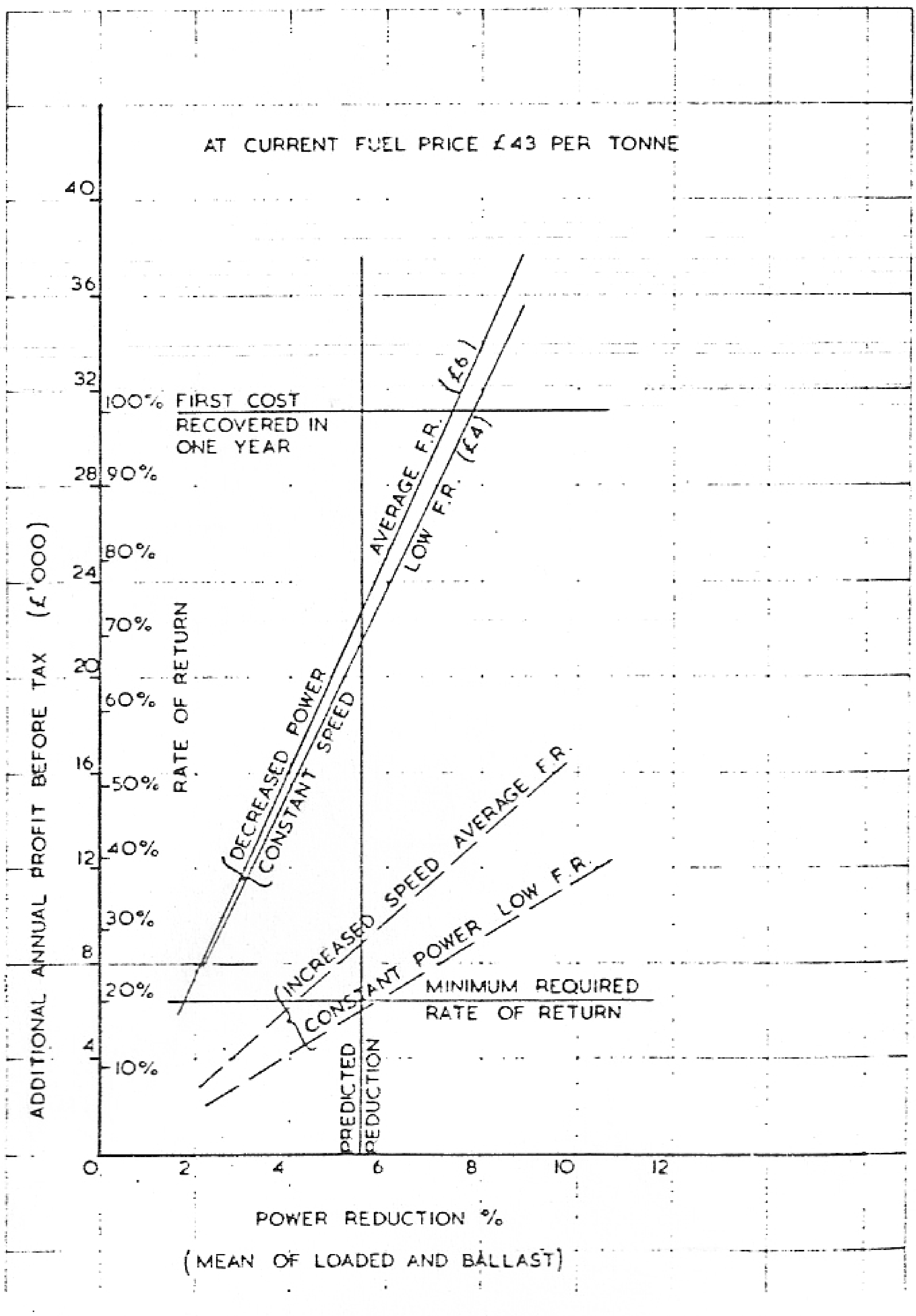

*Fig. 2—Profit vs. power reduction (given fuel price)*

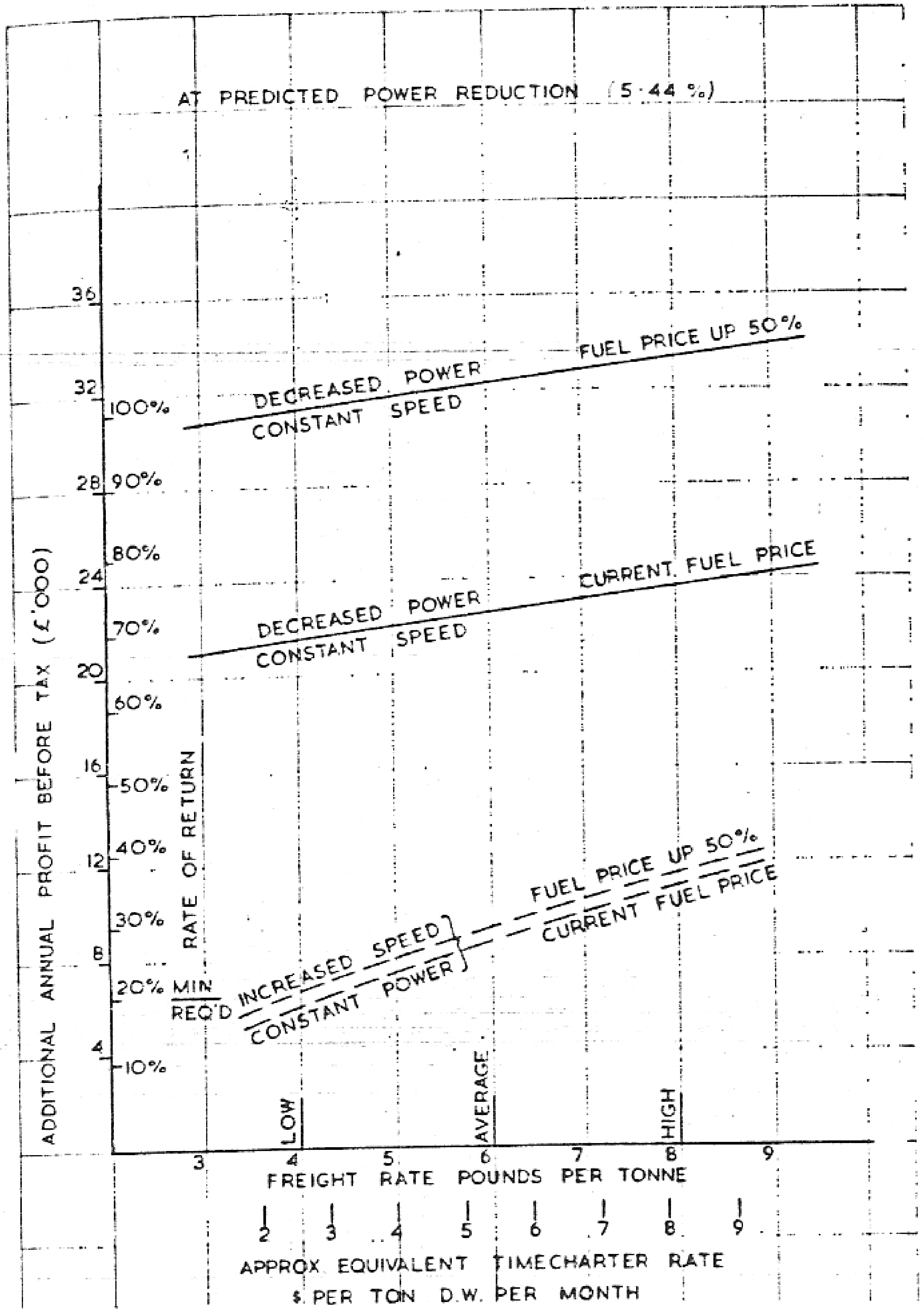

*Fig. 3—Profit vs. freight rate*

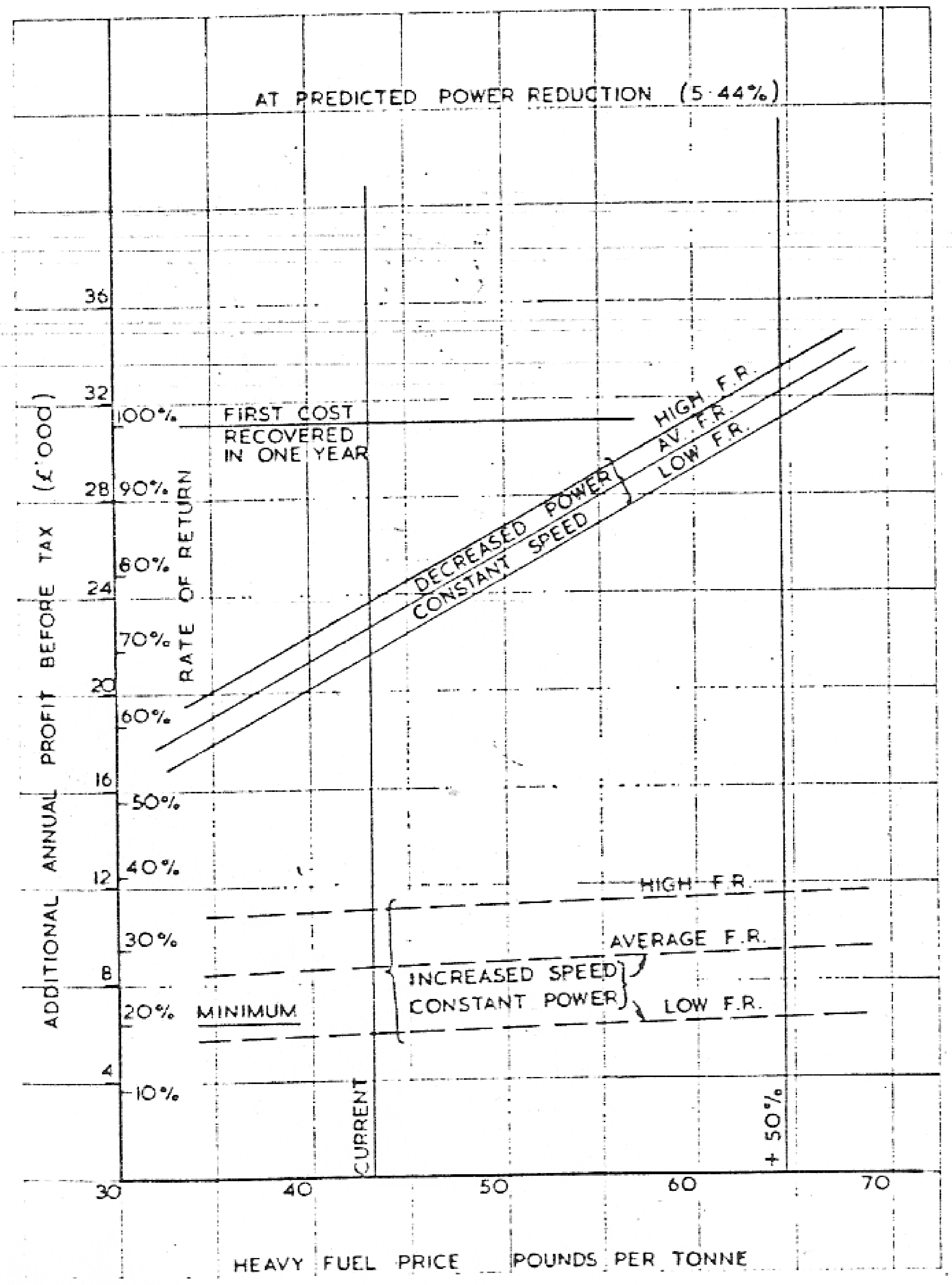

*Fig. 4—Profit vs. fuel price*

made for both the constant speed and constant power cases. The details of one of the calculations are shown in Appendix 1, for a 12,000 mile round trip, which is representative of the voyage pattern of such a bulk carrier. It is therefore possible to insert any alternative assumptions desired and rework the calculations, although interpolation in the graphs provided covers the range of the important variables.

**Results**

Figs. 1 to 4 summarise the results of a number of calculations. From this it is clear that a rate of return well above the necessary minimum is achieved for almost every combination of assumptions. The ducted propeller is thus shown to be a very worthwhile investment, which can be paid off in little more than a year.

The principal conclusions are:

(i) The most profitable option is to run the ship at the same speed on decreased power. The increased speed/same power option only shows to advantage if freight rates are very high or bunker prices very low (or a combination of the two), but these would be outside the range covered.

At the predicted power reduction for constant speed:

(ii) The additional annual profit is about £22,600. This is equivalent to a rate of return on the £31,100 investment of about 72 per cent, or a payback period of about 17 months (fig. 1, also figs. 2 to 4).

(iii) The extra profit is not very sensitive to the level of the freight market; even at low freight rates, the gain is at least £21,000 (fig. 3).

(iv) The investment is worthwhile even if the actual power reduction should turn out as low as 1.7 per cent rather than 5.44 per cent, as the extra profit is at least the necessary £6,380 (figs. 1 and 2).

(v) If fuel prices should rise further, the investment would be even more profitable. At a 50 per cent increase, the rate of return is 100 per cent, that is the investment pays for itself in one year (fig. 4).

(vi) The ducted system could cost up to £110,000 more than the conventional and still be profitable (£22,600/0.205).

(vii) Additional annual costs of up to £16,220 could be tolerated before the ducted system became unprofitable, e.g. for additional repair costs (£22,600—£6,380).

(viii) Additional off-hire of 9 days at average freight rates could be tolerated before the ducted system became unprofitable.

(ix) The owner of a ducted propeller ship could accept a voyage charter rate 20 cents per tonne of cargo lower than a non-ducted ship for the same daily profit.

(x) The owner of a ducted propeller ship could justify asking a charterer for a time charter rate 14 cents per dwt per month higher than normal on account of the lesser fuel bills which the charterer would have to pay.

(xi) For the increased speed/same power option, the effect of variation in fuel price is small (fig. 4).

(xii) By operating at reduced power, there should be additional savings from lower maintenance and repair costs and reduced lubricating oil consumption.

## PART II
## GENERAL ECONOMIC CONSIDERATIONS

**Speed or Power**

Increased propulsive efficiency can be used as an increase in ship speed at the same power or as a reduction in power at constant speed. The latter alternative which is preferred in the earlier example for the 26,000 tonne bulk carrier could in certain cases lead to an installation of reduced power and bunker capacity and thus diminished first cost. On the other hand the former alternative results in more round trips per annum and, assuming the same operating expenses, this results in higher income which can be used to offset additional first costs. Experimental evidence suggests that ideally, by the use of ducted propeller systems, power reductions exceeding 10 per cent can be achieved which are equivalent in the majority of ships to speed increments in excess of 0.3 knots.

### Consideration of Increased Speed

In order to study the effect of certain parametric variations on the economics of increased ship speed for a certain trade, a computer programme has been developed, see Appendix 2.

The programme makes allowance for all the possibilities in the installation of a prototype system and may on the face of it seem rather pessimistic. It makes provision for:

(a) type of financing;
(b) difference of alternative machinery costs for ducted and conventional propellers;
(c) difference of maintenance costs for the machinery for ducted and conventional propellers;
(d) air injection if required as a palliative to cavitation erosion;
(e) number of days out of service per year should extra maintenance be required;
(f) state of loading between ports;
(g) distance between each port;
(h) loading and unloading speed in each port;
(i) lost time in each port;
(j) port expenses;
(k) freight rate between each port.

The theory is based on the annual transported tons for a ship which can be expressed as:

$TY$ – the tonnes of cargo transported per year $= \text{tdw} \,.\, c \,.\, n$

where

tdw = the deadweight tonnage
$c$ = the ratio between number of transported tonnes and the deadweight
$n$ = the number of round trips per year

The number of round trips per year ($n$) can be expressed as:

$$\frac{365-t}{\dfrac{d}{V.24}+\dfrac{2.\text{tdw}.c}{N}+v}$$

where

$t$ = number of days out of service per year
$d$ = distance in nautical miles between ports
$V$ = ship speed in knots
$v$ = number of lost days per round trip
$N$ = loading/unloading speed in tonnes/day

$n$ can also be written in the form

$$\frac{(365-t)\,.24.V.N}{2.\text{tdw}.c.V+N(d+24.V.v)}$$

in which the influence of the different parameters becomes more clear. The important factors are:

(i) Number of days in service per annum, generally in the region of 350 days per year for a tanker;
(ii) the mean ship speed;
(iii) loading/unloading speed;
(iv) distance between ports;
(v) lost time in the ports due to manoeuvring, waiting, etc.

Clearly the mean ship speed plays a minor role for short distances while the opposite is true concerning the loading/unloading speed. Some examples will illustrate this point.

Assuming idealised conditions, i.e. loading/unloading speed, lost time and number of transported tonnes, the simple relations above are computed for a 106,000 tonne dwt bulk carrier transporting ore. Relevant loading/unloading speeds for this example are 5-10,000 tonne/hour, whilst at Seven Islands for example, a loading speed of 30,000 tonne/hour is planned. The comparisons are then:

| Distance between ports, n. miles | 2,500 | 5,000 | 10,000 |
|---|---|---|---|
| Mean loading/unloading speed, t/h | 5,000<br>10,000<br>20,000 | 5,000<br>10,000<br>20,000 | 5,000<br>10,000<br>20,000 |
| Lost time in hrs. per round trip | 24 | 24 | 24 |
| Loading factor (c) | .96 | .96 | .96 |
| Speed increase (knots) | .2<br>.35<br>.5 | .2<br>.35<br>.5 | .2<br>.35<br>.5 |
| Mean ship speed without duct (V) | 15.5 | 15.5 | 15.5 |

The calculated results are shown in fig. 5. The increase in transported tonnes is drawn as a function of $d$ and different speed increments. It is clear that both the speed

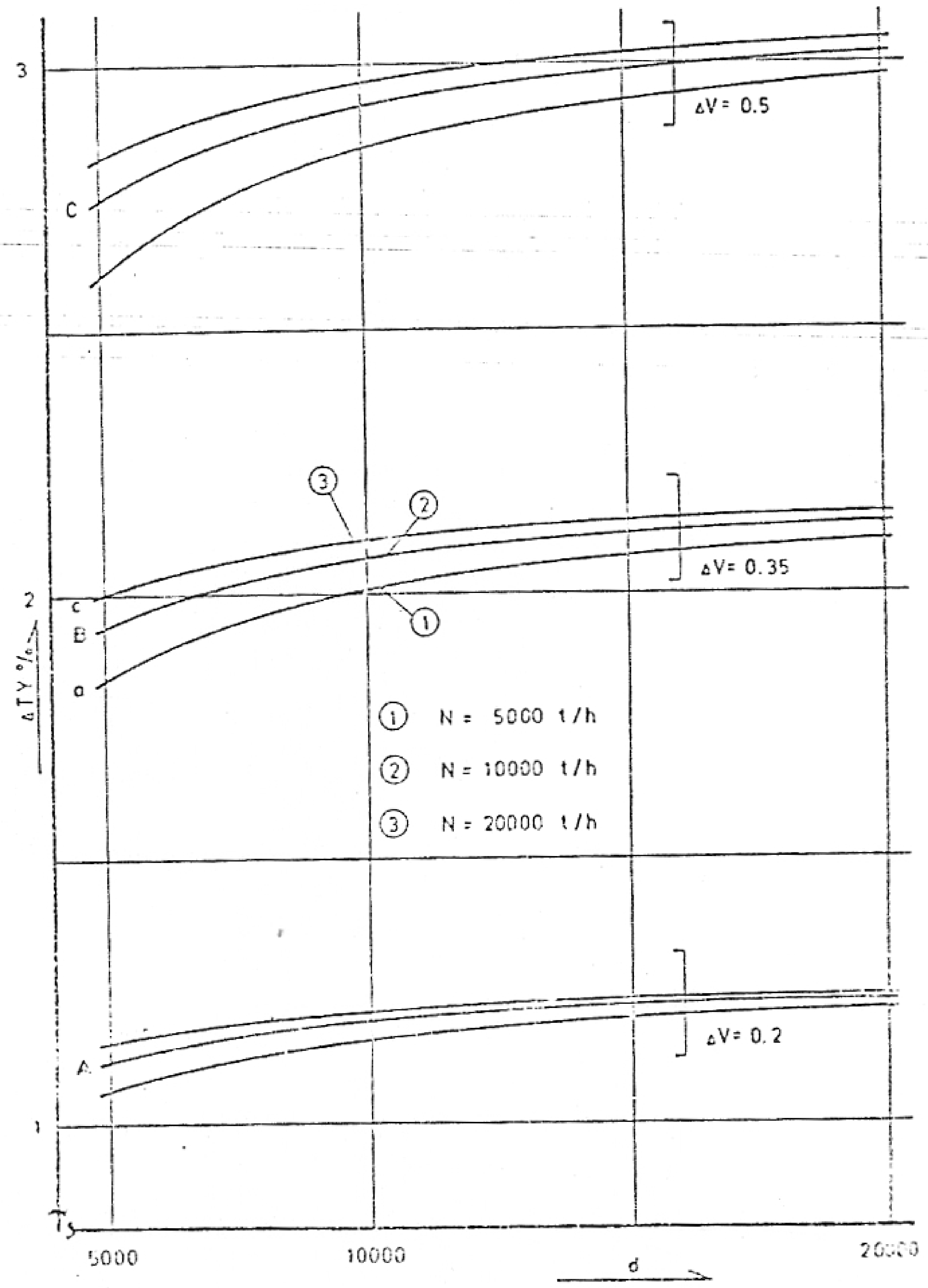

Fig. 5

increase and the loading/unloading speed give increased transport. Looking at the difference between the curves denoted by A-B or B-C we find that the difference is nearly constant as a function of the distance between the ports. This means that the increase in transported tonnes by increasing the ship speed is only very slightly dependent on the distance. However, the curves a-B-c show that an increase in transported tonnes as a function of the loading/unloading speed is markedly influenced by the distance. For larger distances the influence of the loading/unloading speed is considerably reduced.

### Factors affecting Economy

Before covering specific examples, it may be useful to discuss some of the important factors required in more detail. Some of these are extremely variable and in addition vary with the ship owner concerned. These notes are therefore broad generalisations and for an actual project more detailed consideration will be necessary.

### Duct Costs

Clearly the cost of a duct varies enormously depending on a variety of factors. In general the proportions of the duct are fairly closely related to its throat diameter and a rough guide to the price on a qualitative basis is given in fig. 6. In this case the price in U.S. dollars is given on a base of diameter in metres. Clearly this will be a 'ball park' figure and in the case of a specific project a reliable figure based on accurate cost data would be necessary.

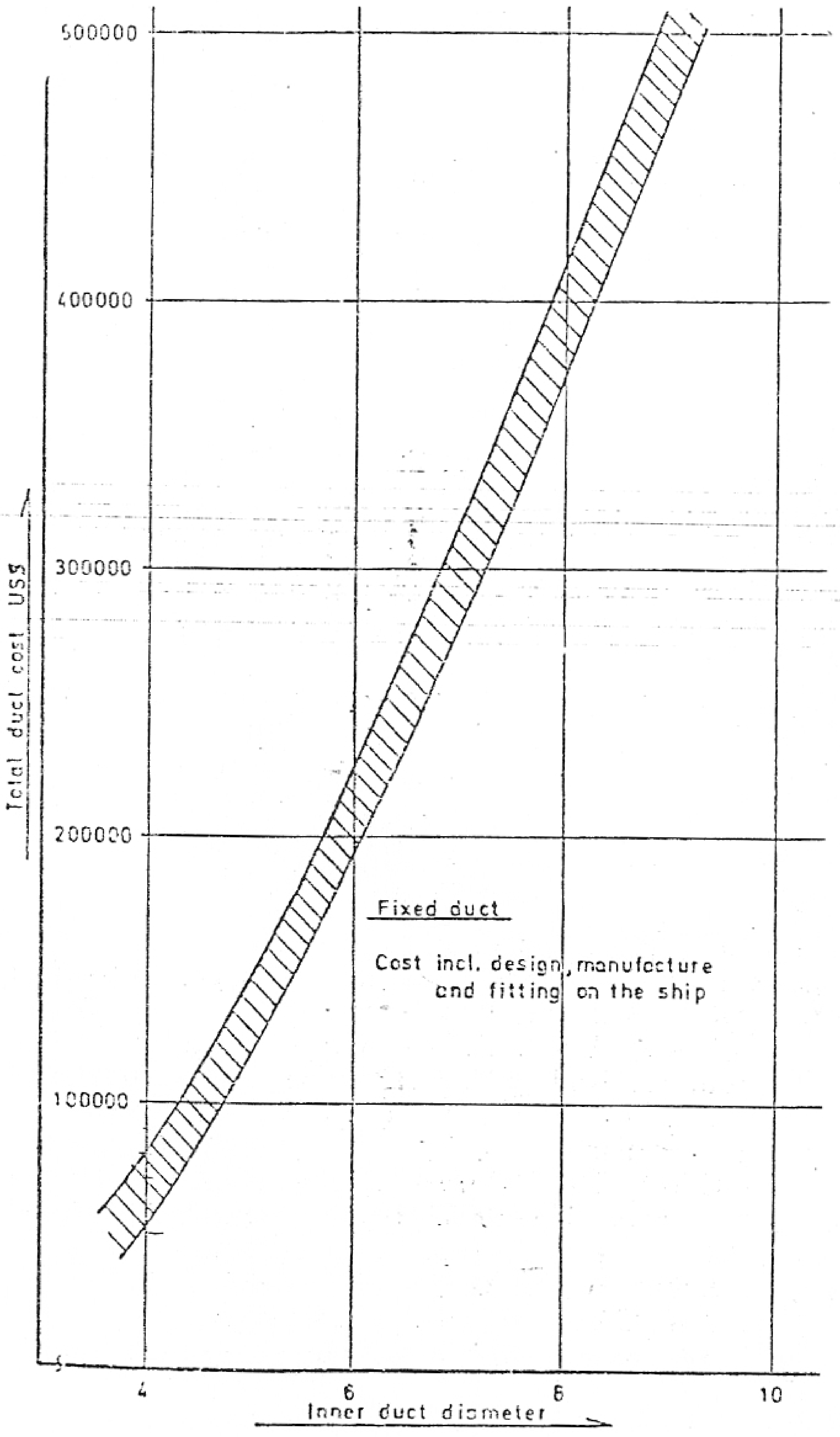

*Fig. 6*

### Propeller Costs

Ducted propellers are somewhat smaller than the equivalent open propeller for a given power and RPM. This usually amounts to a reduction of some 5 to 10 per cent of diameter and thus effects some economy in first cost. In addition, as the duct takes a proportion of the thrust, the blade strength and thickness and blade area can be reduced to some extent. This provides a reduction in cost for both working and spare propellers if such is needed. Fig. 7 gives the price differential in U.S. dollars for the service and spare propellers as a function of RPM and power.

### Duct Repair and Maintenance

One of the major difficulties afflicting the very large single screw tanker and bulk carrier, has been that the ever-increasing power has not been accompanied by significant and necessary improvements to the ship stern design. As a result, the flow conditions are such that the propeller is inevitably subject to cavitation, particularly at the top of the stern frame aperture, where the wake influence is greatest. For the normal propeller, long experience in material and design has made it possible at least to avoid serious blade erosion. In the case of large ducts on such ships, a relatively recent innovation, experience is only now being obtained so that, certainly at this stage, some possibility of duct erosion exists.

There is furthermore little available assistance from the cavitation tunnel because of scale difficulties with such appendages and the problems of correctly simulating the ship wake distribution. Perhaps the greater capability of some of the new European cavitation tunnels will be helpful in this. Meanwhile, because this cavitation problem is not yet completely solved, some allowance must be made for periodic reconditioning of the duct in any meaningful economic appraisal of the ducted propeller installation.

Based on maintenance statistics from three ships of between 200 and 250,000 tonnes deadweight each, having been in service with first generation ducts for some 30 months, a mean maintenance cost of around U.S. $450 per month was needed. More recent ships fitted with second generation duct designs have shown considerably greater durability such that the monthly repair bill could be halved, i.e. around U.S. $225 per month. In the earlier example, Part I, it will be seen that an allowance for duct maintenance much greater than this could be made while still making the required desirable return on the investment.

### Air Injection

In certain cases of ships with special flow problems, and thus difficult cavitation conditions, it has been found necessary to take some special measures to avoid duct erosion. Hydrodynamic design measures will no doubt in the long term solve the problems and work is going on using theoretical means, model cavitation tests, and in certain cases full scale television/high speed film studies. In addition the use of stainless steel in particularly vulnerable areas is becoming an established practice. One of the most successful measures at this stage has however been the use of air injection along the inner duct plating where the cavitation is intense, i.e. in the upper part of the duct. The erosion rate is thus considerably retarded as a result of the cavitation bubbles collapsing with reduced intensity.

The cost of air injection is that of the air compressor, piping and fitting, which is dependent on the amount of air and the pressure required which of course is related to ship size, propeller diameter and RPM. The introduction of

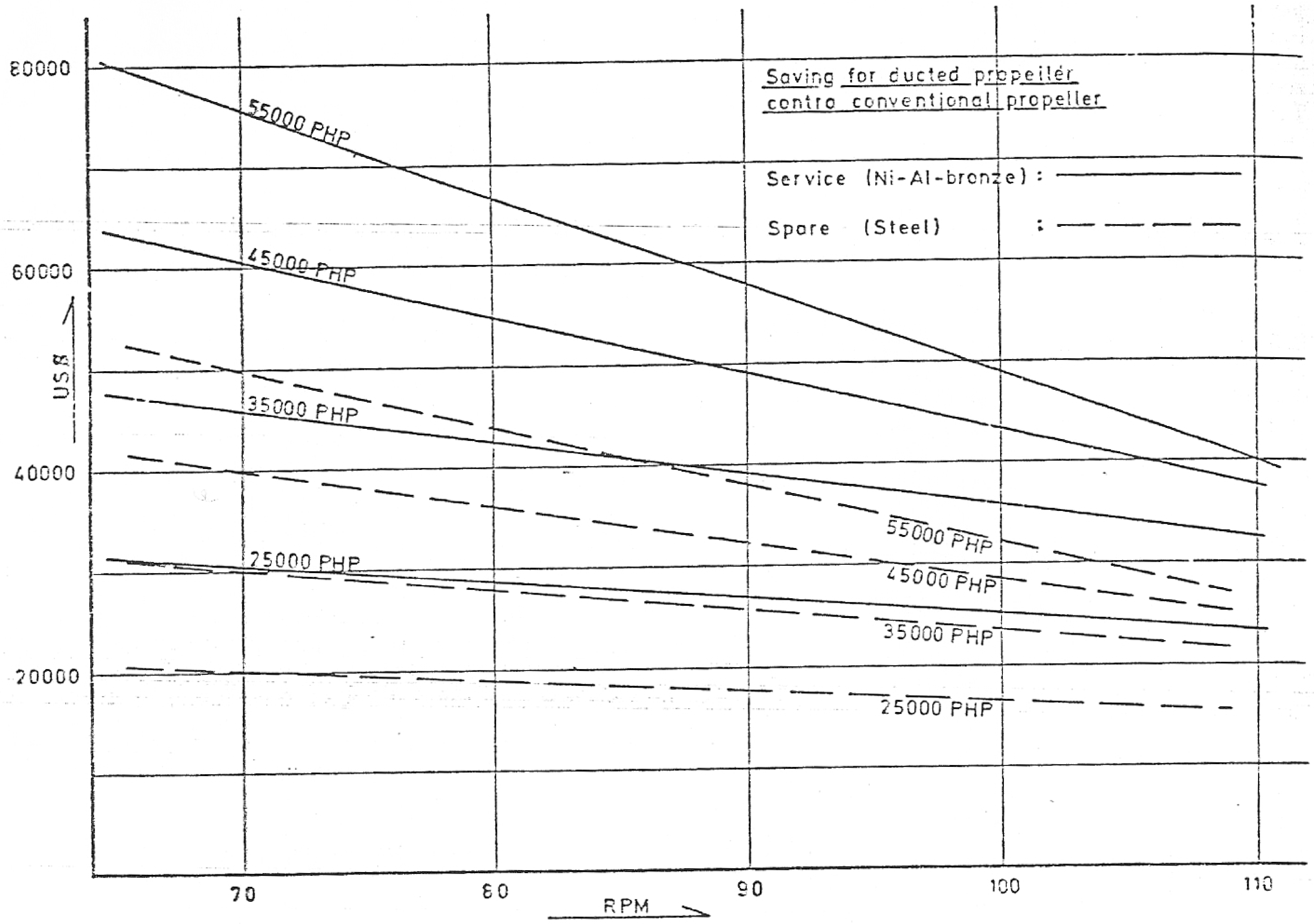

*Fig. 7*

such equipment is considered again later in examining the example of a 215,000 tonne dwt tanker. The actual cost in this case was U.S. $36,000 and the required power estimated to be 90 HP.

### Cost of Machinery

With efficiency gains in certain cases exceeding 10 per cent, it may be possible to install less horsepower and thereby effect a reduced first cost and it is possible to account for this alternative in the computer programme. In many cases this efficiency gain is too small to result, for example, in machinery having one cylinder less. In certain cases however, the owner may want to use only 90 per cent power in service for the conventional ship and 100 per cent for the ducted ship as in the case in example 3 to be shown, then the evaluated result can allow for this.

The total investment for the machinery amounts to approximately 25 per cent of the total cost of the ship. Often it is assumed that the cost of the machinery is a linear function of the power. Ref. 1 gives the cost of machinery as U.S. $ (440,000 + 193 HP) in 1974. This relation is used in example 3.

### Machinery Maintenance

Commonly it is assumed that these costs are proportional to the power. Assuming the same ship speed, the difference in power then should lead to improved results for the ducted alternative. Explicit figures are of course difficult to obtain and particularly as they are dependent on the ship age and also on the owners' particular requirements. Neglecting this difference, it should still be allowable to compare the ducted alternative with conventional propulsion, thus erring on the conservative side.

### Bunker and Lubricating Oil Costs and Fuel Consumption

In considering the economics of the duct system, the price of bunker oil on 1st May 1976 has been taken as U.S. $66.0 per tonne and of lubricating oil U.S. $535.00 per tonne.

Specific fuel consumption varies to some extent from ship to ship because the age of the vessel and its standard of maintenance plays a significant part. However, the best general criterion is the power and it is suggested that the following values can safely be used (ref. 1).

STEAM TURBINE fuel oil in grams per horsepower/hour equals 217-0.0006 HP for powers less than 45,000 and 190 grams per horsepower/hour for powers greater than 45,000.

DIESEL ENGINE fuel oil in grams per horsepower/hour equals 168-0.0002 HP for powers less than 45,000 BHP and 159 grams per horsepower/hour for powers greater than 45,000.

LUBRICATING OIL consumption is taken as 0.4 grams per horsepower/hour.

### Port Expenses

These cover the expenses paid for service in each port of call, i.e. tugs, moorings, etc. They are of course dependent on local conditions as well as on ship size and type. For a 120.000 tonne bulk carrier a charge of U.S. $25,000 per harbour is estimated (ref. 2). From ref. 3 for a 215,000 tonne deadweight ship, U.S. $50,000 is the cost per port of call in Rotterdam and the Persian Gulf.

**Freight Rates**

The freight income from shipping and especially for tankers, varies enormously and at this moment the future trend is difficult to forecast. For the present purpose in order to evaluate the increased income by increasing the speed of the ship, a rate of U.S. $4.812 per tonne has been used for the 215,000 tonne deadweight tanker. Ship speed must in itself favourably influence the freight rate but this has not been taken into account in the present assessment on the assumption that this is a small influence in favour of the ducted system.

**Full Scale Examples**

First the economy of a 215,000 tonne deadweight tanker with ducted propeller is compared with a sister ship with a conventional propeller, both engaged carrying crude oil from the Persian Gulf to Europe. The ducted propeller ship has been in service from 1971 and has operated at full speed. This ship has sister ships both with and without ducts. The duct was of 'first-generation' design, and some erosion was experienced which was reduced by 'welding-in' stainless steel doubling plates into the relatively small critical area. In 1975 air injection was installed as a further palliative treatment.

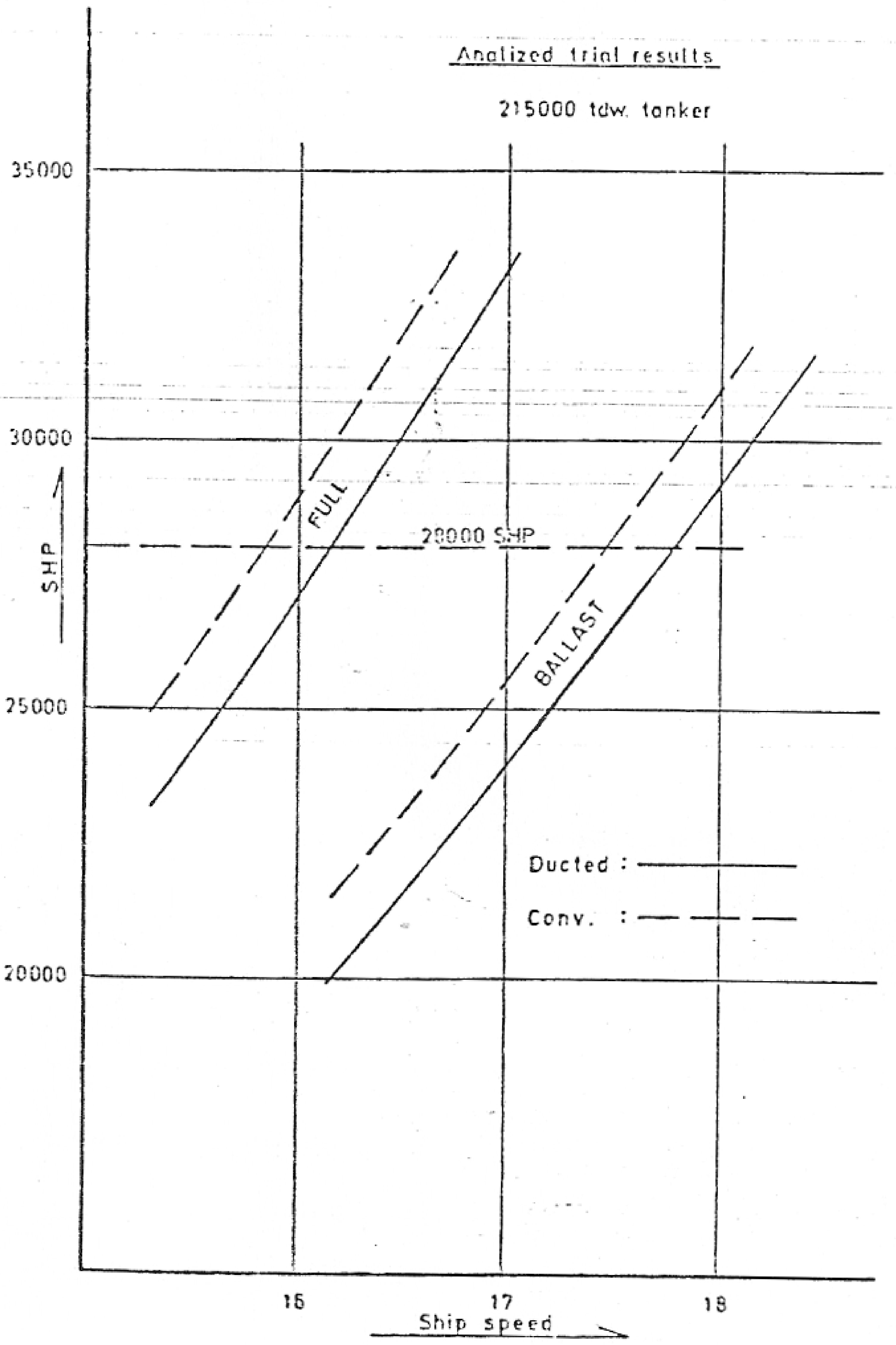

*Fig. 8*

From this ship and her sister ships with and without ducts, trial and service performance data were taken and analysed. A detailed study was made of the influence of maintenance costs on the economy, the influence of the freight rate and the influence of the cost of air injection.

Fig. 8 shows the analysed trial results as mean values for three sister ships with duct and three without duct. The results indicate a speed gain of 0.3 knot in both full and ballast load. Based on measured data for the ships over a period of approximately 30 months and analysed to a standard condition of sea and wind, it has been found that the mean speed gain for the ducted propeller ships has been 0.3 knot in full load and 0.6 knot in ballast. Taking into account the broad statistical material on which all these results are based, the reason for the difference in ballast may be due to the Captain's experience of the ducted propeller ship in rough weather. Reports from the ships with duct state that the variation of RPM in rough weather and ballast condition is smaller than for ships without duct or it is said "the ducted vessel has better speed-holding ability". In the coming examples the service performance is used.

**Example 1**

This is the basic example. Computer input is shown in fig. 9 and output in fig. 10.

*Ship information*

| | |
|---|---|
| Ship type | Tanker |
| Deadweight | 215,000 tonnes |
| Machinery | Turbine |
| Max. power/RPM | 30,000/90 |
| Service power (conventional) | 28,000 |
| Ship speed, full/ballast | 15.85/17.50 |
| Power saved with duct load/ballast | 1,800/3,000 |

From fig. 10 it will be seen that the annual additional cost of the duct is calculated to be U.S. $39,000. The oil savings amount to U.S. $252,184 per year. The net income is obtained by subtracting U.S. $39,000 from the oil saving. Finally the necessary time to pay back the additional cost is calculated to be 1.38 years.

**Examples 1a, 1b, 1c and 1d**

It can now be shown how the maintenance cost will influence this 'pay back' period, see fig. 11. From U.S. $450 to U.S. $150 per month the pay back period varies only slightly (8 days). It might appear however that air injection is a bad investment as the pay back period will increase by 2¾ months. This is however far from the truth as the necessary maintenance for the duct without air injection occurs more frequently than the normal docking dates. This leads to extra off-hire which is not included, for example in the U.S. $450. It is therefore a good economy to install air injection in order to secure maintenance intervals at least corresponding to the normal docking periods.

Example 1d makes allowance for three days off-hire every second year. Explicit figures for the off-hire have been difficult to obtain but if we assume U.S. $40,000 per day, the monthly maintenance cost will approximate to U.S. $5,000.

Assuming this duct has no other means for reducing the erosion rate and that the ship has an unfavourable wake distribution, the results from example 1d show an economically sound investment.

**Examples 2, 2a and 2b**

To consider the influence of the freight rate, the speed gain must be taken into account and this is now considered.