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Some Operational Aspects
of
Speed and Fuel Consumption

by

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The contents of this paper reflect my own personal views and are not necessarily endorsed by the UNIVERSITY.

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ABSTRACT

In this paper, an attempt has been made, to give a description of the Shipping environment with emphasis on the need for optimisation; New Ships being purpose designed for a particular trade and Existing Ships to be optimised for a particular trade.

A discussion on what influences the optimal speed of a Ship, how to optimise fuel consumption and maximise profit for a given ship in a particular trade, is made.

The factors on whether it is economically viable to dry-dock a given ship, continue to operate with a rough hull or take advantage of underwater maintenance are also discussed.

In the context of economy, the advantages of passage planning, from a technical and commercial aspect are brought to light.

In the conclusions various thoughts, as a result of the work conducted, are expressed.

PREFACE

As the purpose of my training is to return to my country and to help to improve the efficiency as well as expand the scope of services rendered to the maritime community at present, by my Sponsoring Company, I propose to endeavour to direct the research effort in preparing my thesis, towards the acquisition of knowledge designed to be of assistance to my stated purpose.

My Sponsors, CARENCO LTD trading under the name of Carenco Surveyors, are the successors of the operations of the founder who acted as an independent and part time marine surveyor.

As the activities in the marine field multiplied, the present company was established in 1972 for the purpose of formalising and at the same time expanding its marine activities.

Ships Classification Societies were and still largely are represented in Cyprus by non technical but prestigious Agents such as the local Consul of the flag country to which the Society belongs nationally or, as is the case with Lloyd's Register of Shipping, by the local Lloyd's Agent.

The Agents used to appoint surveyors on a case by case basis, usually employing officers from visiting vessels, Chief Engineers for the engine and Masters for the hull sides.

With the arrival on the scene of the founder of Carenco in 1962, he was regularly and increasingly more frequently appointed to carry out the surveys which were previously commissioned from visiting seafarers.

This development quickly proved to be beneficial to all concerned because it provided the elements of continuity and record keeping which are the two essential ingredients for the creation of an infrastructure and database in the field of marine surveying which was totally absent from the island up to that time.

The purpose of the formation of Carenco was twofold. The first objective was the obvious necessity of the consolidation of the variety of knowledge being acquired in the course of work execution and the second was to pass on this knowledge to professionally qualified persons with a view to the expansion of the services offered.

A list of the services presently on offer is to be found below.

A scrutiny of the said listing leads to two alternative conclusions

- The Company has grown in size and employs a large number of specialised surveyors
- The Company has grown versatile and multidisciplinary by virtue of the small volume of work available in each field by employing and training a small number of suitably inclined professionals who are able to change fields several times in the course of their working day if necessary and cope successfully with the problems as they present themselves.

The size of the island of Cyprus is such that it dictated the second alternative.

It is however true that by practicing in the aforementioned mode, the Company has over the years accumulated and effectively stored in its archives, both of the traditional and electronic types, a comparatively large data bank of information which when correctly exploited leads to the possibility of effective diversification to cushion times of crisis in the main fields of operation or to expansion into new and promising fields by the formation of subsidiaries or by taking on extra staff, as the situation may warrant.

Description of the range of Services offered by CARENCO SURVEYORS

A. Ship Surveys

1. Classification Surveys

- (a) Hull in drydock and afloat.
- (b) Machinery, boilers, steering gear, tailshafts.
- (c) Lay up and reactivation.

2. Statutory Surveys (subject to individual Government authorisation)

- (a) Safety Equipment.
- (b) Radiotelegraphy and Radiotelephony Safety Certificates.
- (c) Annual Load Line.
- (d) Annual Cargo Gear.
- (e) Factories Act for proper maintenance and installation of steam and other pressure vessels, lifting equipment and their periodical inspection.

3. General Surveys

- (a) Damage Surveys.
- (b) Change of Owner.
- (c) On Hire, Off Hire.
- (d) Recommissioning.
- (e) Refrigerated Cargo Spaces before loading.
- (f) Opening of Refrigerated Cargo Spaces.
- (g) Ventilated Spaces before loading.
- (h) Cargo tanks before loading.
- (i) Maintenance and Watertightness.
- (j) Supervision of Repair Works.
- (k) Ultrasonics thickness measurements of plating and scantlings.
- (l) Vessel valuation and condition reports. (Insurance, P+I, Sale and Purchase).
- (m) Feasibility studies concerning operational economics of vessels on given routes on trading or passenger services.
- (n) Bunkers analysis service in cooperation with approved laboratories.

B. Cargo Surveys.

Specialisation on surveys to damaged cargo of a technical nature.

Complete reports are prepared and repair cost estimates submitted.

Repair work is followed up and repair accounts scrutinised.

C. Marine and Industrial Consultation.

Study, design and preparation of drawings and specifications as well as evaluation of tenders, for the Electrical, Mechanical, Propulsion, Air Conditioning, Pumping, Fire Fighting and associated installations for Marine and Industrial Applications including shipboard.

D. Naval Architecture

1. Drawings and specifications for vessel conversions.
2. Drawings and specifications for the construction of small vessels.
3. Preparation of loading booklets.
4. Inclining experiments.
5. Intact and Damage Stability.
6. Floodable lengths.
7. Tank calibrations.(Land and Marine)

A study and comparison of the listing of the fields of possible operations which Carenco is capable of, with the formal functions expected of a well run and managed Technical Department of a Shipping Company clearly shows the road to the additional Source of Income.

It is with suggestions for practically attainable methods to achieve this that the present thesis is going to be concerned with, by making a survey of published literature so as to compare various thoughts and attain a more lucid view on speed and Fuel Consumption of Maritime Craft.

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Introduction

1.0 The Environment

It is well known that shipping and the world economy are two unbreakable magnitudes with respect to the transportation of commodities.

Due to the oil crisis, prices of bunker fuels went up and along with the result of an overcapacity in the global shipping volume which had developed, the world fleet went through a tremendous availability which led to a throat cutting competition, while the world economy receded.

As a result of this, the situation in shipping deteriorated sharply with the inevitable result that many ships were laid up, and those which remained operational could only remain in the market by applying stringent cost-cutting programmes.

The obvious costs, such as those of crew, maintenance and dry-docking had been tackled first, but this did not always give the necessary contribution needed.

A greater appreciation of the cost distribution for voyage cost, of several types of ships over the period of 1973 to 1981, may be acquired by studying the table and the respective barchart to be found in Annex A.a.

A comparison of voyage costs with regard to those of capital costs and operational costs, for the same vessels over the same period is made in Appendix A.b.

As the fuel costs became to be regarded as a dominant part of the total operational cost, fuel saving methods were introduced, which could help substantially, to such a degree that turbine ships were laid up and replaced by motorships, with research and development

being emphasized for designing engines with lower fuel consumption, whilst attempts were carried out to render existing ships the most profitable, under the circumstances, through slow steaming.

From the Annual Report of Stena 86/87, it may be quoted from page 10, that,

"The RoRo Market depression starting in 1981-82 has been broken this past year, resulting in a stable freight market and increasing sub-purchasing prices." (Ref 1)

The publication then expresses the following market forecast:

"The general opinion seems to be that we can expect a steady increase in market rates up to a sound market level, equivalent to approximately double the rate obtained during the last recession." (Ref 1)

To this effect, the following is stressed by the same;

"Our strategy is to replace unprofitable tonnage with larger tonnage. This larger tonnage will be fully employed and thus cover capital cost." (Ref 1)

This view is not shared by G. Grimaldi of SICULA OCEANICA SPA, ITALY, who expresses the following opinion:

"The recent crisis of tankers and bulkers have orientated much more investments towards the car carrier sector, which looked like an oasis in the gloomy situation of shipping." (Ref 2), and continues with;

"The race for giantism, giving apparently, some benefits for scale economy, at the end may prove detrimental because sooner or later the economy will be transferred to the contractors who will claim for lower rates and this will affect also smaller vessels which will become anti-economical even if not yet technically obsolete."

(Ref 2)

Grimaldi then expresses the following within his recommendations:

"to put a stop to giantism; remembering the last decade when small and middle size tankers were still operated with a margin of profit, whilst very large and super large tankers were forced to be laid up." (Ref 2)

The President of Sicula Oceanica, finally recommends;

"to avoid over tonnage also in the sector of car carriers, all companies, when planning new buildings, should look to the renewal of their fleet rather than expansion.

In this form, the companies should prefer to scrap their older ships instead of selling them for further cheap operations by small companies with underpaid crew, minimum general and financial burden." (Ref 2)

On reading the report on the "Annual Meeting of the International Association of Independent Tanker Owners", in Fairplay, 2nd June 1988, it is evident that Tanker Owners are not for newbuildings, let alone for scrapping.

The following quote from the article is most probably representative of the general feeling of the persons present.

"Most tankers, maintained Mr. Hoegh, will go through the third Major Survey at 18 years. Many will be taken through fourth survey five years later, even though the cost of bringing the ships upto scratch could be as high as \$4M."

The 20-year survey will carry a price tag in-excess of \$5M in today's dollars, but Mr. Hoegh feels that Owners may well decide to keep their ships 'going for ever' given the penal cost of replacement. "Ultimately it will be the market which decides how long we keep the ships, not their physical condition," he added. (Ref 3)

The preceding quoted view obviously came from the current high prices of new buildings and thus inflated prices on the second hand market.

"It was the price of new tonnage, which occasioned much debate over the Merits of extending the life of existing tonnage well beyond the 15-20 year life span, previously assigned to VLCCs. There was general consensus that replacement tonnage would cost around \$70M in today's market, although there were some who argued that prices may soon move closer to \$100M." (Ref 3)

Following this, the following was said about the second hand market: "one London based broker suggested that \$50M could soon be the going rate for 15 year-old VLCCs." (Ref 3)

From the preceding quotes it is evident that Tanker Owners are, in general not prepared to invest in newbuildings yet, but to continue to operate and reactivate laid up tonnage.

The RoRo Owners, it seems, would enjoy new tonnage, but not to expand their fleet but for replacement. The question lies in what they would do with their old tonnage?

The decision would most probably be taken after analysing the following constraints in conjunction with each other. The Market Value versus the Scrap Value and the possibility of increased competition if the vessel is not scrapped.

This obviously will lead to older ships plying the seas, some in direct competition with the newer generation and others owned by small operators, trying to make a profit competing against ships of their own "class."

As pointed out by Heaver in "The Treatment of Ships' Operating Cost", (Ref 4)

"Owners want to make their decisions based on good estimates of the cost of owning and operating particular types of vessels." (Ref 4)

Heaver also states in the same article that,

"An accurate knowledge of operating costs is important to the efficient management of vessels by Shipowners. Shipowners need to have a good basis for cost estimates and to be able to account for deviation from these estimates. They must also have a knowledge of operating costs to select the optimal design of a new vessel."

(Ref 4).

It shall be with the "deviation from these estimates", with regard to fuel consumption and speed that this paper will deal with, by bringing to light the factors which influence the said deviations thus giving an appreciation of the need to monitor and minimise them to what would be thought as the best overall decision, with respect to short and longterm planning, so as to ensure the competitiveness of the vessel.

From 'Engineering Economics and Ship Design' by I.L. Buxton (Ref 5), it is evident that the features of the design of a ship are influenced by "the division of responsibility for cost and ship's time between Shipowner and charterer."

This may be better expressed by a quote from the same book, (Ref 5, page 27).

"Time chartered tankers may be designed to oil company specifications. With bare boat charters less than the life of the ship, the charterer has less incentive than an Owner-Operator to reduce fuel consumption, while time in port is more significant for Owners of Owner-Operated, or voyage chartered ships than for time chartered ships." (Ref 5)

The following factors on ship size and speed, pressed home by S.C. Ryder and D. Chappell in a commentary for Maritime Policies and Management, 1980, Vol.7, (Ref 6), are also important when regarding the perspective of the environment of trade.

"Although economies of size apply to construction for all types of ships, they do not always apply to operating costs. In this context, two factors distinguish the general cargo sector, and particularly the liner trades. The first is the relatively high proportion of time spent in port, and the second is the limited cargo available. The former suggests a trade-off between economies of size at sea and diseconomies in port (since daily costs in port, increase with ship size)." (Ref 6)

The Cruise Industry also has to be aware of economizing. According to S.R.C. Wanhill in an article on "Some Aspects of Cruise Ships", (Ref 7), it is evident that the evolution of Cruise industry from a passenger liner service to what it is today, has been brought about by emphasizing "the cruise liner itself as a destination." (Ref 7).

This may be seen by the following statements made by Wanhill;
"Ports of call are offered as sightseeing excursions rather than holiday destinations. One consequence of this reformulation of the product is that it has enabled the industry to re-schedule itineraries, to reduce sailing speed and conserve fuel." (Ref 7)

In general, it may be said, that Shipowners choose a speed which maximises the net return from sailing, making sure that the Revenue at the chosen optimum speed is at least greater than the lay up costs.

This is expressed rather cooly by Buxton in an article "Fuel cost and their Relationship with Capital and Operating Costs." (Ref 8).

"Minimizing fuel costs therefore requires minimising daily consumption (at any particular speed) and fuel price, but not minimizing sea days; one can certainly minimize fuel costs by laying the ship up, but this is hardly to be a profitable exercise!"
(Ref 8).

The same point is pressed further home by P. Jamin, Technical Manager of SITRAM (Ref 9), who states the following;

"The intelligent Shipowner regularly operates his fleet at the economic speed, he gives attention to the profit-earning capacity of his capital and seeks out the profitable speed which gives him maximum profit, and not the economic speed which gives him minimum expense." (Ref 9).

The above reasoning, apparently comes from the following school of thought.

"a 10% decrease in speed gives a reduction in bunker costs per day at sea of the order of 30%, but increases the number of days at sea of the voyage by 10%. If about a half of the voyage time is spent at sea, this time is prolonged by 5%. It will thus be seen that the saving is not as much as might be hoped and that in any case the transport capacity of the ship has decreased by 5%." (Ref 9).

However, the fuel consumption of a ship is not only dependant on the power plant operation, but also on many other factors such as listed below.

Main Engine - Fuel oil quality

- Injection quality and timing
- Blower matching in relation to engine load
- Valve timing and valve tightness
- F.O. temp.
- Inlet air temp.
- Blower condition

Propeller - Pitch/R.P.M. ratio

- Blade roughness
- Damage to blades
- Accuracy pitch positioning for C.P.P.

Hull - Surface condition of the ship.

Ballast Condition - waves

- current
- wind

Fuel consumption may be reduced by designing an optimal power plant by taking into consideration the basic design requirements for a given ship, such as, shipspeed, deadweight, draft, etc.

After this has been realised, only three disciplines, providing the power plant is well maintained, remain in order to observe the fuel consumption.

- 1) Nautical
- 2) Submerged hull
- 3) Engine

The nautical aspects such as routeing and shipspeed are evident, but the influence of the trim is more difficult to determine.

With fouling being the predominant factor, the evaluation of hull maintenance alternatives are concentrated almost entirely around the problem of finding the optimum point of drydocking with underwater maintenance as a soother to a growing problem.

In order to strive for an optimal fuel consumption on the engine side, at least the following three magnitudes should be recorded.

- 1) Fuel consumption
- 2) Shaft torque
- 3) Revolutions per min.

Engine output may be evaluated on the basis of several other quantities as well and the measurements compared with the builders sea trials.

It may be noted that all these elements refer only to diesel engine efficiency, as will be the trend throughout the paper.

1.1 New Ship - purpose designed for a particular trade.

Expressed very clearly in an Article on "Improving the Efficiency of Propulsion Machinery" by Fagerjord and Rein is the fact that, "The majority of ships have been designed on the assumption that the ships would be operated almost exclusively at the design speed". (Ref 10).

This being reflected in the plants being designed to run efficiently at the designed speed of the ship, but because of low charter rates they were operated at other than that they were designed for, with a result of great inefficiency, (Ref 10), but most probably with a level of profitability equal to or higher than the cost of lay up of the particular vessel.

The Authors point out, that this has brought about the thought of attempting to design an engine with a greater range of economic operation.

In parallel to this, they also express the view that the trend will be to have smaller service speeds and warn that this should not be too small as the earning potential would be much less, especially if the freight rates were to be high. (Ref 10).

Irrespective of the service a vessel may render, the design of the underwater hull plays an important part in the overall performance of a vessel.

As pointed out by C.N. Hughes, (Ref 11, p.2.);

"For bulk carriers and tankers a compromise is generally reached between maximising cargo cubic capacity without having too fine underwater lines.

The fine lines are normally associated with high speed passenger ships and a different approach is necessary for these specialised vessels." (Ref 11).

In a publication of M.A.N.- B+W by Klintrop and Jacobsen (Ref 12), it is pointed out that for a new construction, it is possible to calculate, amongst other things, the daily fuel consumption on the basis of the required ship's speed and thus the propulsive power.

Several alternatives may be found and the corresponding cost difference in \$ per day may be calculated taking into account, lub oil consumption, maintenance cost, etc., over an expected lifetime. (Ref 12).

With regard to new buildings, the general trend is towards "Father and Son" or "Father and Father" Machinery arrangements, where the Father is used for main propulsion and the Son for auxiliary power with the capability of being coupled through a gear box to the propeller shaft.

This gives a great flexibility in operation as the Father may be used for main propulsion and the auxiliary power may be got through a shaft generator or the Son in turn may be used as the main propulsor also generating the auxiliary power required, thus operating the plant efficiently whilst slow steaming.

A combination of Father and Son would produce a plant with higher power output if the need arose.

The main difference between a Father and Son plant and that of a Father and Father plant, being that in the first case the Son is a "smaller" engine than the Father and in the second case, both are of the same type but the latter may be of less output, due to having less cylinders, than the former.

The obvious advantage of the Father and Father layout over the Father and Son is that less spare parts are needed to be kept on board.

This type of plant arrangement may be thought as for medium speed, high speed engines or a combination of both for reasons of space and weight, but this does not cross at the possibility of the application to include low speed engines.

So as to provide a greater flexibility in Main Engine operation, M.A.N.- B+W has come up with the solution of interchanging fuel injectors and/or shutting down turbochargers. The following is a quote from "Development Aspects for Modern Low Speed Diesel Engines", (Ref 13), by Groene and Jensen:

"On modern, low speed, diesel engines with standard fuel nozzles, all engines are capable of continuous operation down to approximately 30% load, whereas low load nozzles are feasible from a fuel economy point of view when even lower loads are required.

For an engine with two turbochargers it is possible to perform low load operation down to 20% load with one turbocharger cut-off. Similarly, in the case of three turbochargers, the limit is about 13% load when two turbochargers have been cut out, still without any change of nozzles.

The valve for turbocharger cut-out can be automatically controlled, thus maintaining flexible and economical operation." (Ref 13).

The general effort to increase diesel engine efficiency has been achieved by increasing the maximum as well as the mean effective pressure in the cylinders, by using constant pressure turbocharging and variable injection timing with a reduction in exhaust gas temperatures.

With regard to increasing plant efficiencies, waste gas has been used in heat exchangers and to drive gas turbines.

Unfortunately, as expressed by Fagerjord and Rein (Ref 10) there are limitations introduced by the modern trend of development as they "may in some ways be on a collision course." (Ref 10).

The Authors argue that "Improvements in main engine efficiency result in less fuel required for propulsion and thus less available waste heat energy; which in turn makes it more difficult for sophisticated waste heat recovery systems to be cost-effective." (Ref 10).

The Authors then point out that "one should not lose sight of the fact that, to the Shipowner, it is the overall fuel costs that count and not just the fuel cost of the main engine alone." (Ref 10).

It should be noted that the four stroke cycle, diesel engine requires less excess air ratio than its two stroke counterpart, with the result that it "sends out exhaust gas of some 100°C higher temperatures than that of two stroke diesel engines." (Ref 14).

This gives the four-stroke an advantage over the two-stroke for waste heat recovery potentials, but unfortunately with the commonly known disadvantage that four-stroke engines require higher maintenance and repair than their two-stroke counterparts.

1.2 Existing Ship - optimise for a particular trade.

A vessel's trading pattern will depend on the current market conditions and invariably the desired speed of the vessel will depend on these and in particular the current freight rates and bunker prices.

If the trading patterns of a vessel were to change due to reallocation of a fleet or the purchase of an existing ship, drastic measures may have to be taken so as to make the vessel compatible with the route or trade it is to be subjected to, which may be in the form of modification of the power plant or the hull, so as to get the best possible out of the ship in commercial terms, with regard to current and forecasted freight rates and bunker prices.

The purchase of second hand tonnage is rather restrictive with regard to choice on performance. One of the most important aspects when contemplating the purchase of a second hand vessel is to pursue the log and work books. If these have been filled in correctly a great deal of information relating to the vessel's performance may be extracted.

A service is provided by Lloyd's Intelligence, at Colchester, U.K., who, for a fee, give all reported incidents of any vessel, when under consideration for purchase or alternatively one may sift through the Lloyd's weekly casualty reports, which may be found through a marine related library.

Any queries arising on damage may be clarified by scanning the certificates of the vessel at the respective Classification Society it is classed with, if it is a classed vessel.

As expressed by Hughes in his book on Ship Performance (Ref 11), "With the advent of progressive fuel cost experienced, starting from Autumn 1973 until Spring 1986, many innovative ideas to improve the performance of vessels have been introduced", (Ref 11). This may still hold for a ship which has been reallocated to a different type of trade within the same consortium or second hand tonnage purchased for a specific service to which it was not designed for.

According to Hughes (Ref 11), "when carried out properly, slow steaming requires special fuel nozzles to be fitted, which basically increase fuel injection pressures to sustain acceptable combustion conditions below that originally thought necessary in the original design." (Ref 11).

Other measures to obtain more dramatic improvements in slow steaming performance involve fitting new propellers.

Jan-Eric Carlson of KaMeWa, advocates that;
"considerable fuel savings can be achieved by modifying the propeller blades or by replacing the existing blades with new ones, which are optimised for the new operating conditions." (Ref 15).

It may be noted here the above refers to controllable pitch propellers, but the replacement of a fixed pitch propeller with a new one along the same school of thought is possible.

Due consideration would have to be taken though, if this were to be a cost effective measure, taking the expected pay back period into account.

Carlson continues by refering to a change of diameter in the existing propeller; a smaller one, being suitable for medium speed installations with a number of engines per shaft, whereas an increase of diameter, if allowed by the propeller aperture, would be considered for directly coupled slow speed engines, pointing out that for controllable pitch, highly skewed blades may be used with results "in vibration levels which are only 30-50% of the levels occurring with conventional blades", (Ref 15), thus giving a new dimension to the range of operation with regards to resonance, which if excited in the bearings and/or shafts may result in an amplification of the bearing forces.

It must be emphasised that most owners do not want highly skewed blades due to the fact that the stress created in the propeller blades differ both in intensity and distribution when compared to those produced in ordinary propellers, thus making the owners weary of the ability and possibilities of having the propeller maintained or repaired in the more remote parts of the world.

Caution must be taken when fitting a larger propeller though, as according to Fagerjord and Rein (Ref 10), "an increase in propeller diameter may result in a reduction in hull efficiency." (Ref 10).

This is explained by the Authors (Ref 10), by the fact that, "when the propeller diameter is increased, a larger percentage of the thrust developed by the propeller will be coming from the flow outside the wake field." (Ref 10).

Along with this, the Authors also point out that, "By using a large propeller tip clearance, thrust deduction may be reduced. But when the propeller diameter is increased, the thrust deduction penalty will become more severe." (Ref 10).

There also exist certain possibilities to upgrade certain diesel engines by replacing old turbochargers with modern ones (Ref 14), or, in certain cases by converting from impulse to constant pressure turbocharging (Ref 14, Ref 11), which increases thermal efficiency by around 10%. (Ref 11).

It is also possible to increase the stroke/bore ratio of some of the older, less economical and over-dimensioned two stroke engines, by replacing the major components with a smaller bore diameter from the latest highly economical models. (Ref 14, Ref 11).

The specific fuel consumption, in such circumstances is said to improve some 15%. (Ref 14).

The main disadvantage of this option, is that the output of the engine is considerably reduced which may not suit future requirements (Ref 11), and the inevitable question as to what power output should be chosen, to redesign the propulsion machinery to, arises.

If too low a rating is chosen, thus a too low speed, the ship is bound to suffer in a substantial loss when the charter rates are high, (Ref 10).

The economy fuel pump was introduced to improve the specific fuel consumption of older diesel engines. The theory behind it is that it increases maximum combustion pressure at lower powers. According to Hughes, "The economy fuel pump loses it's effect above 85% and below 40% output." (Ref 11).

Shipowners seeking to optimise fuel consumption have a great number of options to achieve their goal.

Whatever measures are chosen they should be correlated so as to obtain the best possible performance, by weighing the technical and economical advantages with the disadvantages, such as capital costs and the duration of the pay back period, keeping in mind the important aspect of flexibility with respect to that of speed and fuel consumption.

The practise of slow steaming, with or without modifications to the power plant, hull and propulsion system, is arguably the most cost-effective method of improving performance as a measure on a tonne per mile of fuel basis, (Ref 11), or in any other suitable measure.

Chapter 2

The Relationship between Speed and Fuel Consumption

2.0 Synopsis

The fact that the new buildings of today burn upto 40% less than those of yesterday, must not overcast the reality that some 70,000 ships of yesterdays design are still ploughing the seas. (Ref 16).

In a slump market, as denoted by Heggelund (Ref 16), the Owners are squeezed and, perhaps, sign a Charter Party specifying consumption rates which the ship has not been achieving since she was built." (Ref 16).

Quite correctly pointed out by Shiraishi and Okayama (Ref 14), is the fact that; "another task imposed on ships as a King of Transportation Media is to deliver cargoes on time, observing the contract. Optimum speed and fuel consumption is not universally constant but will be dependant upon a particular Charter Party." (Ref 14).

A quote from the Bimco Bulletin (Ref 17), gives a clear and representative idea on the need for monitoring speed and fuel consumption.

"The vessel Al Bida was time chartered for two consecutive periods of one year under two tanker Charter Parties in the standtime form. The Charter Parties, which were in all material respects identical, described the vessel as:

'Capable of maintaining under normal working conditions an average sea speed of about 15.5 knots in moderate weather when fully laden on an average consumption of 52 metric tons, IFO 1500 fully laden and 30 metric tons in ballast...per 24 hours'.

The time-charterers claimed that the vessel had excessively consumed fuel oil in the course of 24 voyages over the two year period. The vessel in fact achieved a speed of 19.9 knots and had no difficulty in achieving the warranted speed throughout her chartered service. The charterers' complaint was that she consumed more fuel at those speeds than she would have done had she been capable of performing the warranted speed at the warranted consumption level.

The arbitrators awarded the charterers damages for breaches of the consumption warranties." (Ref 17).

To be able to be in a position so as to avoid the above, it is evident that the Ship's Officers as well as the chartering departments should be able to have access to the relevant information required.

This is well expressed by Heggelund (Ref 16),

"To enable the Ship's Officers to optimise performance a system providing real time data of fuel consumption and speed through water is essential. Water-speed logs are available in various types; electromagnetic, doppler, impeller and pitot tube. Although the essential distance related to a charter is distance made good, performance must be related to speed through water." (Ref 16).

and continues with the following on the subject of fuel monitoring.

"Fuel consumption monitoring has, for years been provided by a single flow-meter, measuring net flow from service tank to engine, with registration on a mechanical counter." (Ref 16).

pointing out that,

"This has shown weakness, once signals of the rate of flow are required." (Ref 16).

The events leading to, and the solution of the monitoring problem, are discussed by the Author of reference 16;

"Unstable flow, back flow and the need for calibration ashore has led to new methods, whereby sensors are placed after the booster pump and in the return line to either service tank or de-aerating tank.

In this way one can balance the system to zero with the engine stopped. Drift in calibration will thus be detected when the system fails to balance out." (Ref 16).

"Fuel consumption," according to Buxton (Ref 8), "has a further impact on shiploss via the weight and space occupied by bunkers."

To illustrate this, the following example is cited by Buxton.
(Ref 8).

"Modern deep-sea ships have a bunker capacity sufficient for 15,000 to 20,000 miles at full speed, which takes up 2000 dwt to 5000 dwt."
(Ref 8).

It is then pointed out by the same, that,

"Although not always full, such capacity allows more bunkers to be loaded at cheaper ports, especially when the freight rate is below the fuel price differential at ports en route." (Ref 8).

Buxton (Ref 8), continues by stating that,

"The difference between a ship at deep draft and poor hull conditions compared with light draught and good hull can easily be an extra 50% in power or a loss of 15% in speed, even in the same weather conditions." (Ref 8).

"But," as Buxton (Ref 8) points out, "speed is not the goal, saving time is."; one may easily incorporate saving fuel as being an equally important goal, which is attained along with that of saving time through "weather routeing, more accurate navigation and steering, passage management and performance monitoring, fitting the appropriate instrumentation where necessary." (Ref 8).

Buxton then goes on to say that,

"The value is different between essentially constant speed ships like liners, where gains are taken as fuel savings, and constant power ships like bulk carriers, where gains are taken as increased speed/reduced time." (Ref 8).

2.1.0 Fuel Consumption Versus Speed

Zachariades (Ref 18), argues that if the selection of optimum speed is done on the basis of "the best average speed over both the laden and ballast leg," it is almost certain that the ship is never operating at its real optimum speed.

This conclusion was drawn by Zachariades from a detailed computer analysis, based on performance data and voyage economics obtained under very different conditions, which proved that, regardless of the proportion of ballast distance to total voyage distance, for each optimal laden speed, there is only one optimum speed for ballast.

The said conclusion derived by Zachariades was that both speeds corresponded to the same fuel consumption, meaning that in fact it was the delivered power which was optimised.

This theory was found to be backed by Shipowners, who admitted to Zachariades that they kept the fuel rack setting constant on both laden and ballast legs.

The revelation is treated as a blessing by Zachariades, who from his conclusion, states that,

"This is of immediate advantage to the Shipowner, in that he only needs to find accurate speed/consumption data for the fully laden condition." (Ref 18)

Thus, the ship designer must understand this when designing the hullform and for engine/propeller/hull matching.

Zachariades goes on to say that with the fuel rack constant the optimum speed for the ballast leg will be "a knot or so" above that of the laden leg, and even for part load conditions, the optimum speed will be somewhere between that of loaded and ballast, which would equal the fuel consumption under full load conditions.

In this light, Bjorkman (Ref 19), who is a firm believer that it is much easier for the crew to maintain a constant fuel consumption than a constant speed at sea, came up with the following exponential relationship between fuel consumption and speed for a diesel powered ship.

$$F_v = nAe^{(BV+CA)} \quad \text{--- (1)}$$

where F_v = Fuel consumption at speed V (tonne/day)

n = sea margin

A, B, C = Constants which define the shape of the curve

V = Speed (knots)

Δ = displacement (tonne)

e = exponential function

The Sea margin, (n), would have a value equal to unity for a clean ship and would be increased by a fraction corresponding to the amount of fouling (1.1 with 10% sea margin corresponding to 10% extra fuel required to maintain speed).

Bjorkman points out that for the initial analysis the sea margin is assumed not to depend on speed, but also recognises the fact that corrections would have to be made when the sea margin varies with speed.

By plotting a diesel ship's trial fuel consumption on a logarithmic scale, for a constant displacement, the slope of the straight line of fuel consumption versus speed would be the value B . By plotting similar lines for various displacements, one may get the value C , denoting the influence of displacement depicted by the distance between the parallel straight lines.

The constant A fixes the speed lines with regard to actual fuel consumption.

Bjorkman states that,

" A, B and C should be constant throughout the life of the vessel and only sea margin will change, due to the conditions of hull and operational circumstances." (Ref 19).

From a study carried out by the same, involving over 20 ships, B was found to have been between 0.21 and 0.24 for ships >100,000 dwt and ships <30,000 dwt, and 0.24 for ships around 60,000 dwt.

The fuel consumption formula (1) is claimed by Bjorkman to be superior to one assuming that the fuel consumption is proportional to the cube of the speed.

This is partly supported by Alderton (Ref 20), who is of the belief that if the cubic assumption is used as a basis for optimum speed calculation, the operational decision could be of significant error, as at higher speeds it would probably be exaggerated upwards of the actual optimum figure.

To overcome this, Alderton devised a formula to be used in the place of the ratio of the desired and set speed to the cube, as suggested by the Admiralty law. (Ref 20).

The formula was derived from the so called "J Curves", which are curves which hook upwards at lower powers to reflect the characteristics of a misleading favourable view of the advantages of slow steaming.

In order to be able to handle these curves mathematically the following was devised. (Ref 20, Ref 21).

$$\text{New consumption} = C_d * J \quad \text{--- (2)}$$

Where $J = A * \text{speed}^3 - B * \text{speed}^2 + C * \text{speed}$

C_d = Consumption at designed speed

Alderton claims that the advantage of putting the consumption in this index form is that providing the consumption is known for any given draft or hull state at a given set speed, the consumption at the required speed for that particular draft or hull state can be found. In the long term, if a vessel is found to behave in a slightly different way when the speed is altered, it is comparatively simple to modify the equation and obtain a modified curve.

The values of A, B and C, may be found by Ordinary Least Squares (OLS) methods (Ref 22), given sufficient empirical data connecting fuel consumption and speed, as well as on the draft, trim, weather and time elapsed from drydock. (Ref 20, Ref 21, Ref 22).

The ideal would be to start collecting data as soon as possible on leaving drydock, putting the ship on as near an even keel as possible and then measuring with a great as possible accuracy, the ships speed and fuel consumption during days when the weather is fine, sea slight and little current is anticipated. (Ref 20).

Once fine weather curves for loaded and ballast conditions on an even keel have been established, the effect of trim, hull roughness and bad weather may be considered. (Ref 20).

The following two subsections, on Time and Voyage Charter Party, give an indication of the physical parameters involved in the computation of these, with regards to their effect on speed and fuel consumption.

Worked examples are given in Appendix B for clarification of the possible use of the formulae.

2.1.1 Time Charter Party

Time charter parties will almost certainly contain an entry specifying the vessel's average speed and bunker consumption, in some cases giving both the ballast and loaded speeds, as well as detailing the port bunker consumption and perhaps, the extra consumption required to work cargo gear, or to pump cargo, or to clean and gas-free tanks, should the vessel perform at speeds less than described or consume a higher amount of bunkers than allowed, it is more likely that the charters will institute a claim against the Owner. (Ref 23).

According to Bjorkman the daily bonus or penalty for a time chartered vessel at sea, is given in most Charter Party forms as:-

$$P_v = R * \left(\frac{V}{V_{cp}} - 1 \right) + F_{cp} * S * \left(\frac{V}{V_{cp}} - \frac{F_v}{F_{cp}} \right) \quad \text{--- (3)}$$

where P_v = daily bonus for a speed V and Fuel consumption F_v
(\$/day)

R = daily rate (\$/day)

V_{cp} = charter party speed (knots)

F_{cp} = charter party consumption (tonne/day)

S = fuel price (\$/tonne)

V = Speed (knots)

F_v = Fuel consumption at speed V (tonne/day)

A Shipowner wanting to optimise the total bonus TPv for each leg of Nautical Miles (N), carried out under a Charter Party is advised by Bjorkman to differentiate the following expression, derived from formula No.(3) and equate it to zero.

$$TPv = \frac{N}{24} \frac{Pv}{V} \quad \text{--- (4)}$$

where N = Miles

Pv = daily bonus for a speed V and fuel consumption Fv (\$/day)

V = speed (knots)

By solving the derivative of TPv with regard to V and equating to zero the following is obtained:

$$FV = \frac{R}{S(BV-1)} \quad \text{--- (5)}$$

where B = constant

R = daily rate (\$/day)

S = fuel price (\$/tonne)

V = speed (knots)

Formula (5), defines the relationship for optimal fuel consumption which can be derived by solving (1) and (5), and is independent of Charter Party speed and consumption but depends on Charter Party rate and fuel cost as well as the constant, B, which is the slope of the fuel consumption versus speed curve. (Ref 19).

The following expression is advised by Zachariades to be used as a first approximation in deciding whether or not a slowdown from V max. to V opt. need be contemplated at all.

$$V \text{ opt.} = V \text{ max.} \left[\frac{\text{Daily hire} + \text{Aux. fuel cost/day}}{(K-1) * \text{Fuel Cost/day at V max}} \right]^{1/K} \quad \text{--- (6)}$$

Where K is a constant that may change with ship condition, with a value of three, [3], for diesel engines. In this approximation for optimum speed for a time-chartered ship to minimise cost per ton cargo, it is assumed that cargo carried is independent of speed. (Ref 18).

The time charterers main concern is moving cargo at minimum cost. For a given ship this is divided into two possibilities, the first, when the ship's costs are included and the second, when the value of the cargo is also included. (Ref 24).

The least cost speed for one ship on a given voyage, the cargo costs not being included is given by Alderton, (Ref 24), as,

$$Lcs = \left(\frac{N}{2k} \right)^{1/3} \quad \text{--- (7)}$$

where N = time charter daily rate (\$/day)

k = (daily speed fuel consumption at speed V * cost of fuel per ton) / V_s^3

V_s = ship's designed operating speed (knots)

Alderton states that the value k varies with draft, the state of the hull and the weather, but for more practical purposes he suggests one average loaded value for k and an average ballast value for k .

The least cost speed in taking into account the value of the ship and cargo may be subdivided into the three following groups, as indicated by Goss in the "Cost of Ships' Time." (Ref 25).

First, the cargo may be an integral link in some project where any delays could cause a serious effect. Secondly, various costs associated with the need of maintenance or deterioration of specific cargoes, and thirdly, the cost of the loss of interest of goods, were they to be invested at the current bank rate.

However, the first two are difficult to quantify but the third, as suggested by Alderton, (Ref 24), may be quantified in the form of interest earned per day, with the result of the currently known least cost inventory speed.

$$L_{cis} = \left(\frac{I+N}{2K} \right)^{1/3} \quad \text{--- (8)}$$

where $I = \frac{\text{Value of cargo} * \text{interest rate}}{365 * 100}$

$N = \text{time charter daily rate (\$/day)}$

$K = (\text{daily speed fuel consumption at speed } V * \text{cost of fuel per ton}) / V_s^3$

$V_s = \text{ship's designed operating speed (knots)}$

A similar approach is supported by Zachariades (Ref 18), who advocates that cargo costs could influence the speed on a laden leg, but, he points out, it is up to the Owner to press for speedy delivery such as in the case of oil corporations where the Shipowners are also the cargo Owners.

In such cases, Zachariades suggests the result of the following expression to be added to the daily expenditure of the vessel;

$$\frac{(DL - dL) * \text{cargo value} * \text{cargo payload} * i}{\text{Total voyage time} * 100 * 365} \quad \text{--- (9)}$$

where $DL = \text{Duration of laden passage (days)}$.

$dL = \text{Full speed duration of laden passage (days)}$.

$i = \text{Net interest rate in percent per annum or interest rate, less any appreciation of cargo value.}$

$\text{Cargo value} = \text{Money unit per tonne (\$/tonne)}$

$\text{Total voyage time in days}$

As an example, Zachariades (Ref 18) gives a typical increase in optimal speed based on cargo value for a loaded 260,000 dwt tanker to be in the order of 2 knots on laden passage, but stresses that the optimal ballast speed would then be that of the speed resulting in the same consumption as the optimal laden speed, before the addition of the two knots.

It is pointed out by the same, that only high-value cargoes will have a significant effect, and that increased time spent in port will reduce optimal speed, as port time would be automatically incorporated in voyage time, thus influencing expenditure calculated on a daily basis and hence optimal speed. (Ref 18).

2.1.2 Voyage Charter

Voyage or trip chartering are considered the basic form of chartering business, differing in detail from time charter since the daily running expenses of the ship, including bunkers, lub oils, etc., are covered by the Owner.

According to Alderton (Ref 24), for ships on voyage-charter, the most profitable strategy is a speed which maximises the daily operating surplus. The ship earns more revenue in less time, but at a higher fuel cost. Thus the most profitable speed is that which optimises the increased revenue against the increased fuel cost and Alderton claims that this is the speed which satisfies the following equation;

$$16KPV^3 + KDV^2 - 8F = 0 \quad \text{--- (10)}$$

where F = Freight earned (\$)

D = Nautical miles

P = Days in port

K = (daily speed fuel consumption at speed V * cost of fuel per ton)/V_s³

V_s = ship's designed operating speed (knots)

when P = 0, form (10), most profitable speed (MPS) is;

$$MPS = (8F/KD)^{1/2} \quad \text{--- (11)}$$

Alderton stresses, that after an unexpected day's delay, the most profitable speed would be slower and not faster, although of course it may be commercially necessary to increase speed to maintain schedules. (Ref 24).

From Bjorkman's point of view, when the objective is to maximise the total profit, the optimal fuel consumption is independent of freight income, distance sailed and port time. This conclusion is brought about by assuming that the voyage is N miles, time spent at sea is $N/24V$ days and T days are spent in port. The maximum profit as a function of speed, MPv, is the freight income RI, minus the total daily costs at sea and in port, minus total main engine fuel cost.

$$MPv = RI - \frac{N(RC + RO + RD + Fv \cdot S)}{24V} - T(RC + RO + RD) \quad \text{--- (12)}$$

where RC = daily capital cost (\$)
 RO = daily operational cost (\$)
 RD = daily cargo inventory cost (\$)
 V = speed (knots)
 RI = Freight income (\$)
 N = nautical miles
 Fv = Fuel consumption (Tonnes/day)
 S = Fuel price (\$/Tonne)
 T = Port days

By solving the derivative of MPv with regard to V and equating to zero the following expression for optimal fuel consumption is derived;

$$Fv = \frac{RC + RO + RD}{S(BV - 1)} \quad \text{--- (13)}$$

where S = Fuel price per tonne (\$/Tonnes)
 B = Constant
 RC = daily capital cost (\$)
 RO = daily operational cost (\$)
 RD = daily cargo inventory cost (\$)
 V = speed (knots)

Bjorkman points out that if the daily cost in (13) is taken to be equivalent to a time charter rate R, the formula becomes identical to (5) and may be solved in the same manner.

He then goes on to argue that it is only the time and cost at sea as well as the fuel consumed at sea, which have an effect on the total profit and will thus have an influence on the optimal fuel consumption.

Freight income, distance sailed and port time, on the other hand, he points out, are not dependant on speed and main engine fuel consumption and have no influence on the optimal fuel consumption.

This view is supported by Zachariades (Ref 18), who states that freight income is net revenue after deducting fixed costs, such as port charges and cargo handling, expressing the optimal speed for a voyage chartered ship to maximise profit per day as:

$$V_{opt} = \left[\frac{24 \text{ Freight income} * (V_{MAX})^k}{k * \text{Fuel cost/day at } V_{MAX} * \text{miles/RT}} \right]^{1/(K-1)}$$

where miles = Nautical miles

--- (14)

k = 3

RT = Round trip

It is proposed by Zachariades that the voyage-charter equation can be solved by trial and error using a pocket calculator.

2.2 Trim Effect

Trim is usually small when loaded, according to Zachariades (Ref 18), so its effect, if any, will only influence the optimal ballast speed.

The following four paragraphs are quoted from Principles of Naval Architecture by the Society of Naval Architects and Marine Engineers U.S.A., pages 319 and 320, for a comprehensive understanding on the resultant effect of speed on trim, being comments valid for 1967, thus for existing ships built during that era, and thereafter, provided that the school of thought of the design was that of the said time.

"Owing to change in pressure distribution around a ship at different speeds, it will rise or sink bodily and also trim. At low speeds there is a general sinkage and a slight trim by the bow as compared with at-rest condition. As speed increases the movement of the bow is reversed and at $V/\sqrt{L} = 1.0$ or thereabouts the bow begins to rise appreciably, the stern sinks still further and the ship takes on a decided trim by the stern."

"In the average merchant-ship form, additional trim by the stern in the at-rest condition usually results in an increase in resistance at low speeds and a decrease at high speeds. At low speeds the increased draft aft makes the stern virtually fuller, with a consequent increase in form and separation resistance, whereas at high speeds this is more than offset by the reduction in wave-making, due to the finer entrance in the trimmed condition."

"In ballast conditions at level trim, the wetted surface per ton of displacement is much increased, so that the frictional resistance per ton is increased also, but because of the finer form at the reduced draft, the residuary resistance per ton is decreased.

In general, except in high-speed ships, the total resistance per ton of displacement will be greater, but because of the lower displacement the total resistance and power will be reduced and the ship in ballast will make a higher speed at the same power."

"In ballast conditions it is usually necessary to carry considerable trim by the stern in order to ensure adequate immersion of the propeller, and this will have similar effects to the fore-going, higher resistance at low speeds, less at high speeds." (Ref 26)

With modern designs the effect of trim on speed and power is highly dependent upon the size and extent of the bulbous bow.

It is pointed out by Zachariades (Ref 18), that most ships are trimmed by the stern so as to ensure adequate propeller immersion and that existing information tends to invoke an increased optimum ballast speed with trim by the stern.

He stresses though, that whatever the case, the effect would likely to be small and the basic rule of maintaining constant fuel consumption should be held. He then goes on to say that if the machinery-propeller combination is not capable of transmitting in ballast condition the same power as in loaded condition, then the optimum is simply the maximum power that can be absorbed.

It is appropriate to point out that according to Regulation 13 of Annex 1, to be found in MARPOL 1973, "Every new oil tanker of 70,000 tons dead weight and above shall be provided with segregated ballast tanks and shall comply with the requirements of this Regulation." (Ref 27).

The requirements being that the moulded draught amidships shall not be less than $dm=2.0+0.02L$, in meters, trim by the stern shall not be greater than 0.015L and "in any case, the draught at the after perpendicular shall not be less than that which is necessary to obtain full immersion of the propeller(s)." (Ref 27).

These requirements, obviously being to ensure that the concerned oil tankers are so designed and operated so as to meet the regulation, thus avoiding any eventual discharge of dirty ballast from cargo tanks which may have been taken on board, in severe weather conditions, so as to immerse the propeller.

This measure would subsequently ensure that the vessel would have adequate steerage at all times due to the rudder also being immersed.

As advocated by Hughes (Ref 11), most vessels have the possibility of obtaining an optimal trim by adjustment of loading or ballasting operations within certain limits, but the main problem lies in knowing what the optimum trim actually is. He points out that micro-processors exist on the market, but the technical aspects the calculations are based on are not sound, meaning that a tank test would have to be carried out for various draughts, trim and speeds.

Laurence (Ref 21), is of the same school of thought and points out that very few vessels exist with data on the effect of trim as tank tests are very expensive and some Owners who have carried them out doubt their effectiveness.

The above views enter into conflict with an article on computers in Shipcare and Maritime Management of May 1985 (Ref 28), where on page 21, there is a description of a system for optimising performance.

The said computer program is developed to accept parameters entered on a daily basis being the following: "date, draught, hours run, ship speed, shaft rev/min, shaft h.p., mean windforce, mean wind direction and fuel consumption." (Ref 28).

From then on the daily performance is evaluated on the basis of the resultant performance of the day with that of the sea trials.

The following is a quote from the same article,
"From model tests carried out during the design of the ship (or afterwards if necessary), a set of curves are drawn of ship against speed for various draughts. These curves represent the predicted performance of the ship at any draught and any power in fine weather, deep water with new clean hull and propeller. When the ship actually goes on trials, it's performance is carefully measured at some known draught. The results from the trial run at various ship's draughts are then compared with the prediction for that draught from the model curves.

If there is a discrepancy, the set of model curves is adjusted so that they represent that actual trial performance of the new ship at any draught. These curves are then used as the basis for comparison for future service performance." (Ref 28).

It is clearly admitted in the above that the possibility of discrepancies is present, the possible reason being brought to light by Major and Brown, (Ref 29),

"Cargo-ship trials, are run in ballast, in a hectic atmosphere of miscellaneous concurrent and consecutive tests, with builders intent on meeting their contracted speeds." (Ref 29).

The Authors press their point further home by stating that, "this is not conducive to providing accurate and reliable data on which efficient ship operation can be based." (Ref 29).

On page 35 of the January 1986 Shipcare and Maritime Management, there is an article, in which it is claimed that a consulting company "has developed a method for working out the trim optimisation of existing vessels and new buildings." (Ref 30).

No mention is made in the article of model tests, although a photograph portrayed, leads one to believe that it must form part of the package of the "test programme."

"The test programme has to include at least four different displacements of the ship and optimum trim can be easily obtained for a certain ship speed and displacement." (Ref 30).

Graphs are plotted with the derived results enabling the optimum trim for each displacement, at mean draught, to be decided for different speeds as well as the optimum trim for different displacements at a constant speed. (Ref 30).

It is also made quite clear in the article (Ref 30), that the results may be stored in a computer on board the ship and that reductions of between 4 to 5% in fuel consumption have been achieved.

A valid remark made by Hughes (Ref 11), is that most merchant vessels spend half their time at sea loaded and the other half in ballast, giving an example of a panamax bulker having a difference between light and heavy ballasts of 10,000 tonnes resulting in a speed difference of 0.2 knots.

In such a case one should ensure that if the vessel is fitted with a bulbous bow that it is suitably immersed so as to have a positive effect on the economy of fuel by reducing and not increasing the viscous resistance.

A change of trim may not be easy to achieve in a fully-loaded ship or a fast ferry which operates at nearly constant draught but it should be a simple matter with tankers which spend half their time at sea in ballast.

Thus if applicable, trim should be adjusted by shifting ballast until a minimum result of fuel consumption is achieved, maintaining constant power.

But as pointed out in Laurence's (Ref 21) very own words,

"Few Masters and Chief Officers care to face ocean storms with cargo-induced stresses of the order of 99% of permissible maximum. They ballast to reduce these loadings, some say to 80%, and some to 50%. To achieve this reduction in stress, may need an extra 600MT of WB, the carriage of which might lead to a consumption increase worth \$1,500 over one ocean passage. The natural desire to reduce stress may also result in trim suspected to be unfavourable, further increasing consumption." (Ref 21)

From the above it is evident that the best recourse would be to educate the crew in this field and to motivate them to have the minimum ballast possible, to the Masters discretion, subject to adequate propeller immersion and appropriate trim.

As a Master would not want to cause his ship to face storms at sea with high stresses, in calm seas the then excess ballast could be removed.

The operations department should also be in a position to be able to take advantage of cheaper fuel and fresh water, when plausible, to be used in lieu of seawater ballast, if the ships construction permits.

2.3 Performance Monitoring

According to Hughes (Ref 11), the most important consideration of all performance aspects is the vessel's speed against consumption, both in laden and ballast conditions. This is contrary to Zachariades and Bjorkman, who are of the belief that fuel consumption is of priority and it should be the parameter which regulates the laden and ballast speed through utilising constant power for both legs.

The sea margin introduced by Bjorkman (Ref 19), in formula (1), should be monitored by receiving reports from the vessel, although he stresses that it will depend on the sea state and the speed of the vessel, if it were to be found to be high even in good weather it would invariably mean that the hull would need maintenance.

Bjorkman mentions the fact, that if a diesel vessel is fitted with means to reduce the fuel consumption when slow steaming, two different A constants will appear in Formula (1) due to the steps that would arise in the speed/consumption curve. The values of A would be one for when Fv is below a certain value and the other when it is above.

Zachariades (Ref 18), has a similar view on the subject stressing that an accurate laden speed/consumption curve should include all steps or discontinuities which occur due to changes in the mode of operation of some components.

Giving figures to be in the order of 2-3 tonnes per day of diesel oil, corresponding to cost of 4-5 tonnes of heavy fuel oil on changing from a shaft-driven generator to a diesel, or from a turbo-alternator powered by waste heat to a diesel generator. (Ref 18).

2.4 Optimal Fuel Consumption

The actual optimum fuel consumption is the same for a vessel operating on time or a voyage charter and is expressed by Bjorkman from equ.(5) and (13) as follows:

$$F_o = \frac{R}{S(B V_o - 1)} \quad \text{--- (15)}$$

where F_o = optimal fuel consumption at a speed V optimal (tonnes/day)

$R = RC + RO + RD$ = daily time charter rate or total daily costs (\$)

S = fuel price (\$/tonne)

V_o = optimum speed (knots)

B = constant

The view is expressed by Bjorkman that formula (15) may be used to check whether the designed consumption of a newly projected ship is correct, with R being the average rate to pay for and operate, the vessel allowing for profit during the pay back period.

He goes on to say, that apart from the total daily cost including profit, the fuel cost and the sea margin have a major influence on the relationship. Otherwise only constant B would have an influence and is in most cases between 0.21 and 0.24. (Ref 19)

2.5 Speed - Fuel Optimisation

The need for speed fuel optimisation is paramount and may be controlled by utilising, as a basis, the constant power derived from the power plant at maximum efficiency, as a regulator for the speed.

Any variations of speed would reflect a variation in consumption, assuming constant draught, which should be weighed against the expected income, inevitably determining whether the voyage would be profitable or not.

Factors that should also be taken into consideration for the planning of the voyage are, convoys through canals, tides and working hours of ports which undoubtedly have an effect on the "Estimated Time of Arrival" of a ship on a given voyage. These must be seen in conjunction with the cost of extra fuel consumption so as to be on time, or the overtime to be paid to the crew, if the ship were to arrive too early and had to lay at anchor, with regard to the cost of the extra fuel consumed by operating at a lower power output than that of the optimal range, within the mechanical constraints of the power plant.

From the section on optimum trim, one may deduce that in most cases the ship has to be trimmed by the stern when in ballast (Ref 26), so as to ensure adequate propeller immersion. It is also known from the same reference that for ships designed along the School of Thought prevailing in 1967, at slow speed the ship will have a relatively greater viscous resistance than at a higher speed when trimmed by the stern.

The above would not always be true for ships of modern design.

It is the experience of a visiting Professor to the W.M.U., Mr. F. Arbeider, currently Senior Lecturer at Vereenig "Cornelis Douwes" and Nautical College, Amsterdam, which depicts that on a certain smallish bulk carrier for full propeller immersion a trim by the stern of 1-2% on the length was required.

However, it has been pointed out by the same that, for the same ship, experience had proven that when trimmed so that 20% of the propeller was unsubmerged, (when in ballast), the best results for fuel economy had been achieved.

Due to great vibration, operation in this mode was not possible.

This also brings to mind that even if there were no mechanical constraints set up by operating in this mode, for an oil tanker of 70,000 dwt and over there are regulatory constraints as set by Reg.13, Annex 1, of MARPOL '73.

It is thus clear that to have the fuel rack at constant power is an advantage, but the state of the trim of the vessel, for best fuel economy, will depend on the loading of the ship, the hullform, the type of propeller, mechanical constraints set by the matching of the engine/propeller/hull, as well as the type of ship with regards to compliance with regulations.

In considering fuel consumption from an entirely commercial point of view, according to Buxton (Ref 8),

"A regression analysis of bulk carriers in 1980 suggested that one tonne per day saving fuel commanded an extra \$93 per day in time charter hire."

The extra fringe of \$93 being "just over half the cost of a tonne of fuel" (Ref 8), at the time.

This certainly would give an Owner an incentive to improve his fuel efficiency so as to place his vessel on time charter, let alone on voyage charter when the fuel costs are on the Owner.

In all the formulas presented, there is a dependence on the function of fuel consumption which is affected by the total resistance of the ship, where as in formula (1), as indicated by Bjorkman, the hull state is taken directly into account by the factor designated as "n", being the state of the sea margin.

Prior to an attempt to monitor and correct excess fuel consumption and loss of speed, the variable parameters causing the alteration, must be examined, as done in the forthcoming chapter.

Chapter 3

Dry-dock Interval

3.1 Synopsis

Any given Shipowner would naturally be concerned with the effect of the drop in speed of his ship and increase in fuel consumption with respect to meeting the Charter Party commitments.

In such a case, the Shipowner would most certainly like to know if he should dry-dock the ship, bringing it back to its normal service speed and fuel consumption, to apply underwater maintenance, or to continue to operate the ship declaring a higher fuel consumption and slower speed.

It is assumed that the condition of the powerplant would be taken care of by the planned maintenance system, although one must stress the necessity of taking compression cards to check the integrity of the combustion components.

The fuel quality is, for all practical purposes, outside the jurisdiction of the paper, but never the less, it is pointed out that test kits exist for use on board and specialised laboratories give worldwide services, with advice on how, where to take samples from and how to treat fuel.

These laboratories may even give operational advice on fuel management of each monitored batch as they have the necessary information required, that has been given by the Owner upon making the contract.

Having assumed the above one may proceed to narrow down the causes of excess fuel consumption and loss of speed to submerge hull deterioration and propeller roughness, neglecting for the time being, the weather and navigational effects as well as assuming optimum trim.

The problem of increased resistance with its effects is well depicted in a paper entitled "An Operational Research Approach to Shipping" by Sparshott. (Ref 31).

"A casual chain of effects is set up and is illustrated in Fig.1. As a result of deterioration, the ship's resistance increases."
(Ref 31).

Sparshott goes on to say,

"it is impossible to measure the monetary effect of this directly, but it is possible to measure the effect in terms of two variables: more horse power must be developed, and in order to do this more fuel is necessary - this is measurable and can be costed; the other variable is the decrease in speed - this, too, is measurable and from the decrease it is possible to calculate the loss of earnings."
(Ref 31).

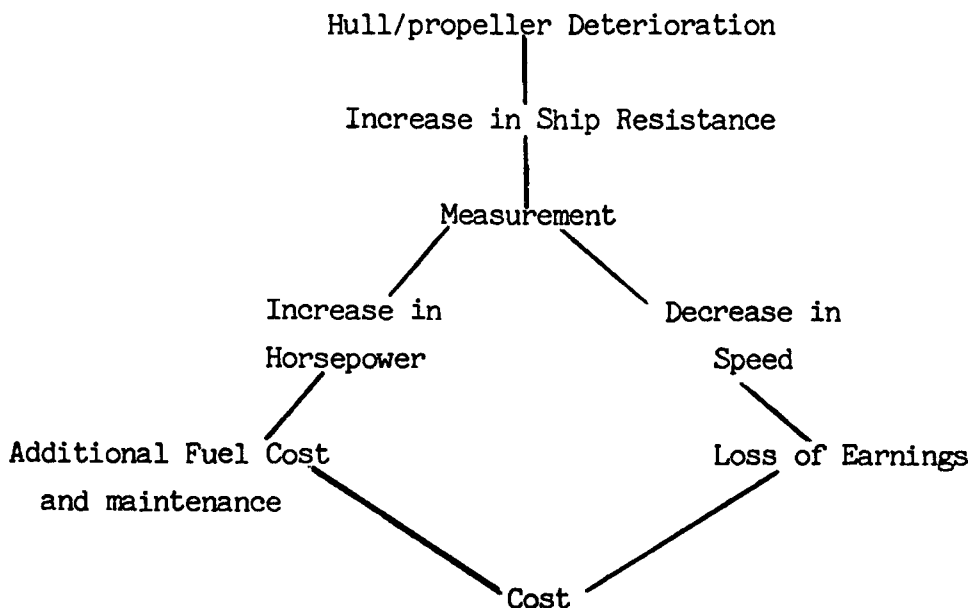


Fig.1 - Casual Chain of Events Due to Deterioration. (Ref 31).

3.1.0 Submerged Hull Deterioration

The cause of hull roughness may be broken down to four categories being, structural roughness, paint roughness, corrosion incurred resistance and fouling incurred resistance. (Ref 26, P.451)

The first being a result of the method of construction of the shell and may be not altered save at great expense.

The latter three are due to deterioration of the hull surface, the first of them due to bad application and/or choice of paint, the second due to the breakdown of the paint film causing corrosion as well as erosion and the third, caused by marine organisms. (Ref 26).

The various causes of increasing hull roughness may be summarised as done by Tor E. Svenson, (Ref 32).

- Corrosion of steel substrate.
- Build-up of old coatings.
- Paint system blistering and detachment.
- Mechanical damage.
- Poor quality of paint application in dry-dock.

Svenson (Ref 32), then breaks these down to the following three categories;

- New ship roughness.
- Change in roughness due to dry-docking.
- Change in roughness in service.

A quote from section 6 of the "Hull Preservation" in the "Principles of Naval Architecture" (Ref 26), emphasises the problem of roughness during service.

"Ships in service show a progressive increase in roughness caused by mechanical damage to the coating system and the accompanying corrosion on poorly maintained vessels the increase in hull roughness can amount to some 125 μ m/yr (5 mil/yr), which can be translated into an effective increase or 15% in shaft horse power if speed is to be kept." (Ref 26).

Relative minor deformation of plating will also cause the hull roughness to increase.

The severity of this problem is emphasised in (Ref 33),

"If serious corrosion of the steel substrate has been prevented, a 'nearly new' condition can be regained. However, if the blast cleaning is delayed until severe corrosion of the substrate has occurred, the hull cannot be returned to the "nearly new" condition by blasting." (Ref 33).

As expressed in section 6 of Hull Preservation of Ref 26;

"Roughness due to fouling is the most widely recognised cause of roughness which when present will significantly affect performance.

Since the dimensions of roughness associated with fouling are much larger than those of physical roughness, it is obvious that complete control of fouling is essential." (Ref 26)

This point is pressed home in the same publication with the following;

"Practical observation from ships in service have shown speed losses of over three knots on a 15.5 knot tanker caused by fouling." (Ref 26).

This is further elucidated in a paper on "An investigation into the variation of ship skin frictional resistance with fouling." (Ref 34)

"Over the two year period, an increase in skin friction of about 80% was recorded together with a 15% loss in ship speed." (Ref 34).

In the conclusions of Townsin, Byrne, Svenson and Milne in a paper on "Fuel economy due to Improvements in Ship Hull Surface Condition 1976-1986" (Ref 35), the following two points are emphasised.

1. "The greatest savings have resulted from improved in-service maintenance rather than improvement in initial finish." and
2. "Fouling should no longer be a problem." (Ref 35).

It may be further emphasised that slow speed, full hullform vessels that have most of their resistance in the form of viscous resistance would benefit most from improved in service hull finish maintenance.

It is suggested by Grigson in his paper on "Hull Condition-Frictional Drag and Power." (Ref 36) that

"Shipyards need to build up their own data banks relating coating methods, ambient conditions and kinds of paint to the Clauser functions, and to full-scale extra drag caused by the roughness which they actually produce on their ships." (Ref 36).

As stated in (Ref 37), being a resume of Per-Olaf Queseth, Chief Research Engineer and Programme Co-ordinator at Marintek, Norway, findings,

"There is an obvious and obtainable profit in paying particular attention to the choice and maintenance of the protective system on a ship's underwater hull."

3.1.1 Submerged Hull Roughness Survey

In a feature on Paints and Coatings in Shipcare and Maritime Management, April 1985, (Ref 38), the following is stated:

"Roughness surveys are usually performed in a standard manner devised to provide a truly representative statistical sample for the whole of the underwater surface area." (Ref 38).

According to Perry in an article on "An underwater hull painting strategy." (Ref 39)

"Surveys of underwater paint should be made at regular intervals, usually at each dry-docking, to determine the average hull roughness." (Ref 39).

Perry then goes on to say that "Roughness Surveys must provide a truly representative statistical sample. Typically a minimum of 100 different locations are measured, half on the flat bottom area and the remainder equally divided between the port and starboard vertical sides. The average roughness, measured in microns, is derived for each location." (Ref 39).

As a point of note, the average hull roughness at particular locations has varying contribution to the overall average hull roughness (AHR).

The effect of the A.H.R. is a function of several factors, some of which are, boundary layer thickness and velocity as well as dynamic pressure on the hull surface.

The survey may be done in dry-dock or when the vessel is afloat by suitably experienced divers, although such surveys are potentially more expensive than normal dry-dock surveys, and the results are subject to be larger than those taken on the dock.

On conducting hull roughness surveys, the following which is pointed out in reference 34 should be born in mind:

"It should be noted that the stylus pressure of the BSRA Analyser is such that only hard roughness features are registered and it will cut through soft fouling such as slime." (Ref 34).

3.1.2 Prediction Approach to Roughness Survey

As deduced from a great variety of available literature, mathematical relationships have been developed relating the roughness with fuel consumption, thus the cost of changing the paint surface may be determined.

Perry (Ref 39), recommends the predictions are to be used in parallel to the traditional method, or for an indication, as,

"Fuel penalties obtained from actual service performance do not always agree with those predicted from roughness measurments and it would appear reasonable to assume that the texture or type of surface profile, which can vary dramatically, needs to be taken into consideration." (Ref 39).

3.1.3 The Relationship of Submerged Hull Roughness to Propulsion Losses

The familiar relationship of 1% more power per 10um has now been replaced by the following,

$$\frac{\Delta P}{P} \% = A(K_2^{1/3} - K_1^{1/3}) \quad (\text{Ref 35})$$

where P = Power

ΔP = Power increment due to roughness

K_1 = Original surface roughness in μm

K_2 = New surface roughness in μm

A = 2.5 for single screw ships (Ref 34)

3.4 for twin screw ships (Ref 34)

The above stated formula should be related to the percent of power needed to overcome viscous resistance.

Two examples, as given in reference 35, are reproduced in Appendix C.a.

3.1.4 Contribution by Ships' Hull Maintenance Contractors

The following points are emphasised in (Ref 38) as to be the contribution on the ships' hull maintenance contractors side for a successful completion of the painting operation.

- * Provision of the most suitable access facilities for painting preparation and application.
- * Provision of well maintained and good quality spraying equipment as well as a system for rigid control of paint work quality.
- * Ensuring that sufficient priority is attached to paint related work and that those performing it are afforded the opportunity, sufficient time and facilities to perform the task and achieve the standard expected from them.
- * The management should provide adequate training and instructions regarding correct methods, as recommended by paint manufacturers, of paint preparation work and application, stressing to the work force the importance attached to this type of work.
- * Ensure a good liason exists with the paint manufacturers representatives and local technical supervisors.
- * Maintain relatively clean conditions in the dry-dock, particularly functions such as the removal of spent grit prior to major paint spraying commencing. (Ref 38).

3.1.5 Painting Supervisors Contribution

The paint supplier's supervisor should attend the vessel as soon as it dry-docks, so as to be able to evaluate the performance of the paint system, with reference to the intended period in service and that, the system was actually subjected to.

Having made his recommendations, the supervisor should ensure that the painting is carried out correctly and in accordance with the work specifications, also recording air and hull surface temperature, relative humidity readings, how paint has been allocated and used, its batch reference as well as checking wet and dry film thickness. (Ref 38).

It should be fairly obvious, but there is an apparent need to point out that owners should not try to pinch pennies here!

3.1.6 Experience with Conventional Coatings

With conventional coatings or non-self-polishing type paint systems, the total dry film thickness increases due to over-coating at each dry docking thus increasing the overall roughness value. (Ref 38).

"Generally better performance has been achieved where there was a high standard of supervision during preparation and application." (Ref 39).

As very well expressed by Dr. Van Der Poel; (Ref 40)

"It becomes increasingly difficult for deeper-lying toxins to diffuse completely out of the coating. Large amounts are released initially but the amount soon diminishes until it reaches such a low level, that the lethal dose can no longer reach the laminar layer; which means that fouling can then occur." (Ref 40)

In conjunction to this

"the traditional types of antifouling have always created a degree of extra roughness, because the leaching process produces a somewhat porous (or rougher) paint surface." (Ref 40).

3.1.7 Experience with Self-Polishing Coatings

With self polishing coatings, rougher areas polish faster than the smoother with the wash off rate in service being found to be in line with what is claimed, or marginally less to that claimed by the manufacturer.

Perry (Ref 39), states the following:

"Total dry film thickness should not be allowed to build up as this generally results in increased surface roughness; in extreme instances local areas suffer interlayer detachment." (Ref 39).

According to Dr.H. Van Der Poel (Ref 40),

"In practise the release of biocide from the coating is reasonably constant and it is possible to predict much more reliably the degree of protection provided against fouling. The period of effective protection can be extended simply by increasing the thickness of the coating." (Ref 40).

Dr. Van Der Poel, then goes on to say that:

"Initially, self-polishing paints were applied to new ships and to vessels undergoing major overhauls. However, the consequent fuel savings proved rather less than expected. Predicted savings as high as 10% were not apparent and it is now considered that the most an SPC can save in fuel is about 2%." (Ref 40).

3.1.8 Roughness Changes During Dry-dock Periods

According to (Ref 38), when normal paint work is performed,

"increases in roughness should vary from 10 microns to possibly 30 microns." (Ref 38).

"This increase is expected as whilst the initial coats of paint applied to a grit-blasted substrate usually reduce the surface roughness, above a nominal dry film thickness, any subsequent coats applied generally increase the surface roughness." (Ref 38).

A summary of the observed causes of roughness increase in drydock is given in reference 33, as;

- * Thixotrophy of paint resulting in poor flow characteristics of the applied paint.
- * Poor paint application standards, including inadequate hull cleaning.
- * Adverse environmental conditions.
- * Limited dimensions of drydock relative to ship.

Reference 33, goes on to say that a combination of the above factors may result in overspray, runs, sags and detachment of paint, emphasising that on the exposed sides of the ship the problem is most apparent and that on average, the flat bottom roughness is at a much lower rate than the sides, after dry-dock, despite the keel blocks. (Ref 33).

According to reference 38,

"some evidence indicates that lower increases in roughness are often achieved when re-coatings with conventional, compared with the majority of self-polishing coatings."

3.1.9 Roughness Change During Service

Reference 33, gives the following as causes for roughening in service;

- * Corrosion of steel substrate. The rate depends upon the cathodic protection system fitted, if any, and the performance of the anti-corrosive coatings.
- * Paint system performance; typical symptoms of failure will be detachment or blistering of the paint film.
- * Build-up of old, spent anti-foulings; this accelerates paint system failure.
- * Mechanical damage caused by
 - berthing
 - cable chafing
 - grounding
 - operating in ice

And as advised by visiting Prof. F. Arbeider;

- river plate

3.2.0 Propeller Deterioration

Propellers experience fouling in service, particularly if the ship remains stationary for some length of time.

Svenson emphasises in his paper on "Techno-economic reasons for selecting Fuel Saving Priorities" (Ref 41), that,

"The effect of microscopic fouling upon frictional drag is equal or greater than that of the worst roughness." (Ref 41).

Patience, in his paper, "The Contribution of the Propeller to Energy Conservation in Ship Operation" (Ref 42), states the following:

"Due to its position, a propeller is highly prone to neglect since not only is it out of sight, but also inaccessible and some effort is required simply to properly establish its condition even in dry-dock. Yet because the propeller is the interface between the ship and its performance, its importance should never be ignored. The performance of the propeller, and therefore that of the ship, should be given a high priority in maintenance programmes. In practice this is not really difficult, since sensible, simple maintenance and servicing is all that is necessary to ensure a satisfactory result." (Ref 42).

The same is advocated by Svensen (Ref 41), who recommends that, "Regular in-water inspection and cleaning of the propeller is consequently highly justified in economic terms and should be a part of normal operation routine." (Ref 41).

3.2.1 Roughness Effect On The Propeller In Terms of Power Increment

The value of penalties of a propeller may be expressed in terms of power and speed and derived by utilising the thrust and torque characteristics of the propeller for various degrees of blade surface roughness. (Ref 43).

In Reference 43, the torque characteristics of the propeller for each condition is expressed as a linear equation for the operating range and given as, $K_T = AJ + B$,

where A and B are constants, A remaining constant for increasing values of roughness, with B only changing.

$$K_T = \text{Thrust coef.} = \frac{T}{\rho N^2 D^4}$$

$$J = \text{Advance coef.} = \frac{V_a}{N D}$$

$$\rho = \text{Fluid density} \left(104.6 \frac{\text{Kg} \cdot \text{S}^2}{\text{M}^4} \right)$$

$$N = \text{Propeller rps (1/S)}$$

$$D = \text{Propeller diameter (M)}$$

$$V_a = \text{Speed of advance (M/S)}$$

$$T = \text{Thrust (KgF)}$$

On substituting K_T and J in the preceding equation it is expressed as follows;

$$\frac{T}{D^4} = \frac{A V_a}{D} N + B N^2 \quad (\text{Ref 43})$$

"Based upon the assumption of thrust identity this equation can be used to calculate rpm for each roughened condition." (Ref 43).

As expressed in Reference 43 from the torque characteristics and the following relationship, the power increments for the various roughened conditions may be calculated. (Ref 43).

$$PD = \frac{K_Q}{95.1} * N^3 \left(\frac{D}{10}\right)^5 \quad (\text{Ref 43})$$

where PD = delivered power (input to propeller)

95.1 = numerical constant

$$K_Q = \text{torque coefficient} = \frac{Q}{PD^5 N^2}$$

Q = propeller torque (Kg-m)

3.2.2.0 Propeller Maintenance

In Reference 37, it is viewed that,

"with the introduction of self-polishing coatings, it has been the experience that operators do forget the efficiency reduction due to propeller roughness."

The need for maintenance is emphasised in the same article:

"Propeller roughness is extremely harmful for the performance efficiency of a ship and should be monitored to ensure that peak performance is maintained." (Ref 37).

Patience (Ref 42), is of the same school of thought;

"In the event that existing propellers are operating at conditions compatible with their design, maintaining the efficient performance of the propeller by means of regular servicing and maintenance should not be overlooked, since a valuable contribution to reducing the fuel consumption can be thereby realised." (Ref 42).

In an article on Energy Saving in the Marine Engineers review of March 1986 (Ref 44), under the title of "Maintaining Propeller Efficiency", the following is expressed;

"Roughening of propeller blade surface is inevitable in the normal course of service. The cause of attack may be by marine growth, impingement attack, corrosion, cavitation erosion or inexpert maintenance."

The article goes on to say that,

"In its worst form, marine growth will cause a significant loss in propeller efficiency which will increase the power absorption, thus reducing propeller speed." (Ref 44).

The same is advocated in Reference 37, which states that,

"The more serious cases of propeller roughness, which indeed is hard growth roughness, will give a significant reduction in a vessel's performance. In more extreme cases, speed reduction on the average hull forming upto 1.5 knots, are experienced, and power increases of some 32% have been recorded to maintain speed." (Ref 37).

Reference 44 does not have such a morbid experience as Reference 37, giving the following figures.

"The penalty in power due to increasing roughness obviously varies; typical values are between 4-6%, but it could be as much as 8%."

The important fact is not the amount of power required, but that the increase in power is recognised and the cause for the demand should be eradicated.

The remedy is well expressed in Reference 44,

"If treated at an early stage the roughness can be removed by fine grinding with little loss of blade thickness. If maintenance is delayed, the increase in depth of the roughening will be accelerated.

This means that the loss in efficiency, and thus increase in fuel consumption will be greater and, because more grinding will be necessary, the cost of rectification will increase. Therefore, the general rule is that maintenance should be little and often."

(Ref 44).

According to Reference 37,

"It has been proven experience that under average operating conditions, vessels' propellers should be polished at intervals no longer than six months. It is in this connection of importance to note that the outer 1/3 of the propeller area, the leading edge and particularly the suction side are the primary areas of the propeller in which fouling is most harmful." (Ref 37).

The same article goes on to say, that the aforementioned parts of the blade should be taken care of whilst the ship is in service, by underwater cleaning and polishing.

Reference 42 stipulates that, grinding and polishing should take place at every dry-docking, but as the periods between are extended the ship should be trimmed by the bow so as to expose the outer parts of the blades from the water.

"While it is desirable to polish the entire surface of the blades, it is worth noting that about 75% of the benefit is obtained by polishing only the outer halves." (Ref 42).

3.2.2.1 Propeller Roughness

The surface roughness will affect its frictional drag, which as a component of torque will affect its performance.

As stated in a paper on "The Influence of the Propeller Blade Surface Quality on the Ships Fuel Consumption", by KA-ME-WA, (Ref 45).

"Propeller blades for merchant ships are manufactured with a surface quality usually according to Class 1 of the ISO 484 standard requirements. During the operation the blade surface quality deteriorates, friction losses increase and the propeller efficiency decreases. The rate of deterioration depends on the material." (Ref 45).

The following quote from Reference 42, throws some light onto the issue of the ISO standards for propeller blades.

"It is interesting to note that when the 1966 figures are converted to μmRa , which would give about 0.8 for class S and 2.5 for class 1, the latest ISO document specifies a more liberal requirement. This

is difficult to understand in these more economy - conscious times, particularly since the normal finish for a propeller using existing practice should achieve 2µmRa without difficulty. As a result, therefore, it is recommended that manufacture of merchant propellers to suit ISO 484/1 1981 should be specified to meet class 1 tolerance, as is normal, but with a class S standard of finish." (Ref 42).

From the manufacturers point of view, one may be in a position to gather why the difference in tolerance exists, "Further improvement of the propeller efficiency can be gained by a blade surface finish according to ISO 484, Class S, instead of Class 1. It does, however, not seem to be worthwhile to spend money on a NiAl-bronze propeller in this respect, because its surface will only very quickly deteriorate to class 1, when in operation. With stainless steel, the surface will last, and a further efficiency increase of more than 0.5% is obtained." (Ref 45).

Cases of surface deterioration down to Class 1 whilst the propeller was still in the shipyard, have been recorded.

3.2.2.2 Propeller Damage

A propeller may be damaged either mechanically by contact with an obstacle, by erosion due to its action or by corrosion in polluted waters, either of which affect the performance.

It is thus imperative that the propeller be rectified at the first opportunity, depending on the type and magnitude of the damage, whilst afloat, on the dry-dock, whilst still on the shaft or at a propeller workshop.

Before any hot work of any kind is carried out on a propeller, the respective Classification Society should be advised, who generally only allow such work to be carried out at a distance greater than 70% of the radius, being measured from the centre of the hub of the respective propeller.

When a blade is subject to cavitation it should be filled in by welding and ground.

If the pittings are filled with plastic bronze, this will come off due to the centrifugal and hydrodynamic force the blades are subjected to and will only aggravate the situation.

It is imperative to mention that the work should be carried out professionally as indicated by the following quote;

"Surface roughness can be accelerated if the propeller has been ground by inexperienced operators, perhaps using too coarse grinding discs." (Ref 44).

3.2.2.3 Propeller Fouling

The effect of propeller fouling is much more considerable than that of propeller roughness.

Due to the hydrodynamic forces and that of cavitation it is most probable that there would not be any fouling attached to the blades, at least in the most critical parts being the outer sections and the leading edge of the blades.

If the propeller is heavily fouled due to the ship being stationary for a prolonged period, it should be cleaned or run at low revolutions until it is relatively free of fouling, as the increased resistance will overload the engine, which will then operate at less efficient thermal conditions, raising not only the cost of fuel but that of maintenance.

3.2.3 Economic Effect of Propeller Roughness

According to the British Ship Research Association (Ref 46), who compiled records for over 30 years, involving over 130 propellers, although the propeller has a relatively small surface area, the energy loss through blade roughness can be large.

"For a 30,000 dwt container ship, for example, the power loss when running at 23 kts can be as much as 6%. This could be equivalent to a third of the losses associated with hull and propeller deterioration combined." (Ref 46).

Whilst a Superintendent Engineer, Spyrou (Ref 47), experienced the following:

"Experimental results from analytical and model tests predicted a 0.15 knot speed loss with a propeller surface roughness of 100 microns mean height (0.1mm).

Thus by maintaining a surface roughness of 10 microns (0.01mm), a fuel saving of 2.5% at 15 knots would be possible on a VLCC."

(Ref 47).

As pointed out in reference 44,

"The cost of grinding and polishing varies, depending on the condition of the propeller surface, the situation of the propeller, and labour charges. However, a world-wide average rate would be about \$170 per square metre of blade surface area. Assuming that both face and back of the propeller have been treated, then the typical cost for a 6.9m diameter four-bladed propeller with a blade surface area of 19.24m² would be \$6540. This figure is insignificant when compared to the cost of incurring a 4% loss in propulsive efficiency." (Ref 44).

However, it is stressed in Reference 46 that,

"If the polishing process results in a poor texture, the cost of polishing could be wiped out. Therefore only highly skilled operatives should be used."

With the above in mind a figure of \$70 per square metre for maintaining propeller smoothness for every dollar spent on maintaining hull smoothness, as reported by BSRA, does not seem to be unreasonable. (Ref 46).

In this context;

"Typical cost for polishing a propeller are assumed to be from \$6000 to \$12,000 with propeller removed. If only the outer half of the propeller were polished rates could be cut by about 30%." (Ref 46).

3.3 Dry-docking as Opposed to Underwater Maintenance or Continued Operating

Hull deterioration is not only a technical but also a commercial problem, as reduced service speed reduces the earning capacity of the ship, or by attempting to maintain constant speed, the fuel consumption increases.

To arrest hull deterioration, a ship would either have to be cleaned in dry-dock or by divers whilst afloat. To obviate this the Owner could continue operating the ship to avoid the costs that would be incurred but this would mean less earning capacity and most probably, serious damage may be caused to the hull.

At a time of low freight rates a Shipowner would not be in such a dilemma to dry-dock for three to seven days, but with high freight rates a Shipowner would be quite reluctant to dock his ship.

"Underwater cleaning offers a quite suitable alternative, the ships being cleaned as soon as a speed loss of 0.5 knots is observed." (Ref 48).

According to Reference 48,

"At this stage of their growth foulings are easily removed with flexible nylon brushes. The operation at the same time, regenerates the top toxic paint coat, extending it's anti-fouling effect for a few more months. After cleaning, 95% of the ships original speed is registered." (Ref 48).

The same article also points out that the cleaning may be done whilst the ship is loading or discharging, unhampering in anyway cargo or any other ship operations and that cleaning should take place at roughly four months intervals.

A claim of 34% smoother hull after the first pass, is made in reference 49 on page 137.

"In a series of tests recently carried out, The Underwater Maintenance Company of the U.K. claims it has shown that it's Pamper hull cleaning system can reduce the average hull roughness of conventional antifoulings by as much as 34% after just one pass of

the machine. In four separate trials, Pamper was used on conventional, copper-based and antifoulings applied over a coal-tar epoxy. After only one pass of the machine, UMC used a digital hull roughness gauge to check the results." (Ref 49).

On assuming that the hull does not suffer deterioration due to anti-corrosion paint and self polishing coating which has been applied for the maximum of five years interval between dry-dockings, the only "submerged" problem would be that of the propeller.

To overcome this, Hydrex, in collaboration with Lips B.V. (Ref 50), have devised the following formula so as to work out the savings from underwater propeller maintenance.

$$\text{Yearly fuel savings in \$} = \text{BHP} \times S \times V_s \times \text{SFC} \times 24 \times n \times P$$

where BHP = propeller shaft power (BHP)

S = propeller efficiency (%)

SFC = specific fuel consumption (kg/BHP/h)

n = sailing days per year (days)

P = fuel price (\$/kg)

Vs = propeller efficiency loss (%)

The outcome of any alternative chosen will undoubtedly incur some cost.

Dry-docking is a one off cost, where as underwater maintenance and continuing to operate, are costs which are dependant on the time the ship spends in the water.

Evidently, the criterion for the decision to be taken is one of minimum total cost over the expected life of the ship, being the sum of the loss of earnings due to loss of speed by continuing to operate and the total cost of dry-docking, in the first instance.

In the second instance, it would be the sum of the total expenditure due to the underwater maintenance and the loss of speed with the total cost of dry-docking.

Chapter 4

Passage Planning

4.0 Synopsis

Passage planning is one of the problems to be faced by a Master prior to setting out to sea.

By making use of a professional service he may minimise sailing into heavy weather and thus save time and fuel.

According to Reference 47,

"It is not unusual on a mid-winter Pacific Ocean crossing to save 24 hours or more."

Spyrou (Ref 47) goes on to cite the following average savings in time.

- * Nine hours for Pacific Ocean crossing.
- * Six hours for Atlantic Ocean crossing.
- * Five hours for Indian Ocean crossing.

The following is a quote from an article by Captain G.V. Mackie, Marine Superintendant of Bracknell Meteorological office.

"Weather routeing is generally most effective on westerly or easterly ocean crossings outside the tropics. Accordingly, there are five main areas where weather routeing may be of benefit to the user. These are the North Atlantic, the North Pacific, the Southern Indian, the South Atlantic and the South Pacific Oceans." (Ref 51).

With the aid of such a service, during its passage, the ship is monitored on a daily basis, receiving updated weather forecasts with advice for any necessary diversions so as to avoid encountering bad weather.

As put by Spyrou (Ref 47),

"In addition to time-saving 'weather routeing' can position a ship

more favourably to take advantage of following seas thus reducing seawave height." (Ref 47), with respect to the ship in the seaway.

In this context a quote from The Guinness Book of Weather Facts and Feats (Ref 52) is appropriate.

"Statistical calculations on the frequency of these large waves agree remarkably well with the practical experience of sea men.

- * one wave in 23 is twice the average wave height.

- * one wave in 1175 is three times the average wave height.

- * one wave in 300,000 (which is the normal number that a ship encounters during 1 month at sea), is four times the average height." (Ref 52).

This problem would be emphasised on a ship with a de-rated engine and a rather bluff bow, where unavoidably the ship would slow up when running into head seas or a swell, meaning that great care must be taken to obtain all available weather information and advice from the services that offer them.

Due attention should be also paid to the fact that container and ro-ro ships need to have a wide pram-shaped afterbody, having a soft run thus giving maximum stability and cargo space aft.

With this form of design it is a fact that rolling angles for the wide pram-type stern are smaller in comparison to fine-lined cruiser-stern vessels under the same conditions at sea, but due to the narrow underwater part of the stern and the wide upper-part, when such a ship is subjected to a wave in the stern, the stern will rise and the GM will decrease with capsizing occurring when it becomes negative.

In practice such a catastrophe would be avoided through good seamanship, which in turn may be more effectively performed with the aid of passage planning.

As stated by Spyrou (Ref 47),

"In general the higher the latitude of the voyage, the greater the benefit from a great circle track, but the possibility of adverse weather is also greater." (Ref 47).

The problem of 'adverse weather' is well put in, in an article entitled "Meteorological Bombs Explode on the High Seas." (Ref 53).

"For route analysts who strive to provide accurate and timely advice to Masters, explosively intensifying lows present a special problem. If a storm shows the potential for rapid intensification, there are the inevitable delays in receiving and processing ship observations when the time required to prepare forecasts and transmit warnings is added in, it is easy to see how a ship might be already experiencing very heavy conditions by the time an appropriate message is received." (Ref 53).

A major problem these storms present is that they often move across the ocean quickly as they intensify, which boils down to the fact that use of the routing service offered must always be, "the prerogative of the ship's Master." (Ref 47).

4.1 The Contribution of Navigation to Fuel Economy

If course changes are made frequently, due to lack of passage planning prior to the commencement of the voyage, the net effect on the fuel consumption could become important.

This is shown in a study made and referred to in Reference 54, where "a time mean drag was calculated assuming that the turn rate could be described by Nomoto's equation."

"For the cargo ship executing a 90 deg. turn using either 5 deg. or 20 deg. rudder angle, the calculation indicated that at the larger rudder angle the ship consumed some 28% more fuel than at the smaller angle." (Ref 54).

According to Svenson, in a contribution to Reference 54, and based upon an Msc Thesis of Zachariades, the following holds.

"Irrespective of whether the speed is optimized with respect to maximizing profits per day (Owner-operated) or minimizing costs per unit cargo carried (time-chartered), it can be shown that, for a vessel operated at constant power (or fuel consumption), the presence of ocean currents on a round voyage will only have a minimal effect upon the optimum speed through the water and can therefore be ignored." (Ref 54).

Svenson then goes on to conclude that;

"For most commercially-operated vessels therefore, the presence of ocean currents will have no effects upon the process of optimizing fuel economy, unless of course advantage of currents can be taken by selecting a different route." (Ref 54).

According to Clarke (Ref 55), propulsion losses are incurred in an attempt to steer a straight course.

"When a ship is under way, the action of the external influences - such as wind and waves - gives rise to a continuous yawing motion to either side of the desired course.

This motion increases the drag of the ship, which in turn reduces it's speed and also causes the ship to follow a longer sinusoidal path, which further reduces it's downtrack speed. The action of the auto pilot in trying to correct the heading deviations gives rise to rudder movements, which also cause an increase in drag." (Ref 55).

Clarke then concludes by stating the following;

"In an attempt to produce more efficient ships' autopilots, there has been a move away from PID Controllers, designed using classical frequency domain techniques, to adaptive optimal controllers, using modern state space techniques." (Ref 55).

4.2.0 Routeing Methods

The application of meteorological information, due to experience or from observation, has been carried out in navigation for many centuries.

The planning of a passage, ideally, would minimize the damage to cargoes and ships, save time at sea, thereby saving money by reducing operating time and to attain punctuality so as to meet the special requirements of the individual voyage.

For the above to be evident an optimum time track should be evaluated for the planned passage and modified so as to avoid adverse weather conditions throughout the voyage with the aid of weather forecasts.

The principal routeing methods are as follows;

- 1) Climatological navigation.
- 2) Routeing aided with Facsimile recorders.
- 3) Tactical routeing.
- 4) Storm pattern.

4.2.1 Climatological Navigation

Climatological navigation is the art applied, due to documented historical observations, of sea states throughout the year, over the years since navigation began.

This form of passage planning may be applied only for voyages where the weather is in a settled state for a long period of time.

The phenomenon occurs approximately between 30° North and 25° South (Ref 56), providing there are no tropical cyclones in the area.

These cyclones may be avoided if an early enough warning is given to the Master of the vessel. North of 30° North and South of 25° South the weather is too unpredictable for climatological navigation to be used, according to Moens (Ref 56).

Cap. R. Motte, (Ref 57) Senior Lecturer in Meteorology, Plymouth Polytechnic has the following to say about climatological routeing "... particularly valuable in those areas of the world such as the Indian Ocean and China Sea, where a regular monsoon cycle predominates and in other areas, mainly tropical, where weather and wave conditions are in a settled state for long periods of time." (Ref 57).

As indicated by Prof. Pierre Houssin of the W.M.U, there are local weather conditions which must be taken into account, such as the "Mistral", which blows every year during the same season, for a period lasting either three, six or nine days in the southern region of France.

4.2.2 Routeing Aided with Facsimile Recorders

With this type of routeing the officers of the vessel have to have a sound knowledge of meteorology and apply it to weather charts received over the facsimile so as to be able to avoid adverse weather conditions which might crop up on their chosen track.

Apart from the fact that the process of forecasting from the weather charts requires a sound knowledge of meteorology it is a time consuming and laborious process which must be carried out every twelve hours when the weather charts are received, thus putting additional strain on a possibly reduced crew.

4.2.3 Tactical routeing

This is a service which is offered by governmental or private agencies, who, having knowledge of the speed and performance characteristics of a certain ship may issue tailored advice to the Master, by taking into consideration the latest information of weather conditions as well as the latest forecasts available, in combination with the expected future development based on circulation types, and experience of the personnel.

The information given to the Master must be continuously updated, as in the case of Facsimile Recorders, but the advantage of the 'shore routeing' is that there is no need for interpretation of the information received by the ships officers as with the Facsimile routeing method.

The basic need for updating weather information is due to the fact that "forecasting skill permits prognostic wave charts for only three days ahead at the very most." (Ref 56), and crossing of the North Atlantic would mean looking 6 to 10 days ahead and that of the Pacific, 14 to 20 days. (Ref 56).

According to Mr. Y. Draaisma, visiting professor of the W.M.U. and currently senior lecturer at Vereeniging "Cornelis Douwes" and Nautical College at Delfzijl, ships below 12-13 knots do not benefit much from weather routeing.

It should be noted that with regard to routeing, in a lecture on "What Should be Taught on Passage Planning", (Ref 58), being part of a workshop on passage planning, held in 1983 by The International Maritime Lecturers Association, Draaisma expressed the following opinion:

"taking into account the very small cost compared to the daily operating cost of the ship, this routeing service should always be taken, thus to profit from the extensive experience of the professional advisers." (Ref 58).

4.2.4 Storm Pattern

Similar to Tactical routeing, Storm Pattern Routeing takes into account the change in weather. A strategic route is first sought, by taking into consideration the recent history of storm patterns. The strategic route must allow for possible deviations to the north or south of the proposed route so as to avoid adverse weather.

Storm pattern routeing is successful because it does not rely on long-range forecasts which are subject to be inaccurate, but to shorter term forecasts.

In this context a quote from Reference 59 is appropriate:

"But even in the face of improved communications and forecasting it is obvious that severe weather situations can never be totally avoided,...., it must remain the undiluted responsibility of the Shipmaster to make tactical decisions regarding shiphandling in elevated sea states. This is particularly so when severe or rapidly moving weather systems have to be contended with." (Ref 59)

4.3 The Evaluation of Routeing Advice

With regard to the evaluation of routeing advice, Moens (Ref 56) has the following to say:

"From the very beginning of ship weather routeing, routeing services have tried to translate the degree of success achieved into figures which could be used by the shipping companies in order to make 'cost-benefit' analysis." (Ref 56).

Captain Mackie (Ref 51), gives the following explanation to the fact that an accurate evaluation may not be made,

"It is not usually possible to tell a Shipowner what his real profits are when he has his ships regularly routed because the service is not in a position to know anything about the cost of repairing damage to ships caused by bad weather, the yearly amount of claims which had to be paid before the ship was routed, the penalty which had to be paid to shippers because the ship is not on schedule, etc." (Ref 51).

Reference 56 stresses that,

"the construction of a least time route should be realistic. However, a construction based entirely on theoretical assumptions (for instance, a retrospective use of data known before the ship started), can be attractive to people who approach the problem from a purely scientific point of view. This hindsight can produce results that look better at first because large detours can sometimes be avoided." (Ref 56).

Captain Mackie (Ref 51), admits that time gains in the North Atlantic, on average are not spectacular, but even though savings in fuel are important, he points out that for some operators it is more important for them to know that the ships leave and arrive on schedule.

4.4 The Effect of Errors in Weather Forecasts

There is no doubt that weather forecasting, particularly for long term, needs to be improved, but to what extent, it is not possible to quantify as one can not tell how good it must be for guidance and routeing of ships.

The importance of tailor made advice from shore or the adequate information for onboard analysis may be emphasised by the fact, that an error of one metre in wave height may mean that a specialised vessels such as a drill ship or a heavy-lift crane may not be able to operate, whereas a Tanker would be relatively unaffected, as the

rolling behaviour depends also on the encounter frequency and the natural rolling period of the ship, where as loss of speed depends on wave height and relative direction.

Gathering of data on loss of speed is important because routeing is affected to a great extent by the phenomenon.

The following quote has been taken from reference 59:

"The rate of change in voyage cost increases for larger waves, but costs decrease asymptotically for smaller waves." (Ref 59).

Thus the total voyage cost seems to be heavily dependent on the wave height and period, because the intensity of the storm is what shall, in the end, determine the speed loss, the additional fuel consumed and damage by weather.

CONCLUSIONS

Rising fuel costs tend to encourage operation at lower speeds due to the ship's resistance reducing, roughly, at the square of the speed, but owing to characteristics of the power plant the fuel cost may not decrease in the same fashion.

Reduction in speed, invariably, results in fewer voyages per year (depending on the trade) and most probably less revenue.

The consequences of operating at reduced power, and its effect on a vessel's performance in typical at sea conditions, should be evaluated as precisely as possible, taking into consideration that existing ships may have been de-rated and will be more susceptible to weather conditions.

The gradual increase of hull surface roughness and that of the propeller due to fouling and/or corrosion, and the concurrent decrease in efficiency of the propulsion plant between overhauls, results in a reduction in service speed, increased fuel consumption or a combination of both.

From Chapter Two it is evident that whether the vessel is Owner operated or not, or whether the cargo value is taken into account or not, in the formulas used to compute the optimum speed or optimum fuel consumption, there is, invariably a constant factor, which is directly related to the vessel's condition and is invariably subject to change with respect to the condition of the ship.

Lower fuel costs have temporarily reduced the momentum in programmes aimed at achieving the most efficient use of fuel. This, however, will not last forever and there will be a continuing emphasis on both fuel cost and quality, in parallel to other alternatives such as wind power, which can provide a very useful supplement on certain trade routes.

In view of the fact that the most important considerations of all performance aspects is the vessel's speed against consumption, both in laden and ballast conditions, at constant fuel rack setting, a set of curves should be constructed for loaded and ballast conditions so as to be able to detect any variation that would be brought about by roughness and/or fouling.

A vertical deviation on such a curve would indicate a change in fuel consumption and a horizontal would indicate a difference in speed.

An example of such a set of curves is given in Appendix B.a., along the train of thought of Bjorkman, the following data being used as extracted from reference 19:

$$F_v = nAe^{(BV+C\Delta)}$$

where F_v = fuel consumption at speed V (tonnes/day)

$$A = 0.708$$

$$B = 0.23$$

$$C = 7.14 \times 10^{-6}$$

$$\Delta \text{ (loaded)} = 72,000 \text{ tonnes}$$

$$\Delta \text{ (ballast)} = 37,000 \text{ tonnes}$$

$$V = \text{speed (knots)}$$

$$n = 1 \text{ (for a clean ship)}$$

Similarly, a curve is reproduced along Aldertons Scepticism, by assuming the consumption at 14 knots, for a given ship, to be 50 tonnes per day, and using Aldertons formula (Ref 20) of

$$\text{New Cons} = C_d * J$$

$$\text{where } J = AV^3 - BV^2 + CV \text{ and } A = 0.000459$$

$$B = 0.0048$$

$$C = 0.04868$$

$$C_d = \text{consumption at designed speed}$$

An example of a curve may be plotted for a given loaded condition of a ship, as illustrated by the graph in Appendix B.b..

From the said graph it may be assumed that at low speed, i.e., less than 5 knots, the consumption is less than 9 tonnes per day, but it is questionable whether it is possible to operate at such a low

speed, even if it were to be commercially viable, due to mechanical constraints which would invariably depend on the type of power plant installed.

Such slow speeds may also be responsible in making the ship more susceptible to wind and waves which would result to a false economy, if the advantages of a routeing service were not taken to overcome the possibilities of drift.

Another problem of slow steaming which is more evident with self polishing coating than with traditional coatings, is that if the speed is too low for that of the rate of polishing, thus the leaching rate estimated upon applying the paint, subsequent fouling will occur as if the ship were to be stationary.

In conjunction with the above, it is a fact that, just as increased fuel costs tend to push the ship speed down, interest rates may create a movement in the opposite direction in some trades, thus an increase of speed would be considered, so as to be able to spread the costs over as many trips as possible, consistent with the availability of cargo.

In such cases determining the optimum speed requires a forecast of both revenues and costs as both freight rates and bunker prices may vary considerably in an unpredictable manner in the long run, meaning that for more accurate results the speed decision for such cases should be made on a short term basis.

In Appendix B.c. various ratios of daily rate (R) and fuel consumption (S), for a given time charter of the same vessel as in Appendix B.a., are plotted against speed (knots).

The next part of the Appendix being B.d., portrays a graph of that given in Appendix B.a. with the graph in B.c. for two ratios being that of $R/S=50$ and $R/S=60$.

From this graph one may find the optimal fuel consumptions and speeds, for loaded and ballast conditions under the given conditions, as shown in the lower table to be found in Appendix B.d.

The graphs in Appendix B.e. and B.f. depict the daily bonus (Pv) and the Total bonus (TPv), for the voyage, with respect to various proposed speeds, for the same conditions of time charter and the same ship as in Appendix B.a. and $R/S=50$.

From these two graphs it is evident that for the given conditions the maximum bonus would be at approximately 13 knots for the loaded condition and 14 knots for the ballast condition throughout the Time Charterparty term.

It is also quite evident from the same graphs that any deviation from these speeds, in either direction will have a negative effect on the daily bonus.

It may be noted that higher fuel prices would lead to a smaller R/S ratio and in turn a slower scheduled speed. In parallel, for single purpose ships such as ore carriers, whose cargo is of less inventory cost, a smaller R/S ratio will imply that the optimum scheduled speed will fall, whereas for oil tankers where the cargo is subject to greater inventory costs, a larger R/S ratio will tend to a higher optimum speed.

This view is not totally shared by Zachariades who maintains that in such a case the optimum speed for ballast and loaded conditions should be treated under a different light, the ballast speed being that of the laden speed less the additional increment of speed applied for the cargo inventory costs which would be added to the respective optimum speed of the laden condition.

In Appendix B.g. the optimum speed has been computed for a Time Charter, considering the same conditions, primarily using Zachariades formula and secondly Aldertons with the resulting speeds found to be 13.29 and 13.27 knots respectively.

The same is done in Appendix B.h., but for Voyage Charter.

Appendix B.i. comprises of a graph of speed versus maximum daily profit for a given voyage charter where one may see that any deviation from the speed which results to maximum profit will render less profit.

It is thus evident from the above that any deviation in the speed/consumption curve will cause the bonus or the profit curve to deviate in a similar fashion and thus shift the optimum, hence the need for adequate monitoring of the variable conditions.

For all vessels, the cost of delaying reblast becomes significant when the in-docking roughness exceeds 300 μ m AHR, but only if an out-docking AHR of 125 μ m or less can be achieved after reblast.

The economic decision between conventional and self-polishing coating systems for an existing ship depends to a large extent upon the ship type and whether fouling problems are being currently experienced on particular trading routes.

Having to introduce uncertainty into the calculations, the most uncertain factor of all is the question whether the ship is going to be continuously operated over the next few years or not. The prospect of lay up or sale of the ship would most probably erase any economic expected benefits from investments in improved hull maintenance procedures.

Knowledge gained by the author whilst attending a seminar held by Hempel is that irrespective of the coating type the following procedure must be adhered to.

1. Surface treatment corresponding to Sa 2.5 of the standard SIS 055900-1967.
2. Correct application of the Anti-Corrosive system chosen as per instructions.
3. Application of Antifouling paint by airless spray at 150-250 Bar.

It has been also concluded, through available literature, that self polishing paint smoothes the surface by 6 to 7 μ m every month.

In Appendix C.a., the percentage power saved with regard to the evolution of surface preparation, as given in reference 35, may be seen.

From Appendix C.b. one may appreciate the different effect on ship speed and required power output for a given vessel coated with either self-polishing or conventional anti-fouling paint, as given in reference 14.

The third part of Appendix C, being C.c. is a financial comparison of painting strategy as taken from reference 39. The table also portrays the evolution of surface roughness and tonnes of fuel consumed per day with respect to a given period of time. For a better understanding of the data presented, graphs have been drawn.

From the graphs, it is interesting to note, that for an S.P.C. coated surface the trend of evolution of the fuel consumption is approximately the same as that of the roughness for the said coating.

To be able to derive the power increments, due to roughness on the propeller, for various roughened conditions with the formula

$$PD = \frac{K_Q}{95.1} * N^3 \left(\frac{D}{10}\right)^5 \quad (\text{Ref 43})$$

The revolutions (N) are required from the equation;

$$\frac{T}{D^4} = \frac{A Va}{D} N + B N^2 \quad (\text{Ref 43})$$

For that to be possible the constants A and B must be known. A is known to remain constant for increasing values of roughness but B will change. This alteration of B would be easily found in drydock with the aid of ships' propeller roughness comparator gauges manufactured by Rubert and Co. Ltd.

Once the ship is in drydock the propeller would be maintained to the required surface preparation as per manufacturers recommendations thus the computation of the power increments in term with roughness would be for investment appraisal reasons.

A more practical approach would be that advocated by Hydrex in association with Lips B.V., (Ref 50) as the ship is still in the water and the operation may be carried out as she is loading or discharging. In Appendix C.d., three worked examples are given, as found in reference 50.

Propeller polishing should be taken to the best of its advantages as the investment is small, especially when compared to that of hull maintenance and the returns are immediate as well as large.

When considering the overall fuel consumption of an existing vessel, assuming that the suitable machinery modifications have been carried out to minimize fuel consumption, it becomes evident that a significant contribution can still be made by the sea staff if they are educated and motivated to implement energy conservation techniques.

Any deviation from optimum conditions will reduce the efficiency of the engine and increase specific fuel consumption, meaning that the sea staff must closely monitor the parameters and advise or take corrective action as necessary, so as to maintain optimum performance.

Accurate and regular performance returns from vessels, by telex or electronic mail, are essential to allow shore-based management to detect deterioration of hull and/or propeller condition, in parallel to the observations made by the sea-going staff by utilising a graph of speed vs consumption, on board.

With the introduction of unmanned machinery space operations on board, work patterns in the engineering department have changed with the result that maintenance is now carried out primarily on a day-work basis and work may be planned much more efficiently with energy conservation placed in its proper perspective.

Education in fuel cost and conservation is of paramount importance to the overall economy, so the sea staff should be briefed in the techniques and the financial impact involved.

As the resistance of a ship is to a great extent dependent on the trim of the vessel it is paramount that the crew should be instructed on how to monitor the state of the trim.

What is important is the trim in actual operation and not that when the ship is static in the harbour. To enable the crew in determining the optimum trim, a trim indicator which gives the actual trim under dynamic conditions should be installed which would make it possible to maintain the trim giving the least resistance at each draught condition.

It may also be concluded, that if the most fuel economic passage occurs when the ship operates at constant power for the whole passage, the optimum speed will be consistent with the schedule that requires no change in power.

This leaves the sea staff with no margin for unavoidable delays, such as those created by machinery failure or adverse weather, meaning that the power plant should be under a planned maintenance scheme and the benefits of passage planning should be taken to the best of its advantages.

During the execution of a planned passage it should be evident that if there are known delays before loading may commence at the port being approached, a reduction of speed might reduce the costs, though much depends on who is going to pay for the delay.

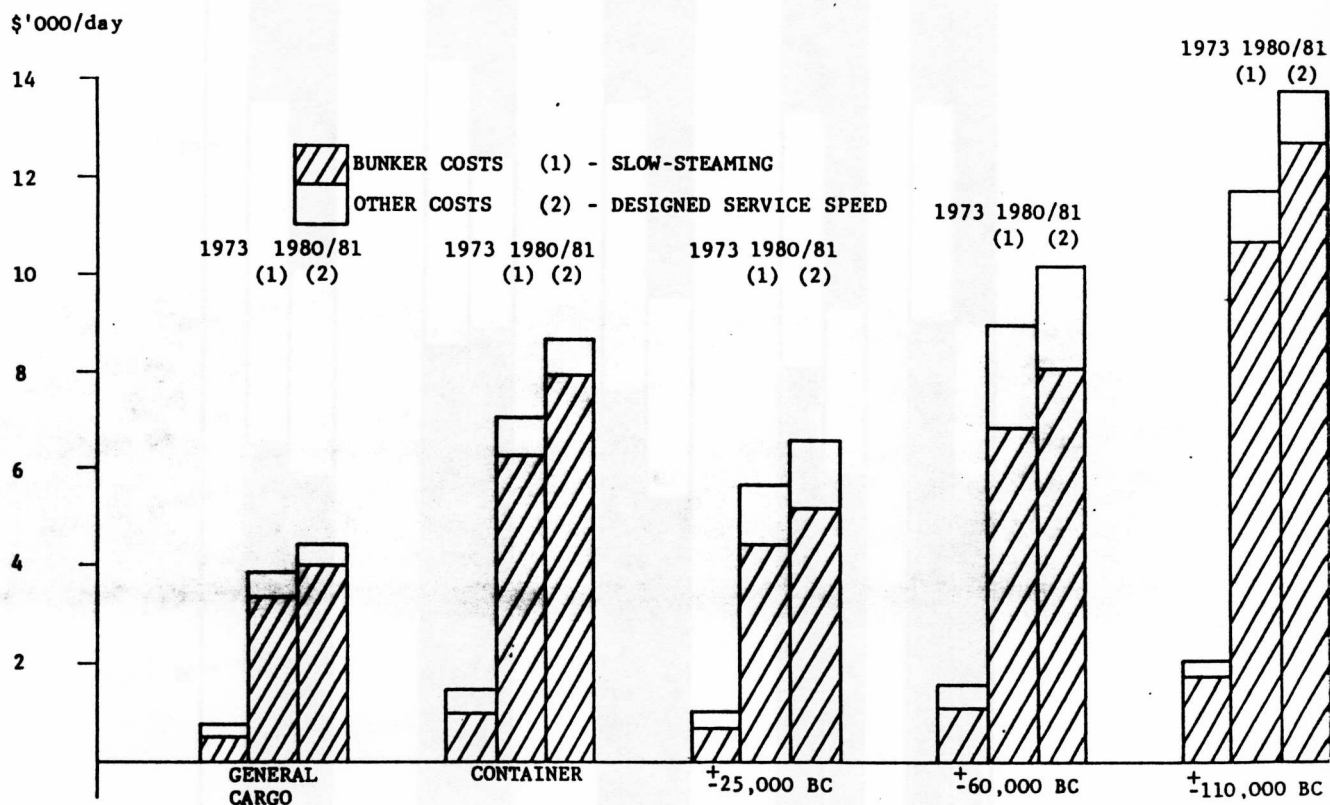
If the financial impacts of the delay were to be bettered by a good demurrage rate, it could be argued that an increase of speed might be beneficial. In this light, the situation could also arise where it might be commercially advantageous to arrive at the next scheduled port a few hours earlier, with an excessive speed resulting in an extravagant fuel consumption being fully justified.

For the above to be possible, a good network of agents would be necessary, with a good understanding of the workings of their port and the ability to give a coherent forecast of likely berthing time and place.

STRUCTURE OF VOYAGE COSTS 1973 - 1980/81
(% of Total Voyage Costs)

VESSEL TYPE	COST CATEGORY			TOTAL
	BUNKER COST	PORT CHARGES	CANAL FEES	
General Cargo				
1973	76	19	5	100
1980/81 Slow-Steamming	88	6	6	100
Service Speed	90	5	5	100
Container				
1973	71	29	—	100
1980/81 Slow-Steamming	89	11	—	100
Service Speed	92	8	—	100
+/- 25,000 BC				
1973	69	18	13	100
1980/81 Slow-Steamming	78	12	10	100
Service Speed	81	10	9	100
+/- 60,000 BC				
1973	70	20	10	100
1980/81 Slow-Steamming	76	17	7	100
Service Speed	79	15	6	100
+/- 110,000 BC				
1973	88	12	—	100
1980/81 Slow-Steamming	91	9	—	100
Service Speed	92	8	—	100

DEVELOPMENT OF VOYAGE COSTS 1973-1980/81
(US \$ per day)

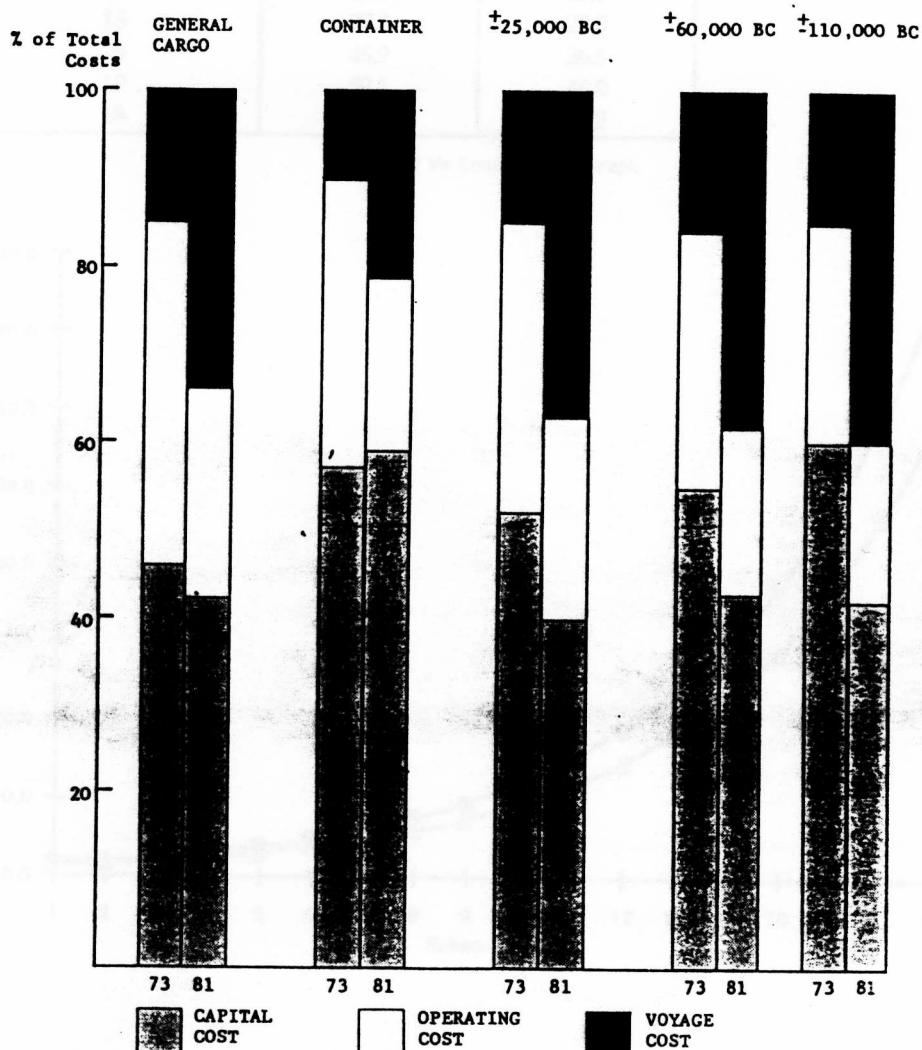


Source : Drevry Shipping Consultants Ltd.

**COMPARISON OF DAILY FULLY BUILT-UP TRADING COSTS
AT DESIGNED SERVICE SPEED 1973 - 81
(US \$ per Day/355 day operating year)**

	1973	%	1981	%
General Cargo: Capital	2,320	46	5,570	42
Operating	1,975	39	3,240	24
Voyage	765	15	4,475	34
Total	5,060		13,285	
Container: Capital	8,500	57	24,225	59
Operating	4,935	33	8,135	20
Voyage	1,480	10	8,700	21
Total	14,915		41,060	
+/- 25,000 BC: Capital	3,510	52	7,025	40
Operating	2,230	33	4,045	23
Voyage	1,075	16	6,335	36
Total	6,815		17,405	
+/- 60,000 BC: Capital	5,775	55	11,630	43
Operating	3,060	29	5,215	19
Voyage	1,635	16	10,180	38
Total	10,470		27,025	
+/- 110,000 BC: Capital	8,665	60	14,535	42
Operating	3,645	25	6,280	18
Voyage	2,040	14	13,815	40
Total	14,350		34,630	

STRUCTURE OF TOTAL FULLY BUILT-UP COSTS 1973-81



SOURCE: DEPARTMENT OF COMMERCE, BUREAU OF ECONOMIC ANALYSIS

Table for Speed Vs Consumption (Bjorkman)

$$(BV + C\Delta)$$

$$Fv = nAe \quad \dots\dots\dots(1)$$

$$A = 0.708$$

$$\text{Loaded } \Delta = 72,000 \text{ tonnes}$$

$$B = 0.23$$

$$C = 0.00000714$$

$$\text{Ballast } \Delta = 37,000 \text{ tonnes}$$

$$n = 1.0$$

Speed - V (knots)	Fuel Cons. at Speed V - Fv (tonnes/day)	
	Loaded	Ballast
1	1.5	1.2
2	1.9	1.5
3	2.4	1.8
4	3.0	2.3
5	3.7	2.9
6	4.7	3.7
7	5.9	4.6
8	7.5	5.8
9	9.4	7.3
10	11.8	9.2
11	14.9	11.6
12	18.7	14.6
13	23.5	18.3
14	29.6	23.1
15	37.3	29.0
16	46.9	36.6
17	59.1	46.0
18	74.3	57.9

Speed Vs Consumption Graph

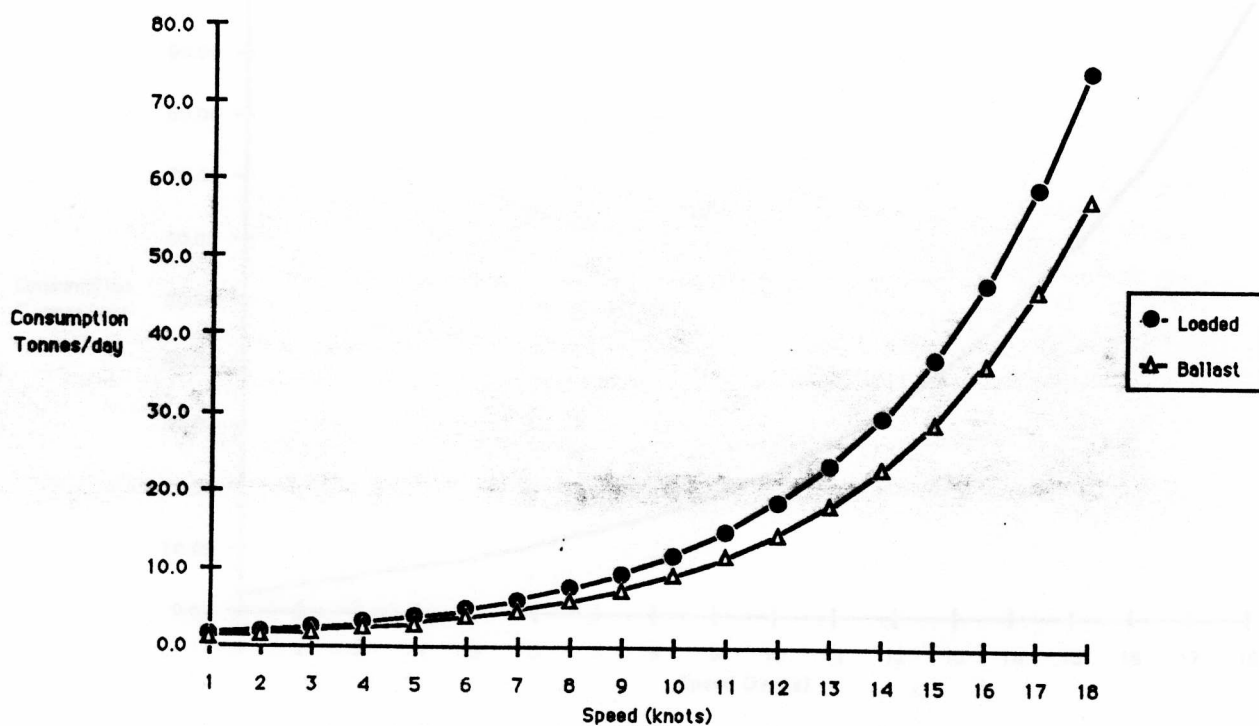


Table for Speed Vs Consumption Curve (Alderton)

New Consumption = $C_d * J$ (2)

Consumption at 14 knots = 50 tonnes /day

$J = A * V^3 - B * V^2 + C * V$

C_d = Consumption at Designed Speed

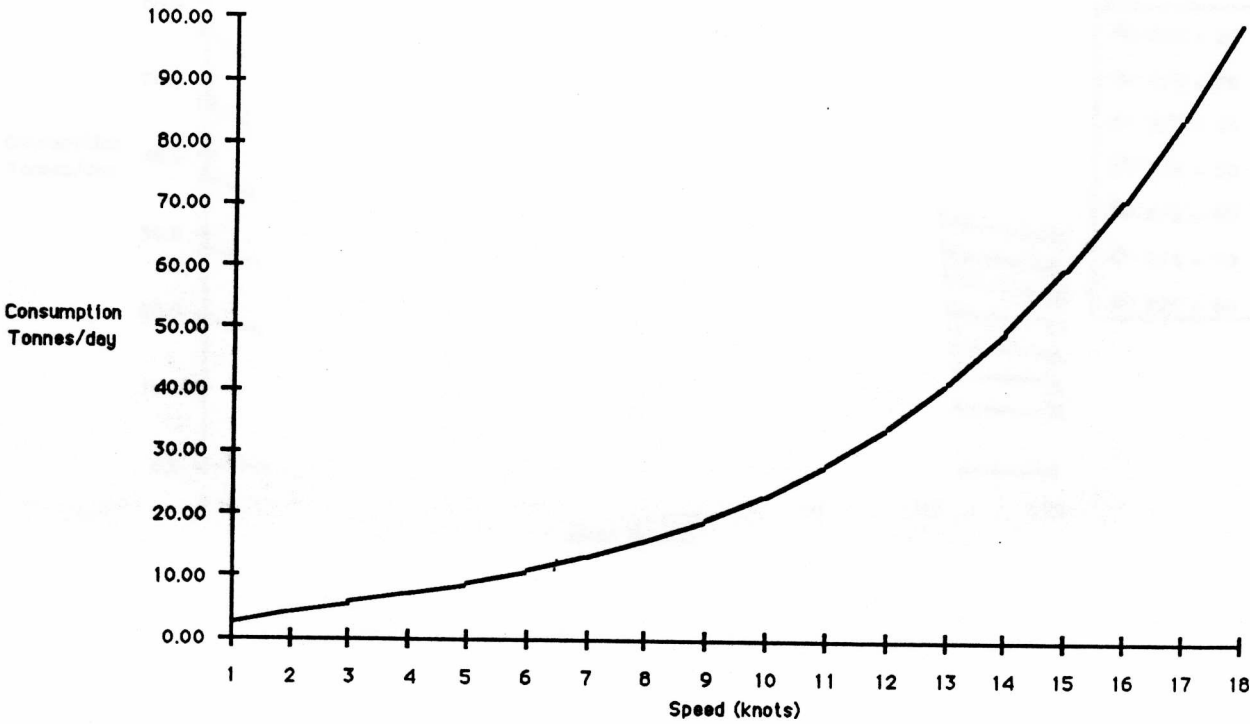
$A = 0.000459$

$B = 0.0048$

$C = 0.04868$

Speed - V (knots)	New Cons.at Speed V (tonnes/day)
1	2.22
2	4.09
3	5.76
4	7.36
5	9.04
6	10.92
7	13.15
8	15.86
9	19.20
10	23.29
11	28.28
12	34.31
13	41.50
14	50.01
15	59.97
16	71.51
17	84.77
18	99.90

Speed Vs Consumption Curve



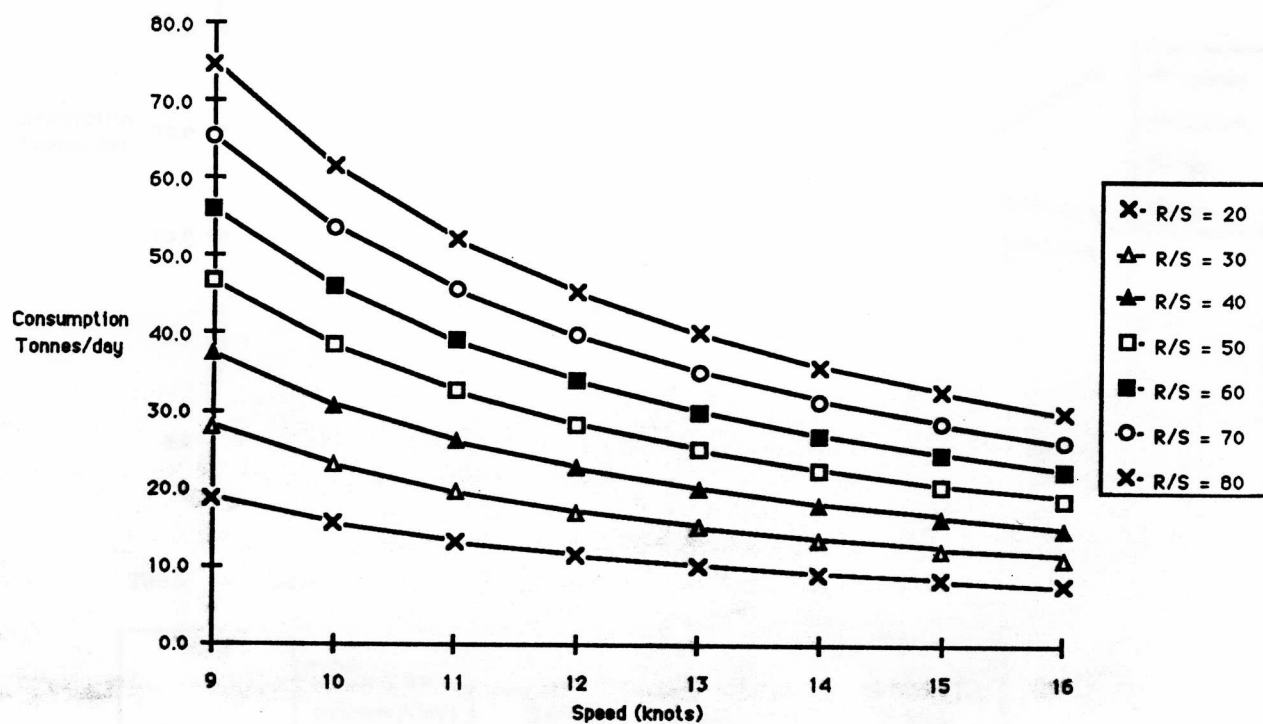
Time Charter**Table for Speed Vs Consumption for different R/S ratios**

$$F_v = R/S(BV-1) \dots\dots(5)$$

$$B = 0.23$$

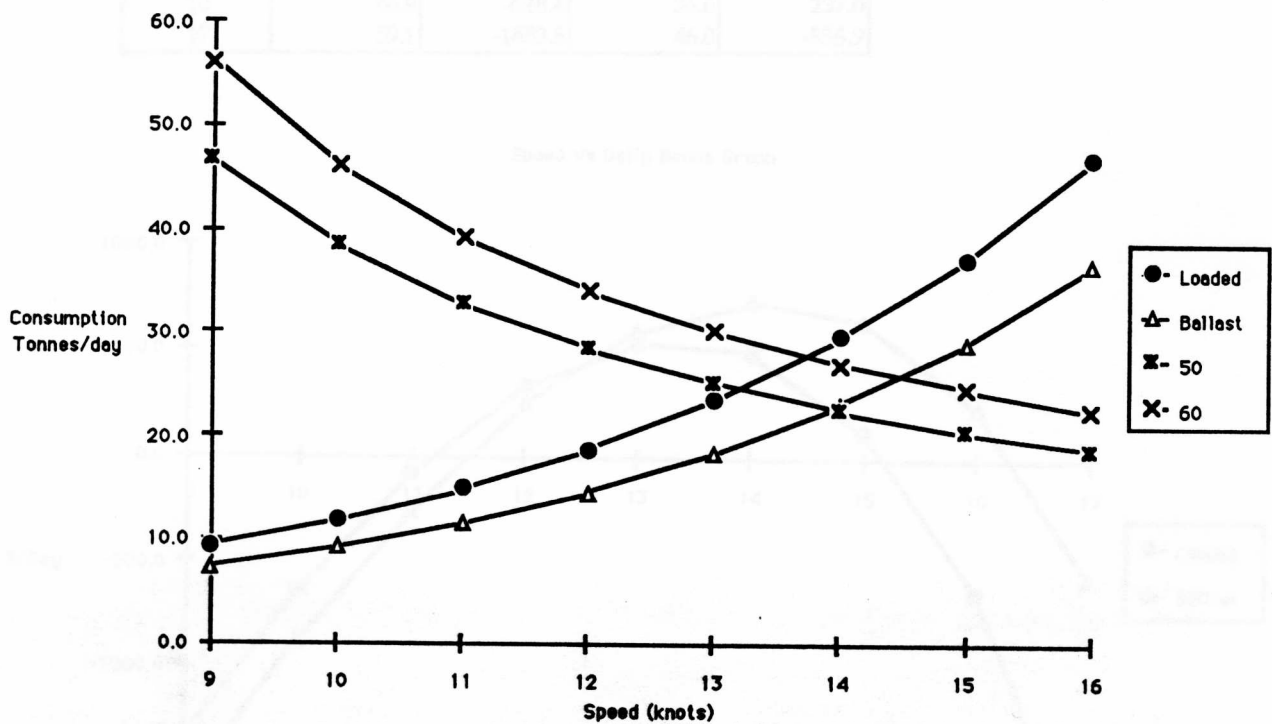
Speed - V (knots)	Fuel Consumption, F_v (tonnes/day)						
	R/S = 20	R/S = 30	R/S = 40	R/S = 50	R/S = 60	R/S = 70	R/S = 80
9	18.7	28.0	37.4	46.7	56.1	65.4	74.8
10	15.4	23.1	30.8	38.5	46.2	53.8	61.5
11	13.1	19.6	26.1	32.7	39.2	45.8	52.3
12	11.4	17.0	22.7	28.4	34.1	39.8	45.5
13	10.1	15.1	20.1	25.1	30.1	35.2	40.2
14	9.0	13.5	18.0	22.5	27.0	31.5	36.0
15	8.2	12.2	16.3	20.4	24.5	28.6	32.7
16	7.5	11.2	14.9	18.7	22.4	26.1	29.9

Speed Vs Consumption for different R/S Ratios Graph



Time Charter**Table for Speed Vs Consumption and R/S ratios**

Speed - V (knots)	Consumption (tonnes/day)		R/S	
	Loaded	Ballast	50	60
9	9.4	7.3	46.7	56.1
10	11.8	9.2	38.5	46.2
11	14.9	11.6	32.7	39.2
12	18.7	14.6	28.4	34.1
13	23.5	18.3	25.1	30.1
14	29.6	23.1	22.5	27.0
15	37.3	29.0	20.4	24.5
16	46.9	36.6	18.7	22.4

Speed Vs Consumption and R/S Ratios Graph**Table for Optimum Consumption and Speed as from the above Graph**

R/S	Loaded		Ballast	
	Cons. Fv (tonnes/day)	Speed - V (knots)	Cons. Fv (tonnes/day)	Speed - V (knots)
50	24.6	13.2	22.7	13.9
60	27.9	13.7	25.8	14.5

Time Charter

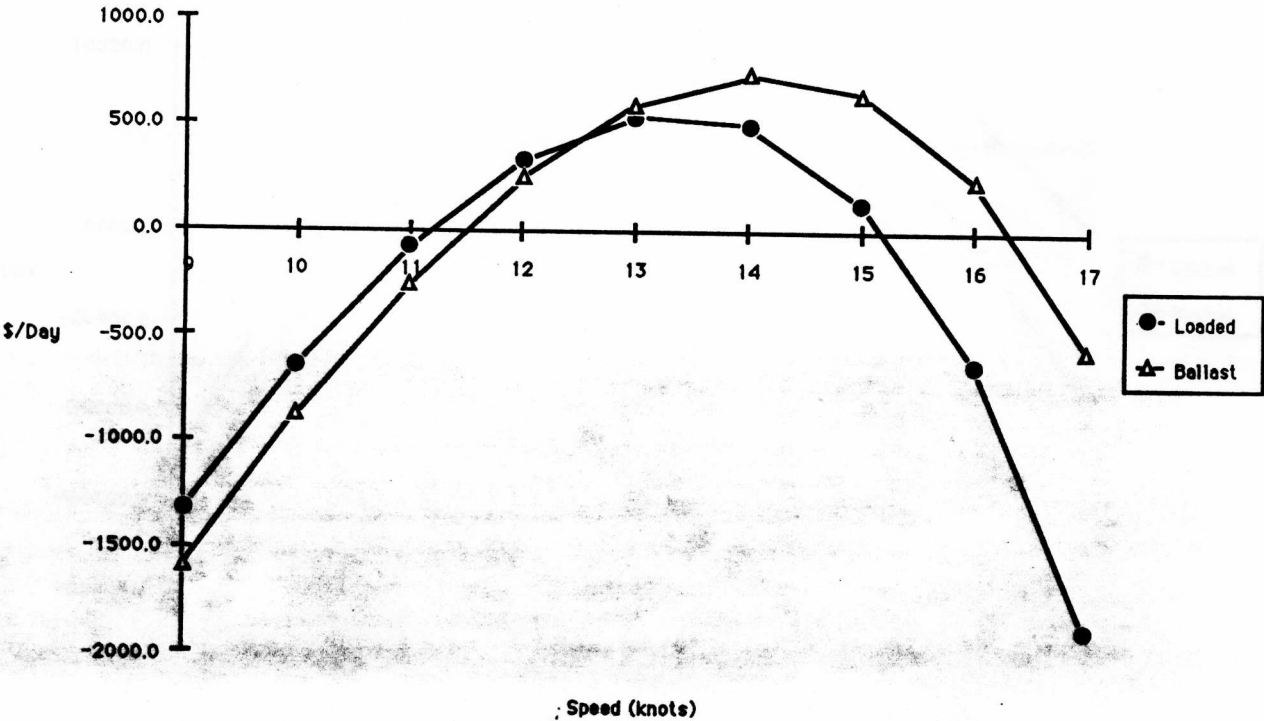
Table for Speed Vs Daily Bonus

$P_v = R[(V/V_{cp})-1]+F_{cp}*S[(V/V_{cp})-(F_v/F_{cp})] \dots\dots\dots (3)$

$R = 10,000 \text{ \$/day}$
 $V_{cp} = 14.5 \text{ kts loaded/15.5 kts ballast}$
 $F_{cp} = 35 \text{ tonnes/day}$
 $S = 200 \text{ \$/tonne}$

Speed - V (knots)	Fuel Cons. (tonnes/day)	Daily Bonus (\$/day)	Fuel Cons. (tonnes/day)	Daily Bonus (\$/day)
	Loaded	Loaded	Ballast	Ballast
9	9.4	-1324.6	7.3	-1590.5
10	11.8	-637.4	9.2	-871.6
11	14.9	-75.7	11.6	-250.5
12	18.7	328.0	14.6	247.6
13	23.5	533.1	18.3	590.9
14	29.6	487.9	23.1	739.3
15	37.3	127.9	29.0	642.5
16	46.9	-628.4	36.6	237.0
17	59.1	-1883.5	46.0	-556.9

Speed Vs Daily Bonus Graph



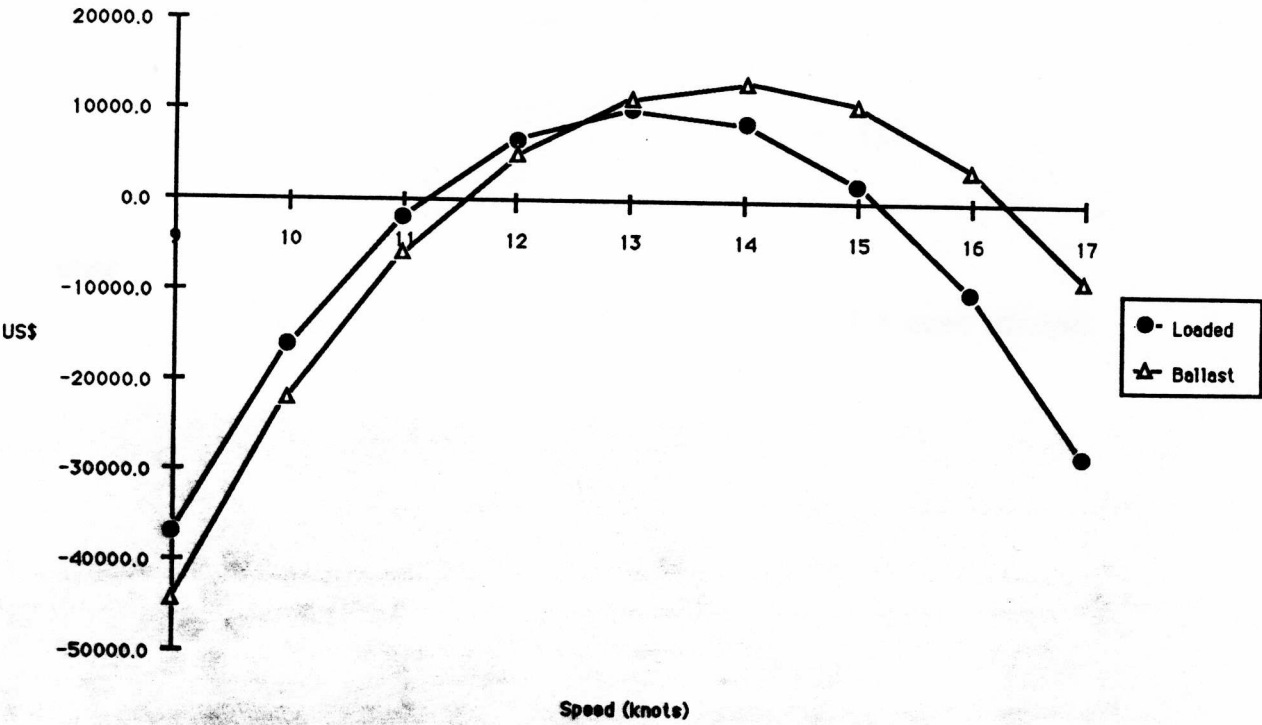
Time Charter
Table for Speed Vs Total Bonus

$TPV = (N \cdot Pv / 24V) \dots\dots\dots (4)$

N = 6,000 nautical miles

Speed - V (knots)	Total Bonus (\$)	
	Loaded	Ballast
9	-36795.2	-44180.1
10	-15936.0	-21791.0
11	-1721.2	-5693.9
12	6834.3	5157.7
13	10251.2	11362.6
14	8712.6	13201.6
15	2131.4	10708.0
16	-9819.2	3703.4
17	-27698.5	-8189.7

Speed Vs Total Bonus Graph



Appendix B.g.

Comparison of Zachariades and Aldertons formulae for optimum speed of a given ship on Timecharter.

$$V_{opt.} = V_{max.} \left[\frac{\text{Daily hire} + \text{Aux. fuel cost/day}}{(K-1) * \text{Fuel Cost/day at } V_{max}} \right]^{1/k}$$

--- (6)

Daily hire = 10000 \$/day

k = 3 for diesel ship

Fuel cost/day at 13kts = s * 23.5 t/day

s = 200 \$/tonne

Auxiliary fuel cost = 1% fuel cost/day

V_{max} = 13 kts

$$V_{opt.} = 13.29 \text{ kts.}$$

$$Lcs = \left(\frac{N}{2k} \right)^{1/3}$$

--- (7)

where N = 10000 \$/day

k = (daily speed fuel consumption at speed V * cost of fuel per ton) / V_s³

V_s = 13 knots

$$k = 23.5 * 200 / 13^3 = 2.139$$

$$Lcs = 13.27 \text{ kts}$$

Appendix B.h.

Comparison of Zachariades and Aldertons formulae for optimum speed of a given ship on a Voyage charter.

$$V_{opt} = \left[\frac{24 \text{ Freight income} * (V_{MAX})^k}{k * \text{Fuel cost/day at } V_{MAX} * \text{miles/RT}} \right]^{1/(K-1)}$$

--- (14)

$$k = 3$$

$$\text{miles/Round trip} = 6000$$

$$\text{freight income} = 240,399 \$$$

$$V_{max} = 3$$

$$\text{fuel cost/day at } V_{max} = 200 * 23.5 = 4700$$

$$V_{opt.} = 12.24 \text{ kts}$$

$$MPS = (8F/KD)^{1/2}$$

--- (11)

$$s = 200 \$/\text{tonnes}$$

$$k = 2.139$$

$$D = 6000 \text{ nautical miles}$$

$$F_v = 23.5 \text{ t/day}$$

$$MPS = 12.24 \text{ Kts}$$

Voyage Charter
Table for Speed Vs Daily Profit

$$MP_v = RI - [N/24V(Rc+Ro+Rd+Fo*S)] - T(Rc+Ro+Rd) \dots\dots\dots(12)$$

RI = 600,000 \$

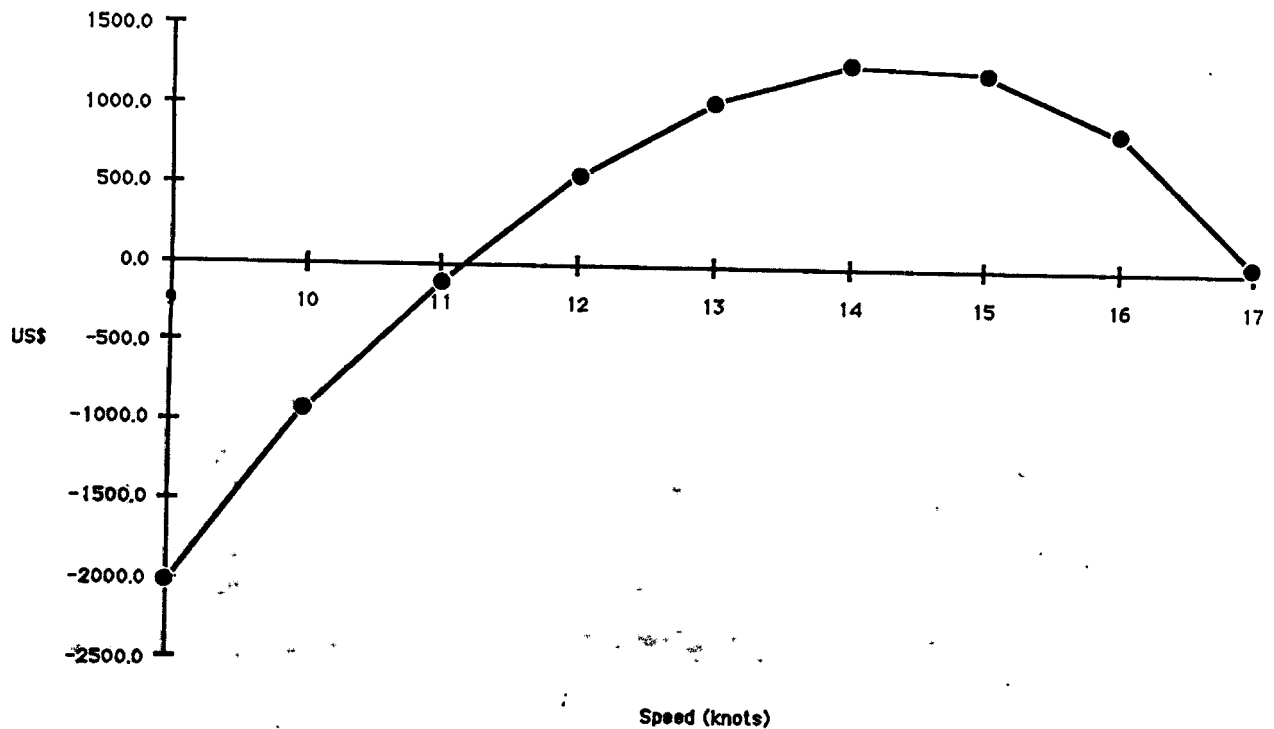
N = 6,000 n.m. loaded / 3,000 n.m. ballast

S = 200 \$/tonne

Rc+Ro+Rd = 14,000 \$

Speed - V (knots)	Fuel cons. (tonnes/day)	Speed - V (knots)	Fuel Cons. (tonnes/day)	Daily Profit (\$)
Loaded	Loaded	Ballast	Ballast	MPv
9	9.4	10	9.2	-2018.8
10	11.8	11	11.6	-924.9
11	14.9	12	14.6	-117.4
12	18.7	13	18.3	555.8
13	23.5	14	23.1	1031.0
14	29.6	15	29.0	1272.3
15	37.3	16	36.6	1228.5
16	46.9	17	46.0	849.5
17	59.1	18	57.9	32.6

Speed Vs Daily Profit Graph



Appendix C.a.

From Reference 35;

$$\frac{\Delta P}{P} \% = A(K_2^{1/3} - K_1^{1/3}) \quad (\text{Ref 35})$$

where K_2 and K_1 are the values of AHR in μm and choosing $A=2.5$ for the whole U.K. fleet.

1. New ship sample changes over the decade, 76-86, yield

$$(129^{1/3} - 111^{1/3}) * 2.5 = 0.6\% \text{ saving in fuel}$$

129 μm = AHR of new buildings in 1976

111 μm = AHR of new buildings in 1986

2. Ten year old ships at the beginning and end of the decade, 76-86, were typically (125 + 400) μm and (125 + 200) μm showing a saving of:

$$(525^{1/3} - 325^{1/3}) * 2.5 = 3.0\%$$

Source : Reference 35.

**Table for Comparison of the effect of self-polishing A.F. paint and Conventional A.F. paint
(12 months since last drydocking)**

	Self-Polishing A.F. Paint	Conventional A.F. Paint	Difference
Increase in Engine Output (%)	2.6	6.3	3.7
Decrease in Ship Speed (%)	3.4	6.5	3.1
Increase in required Engine Output with Ship Speed kept up (%)	19.0	44.0	25.0

Source: NK TECH. BULLETIN 1986, Page 34

Comparison of Effect of
SPC and Conventional Paint

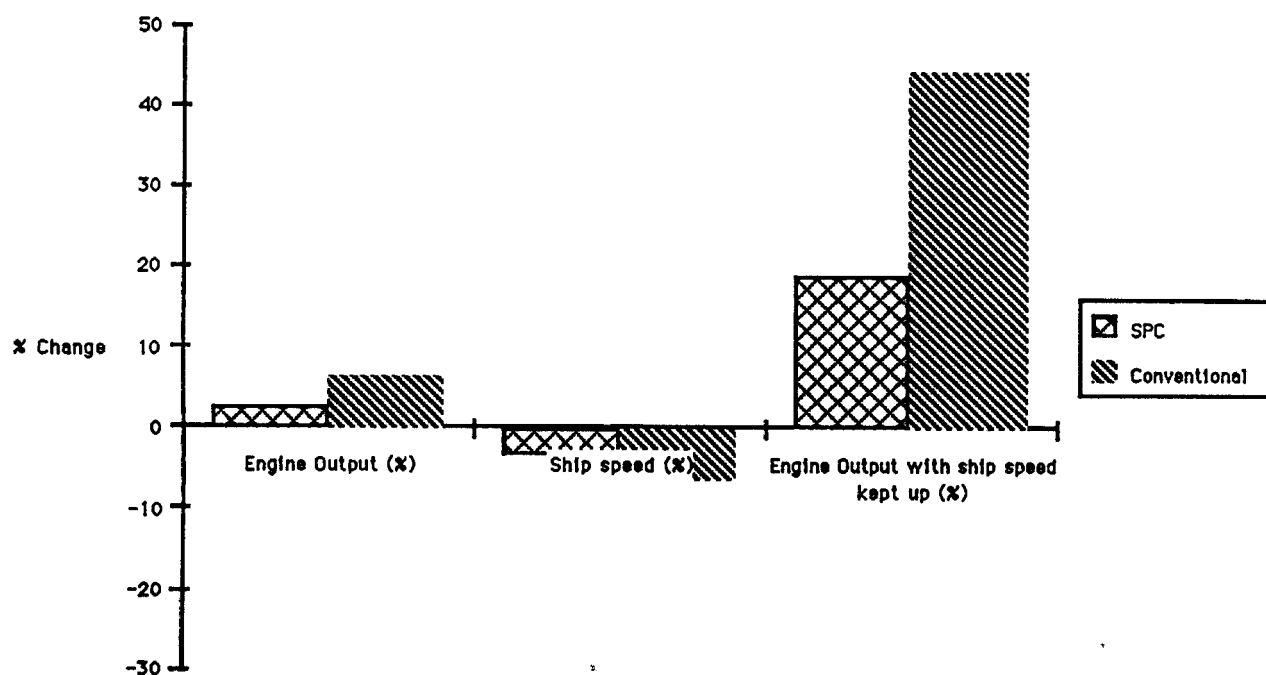


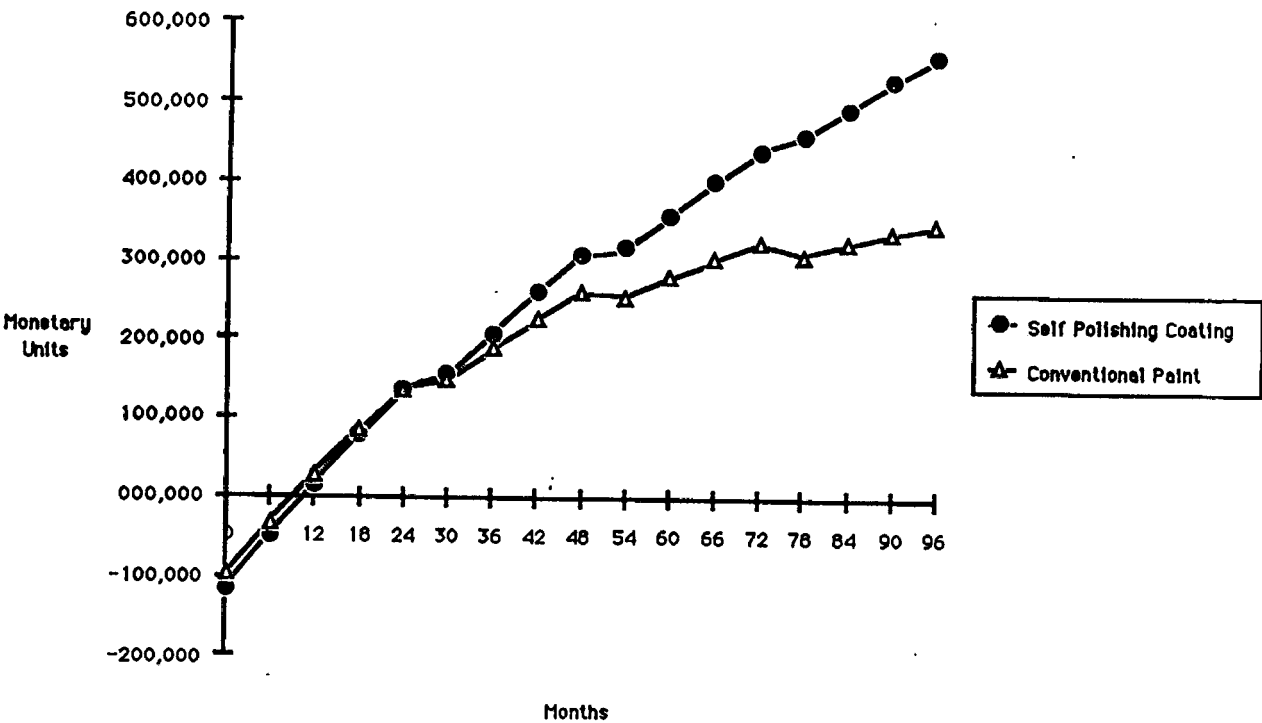
Table of Painting strategy _ financial comparison for a 30,000 dwt. tanker

Pre-gritblasting 575 um, after gritblasting 130 um, operating cost used as datum.

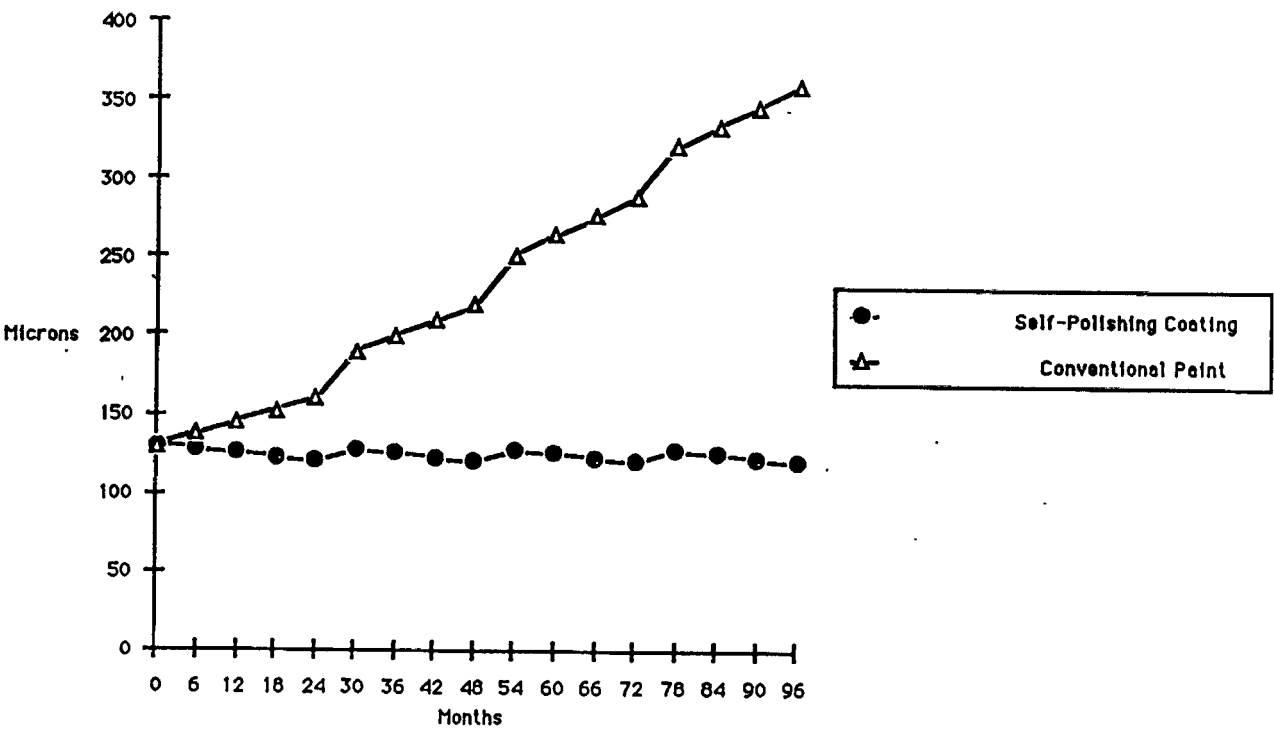
Months	Miles	Self-Polishing Coating			Conventional Paint		
		Microns	TPD	Fin. Status	Microns	TPD	Fin. Status
0	0,000	130	28.71	-115,735	130	28.71	-096,813
6	039,600	127	28.63	-048,296	137	28.87	-031,493
12	079,200	125	28.57	015,264	145	29.04	028,876
18	118,800	122	28.50	076,939	152	29.21	084,657
24	158,400	120	28.44	136,198	160	29.37	136,259
Dry Dock.							
30	198,000	127	28.63	154,793	190	29.97	147,431
36	237,600	125	28.57	207,391	200	30.16	187,643
42	277,200	122	28.50	257,928	210	30.34	224,447
48	216,800	120	28.44	306,486	220	30.51	258,123
Dry Dock.							
54	356,400	127	28.63	315,194	252	31.05	253,629
60	396,000	125	28.57	358,293	265	31.25	279,166
66	435,600	122	28.50	399,704	277	31.44	302,217
72	475,200	120	28.44	439,492	290	31.62	322,998
Dry Dock.							
78	514,800	127	28.63	457,888	322	32.08	307,306
84	554,400	125	28.57	493,204	335	32.24	322,590
90	594,000	122	28.50	527,136	347	32.41	336,251
96	633,600	120	28.44	559,739	360	32.57	348,429

Source: MER, May 1985, Page 20

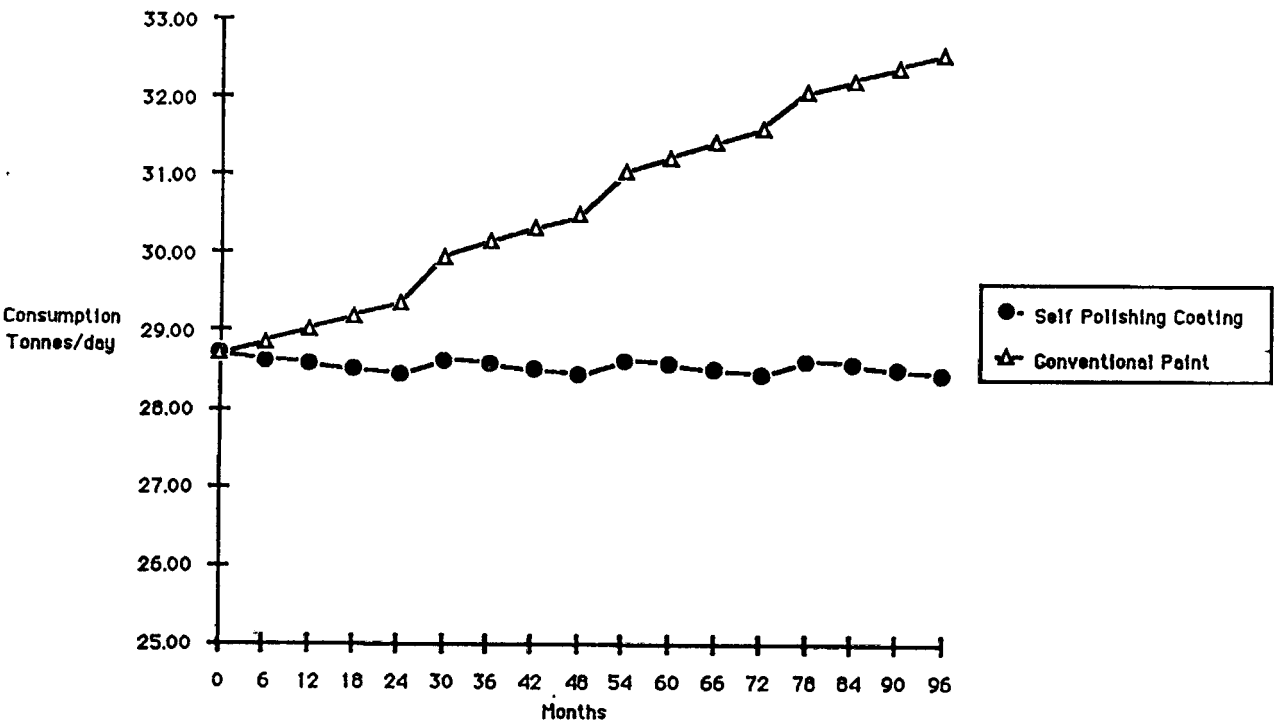
Financial Comparison Graph



Roughness Comparison Graph



Fuel Consumption Comparison Graph



Appendix C.d.

$$\text{Yearly fuel savings in \$} = \text{BHP} \times S \times V_s \times \text{SFC} \times 24 \times n \times P$$

where BHP = propeller shaft power (BHP)

S = propeller efficiency (%)

SFC = specific fuel consumption (kg/BHP/h)

n = sailing days per year (days)

P = fuel price (\$/kg)

Vs = propeller efficiency loss (%)

1. Example of calculation for a twin propeller 52,444 grt container vessel.

BHP = 53,600 BHP

s = 0.6

SFC = 0.15 kg/BHP/h

n = 300 days

p = 0.28

vs = 0.05

yearly fuel saving = \$485,000

yearly propeller polishing cost = \$10,000

economy = \$475,000

2. Example of calculation for a single propeller 11,561 grt general cargo ship.

BHP = 13,800 BHP

s = 0.6

SFC = 0.15 kg/BHP/h

n = 300 days

p = 0.28 \$/kg

vs = 0.05

yearly fuel saving = \$125,000

yearly propeller polishing cost = \$4,000

economy = \$121,000

cont. Appendix C.d.

3. Example of calculation for a 70,827 grt bulk carrier.

BHP = 16,100 BHP

s = 0.6

SFC = 0.15 kg/BHP/h

n = 300 days

p = 0.28 \$/kg

vs = 0.05

yearly fuel saving = \$147,000

yearly propeller polishing cost = \$5,000

economy = \$142,000

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