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A TECHNO-ECONOMIC MODEL OF SHIP OPERATION WITH SPECIAL REFERENCE TO HULL AND PROPELLER MAINTENANCE IN THE FACE OF UNCERTAINTY

by

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ABSTRACT

A description is given of a new computer based techno-economic model designed with particular reference to investments in improved hull and propeller maintenance. The model combines the principles of accountancy with technical and operational variables so as to facilitate an operational simulation of most ship types in a selected economic environment. The technical and engineering economic basis for the proposed new model is discussed with particular emphasis on the relationship between hull surface roughness and ship resistance, the effects of hull roughness and fouling upon propulsion efficiency and quantitative measurements of hull roughness and fouling experienced on ships in service. Results from a set of full scale experiments on two sisterships are also presented in support of a proposed modification to an existing approximate relationship between roughness and ship resistance.

The new techno-economic model is sub divided into three principal parts, based respectively upon deterministic analysis, dynamic programming and probabilistic cash flow simulation. Each part serves a different function in the decision making process between alternative hull and propeller maintenance strategies. A new technique is presented for obtaining probability distribution functions of individual variables associated with uncertainty when only a limited amount of subjective information is available. This new method serves as a basis for the proposed probabilistic cash flow simulation

model, having the primary function of providing quantitative assessments of uncertainty in investment calculation.

The initial requirement for considering the hull maintenance problem within the complete commercial context of ship operation has been confirmed in a series of case studies for different ship types where principal variables and recommended maintenance strategies have also been identified. Quantitative assessments of uncertainty are provided, indicating a potential high degree of uncertainty associated with this type of investment. A separate case study on the hydrodynamic and economic penalties of propeller roughness has established the relative difference between hull roughness and propeller roughness in economic terms. Finally, the deterministic case study evaluations have resulted in the introduction of two simplified methods of calculation from which approximate solutions to alternative hull maintenance strategies may be obtained.

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CONTENTS

NOMENCLATURE

A_T	=	transverse projected area above waterline [m^2]
AHR	=	average hull roughness (used in text) [μm]
α	=	ratio t/w (see context)
C_{AIR}	=	air resistance coefficient
C_D	=	drag coefficient (propeller blade section)
ΔC_D	=	increment to drag coefficient (propeller blade section)
C_F or C_{FS}	=	frictional resistance coefficient (ship)
ΔC_F	=	correlation allowance for hull roughness (ship)
C_f	=	skin friction coefficient (propeller blade section)
C_L	=	lift coefficient (propeller blade section)
ΔC_L	=	increment to lift coefficient (propeller blade section
C_R	=	residuary resistance coefficient
C_T	=	total resistance coefficient (ship)
C_V or C_{VS}	=	total viscous resistance coefficient (ship)
C_{VM}	=	total viscous resistance coefficient (model)
C_B	=	block coefficient
D	=	propeller diameter [m or feet]
E[x]	=	expected value of x
F(x)	=	cumulative distribution function of f(x)
$F^{-1}(y)$	=	inverse function of F(x)
f(x)	=	standard function symbol with x as independent variable

h	=	average hull roughness (used in equations) [μm]
h'	=	Musker's combined roughness height and texture parameter [μm]
η_D	=	quasi propulsive coefficient
η_H	=	hull efficiency
η_o	=	open water efficiency (propeller)
$\Delta\eta_o$	=	increment to open water efficiency
η_R	=	relative rotative efficiency (propeller)
J	=	advance coefficient for propeller
K_Q	=	torque coefficient of the propeller
K_T	=	thrust coefficient of the propeller
k_s	=	sandgrain roughness, diameter of sandgrain [μm]
$(1+k)$	=	form factor
L	=	ship length (between perpendiculars) [m]
μ	=	mean value of variable or distribution function
μ_1	=	joining point of the two truncated halves of normal distributions (see context)
μ^*	=	limiting value of ordinate at non-continuous end of distribution (in cases of high skewness, see context)
N	=	propeller RPM [revolutions per minute]
p	=	probability
p_1	=	lower probability of combined distribution (see context)
p_2	=	upper probability of combined distribution (see context)
P	=	power delivered to the propeller (kW or hp)
ΔP	=	increment to the standard power delivered to the propeller (kW or hp)
ρ	=	density of sea water [1025 kg/m^3]
QPC	=	quasi propulsive coefficient
R_o	=	ship resistance in standard condition [N or kN]

ΔR = added resistance to standard condition [N or kN]

R_{TRIAL} = ship resistance measured on trial [N or kN]

$R_a(0.8)$ = centre line average roughness height using an 0.8mm sampling length [μm]

R_q = root mean square roughness height [μm]

$R_q(2.0)$ = root mean square roughness height using a 2.0mm sampling length [μm]

$R_q(2.5)$ = root mean square roughness height using a 2.5mm sampling length [μm]

$R_{tm}(2.0)$ = mean peak-to-trough roughness height using a 2.0mm sampling length [μm]

$R_{tm}(2.5)$ = mean peak-to-trough roughness height using a 2.5mm sampling length [μm]

r = correlation coefficient (used in regression analysis)

S = wetted surface area [m^2]

S_N = sum of N elements

S , S , K = surface profile parameters defined in the text

σ = standard deviation of distribution function

σ_1 = standard deviation of distribution from which the lower truncated half of the combined distribution is obtained (see context)

σ_2 = standard deviation of distribution from which the upper truncated half of the combined distribution is obtained (see context)

U or U(x) = utility function

u or u(x) = uniform distribution between 0 and 1

V or V_S = ship speed [m/s or knots]

V_A = speed of advance propeller [m/s or knots]

w_F = frictional part of the wake fraction

w_{FM} = frictional part of the wake fraction for the model

w_P = potential part of the wake fraction

w_T = effective wake fraction (Taylor)

w_{TM} = effective wake fraction for the model

w_{TS} = effective wake fraction for the ship

$X_{\bar{U}}$ = certainty equivalent

X = (1) individual cash flow element
(2) a particular value of x (see context)

x = general symbol for the independent variable

x_1 = ordinate corresponding to lower probability estimate of combined distribution (see context)

x_2 = ordinate corresponding to upper probability estimate of combined distribution (see context)

Y = (1) individual annual cash flow element
(2) a particular value of y (see context)

y = general symbol for the dependent variable

Z = economic measure of merit, total sum of cash flows over the project life

z = standardised normal variable, with mean = 0 and standard deviation = 1

$\Phi\left(\frac{x-\mu}{\sigma}\right)$ = integral of normal distribution with mean value u and standard deviation between the limits $-\infty$ and x

$\int_{x_1}^{x_2} f(x)\,dx$ = integral of function f(x) between the limits x_1 and x_2

$\sum_{i=1}^{n}$ = summation of n elements

$\prod_{i=1}^{n}$ = product of n elements

NOTATION:

H.V.F. = high viscosity fuel oil

hp = horsepower

MCR = maximum continuous rating of main engine

µm = microns or m^{-6}

NPV = net present value

ΔNPV = increment to net present value

PROF/INV = discounted profit to investment ratio

ΔPROF/INV = increment to the discounted profit to investment ratio

SFC or sfc= specific fuel consumption of main engine

shp = shaft horsepower

tdw = ship size measured in tonnes deadweight capacity

TEU or teu= twenty foot equivalent units (measure of ship capacity for container vessels)

Special subscripts, superscripts and constants are explained in the text.

Symbols used in the analysis of covariance table are explained in the text in Appendix A.

GENERAL INTRODUCTION

The two sudden increases in the price of crude oil in 1973 and 1979 were followed almost immediately by equally significant reductions in World Trade and corresponding levels of freight rates. Both factors have created among shipowners and operators a new awareness of the importance of ensuring the best possible economic efficiency in ship operation. This new awareness has materialised in a number of research projects, with the specific objective of identifying methods of achieving improved economic performance for new, as well as existing vessels already in service. Freight rates are always subject to market forces, and shipowners and operators are faced with no alternative but to accept the rates offered. In most cases the search for improvement in economic efficiency has therefore been related directly to methods of achieving fuel savings, and the majority of the research effort has been concentrated in this area. A number of alternative energy saving investments have materialised directly or indirectly as a result of this increased research activity. In most commercial companies the available capital resources are limited, and for the shipowner or operator the difficult task is to select the best set of investments with the overall objective of maximising company profits, or wealth. Without proper techno-economic tools this task becomes difficult, and in some cases almost impossible.

Improved hull and propeller maintenance has been identified as one of the available alternatives to other energy saving investments. Over the past ten years a significant research effort has been put into activities related directly to hull maintenance. This includes investigations into the effective life time of alternative coating systems, causes and measured rates of roughness increase with time in service, surface characterisation and the relationship between surface roughness and fluid drag. To the shipowner or operator the results of this work are of little practical interest, unless they can be translated into economic terms and serve as a guidance in the decision making process. Earlier techno-economic models for the evaluation of hull maintenance strategies have been based upon experience with conventional antifouling paints and the assumption that the successful settlement of fouling is unavoidable after a period of time in service. By coincidence, the first sudden increase in oil prices corresponded almost exactly with the first development of self-polishing antifouling paints. The introduction of selfpolishing paints has radically altered the earlier concepts of hull maintenance. These paints are capable of almost entirely eliminating the problems of hull fouling with the result that the economic problem of evaluating hull maintenance alternatives has changed from one of finding the optimum point of drydocking to that of selecting the optimum maintenance strategy over a period of six to ten years, or longer. The introduction of new advanced coating systems has also resulted in a demand for new techno-economic tools based upon the concept of long term maintenance strategies. This demand for advanced techno-economic tools has been the principal reason behind the development of the present work.

The fundamental principles of accountancy are already well established. In addition some special considerations are required in connection with the development of a techno-economic model of ship operation, with particular reference to hull and propeller maintenance. Despite recent research efforts, the technical basis has not yet reached a completely satisfactory level of understanding, and some further investigations are necessary prior to the development of the required model. This includes the extent of hull fouling observed on ships in service, measured rates of roughness increase with some time in service, the relationship betwen hull roughness and ship resistance and the possible effects of hull roughness and fouling upon propulsion efficiency. A comprehensive analysis of hull and propeller maintenance can only be achieved if the problem is considered in the complete commercial context of ship operation, where constant speed or constant power operation may be selected, depending on ship type and operational characteristics. This requirement can only be satisfied with the aid of a complete operational model, taking into account operational and financial variables in addition to the more obvious technical variables related to the maintenance alternatives. The size and complexity of a complete computer based operational model may prevent the general application of this type of decision making tool in the shipping industry. For shipowners and operators without access to advanced techno-economic tools the need therefore clearly exists for simplified methods of calculation, from which approximate solutions to alternative hull maintenance strategies may be obtained. Most investment decisions are based upon uncertain predictions about the future, and a method of identifying and quantifying uncertainties in the techno-economic evaluation of alternative hull and propeller maintenance strategies is considered to be an important part of a rational model in aid of decision making.

The principal requirements outlined above have served as a guideline in the development of the present work, starting in the First Chapter with the assembly of the required engineering-economic and technical basis for a complete techno-economic model. The Second Chapter specifically deals with the concepts of model building and provides a description of the proposed techno-economic model of ship operation, with particular reference to hull and propeller maintenance. In Chapter Three the proposed model is tested in a series of case studies for principal ship types, from which a simplified method of calculation has been developed. The concept of uncertainty in engineering economic calculations is introduced in Chapter Four. A new method of obtaining probability distributions for individual variables based upon subjective estimates is provided, and a probabilistic cash flow simulation model is developed for the purpose of providing a quantitative assessment of uncertainty in investment calculations.

CHAPTER 1

TECHNO-ECONOMIC BASIS FOR A MODEL OF SHIP OPERATION WITH PARTICULAR REFERENCE TO HULL AND PROPELLER MAINTENANCE

1.1 CONSIDERATION OF SOME ECONOMIC FACTORS

1.1.1 INTRODUCTION TO THE PRINCIPLES OF ENGINEERING ECONOMICS

Engineering economics is the name given to economic analysis applied to engineering projects. The principal objective of engineering economic analysis is to provide a framework for the evaluation and subsequent choice between competing alternatives. Technical merit is no longer a valid criterion on its own. A number of feasible technical solutions to a given engineering problem always exist and the emphasis in decision is instead directed towards the efficient use of available capital resources. Engineering economics is therefore primarily concerned with the calculation of differences in economic terms between competing projects as a basis for selection between alternatives.

The evaluation process can be divided into two steps; the transformation of technical parameters into economic terms and the subsequent evaluation procedure using established economic methods and measures of merit. This complete process is often referred to under the name of techno-economic analysis. The calculation of a measure of merit is an attempt to provide a common basis for comparison between alternatives. A number of different measures of merit exist and the choice of a correct measure is important in engineering economic calculations.

Economic criteria alone are not always the only decision factors in the choice between alternatives. Legal, social, human and other non-monetary factors may sometimes over-ride the criteria based entirely on economic considerations. The human factor is of particular importance, both in the attitude towards a project in general, as well as attitudes of decision makers towards various investment outcomes.

Engineering economic analysis is concerned with the evaluation of investment proposals prior to implementation, and the analysis is therefore based entirely upon future predictions of technical and economic variables. Predictions about the future are always associated with some degree of uncertainty and unless the method of analysis used is capable of providing a quantitive handling of the various uncertainties involved, it will be of only limited value to the analyst.

In addition to predictions about the future, a measure of the relative usefulness of distant cash flows is also required. It is generally accepted that money has associated with it a certain time value. A given sum of money now is worth more than an equal sum at some future point in time because it could have been invested or used for consumption during the period. The available methods for dealing with the time value of money are described within the framework of discounted cash flow calculations. The principles behind these methods are quite simple; future cash flows are discounted to their equivalent present value and some pre-determined method of measuring the profitability or desirability of the project is applied. The step of first choosing a measure of merit is sometimes difficult and can be critical for the following comparison between alternatives.

1.1.2 ECONOMIC METHODS AND MEASURES OF MERIT

The various economic methods and measures of merit available for use in marine environment have been discussed in detail by Benford [References (1), (2) and (3)], Buxton [References (4) and (5)], Goss [References (6) and (7)] and others. Only a brief introduction is therefore provided as a basis for the techno-economic analysis in the following chapters.

The choice of an appropriate economic criterion depends entirely on the nature of the problem and the amount of information available to the analyst. Only on a few occasions will different criteria point towards exactly the same decision, and it is therefore necessary for the analyst to have a detailed knowledge of the different methods available so that the correct method for a particular problem can be chosen. Application of the wrong method resulting in a decision on the basis of a wrong criterion may lead to uneconomic investments or, at best, the rejection of more profitable ones. All methods make certain assumptions about the market; the choice of method may depend on which of these assumptions are most acceptable for the case in question. Broadly, the most common methods fall into three distinct groups based respectively upon:

1. Net Present Value
2. Internal Rate of Return or Yield
3. Cost Analysis

Net Present Value is probably the most commonly used and widely accepted criterion. This relies on both the revenue and the opportunity cost of capital for the project being known. Given that a lower limit for the opportunity cost of capital has been defined, then any project giving a positive Net Present Value will be worth undertaking, and the higher the NPV the better. One problem to be aware of is that the simple monetary answer obtained is not related to the actual size of the investment; the result is that large investments are being favoured as if capital resources were unlimited. One way of avoiding this difficulty is to divide the NPV by the present value of the investment. This ratio is usually called the Discounted Profit to Investment Ratio and is effectively a measure of the profit earned for each unit of capital invested. A second problem is that of comparing investments of unequal lives. This can be solved by converting present values into equivalent annuities using a discount factor based on the opportunity cost of capital.

Internal Rate of Return or Yield. This method is based on knowing the revenues that the project will be generating and finding the interest rate for which the Net Present Value becomes zero. The higher the IRR, the more attractive the investment will be and the actual IRR can be compared with a specified opportunity cost of capital below which the investment will be unattractive. The IRR method overcomes the problems associated with investments of unequal size, but the problems of unequal life remain . A further problem may arise if the investment does not consist of a single initial capital investment, but is spread out over the lifetime of the investment in some irregular pattern. If this irregular pattern results in the NPV turning negative at some intermediate point in the life of the investment and then subsequently turning positive again, it will be impossible to calculate the IRR by the conventional technique. It is possible to overcome this difficulty by discounting some of the adverse negative cash flows back to an earlier point in the investment life, but these calculations must be approached with care. This particular problem will usually only occur when calculating the Incremental Yield of an investment. This is a different version of the IRR criteria and is frequently the best available method in engineering economic calculations where alternative additional investments in new equipment and modifications to existing equipment will have to be considered. In this case the IRR is calculated on the basis of the additional or incremental investment, and in order to be acceptable this will have to give a rate of return at least as high as the original investment or alternatively as high as the opportunity cost of capital.

Cost Analysis is used if revenues are unknown while it is assumed that the opportunity cost of capital is known. Usually the measure of merit is expressed as Required Freight Rate and this method will usually be used at a prelimiary design stage only.

Finally, a method which does not fall within any of the three categories described above is Payback Period. This is a widely used measure of merit, mainly because of its simplicity. However, in most cases it is an unreliable criterion. It assumes that revenues are known, it assumes that the opportunity cost of capital is fixed (usually zero) and it ignores the life of the investment after it has "paid for itself". Only in a limited number of cases will this method give reliable results when evaluating alternative investment proposals.

The principal conclusion to be drawn from this brief discussion of available economic methods and measures of merit in investment calculations is that no single universal economic criterion exists, and each case instead has to be evaluated on the basis of its own merits. A comprehensive techno-economic model therefore evaluates a number of different measures of merit simultaneously, allowing the analyst in each case to make the final choice.

1.1.3 METHODS OF FINANCE, TAX CONSIDERATIONS AND THEIR COMBINED INFLUENCE UPON INVESTMENT DECISIONS

Engineering economic studies are not usually concerned with the methods of financing a project and only occasionally are tax considerations entered into the calculations. From the objective of corporate wealth maximisation it may be argued that investments are acceptable only if they produce a net addition to the total wealth of the company. Investments are in principle evaluated on the basis of comparing the additional costs incurred with the additional revenues generated. The method of finance may affect the costs incurred and the investment decision can therefore not be separated from the financial decision without prior consideration of the actual problem.

Two principal methods of finance are available; equity capital and borrowed funds. Equity capital is supplied by the owners of a corporation in the expectation of earning a profit, but the terms on which the capital is supplied contain no guarantees for the repayment or the recovery of the invested capital. Borrowed funds are obtained on the basis of a legally binding agreement in which the borrower promises to pay a fixed rate of interest for the capital and to repay the capital at a specified point in time. Failure of the borrower to meet the terms of the loan may allow the supplier of the capital to seize assets provided as security guarantee to ensure full repayment of the outstanding borrowings with interest. The interest payments on the loan remain fixed, irrespective of the outcome of the investment and the supplier of the capital does not share in the profits of a successful investment. Borrowed funds are clearly less flexible in use than equity capital but carry the advantage that the supplier of the capital has no direct influence upon the decision making process within the company.

Equity capital can be supplied in the form of new stock issues or retained earnings. Fixed costs associated with the issue of new stock are normally high and this tends to limit its use to major re-financing operations in expanding corporations. Retained earnings are available as a continuous source of capital and are the most commonly used internal source of finance, provided adequate profits are available. The reinvestment of profits in the business may meet strong objections from share-holders who instead would prefer to receive the majority of profits in the form of dividends, and this is one of the factors against internal forms of financing using equity capital. A second limitation arises directly from the cost of equity capital. Tax payments always have to be made prior to the repayments of dividends or retention of profits for the purpose of reinvestment, effectively doubling the opportunity cost of the capital if corporation tax rate is 50%. In most countries dividends are also subject to personal taxation making equity capital from share issues a more expensive source of finance than retained earnings.

Debt finance is usually raised in the form of overdrafts, medium or long term loans from banks and other financial institutions or bond issues. All debt finance has the common feature that the principal is repayable and interest payments are due at specified points in time. This legal commitment to repayments puts specific demands on regular positive cash flows from the project and debt capital is therefore less flexible in use than equity capital. In most countries interest payments are tax deductable, effectively halving the cost of finance if the corporation tax rate is 50%. This low cost of capital is the principal advantage of debt finance over equity capital. In theory, there would be an advantage in maximising the ratio between debt finance, also called the level of gearing or leverage, but there is a limit to the amount of leverage which can be undertaken on account of the vulnerability to fluctuations in cash flow and consequently the risk to debtors and stockholders. The limit of debt finance is found in practice to be about one third of the total capital employed.

Irrespective of the method of finance, tax authorities in most countries allow for the recovery of the principal in the form of depreciation allowances, provided the investment is made in a depreciable asset. If the investment is non-depreciable, retains no value at the end of the investment life and the company is liable to income tax, the principal has to be recovered from after tax profits, resulting in a higher net cost of finance.

A medium to large company in expansion will normally undertake a series of different investments of unequal size during the financial year raising capital continuously from a number of different sources. In this parallel stream of investment opportunities and finance, capital from one source does not belong to a particular project, but is instead seen as part of a common pool of finance. The opportunity cost of capital is therefore the weighted average cost from all sources, unless special financial arrangements have been made for a particular project. As a result the weighted average cost of capital to be used in project appraisals is higher than the interest rate on a typical medium term bank loan, typically between 5% and 10% in real terms in most European countries and nearly twice this figure in the United States. In the total absence of tax liabilities the opportunity cost of capital from equity funds is of course in theory the same as the cost of capital from debt finance, and the principle of calculating a weighted average becomes redundant.

Now consider the special case of investment in improved hull maintenance procedures in the light of the preceding comments about methods and costs of finance. The suggestion has already been made that an average weighted cost of capital should be used in investment calculations. In principle, the investment in improved hull maintenance in terms of reblast and the application of advanced coating systems is different from the majority of investments in the marine environment since hull maintenance itself is not defined as a depreciable asset. On the other hand, the additional expenditure may for accounting purposes be taken as an ordinary out-of-pocket cost, and therefore immediately be offset against revenue prior to the payment of taxes. Provided adequate positive net cash flows are available the net cost of the investment is halved directly as a result of the reduction in pre-tax cash flows if the company tax rate is 50%, and therefore compensates for the recovery of the principal from after tax cash flows. This conclusion is drawn irrespective of whether the method of finance is through retained earnings or debt capital. If the cash flows are insufficient to accommodate the intial investment in a single financial year, "carry-forward" provisions normally allow negative cash flows to be offset against positive cash flows in future years, resulting in no significant changes in the net cost of the investment over a period of several years except for a loss of opportunity to re-invest or repay the recovered capital at an earlier point in time. Compared with investments in depreciable assets the only major difference lies in the fact that for non-depreciable investments the initial negative cash flows are offset against revenue with a maximum amount every year until the negative cash flows carried forward are exhausted, while for fully depreciable assets a number of different methods of depreciation may be used with the objective of minimising tax liability over the total project life. The difference in opportunity cost between equity and debt capital of course still applies, but this argument is considered to be unimportant since a decision has already been made to use a weighted average cost of capital from all available sources.

In conclusion, income taxes do not influence the relative ranking between alternative hull maintenance strategies, and tax considerations may be omitted from the techno-economic modelling of the investment problem. If required, after tax net present values are obtained by reducing the before tax present value by the approximate tax liability. The discounted profit to investment ratio remains unchanged since profit as well as investment are reduced by the same percentage tax rate. Only in special situations is the difference in economic terms between two alternative investment proposals affected by income tax considerations. This is when one alternative involves a tax free income or tax deductable expenditure not encountered in the second alternative. In a more general context the situation where assets are disposed of or natural resources are depleted may also be included, but this is not relevant to the present hull maintenance problem.

1.2 PRINCIPAL TECHNICAL FACTORS: IDENTIFICATION AND QUANTIFICATION

1.2.1 AN INTRODUCTION TO HULL MAINTENANCE PROCEDURES

The history and development of anti fouling and anti corrosive paints have recently been described in detail by Milne in Reference (8). Practical experiences with various hull maintenance procedures were reported by I.E. Telfer in Reference (9) where the merits of various coating systems are discussed, with particular reference to the external maintenance of tankers. During the 10 years since this paper was written, a number of new problems have been identified and possible solutions provided. These latest developments in the understanding of the hull maintenance problem .are discussed in detail in References (10) and (11), with particular emphasis on the economic evaluation of hull maintenance alternatives.

The problems associated with the external maintenance of steel hulls were initially found to be the prevention of corrosion and the prevention of fouling growth. In more recent years surface roughness has also been added to the list as a separate problem. From a safety point of view corrosion control is the most important factor demanding principal attention. Solutions to this problem have hitherto almost entirely been provided in the form of paint systems, combined in more recent years with methods of cathodic protection to prevent localised accelerated corrosion in areas with surface damage or paint detachment. The different nature of the corrosion problem compared with the fouling problem have required completely different paint systems to be developed for each individual task. Attempts have been made to provide a combined system, but without much success. A first coat of shop primer is also required in addition to the anti corrosive and anti fouling paint required to protect the steel surface at the new building stage prior to cutting and welding, giving a total of three different individual paint systems for which compatibility is required. Failure to observe the demand for compatibility is one of the principal reasons for major coating system failures.

Modern anti corrosive systems are based upon one of three principal types of resin; Chlorinated Rubber, Vinyl or Epoxy. Chlorinated Rubber systems may have the disadvantage of incompatibility with modern co-polymer systems. According to Telfer, experience has demonstrated the superiority of epoxy coatings compared with other available anti corrosive materials, especially when used in combination with a cathodic protection system. Unfortunately, the superior performance of the system over time is offset by the practical disadvantages that epoxy coatings present a poor surface for adhesion of antifouling materials unless overcoated within a short period from application. Epoxy coatings also cure slowly and are difficult to apply with airless spray at low temperatures. Modern paint application is almost entirely by airless spray. This method has yet to be perfected as discussed in Reference (10), but for large vessels it is the only economically feasible method of application.

Chlorinated rubber and vinyl are also the two most commonly used resins in the composition of ordinary high performance antifoulings. Both materials are insoluble in sea water and sufficient release of biocide with time is therefore achieved by close-packing the pigment particles giving what is commonly known as "continuous contact" antifoulings. All conventional antifoulings using insoluble binders have high initial leaching rates with exponential decay, resulting in a limited effective life. Improvements in lifetime have been made by including water-sensitive resin or soluble plasticiser in the formulation, but the presence of the insoluble binder eventually results in accumulation of a barrier of insoluble materials preventing further release of biocide. Typically, only biocides in the outer 50 to 100 μm thickness of paint film are released, giving an effective life time of only 15 to 18 months under normal operating conditions [Reference (12)]. This spent matrix of binder also presents a poor surface for overcoating with new antifouling paint in drydock, resulting eventually in detachment between layers of paint.

The requirement for a longer effective antifouling life resulted in the development of the re-activating and the self-polishing antifouling systems. Both systems provide extended life-time by removal of the binder material. This is achieved by a process of regular underwater mechanical scrubbing for the re-activating system and by the use of a polymer binder dissolving at a controlled rate at the paint-seawater interface in the case of the selfpolishing system. The latter type of paint has the advantage of constant matrix removal giving a constant leaching rate and a life-time proportional to the coating thickness. Also, the paint surface remains non-porous presenting a good substrate for overcoating without the need for sealers. In addition, the gradual disappearance of the paint prevents the build-up of old coatings, traditionally a major source of hull surface roughness. Indications are that under certain conditions self polishing coatings also become smoother with time in service, [Reference (10)].

The problems associated with hull roughness have been known to exist for a long time, but only after the sudden escalations in energy costs have owners and operators actively taken an interest in methods of reducing hull roughness. Principal causes of increasing hull roughness with time are:

(1) Corrosion of steel substrate

(2) Build-up of old coatings

(3) Paint system blistering and detachment

(4) Mechanical damage

(5) Poor quality of paint application in drydock

Possible solutions to items (1), (2) and (3) have already been described. Items (4) and (5) have hitherto largely been ignored by shipowners and operators and remain the principal sources of roughening with modern advanced hull coating systems. Both problems are discussed in detail in References (10), (11) and (13).

A common feature of modern advanced antifouling coatings is their requirement for good surface preparation. In the case of new buildings the complete coating system may be planned from the shop primer to ensure full compatability between coats. For vessels already coated with conventional antifoulings, problems with compatibility and quality of the substrate may exist and the only safe solution is to completely reblast the underwater hull area and build up a new coating system. Under special circumstances where the vessel has initially been coated with an epoxy anti-corrosive system followed by subsequent coats of conventional antifouling paint the antifouling materials may be removed by a method of sandsweeping, leaving an intact epoxy substrate for subsequent over-coating with one of the new advanced antifouling materials. Paint manufacturers sometimes relax the stringent requirements for surface preparation and compatibility between paint systems in an attempt to win new orders, but this in general is a recipe for disaster where the economic consequences eventually have to be paid by the shipowner. For vessels which have spent some years in service and have repeatedly been overcoated with conventional anti fouling materials, the hull roughness is in any case likely to be of a magnitude to justify, in economic terms, a complete reblast on account of reduced hull roughness alone with no reference to the subsequent paint system used, [References (10) and (11)]. The relationship between hull roughness and added resistance is fundamental for this type of evaluation between hull maintenance alternatives, and this topic will be addressed in more detail in the following section.

Traditional models for the analysis of hull maintenance have been based upon experience with conventional antifouling paints, and the fact that the settlement of fouling after a period of time in service has been almost unavoidable. The introduction of re-activating paints and more advanced self-polishing coatings has practically eliminated the fouling problem. Combined with an improved understanding of the relationship between roughness and drag, the opportunity has been provided for a complete change in the overall concepts associated with the economic evaluation of hull maintenance alternatives. There is no longer a question of determining an optimim point of drydocking, but instead determining an optimum maintenance strategy over a 5 to 10 year time period, possibly even longer.

An important input to this type of calculation is the cost associated with various hull maintenance procedures. Appendix B presents typical costs for some of the principal maintenance alternatives in drydock. The costs were assembled on the basis of a worldwide survey and subsequently presented to shipowners, and a major paint manufacturer, for comments and adjustments prior to final approval and acceptance as representative prices paid by shipowners after allowing for average discounts.

1.2.2 HULL ROUGHNESS: DEVELOPMENT WITH TIME IN SERVICE AND IN DRYDOCK EXAMINED SEPARATELY

An introduction to hull maintenance procedures has already been given and some of the principal reasons for the increase in average hull roughness (AHR) with time in service have been discussed. Due to this large number of reasons for hull surface deterioration, it is clearly impossible to predict with a high degree of certainty the future roughness scenario of any arbitrarily chosen vessel. As a basis for the economic analysis of hull maintenance strategies a series of assumed roughness scenarios could be employed, but this was considered to be an unsatisfactory approach. Information about the practical development of roughness with time in service has been collected by a number of interested parties, and results have occasionally been published in the technical literature. In particular, the recent work of Byrne carried out over a three year period is a valuable source of information, [Reference (13)].

For the purpose of obtaining actual data for the project instead of using a number of fictitious scenarios an analysis has been carried out on a total of 56 independent hull roughness surveys. Independent in this context has the meaning of 56 surveys on 56 different ships and the reasons behind this particular requirement are explained below. The 56 surveys have partly been taken from Reference (13) and partly obtained from other sources. A total of 44 surveys included measurements at indocking after washing but prior to repairs and painting and measurements after painting prior to outdocking. This has enabled an assessment to be made of the change in roughness as a result of the treatment in drydock.

In addition 17 roughness surveys of new buildings have been obtained and from this an estimate has been made of the expected average hull roughness of a new ship.

One of the conclusions drawn from References (13) and (14) is that most ships experience an increase in roughness in drydock, and secondly that the actual change in roughness is correlated to the average hull roughness at indocking. It therefore follows that in the economic analysis of hull maintenance procedures separate consideration should be given to the three following areas:

(1) New Ship Roughness

(2) Change in Roughness During Drydocking

(3) Change in Roughness in Service

1.2.2.1 NEW SHIP ROUGHNESS

In Reference (13) a typical average hull roughness value for new merchant ships was established, based upon a sample of 13 merchant vessels with information collected in the period from 1973 to 1978. This sample has been increased to 17 by the inclusion of an additional 4 surveys carried out in the period 1978-1981.

The new analysis gave the following results:

Mean AHR of new ships = 123 μm

with standard deviation = 22 μm

Table (B-1) in Appendix B gives a summary of the survey results with a corresponding identification of vessel type and building place. The results are plotted in the form of a histogram in Figure (1.1). Superimposed on top of the histogram is a normal distribution with standard deviation equal to that of the actual sample.

1.2.2.2 CHANGE IN ROUGHNESS DURING DRYDOCKING

As demonstrated in References (13) and (14), most ships experience an increase in roughness in drydock, and the magnitude of the increase is correlated to the roughness of the vessel at indocking. The analysis of roughness changes in drydock presented in Reference (13) includes warships as well as the history of roughness changes in drydock for every individual drydocking of a 20 year old passenger vessel. These two groups are not representative of the standards achievable in commercial shipyards today, and it was therefore decided to re-analyse this work by excluding the two undesireable groups of data, and in addition include some surveys from other sources. The total sample is made up of 44 drydockings incorporating both indocking and outdocking surveys. These all represent typical standard drydocking procedures consisting of high-pressure washing, repair of damage by spotblasting and touching up of the anti-corrosive system and application of one or two coats of antifouling paint. In some cases local scraping and sand-sweeping may also be included. None of the sample points include vessels which have been totally reblasted or grit-swept since this is not representative of conventional maintenance procedures, and will have to be considered as a special scheme in the economic analysis.

FIGURE 1.1
AVERAGE HULL ROUGHNESS OF NEW MERCHANT SHIPS 1973 - 1981

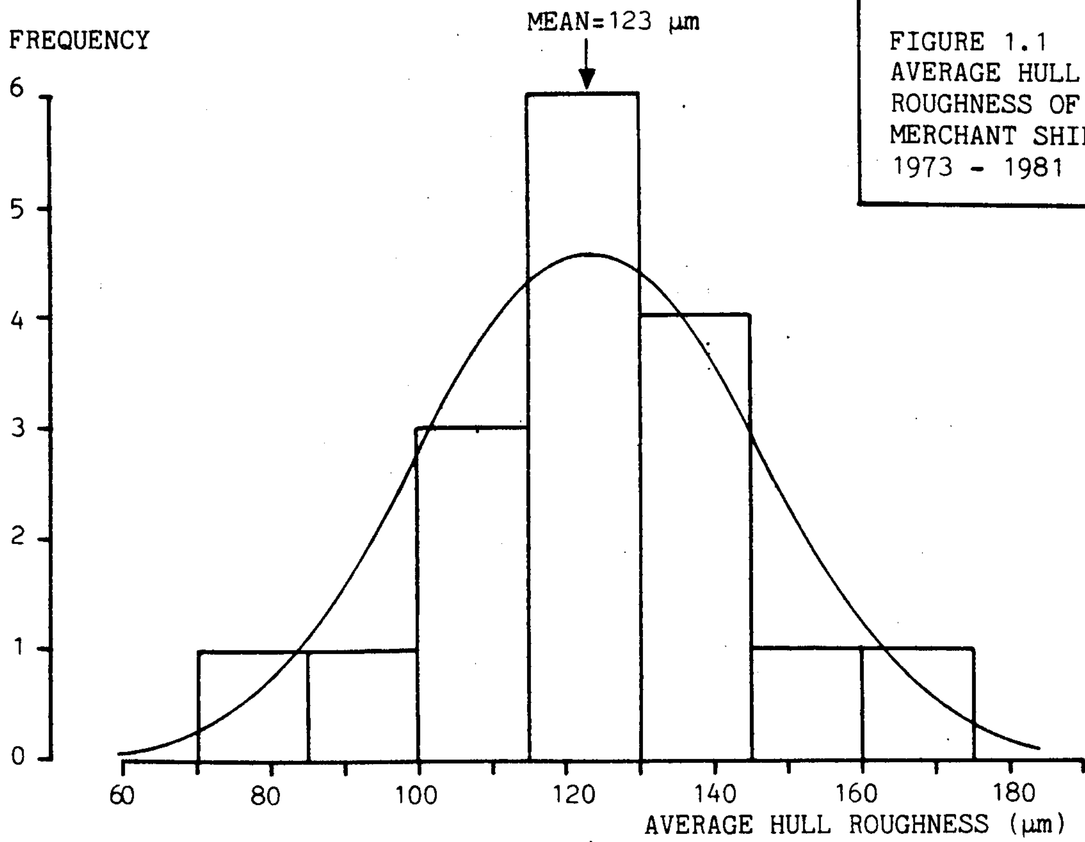


FIGURE 1.2
PROBABILITY DISTRIBUTION OF ROUGHNESS INCREASE IN SERVICE

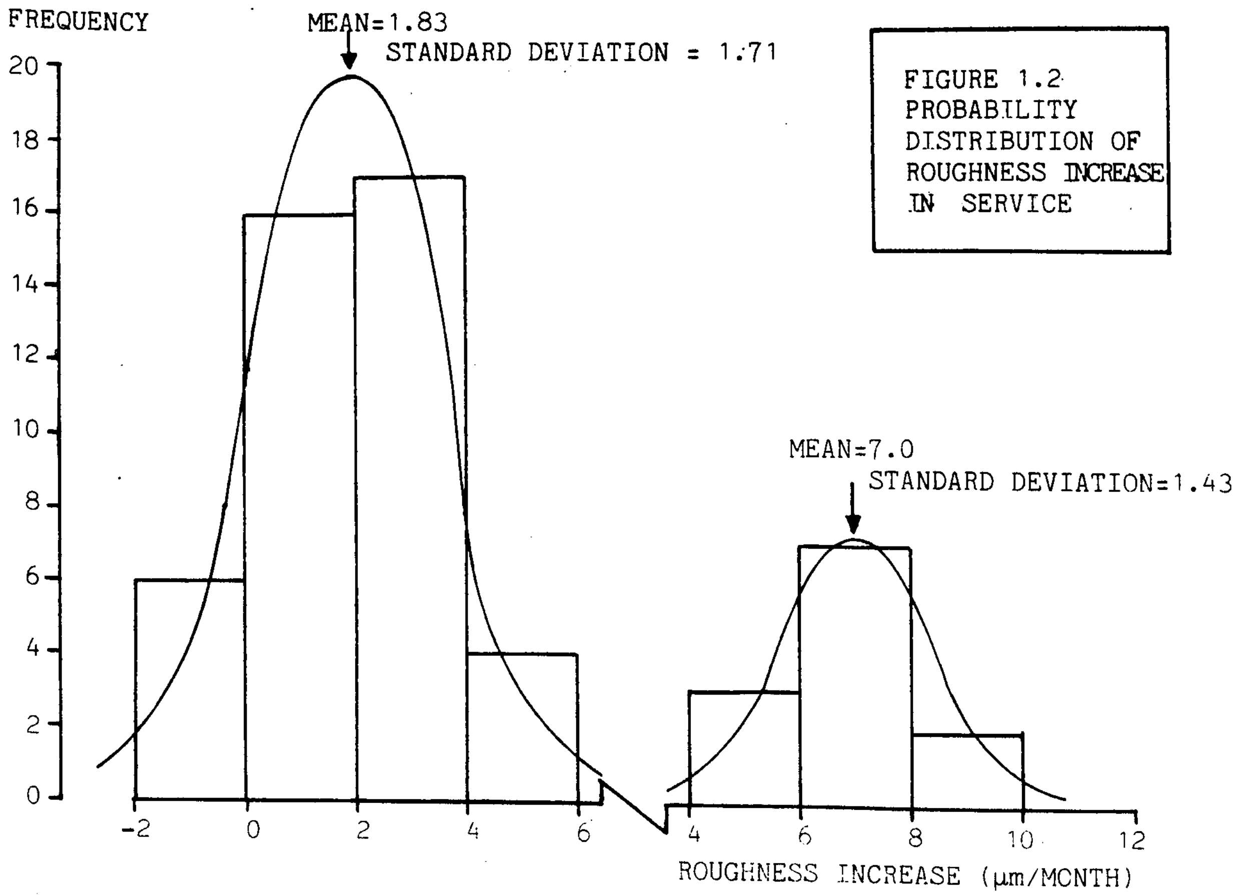


Table (B-2) in Appendix B gives a breakdown of the results for the 44 drydocking surveys in terms of ship type, roughness at indocking, roughness at outdocking and change in roughness.

The changes in roughness as a result of the drydocking procedure have been plotted against indocking roughness in Figure (1.3).

A mean line has been fitted to the data by linear regression. The equation for this regression line is:

$$\underline{\text{CHANGE} = -0.094 \times (\text{INDOCKING AHR}) + 37} \qquad (\mu m)$$

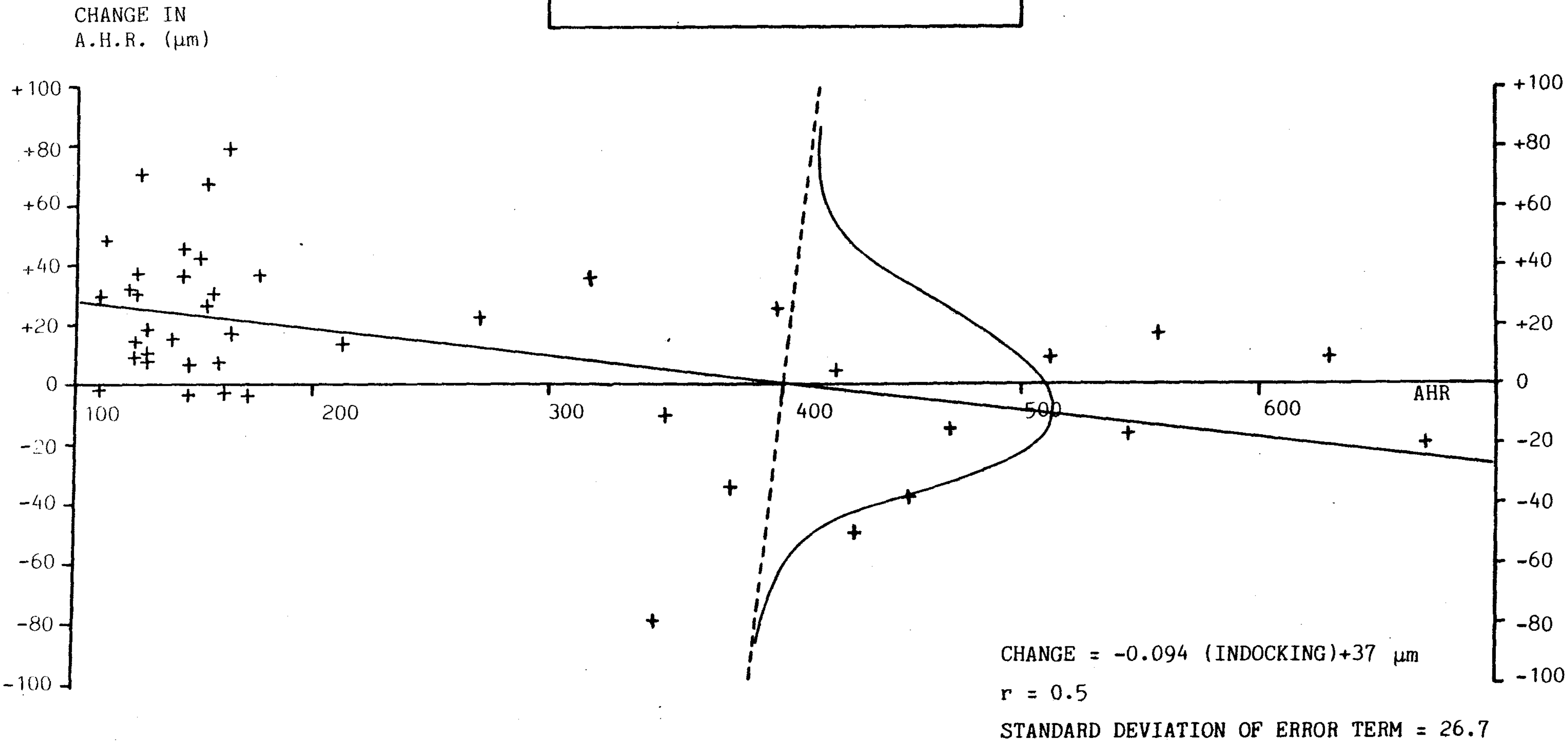
with a correlation coefficient r = 0.5

The value of r confirms that there is a correlation between the indocking roughness and the roughness-increase in drydock. However, a value of 0.5 represents a weak correlation, and the error term will be correspondingly large. Based on the assumption that the error term is normally distributed about the mean line, then the error distribution can be superimposed on the mean line as shown in Figure (1.3). This is one particular method of representing the relationship between 2 variables x and y which are partly correlated:

$$\underline{y = ax + b + e}$$

The error term e will be represented by a probability distribution function and will be calculated on each occasion with the use of random number sampling techniques.

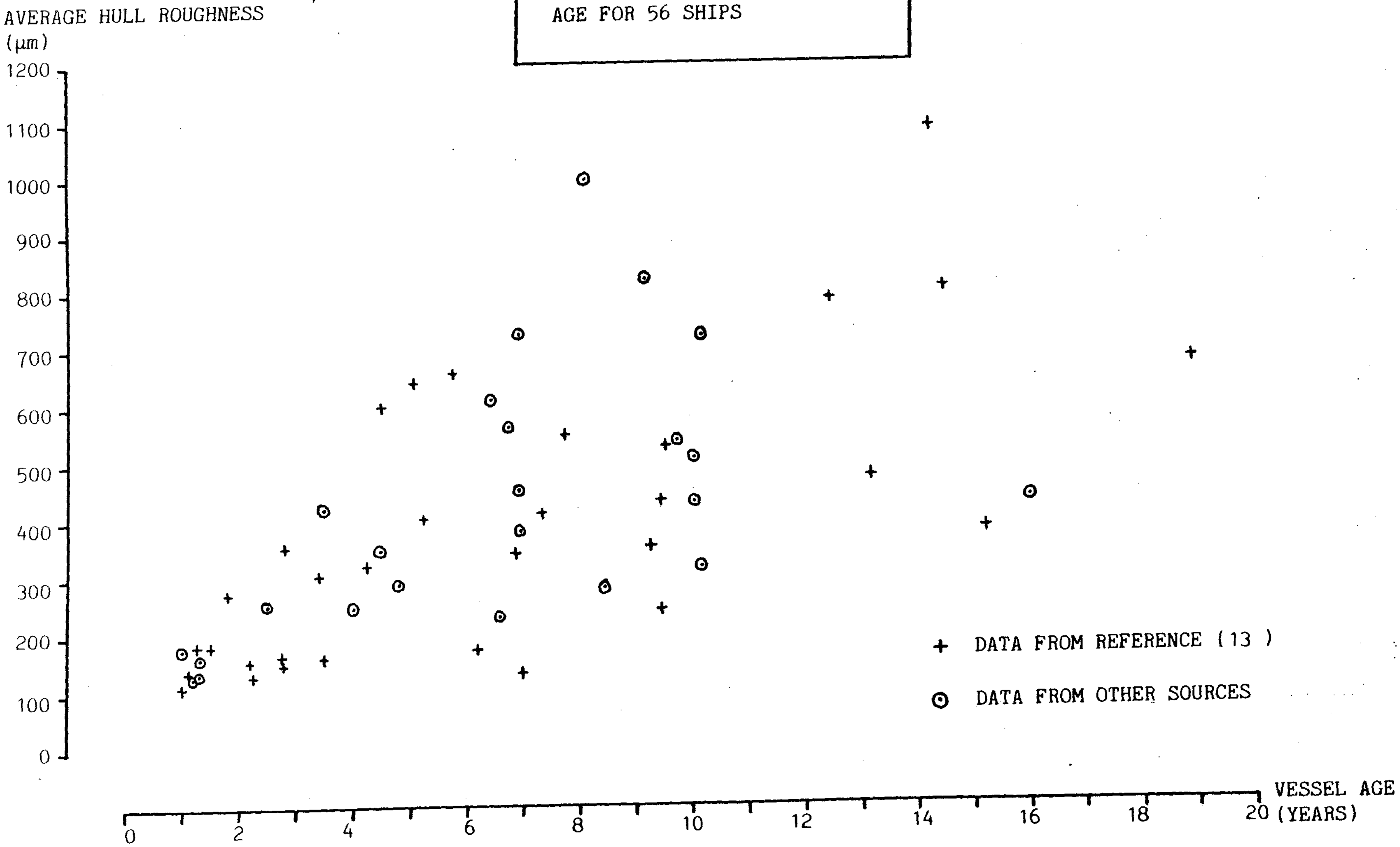
FIGURE (1.3)
CHANGE IN AVERAGE HULL ROUGHNESS
BETWEEN INDOCKING AND OUTDOCKING
FOR 44 SHIPS (EXCLUDING REBLASTS)



1.2.2.3 CHANGES IN ROUGHNESS IN SERVICE

A total of 56 roughness surveys have been obtained for 56 different ships covering a wide range of ship types and age groups. All vessels had been coated with conventional paint systems (i.e. excluding re-activating and self polishing paints), and none of the vessels had been totally re-blasted. The sample has partly been obtained from Reference (13) with supplementary information obtained from other sources. A description of ship type, age and average roughness is provided in Table (B-3) of Appendix B, and roughness values against age are plotted in Figure (1.4). The scatter in Figure (1.4) is large, and it is not possible to draw any conclusions from this basic plot of roughness against age, apart from the estimation of some trend lines. As discussed earlier, the roughness of a vessel at a particular age is made up of three separate components which are additive; (1) New Ship Roughness, (2) Change in Roughness during Drydockings and (3) Change in Roughness in Service. The first two components have been quantified in earlier sections, while the component due to changes in roughness in service is more difficult to obtain. The principal difficulty is that in order to obtain a reliable set of values for the increase in service, a large number of ships will have to be followed over a long time period. Reference (13) reports on measurements on a small number of vessels at repeat drydockings during a three year study, but the data sample is too small for conclusions to be drawn with any degree of confidence. As a result it was decided to follow a different approach by separating out the component represented by average increase in service per unit time from the present sample on the basis of the information already obtained about new ship roughness and change in roughness during drydocking.

FIGURE (1.4)
AVERAGE HULL ROUGHNESS VS.
AGE FOR 56 SHIPS



In addition to the age of the 56 vessels, this calculation procedure also required a knowledge of the number of outdockings each vessel had completed. For the vessels where the normal drydocking interval is unknown, an estimate of 12 months for passenger vessels and 18 months for other types have been used. An iterative calculation routine was employed for finding the average monthly change in roughness subject to the following conditions:

(1) New ship roughness = 123 μm

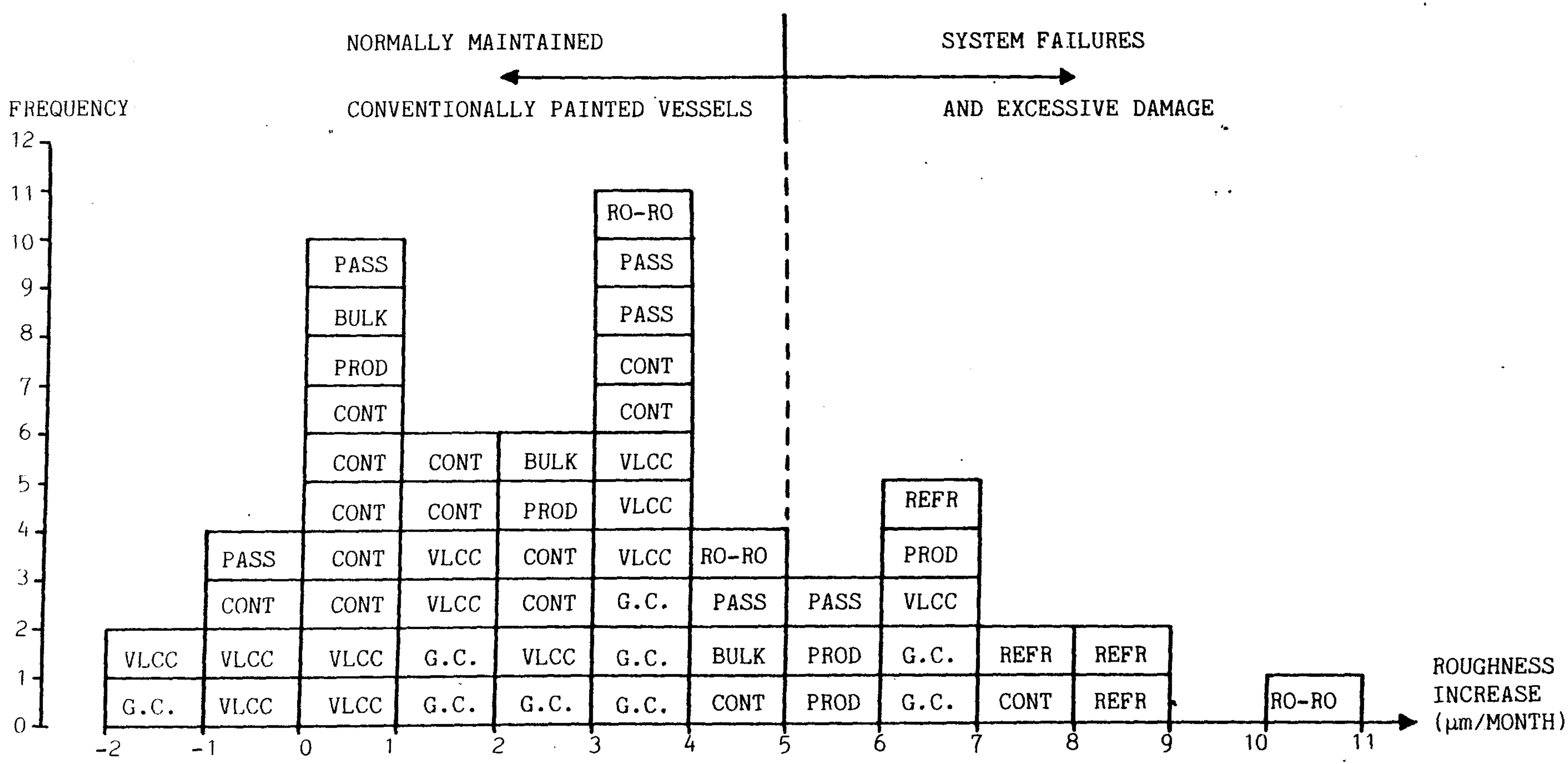
(2) Change in roughness in drydock = 0.094 (INDOCKING AHR) + 37

The results are plotted in the form of a histogram in Figure (1.5). The reason for the requirement of independent surveys, i.e. not including successive surveys for the same ship, now becomes quite clear. The roughness in year n is strongly correlated to the roughness in year n-1, and as a result the calculated average monthly rates of hull roughness increase in service are also strongly correlated. Consequently, the calculation of a mean value and a standard deviation for the purpose of obtaining a probability distribution function for the occurence of various rates of roughness increase is meaningless, unless all individual data points in the sample are independent.

Examination of the histogram of rates of roughness increase in service (Figure 1.5) brings out the following points:

(1) There are negative values of roughness increase. This follows as a result of the two constraints imposed with respect to new ship roughness and roughness increase in drydock. Some of the vessels will have a new roughness less than 123 μm and a

FIGURE (1.5)
ROUGHNESS INCREASE IN SERVICE FOR 56 SHIPS COATED WITH CONVENTIONAL PAINT SYSTEMS AND EXCLUDING REBLASTS



roughness increase in drydock less than that predicted from (2) above. As a consequence the average rate of roughness increase in service will appear as negative. This will not produce any errors later in the later economic calculations, provided the distribution of roughness increase in service is always used in combination with the assumed value of new ship roughness and the equation for roughness increase in drydock.

(2) The histogram indicates 3 different populations; less than 2 μm per month, between 2 and 5 μm per month and greater than 5 μm per month. The history of the vessels representing the values greater than 5 μm per month was examined more closely,and it was found that nearly all the 13 vessels in this group had been subject to some form of paint system failure or excessive damage. The remaining two groups could, to a certain extent, be identified by vessel type with mostly container vessels and VLCC's in the group less than 2 μm per month and general cargo, drybulk, passenger and ro-ro vessels between 2 and 5 μm per month. The principal reason for the difference between these two particular groups is due to the extent of mechanical damage experienced by the coating system.

Statistically, however, it was difficult to justify a separation of the two groups, and it was decided to let all data points less than 5 μm per month remain within one single group representing normal conventional maintenance for all ship types, but excluding paint system failures and excessive damage, which is represented by the second group of 5 μm per month and above. The two groups are plotted in Figure (1.2).

Group 1 - Normal conventional maintenance, but excluding paint system failures and excessive damage

Mean increase in service = 1.85 μm per month

Standard deviation = 1.71 μm per month

Group 2 - Paint system failures and excessive damage

Mean increase in service = 6.99 μm per month

Standard deviation = 1.43 μm per month.

Based upon the assumptiom that the two population groups follow a normal distribution, the probability distribution function of the occurance of various degrees of roughness increase in service has been superimposed on top of the histograms in Figure (1.2).

The above data analysis has been based on the assumption that the increase in roughness in service with time is linear and can be represented by a single average figure.

If the monthly increase was actually increasing with time as the vessel becomes older and rougher, then the average value would also increase with time, and the older vessels in the data sample would be expected to have a greater average monthly increase in roughness compared with the newer ships. This hypothesis was tested, but no correlation was found between average monthly increase in roughness in service and the age of the vessel. As a result the assumption of linearity has been maintained throughout.

1.2.3 METHODS OF ESTIMATING THE RELATIONSHIP BETWEEN ROUGHNESS AND DRAG

The relationship between roughness and drag is fundamental to the economic evaluation of hull maintenance strategies. Without a detailed knowledge of this relationship, the penalties associated with various degrees of hull roughness may not be estimated, and the basis for an economic analysis is drastically reduced. Three different methods are available for estimating the relationship between surface roughness and resistance for ships:

(1) Model to ship correlation analysis.

(2) Ship trials and in-service performance monitoring.

(3) Differential or integral prediction methods for the calculation of turbulent skin friction.

All three methods are associated with various degrees of error, and no single method is therefore expected to produce the required answers to a high degree of accuracy. Possibly the best evaluation procedure is to examine each method in turn and subsequently combine the individual results to obtain a "best estimate" of the required relationship between roughness and drag.

The objective of this section is to follow this suggested procedure and take a look at the available results with each method, and in addition present the results of a piece of new experimental work in support of a proposed relationship between average hull roughness and added resistance.

1.2.3.1 MODEL TO SHIP CORRELATION ANALYSIS

A number of standard procedures have been developed for the extrapolation of speed and power characteristics from model to full scale. On a worldwide basis the methods suggested by Hughes and by the International Towing Tank Conference (ITTC) are the two most commonly used procedures, but the original Froude method is also still in use by some establishments. The basic principle behind all model to full scale extrapolation methods is that the total resistance coefficient may be divided into two components; one part due to viscous effects and a second non-viscous part called the wave making resistance which is the sum of pressure components in the direction of motion resulting from the surface wave system created by the vessel motion through the water.

Hence: $C_T = C_V + C_R$

It is almost universally accepted that C_R is identical for model and ship at the same Froude number, and the viscous component C_V may be calculated for both ship and model from a basic friction or correlation line. Froude assumed C_V was entirely due to skin friction and could be calculated from the resistance characteristics of an equivalent flat plane of the same length and wetted surface area. In practice the viscous component of the resistance is greater than the value obtained from the two dimensional flat plane analogy. This is principally due to the effects of increased speed around a three dimensional body resulting in a pressure gradient, and an additional pressure resistance of viscous origin due to the development of the boundary layer along the length of the ship. On the basis of extensive tests with flat planes Hughes introduced a friction line for two dimensional flow and a form factor method for subsequent extrapolation to three dimensional ships. This is different from the ITTC 1957 correlation line, which is not intended as a basic friction line, and includes an average correction for three dimensional form. Application of the ITTC 1957 line by various establishments has demonstrated that an average correction for three dimensional form is inadequate, and additional form factors are now almost universally applied. Hence the total resistance coefficient may be written:

$$C_T = (1 + k)\ C_F + C_R + C_{AIR}$$

Extrapolation from model to ship using the above formula gives the total resistance coefficient in calm weather conditions for a hydraulically smooth hull. An allowance for hull roughness and length, ΔC_F, is normally added to give the total resistance coefficient for the new ship trial conditions. If an estimate of ΔC_F is not included in the formula for C_T, and the total resistance is measured on trial, then the true correlation allowance for hull roughness may be estimated from the expression:

$$\Delta C_F = R_{TRIAL}/\tfrac{1}{2}\rho SV^2 - C_T$$

Assuming that there is no scale effect on thrust deduction fraction t, then the total resistance may be calculated from thrust measurements on trial. Hence:

$$R_{TRIAL} = (1 - t)\ T_{TRIAL}$$

If only torque and therefore power measurements are available then the total ship resistance may be estimated from the expression:

$$R_{TRIAL} = P_D \times \eta_D \times \frac{1}{V}$$

Unlike the thrust deduction fraction, the quasi propulsive coefficient is associated with significant scale effects and the extrapolation from model to full scale is only approximate. In practice, this method is therefore considered to be an unsuitable method of estimating the total ship resistance for the purpose of calculating the correlation allowance for hull roughness.

As part of the co-operative ship-model correlation programme between the British Ship Research Association (BSRA) and the National Maritime Institute (NMI), an analysis was carried out by Bowden and Davidson on 26 ships for which model tests, thrust measurements on trial and hull roughness measurements were available, [Reference (15)]. The analysis was performed using the above described method, but initially ignoring the form factor correction (1 + k). This work was followed by a new analysis using three different form factor methods from which a mean line was calculated, [Reference (16)]. Unfortunately the sample had to be reduced from the original 26 to only 10 ships in this second analysis due to problems in obtaining the required data for the form factor calculations. The mean correlation line was presented as:

$$\Delta C_F \times 10^3 = 105\left(\frac{h}{L}\right)^{1/3} - 0.64$$

with a correlation coefficient of approximately 0.6.

This formula was adopted by the ITTC in 1978 for the calculation of the hull roughness allowance in the standard model to ship extrapolation procedure.

Some comments are required about this mean line as a predictor for the added resistance associated with various degrees of hull roughness. Although a clear trend may be observed in the original data in Reference (15), the correlation coefficient is low, resulting in a correspondingly low confidence in the mean line. In addition, the data sample is only 10 single screw ships ranging in length from 157 to 267 metres with values of average hull roughness from 144 to 211 µm. Extrapolation of the formula to higher values of hull roughness is therefore in principle invalid. It may also be observed from Reference (16) that the reduction in the data sample alone from 26 to 10 ships resulted in a change in the slope of the mean line from a value of 205 to 148 with a further reduction to 105 as a result of the inclusion of a form factor method in the analysis. The various slopes observed with the three different form factors also range between values of 77 and 124, indicating that in addition to sample selection, the mean line is also highly dependent on the form factor method applied in the analysis.

In the proceedings of the 1978 and 1981 ITTC, [References (17) and (18)], some doubts were raised about the validity of the assumption that there is no scale effect on thrust deduction fraction. It has also been suggested that the form factor is not independent of Reynold's number. Both suggestions give support to the argument that the correlation allowance for hull roughness predicted by the ITTC formula also includes other correlation factors. Furthermore, the correlation formula provides an equal amount of information about the effect of length as the effect of hull roughness. It has been suggested that this considerable dependence on length may be due to an overestimate of the viscous resistance at higher Reynold's numbers when using the ITTC model to ship correlation line, [Reference (18)].

Satisfactory answers to the above problems have not yet been found. In addition, the problem exists that all roughness measurements are based on a single height parameter. The description of a three dimensional surface topography in terms of a single height parameter is clearly unsatisfactory, and an improved correlation may be found if a texture parameter is also introduced. In view of the arguments presented more information is clearly required, and in the meantime the ITTC correlation formula for hull roughness should be used with extreme caution.

1.2.3.2 SHIP TRIALS AND IN-SERVICE PERFORMANCE MONITORING

Ship trials are performed over a measured distance in the best possible controlled environment. This is different from the in-service performance monitoring which is a process of continuous measurement in the actual operating condition and subject to all the normal variations experienced in terms of draught, trim, weather and ocean currents. Both methods have the same objective of obtaining information about the speed and power to fuel consumption performance of the vessel. Ship trials are normally performed only for new ships prior to delivery and are rarely repeated due to the high cost of taking a vessel out of service for a period of one or two days specifically for this purpose. In-service performance monitoring is therefore in most cases the only method of obtaining information about the performance of a vessel after some time in service.

The continuous monitoring of speed and power performance of a vessel for the assessment of hull roughness serves no useful purpose in the short term because the change in roughness from one month to the next will be of a magnitude so small that a difference in performance can not be measured. A monitoring program relating to hull roughness only will therefore be more of an experimental type over a limited period of time where the operator has one of the following objectives:

(1) To measure the performance of an existing vessel in service and relate this to its new ship performance on trial.

(2) To measure the performance of a vessel before and after having undertaken a particular hull treatment, for example, a complete reblast with renewal of the paint system.

(3) To measure the difference in performance between two sisterships with a known difference in bottom condition.

Included in the program will also be the measurement of hull roughness so that differences in performance can be related directly to differences in hull roughness. Thrust measurements are desirable, but since no scale effects are involved they are not of the same importance as when the correlation allowance for hull roughness is estimated by comparing the trial performance with the model results extrapolated to full scale, provided a satisfactory assessment is made for the propeller surface condition. The changes in propulsive efficiency due to increase in hull roughness are examined in Section 1.3.1.

The shortcomings of the ITTC correlation formula have already been discussed in the previous section. Faced with this uncertain basis for the economic modelling of hull maintenance strategies, in particular the limited range of validity and the fact that additional correlation factors are included in the formula, a search for more information was initiated. This search finally resulted in an opportunity being created for the undertaking of a full scale performance monitoring experiment on two container sisterships with a known difference in hull surface condition. A complete report on the experimental procedure and the anlaysis of results is provided in Appendix A, and only a summary of the results is given here in this section.

The first set of experiments was carried out almost simultaneously on both sisterships over a two month period with satisfactory results obtained in the performance monitoring part of the experiment. Unfortunately, the underwater roughness survey technique was at the time not yet perfected, and the survey obtained for one of the vessels was incomplete. A decision was subsequently made to repeat the experiment after the vessels had completed another 12 months in service. The second experiment had two objectives; the first to confirm the results obtained 12 months earlier and secondly to enable new roughness surveys to be carried out and the differences in hull roughness to be related to the measured differenced in speed and power performance. Both objectives were achieved and the statistical analysis of the experimental results confirmed with 99.8% confidence that a true difference in performance existed between the two vessels. In percentage terms the difference in speed and power performance between the two vessels was found in the first experiment to be between 10.7% and 11.6%, depending on the method of analysis used, and in the second experiment the corresponding range was found to be between 9.9% and 12.3%. Hull roughness measurements in connection with the second experiment gave a value of 147 μm AHR for the vessel with the best speed-power performance and 452 μm AHR for the other. The relationship between hull roughness and added resistance was evaluated from the basic linear relationship:

$$10^3 \times \Delta C_F = a \left(\frac{h}{L}\right)^{1/3} + b$$

For the purpose of evaluating differences in resistance between various roughness levels only the gradient 'a' had to be determined. From the results of the second monitoring experiment the gradient 'a' was calculated to take a value in the range between 54.3 and 67.3. This is substantially less than the value of 105 used in the ITTC correlation formula for hull roughness, suggesting that only approximately 60% of the value predicted by the formula is due to hull roughness and the remaining 40% due to other correlation factors. Further information is required before an entirely new formula may be proposed, but the present experiment has provided important information about the validity of extrapolation to higher roughness values as well as an assessment of the part of the complete prediction by the ITTC correlation formula expected to be due to roughness alone.

1.2.3.3 INTEGRAL PREDICTION METHODS FOR THE CALCULATION OF TURBULENT SKIN FRICTION

Boundary layer prediction methods may be subdivided into two principal groups, depending on the type of governing equations employed:

(1) Differential Methods

(2) Integral Methods

The differential methods involve partial differential equations while the integral methods employ sets of ordinary differential equations only. A comprehensive introduction to the various methods available is provided by Reynolds in the introduction to Reference (19). Common to all methods is that they attempt to predict certain mean properties of the fluid flow over a solid boundary. Some more advanced differential methods also have the additional objective of providing predictions of local turbulence structures in the boundary layer.

The equations forming the basis for differential as well as integral methods are derived from the Navier-Stokes equations where the velocity field is subdivided into mean and fluctuating components. Differential methods require additional information about the local turbulent shear stress, also called the "Reynolds Stress". This is, in practice, best obtained from actual measurements. For the purpose of calculating the effects of hull roughness upon boundary layer development the inclusion of detailed assumptions about the local structure of turbulence is an unnecessary additional complication. Furthermore, the effects of surface roughness are more readily incorporated into the equations for the integral method compared with the differential method. From the practical applications point of view differential methods also have the added disadvantage of being more sensitive to the starting values for the stepwise calculation procedure. Hitherto, the differential methods have found the widest application in problems where a more detailed knowledge of the local boundary layer structure is required, expecially over the aft end of the hull. In conclusion, integral methods are considered to be the best choice for the problem of calculating the effects of surface roughness upon the boundary layer, and only this method will be discussed in more detail here.

In order to eliminate the need for information about the local turbulent shear stress, the first step used in connection with the integral method is to integrate the streamwise mean momentum equation across the boundary layer to give the momentum integral equation. This equation is common for all integral prediction methods in use today. Subject to the exact method used, one or two additional differential equations are required. The second differential equation may take one of three principal forms based respectively upon energy integral, entrainment or moment of momentum. The first is obtained by multiplying the mean momentum equation by the local velocity in the boundary layer prior to integration. After integration the mean energy integral may be expressd as the "dissipation integral", which represents the transfer of energy between the mean field and the turbulence in an infinitely thin slice of the boundary layer. Alternatively, the principle of entrainment introduced by Head in Reference (20) may be used. This is defined as the process by which the boundary layer acquires additional turbulent fluid. Finally, the moment of momentum integral equation may be obtained by multiplying the mean momentum equation by the distance from the wall prior to integration. Common to all three methods of formulating the second differential equation is that local or global information about the turbulent shear stress is required. In the energy integral method the global information about the turbulence may take the form of a relationship between the dissipation integral and the properties of the mean field or the entrainment rate and the mean field respectively. The question of whether a third differential equation is required depends on which form the second equation takes, and in particular, the method of solution used.

One particular method which is used later in Chapter 3 and Appendix A was developed by Medhurst, [References (21) and (22)], and is based upon the principle of entrainment using the equation derived by Head from global assumptions about turbulence. The third differential equation used in this method is obtained by differentiating the Wall equation as first suggested by Lewkowicz and Horlock in Reference (23). The Wall equation is that developed by Hama [Reference (24)], but modified to accommodate Coles Wake Strength parameter outside the logarithmic region of the boundary layer. In the Wall equation the effect of surface roughness is described by the roughness function representing a downward shift in the velocity profile. Grigson in Reference (25) has shown that ship surfaces are similar to other irregularly rough surfaces and a modified form of the Colebrook-White roughness function, [Reference (26)], due to Musker, Lewkowicz and Preston, [Reference (27)], is therefore substituted in the Wall equation. The method of solution used is to integrate the three simultaneous equations along the paths of streamlines, a method originated by Hamlin and Sedat, [Reference (28)]. Each streamline can then be treated as if generated about the centreline axis of a body of revolution, and the potential flow may be calculated using the method of Young and Owen in Reference (29). In addition, the effects of streamline convergence are also taken into account. The integration is started near the bow and local values of the frictional coefficient are calculated as the stepwise process of integration in a streamwise direction towards the aft end of the hull. The total frictional coefficient is obtained simply by adding the local coefficients of friction after weighting by surface area and local velocity.

Although primarily developed for the purpose of integrating the boundary layer over three dimensional ship forms, the method may also be applied to two dimensional airfoil shapes, for example, the sections of a propeller blade. In this case the calculation may be simplified by the assumption of no streamline convergence and zero cross flow.

The principal advantage of all types of integral prediction methods is that they present a simple procedure for the modelling of the effects of surface roughness, where the roughness function may be derived by laboratory experiments prior to full scale extrapolation using the prediction method.

1.3 THE EXTENT OF HULL FOULING INVESTIGATED FOR TWO PRINCIPAL ANTIFOULING SYSTEMS

The problems associated with hull fouling are almost universally recognised, but only occasionally included in economic calculations of hull maintenance procedures. The principal reasons for this exclusion are the difficulties in obtaining reliable measures of the fouling-free periods with conventional antifouling coatings, the rate of fouling growth after initial settlement has taken place and the speed loss or power penalty associated with different degrees of fouling intensity. It is generally accepted that the macroscopic fouling of ships' hulls is disastrous in economic terms, but irrespective of the economic consequences, shipowners and operators frequently allow their vessels to become fouled. The objective of this short term investigation is to quantify the extent of fouling experienced by some principal ocean going ship types after various periods of time in service.

The two principal types of fouling are weeds and barnacles. Weeds are plants and are therefore dependent on light, whilst barnacles are classified as animals for which the presence of light is unimportant. This fundamental difference between weeds and barnacles is a determining factor for the location on the underwater hull where they are most commonly found. The settlement of fouling may be prevented by the release of biocides at the surface - water interface. Different types of biocide are required for different types of fouling, and antifouling paints are therefore nearly always loaded with a mixture of biocides. For each type of fouling the presence of a minimum concentration of biocide is required to prevent settlement. This minimum amount is directly related to a measure of the rate of release of biocide from the antifouling paint called the critical leaching rate. The new advanced self-polishing antifoulings have been formulated so as to have a constant leaching rate greater than the critical rate to provide continuous protection against fouling settlement. Conventional "continuous contact" antifoulings are characterised by an exponential leaching rate with time, and in order to obtain an acceptable effective lifetime a wasteful amount of biocide has to be released initially. There is also a physical limit to the amount of biocide which may be close-packed into the binder material resulting in a continuous release of biocide above the critical rate for a period of only 15 to 20 months in service.

When the leaching rate becomes less than the critical rate sufficient conditions exist for successful settlement of fouling, but this does not necessarily imply that fouling settlement will actually take place. The settlement of fouling first of all depends on the availability of spores or larvae, which is controlled by underwater temperature, location, tidal conditions and the season of the year. In addition, the time spent stationary or at slow speed is also of importance. For some vessels operating on a constant route in a particular part of the world it may be possible to identify most of these variables, but for the majority of the ocean going vessels, routes and distances vary to the extent that no such identification and quantification is possible. Despite this argument a need still exists for a quantitative measure of the number of vessels entering drydock in a fouled condition, irrespective of voyage characteristics, to serve the purpose of demonstrating that the hull fouling problem cannot be completely ignored.

In response to the above requirement a survey has been carried out based upon information supplied by "International DATAPLAN", [Reference (30)]. This is a large data bank of information collected for the purpose of a complete monitoring of ship painting, fouling and overall hull coating system condition. The data are collected by inspectors in drydock and subsequently processed and stored on a central computer for immediate access. Fouling data are initially collected on the basis of an assessment of the percentage extent of the fouling, the type of fouling and whether the fouling is localised or scattered. This information is transformed into a "fouling index" using Table (1.1). The fouling index is intended to serve as a measure of the coating performance with scattered fouling considered to represent a more serious failure of the coating system than localised fouling, and heavy animal fouling more serious than slime, weed or light to moderate animal fouling. Although the fouling index is not directly comparable with the percentage extent of

TABLE (1.1)

International "DATAPLAN" Fouling Ratings

EXTENT OF FOULING (%)		FOULING INDEX	
		A	B
0.3	S	0	0
	L	0	0
1	S	1	3
	L	0	1
3	S	3	4.5
	L	1	3
5	S	5	7.5
	L	3	4.5
10	L	10	15
	S	5	7.5
15	L	15	22.5
	S	10	15
25		25	40
33		33	50
50		50	100
75		100	100
90		100	100
100		100	100

A = All slime, all weed or light, moderate animal

B = Heavy animal

C = Scattered

D = Localised

fouling settlement, it provides a similar type of information. In any case, little is known about the difference in added resistance between weed and animal fouling or between localised and scattered fouling settlement.

Two different paint systems have been investigated to provide a comparison:

(1) High performance conventional antifouling (Chlorinated Rubber)

(2) Advanced self-polishing system (Organo-tin Copolymer)

Only the same ship types have been investigated for each paint system to ensure a statistically valid comparison. Large ocean going vessels with world wide trading patterns are of principal interest, and the following ship types were selected for the analysis:

(1) Crude oil carriers greater than 200,000 tdw

(2) Bulk carriers greater than 25,000 tdw

(3) Container vessels greater than 10,000 tdw

The extent of fouling has been subdivided into three groups; a fouling index between 0 and 5 representing clean or negligible amounts of fouling, 6 to 25 representing light to moderate fouling settlements and a fouling index greater than 25 representing heavy fouling.

Results for the high performance conventional system are shown in Table (1.2). The figures clearly indicate that a significant number of vessels enter drydock in a fouled condition, even after a relatively short period

TABLE (1.2) FOULING ANALYSIS FOR CHLORINATED RUBBER HIGH PERFORMANCE CONVENTIONAL ANTIFOULING SYSTEM

VESSEL TYPE	DOCKINGL INTERVAL (MONTHS)	PERCENTAGE DISTRIBUTION OF FOULING INDEX				SAMPLE
		0 - 5	⩾ 6	6 - 25	⩾ 25	
VLCC	7-12	50%	50%	17%	33%	6
	13-18	20%	80%	20%	60%	15
	19-24	47%	53%	18%	35%	17
	25-30	15%	85%	33%	52%	27
BULK CARRIER	7-12	62%	38%	11%	27%	26
	13-18	50%	50%	24%	26%	42
	19-24	38%	62%	28%	34%	61
	25-30	50%	50%	25%	25%	40
CON-TAINER VESSEL	7-12	82%	18%	18%	0%	17
	13-18	55%	45%	18%	27%	22
	19-24	53%	47%	20%	27%	15
	25-30	70%	30%	10%	20%	10

TABLE (1.3) DISTRIBUTION OF DRYDOCKING INTERVAL

DOCKING INTERVAL (MONTHS)	PERCENTAGE DISTRIBUTION OF SHIP TYPE		
	VLCC	BULK CARRIER	CONTAINER VESSEL
13-18	21%	28%	46%
19-24	24%	40%	31%
25-30	38%	26%	21%
above 30	18%	6%	2%

TABLE (1.4) COMBINED FOULING ANALYSIS FOR VLCC's, BULK CARRIERS AND CONTAINER VESSELS COATED WITH HIGH PERFORMANCE CONVENTIONAL SYSTEM

DOCKING INTERVAL (MONTHS)	PERCENTAGE DISTRIBUTION OF FOULING INDEX				SAMPLE
	0 - 5	≥ 6	6 - 25	≥ 26	
7 - 12	67%	33%	14%	19%	49
13 - 18	46%	54%	22%	32%	79
19 - 24	42%	58%	25%	33%	93
25 - 30	40%	60%	26%	34%	77

TABLE (1.5) COMBINED FOULING ANALYSIS FOR VLCC's, BULK CARRIERS AND CONTAINER VESSELS COATED WITH ADVANCED SELF POLISHING SYSTEM

DOCKING INTERVAL (MONTHS)	PERCENTAGE DISTRIBUTION OF FOULING INDEX				SAMPLE
	0 - 5	≥ 6	6 - 25	≥ 26	
7 - 12	100%	0	0	0	6
13 - 18	88%	12%	12%	0	8
19 - 24	93%	7%	7%	0	15
25 - 30	62%	38%	38%	0	21

TABLE (1.6) COMBINED FOULING ANALYSIS FOR ALL SHIP TYPES COATED WITH ADVANCED SELF POLISHING SYSTEM

DOCKING INTERVAL (MONTHS)	PERCENTAGE DISTRIBUTION OF FOULING INDEX				SAMPLE
	0 - 5	≥6	6 - 25	≥26	
7 - 12	88%	12%	2%	9%	43
13 - 18	85%	15%	15%	0	34
19 - 24	93%	7%	2%	4%	46
25 - 30	67%	33%	31%	2%	45

in service. A noticeable difference in the extent of fouling between the individual ship types may also be observed; fast container vessels clearly experience less fouling problems than crude oil carriers operating at slow speeds. In Table (1.4) the results for the three ship types have been combined to give a set of average values for large ocean-going vessels.

The data sample for the self polishing paint system is insufficient to allow the individual calculation of results for each ship type and only a combined table is presented (Table 1.5). From Table (1.4) approximately one third of all vessels coated with a high performance conventional antifouling paint enter drydock in a heavily fouled condition, irrespective of the time out of dock. The comparative figure for the advanced self polishing system is zero. A signif'cant amount of light to moderate fouling is found on vessels coated with self polishing paints after a period of 25 to 30 months in service. This is principally due to polish-through of the antifouling system leaving unprotected areas of anticorrosive paint. The analysis for vessels coated with self polishing paints was also repeated for a larger, non-selective sample including smaller vessels spending a larger proportion of their time in port and therefore with a greater chance of becoming fouled. As shown in Table (1.6) some more fouling is observed, but the number of fouled vessels remains significantly less than for the group coated with high performance conventional antifouling paints.

1.3.1 AN INVESTIGATION INTO THE EFFECTS OF HULL ROUGHNESS AND FOULING UPON PROPULSION EFFICIENCY

1.3.1.1 INTRODUCTION

The standard approach to estimating the speed or power penalty associated with a given increase in average hull roughness has hitherto been to make use of a simplified formula, for example, the ITTC correlation formula for hull roughness, or lately more advanced prediction methods based upon integration of the boundary layer of the ship, to transform roughness values into increments to the frictional coefficient. The changes in frictional coefficient are subsequently transformed into corresponding power increments or speed-loss values, maintaining a constant propulsive coefficient. The basis of constant propulsive efficiency has been assumed for simplicity without being substantiated by an investigation into how the various components of the total propulsive coefficient are affected by the presence of roughness and fouling. Consequently, the purpose of this Section is to examine the limited amount of information available, and from this study present a recommendation as to whether the continued use of a constant propulsive coefficient is justified, and if not, which form a correction procedure should take.

1.3.1.2 GENERAL REVIEW OF THE PROBLEM

The total propulsive efficiency is the product of 3 separate efficiency components:

$$\eta_D = \eta_O \times \eta_H \times \eta_R$$

where: η_D = propulsive efficiency

η_O = open water efficiency

η_H = hull efficiency

η_R = relative rotative efficiency

It is a well known fact that with an externally added resistance, the power required to maintain speed will have to be increased if thrust deduction and wake fraction remain unaffected, and this increase in loading on the propeller will result in a decrease in efficiency. Since the hull efficiency η_H is simply defined as the ratio:

$$\frac{(1 - t)}{(1 - w)}$$

where t = thrust deduction fraction
and w = wake fraction (Taylor),

and since η_R generally remains unaffected by changes in the surrounding conditions, the change in the propulsive efficiency with an added external resistance depends only on the resulting change in the open water efficiency.

Hull roughness results in an added resistance, but because this is due to an increase in the boundary layer thickness and frictional resisitance coefficient, the wake fraction will also be affected by the increase in the boundary layer thickness, and the previous assumptions are no longer valid.

This statement has been supported by two separate pieces of experimental work carried out in Japan. In an attempt to clarify the problem and quantify the effects of fouling upon propulsive performance, the Japanese Shipbuilding Research Association carried out systematic full scale measurements on a small vessel in clean, as well as a series of fouled conditions, [Reference (31)]. The tests were made on a small size training vessel of 20 m overall length with a displacement of 79 tonnes and a wetted surface area of 95 square metres. Principal conclusions to be drawn from this work are first of all that the nominal and effective wake fraction both experience a substantial increase with increasing severity of fouling, and secondly that thrust deduction remains constant even under conditions of heavy fouling. At the same time torque measurements show that the required additional power remains proportional to the change in frictional coefficient of resistance over the complete range of conditions, indicating a constant value for the quasi propulsive coefficient. Having already pointed out the increase in hull efficiency as a result of the change in wake fraction, this constant value of the propulsive efficiency can only be explained by a corresponding reduction in the open water efficiency component due to the added resistance.

Tokunaga, [Reference (32)], carried out tests on a model which was artificially roughened with a wire mesh and investigated the effect of this roughness upon some of the self-propulsion factors. He concluded that the thrust deduction and the relative rotative efficiency remained unaffected by the presence of the roughness. The wake fraction, however, experienced a substantial change with an increase of 31% in the effective wake between the smooth and the fully rough condition, and with a similar change in the nominal wake of 16% . The scaling of model test results with an artificially roughnened surface to a full size ship with "real" roughness is surrounded with uncertainty, and especially because Tokunaga does not give values for the absolute change in the coefficient of friction between the smooth and the fully rough condition, the task in this case becomes quite impossible. Despite the fact that the absolute measurements of changes in wake fraction due to the presence of hull roughness cannot be extrapolated from model to full scale, there are some important conclusions to be drawn from this work. First of all that the thrust deduction and relative rotative efficiency remain unaffected by the presence of roughness, and secondly that the wake fraction does experience an increase with increasing roughness, the full scale magnitude of which will have to be determined by other methods. The changes in the total propulsive efficiency due to the presence of hull roughness can therefore be determined by examining the effect upon the open water efficiency due to the increased loading and the changes in the hull efficiency due to the increase in wake fraction.

1.3.1.3 CHANGES IN WAKE FRACTION DUE TO HULL ROUGHNESS AND FOULING

The effect of hull roughness upon the effective wake fraction w_T has been examined by means of the ITTC 1978 standard procedure for determining the scale effects upon effective wake. This is essentially the method proposed by Sasajima and Tanaka in 1966, [Reference (33)].

Consider an effective wake fraction w_T. This can be divided into 2 principal parts: .

$$w_T = w_P + w_F$$

where: w_P = potential part of wake

w_F = frictional or viscous part of the wake

The potential part of the wake is generally assumed to be independent of Reynold's number. Sasajima suggested that w_P is proportional to the potential part of the thrust deduction, t_P, and since the scale effect upon the frictional part of t is small, the relationship $w_P = t/\alpha$ is approximately true. Sasajima put the constant α tentatively as unity, and hence the frictional part of the wake for the model can be expressed as $w_{FM} = w_{TM} - t$. Although the frictional part of the wake is also a function of a number of variables, it is primarily a function of the coefficient of viscous resistance C_V. Consequently for full form ships where the features of the wake distribution are fairly similar the scale effect can be expressed as a function of the ratio $\left(\frac{C_{VS}}{C_{VM}}\right)$. Sasajima therefore suggested the following expression for the full scale wake:

$$w_{TS} = t + (w_{TM} - t)\left(\frac{C_{VS}}{C_{VM}}\right)$$

The 1978 ITTC adopted this method of wake-scaling in a slightly modified form as:

$$w_{TS} = (t+0.04) + (w_{TM} - t - 0.04)\left(\frac{C_{VS}}{C_{VM}}\right)$$

where $C_{VS} = (1+k)\ C_{FS} + \Delta C_F$

and where ΔC_F is calculated from the correlation formula for hull roughness.

Based on this formula which assumes proportionality between the frictional part of the wake and the viscous coefficient of resistance, it is possible to provide estimates of the effective wake of the ship for various increments ΔC_F to the total viscous coefficient of resistance C_{VS}.

As a part of the continuing work of the Ship Performance Group, a ship performance monitoring exercise was carried out under the supervision of the author on a 350,000 tdw tanker, for which a comprehensive set of model test results were also available. This presented an ideal opportunity to test the ITTC formula for wake-scaling and the assumptions built into it.

For the laden condition, the corrected ship speed through the water with corresponding power and RPM measurements for calm weather condition were found to be:

Speed:	14.605 knots
Power:	30450 shp (metric) or 29840 dhp (metric)
RPM:	84.00

Using the propeller as a dynamometer it is possible on the basis of the measured power and RPM and the propeller characteristics to find the speed of advance of the propeller, which combined with the measured speed of the ship through the water will yield a value of the mean effective wake of the ship.

For a propeller diameter of 9200 mm, the torque coefficient for the given power and RPM condition was calculated to be $K_Q = 0.01885$.

Entering the propeller characteristics at this value yielded an advance coefficient:

$$J = 0.382$$

which gives a speed of advance $V_A = 9.56$ knots

hence: $1 - w_{TS} = 0.654$

hence: The Effective Wake of the Ship is $w_{TS} = 0.346$

Now, turning to the model experiments in laden condition and the nearest comparable speed which is 15.0 knots.

The effective wake of the model for this condition is:

$$w_{TM} = 0.418$$

and corresponding thrust deduction fraction:

$$t = 0.218$$

the total viscous coefficient of resistance for the model is:

$$C_{VM} = 3.8114 \times 10^{-3}$$

and the corresponding value for the ship:

$$C_{VS} = 1.9625 \times 10^{-3}$$

This value for the ship includes correlation allowances and also an allowance for hull roughness and is intended to correspond to a new smooth ship tested under ideal weather conditions. Although it is not specified in the tank report, a "new smooth" condition is generally accepted as 125 μm average hull roughness (AHR). The surface roughness on the vessel under consideration was measured prior to the performance monitoring experiment, and was found to have a value of 305 μm AHR. The increment to C_{VS} due to hull roughness above the new condition assumed in the tank test report then becomes:

$\Delta(\Delta C_F)_1 = 0.260 \times 10^{-3}$ according to the full ITTC correlation formula for hull roughness

and $\Delta(\Delta C_F)_2 = 0.156 \times 10^{-3}$ when taking only 60 percent of the value predicted by the ITTC formula for hull roughness, which is more in line with current thinking as reported in the current Chapter and References (10) and (11).

Using the ITTC 1978 adopted method of wake-scaling, the effective wake of the ship now becomes:

$$w_{TS} = (0.218+0.04) + (0.418-0.218-0.04) \times (2.2224/3.8114) = \underline{0.351}$$

based upon $\Delta(\Delta C_F)_1$ as increment to C_{VS}

and

$$w_{TS} = (0.218+0.04) + (0.418-0.218-0.04) \times (2.1185/3.8114) = \underline{0.347}$$

based upon $\Delta(\Delta C_F)_2$ as increment to C_{VS}.

These results are remarkably good and demonstrate that the ITTC adopted method of scaling the effective wake, with its built-in assumptions about the frictional and potential part of the wake, works well for the full-form ship under consideration.

Increasing the values of hull roughness, h, and therefore the increments $\Delta(\Delta C_F)$ to the viscous coefficient of resistance C_{VS}, and assuming that the proportionality between the frictional part of the wake, w_F, and the viscous coefficient of resistance, C_V, remain true, then a table of values of effective wake against average hull roughness can be constructed.

Two sets of calculations have been made, one giving the full ITTC correlation formula for hull roughness and the second based upon 60 percent of the values predicted by this formula.

TABLE (1.7) CHANGES IN EFFECTIVE WAKE WITH INCREASING HULL ROUGHNESS

AVERAGE HULL ROUGHNESS (h) x 10^6 m	PERCENTAGE INCREASE IN SHIP RESISTANCE	EFFECTIVE WAKE w_{TS} BASED UPON ΔC_F FROM FULL ITTC	EFFECTIVE WAKE w_{TS} BASED UPON ΔC_F FROM 60% OF ITTC
125	0.0	0.340	0.340
200	6.0	0.346	0.344
300	11.3	0.351	0.347
400	16.6	0.355	0.350
500	20.6	0.359	0.353
750	28.7	0.366	0.358
1000	35.1	0.372	0.362
2000	53.4	0.389	0.373

1.3.1.4 CHANGES IN OPEN WATER EFFICIENCY DUE TO HULL ROUGHNESS AND FOULING

A brief description was given earlier of the effect upon the open water efficiency part of the total propulsive efficiency by the introduction of an added external resistance to the ship. This relationship between added resistance, ΔR, and change in open water efficiency, $\Delta \eta_o$, can be obtained for any propeller using a simple method introduced by van Berlekom in

Reference (34).

Assuming constant thrust deduction, we can write:

$$R_o \propto T_o$$

and $$(R_o + \Delta R) \propto (T_o + \Delta T)$$

and therefore $$\frac{R_o + \Delta R}{R_o} = \frac{T_o + \Delta T}{T_o} \qquad (1)$$

The thrust can also be evaluated from the thrust coefficient:

$$T_o = \left(\frac{K_T}{J^2}\right)_o \rho D^2 V^2$$

and

$$T_o + \Delta T = \left(\frac{K_T}{J^2}\right) \rho D^2 V^2$$

and therefore $$\frac{T_o + \Delta T}{T_o} = \frac{(K_T/J^2)_1}{(K_T/J^2)_o} \qquad (2)$$

Combining (1) and (2) gives:

$$\frac{R_o + \Delta R}{R_o} = \frac{(K_T/J^2)_1}{(K_T/J^2)_o} \qquad (3)$$

R = ship resistance

T = thrust

K_T = thrust coefficient

J = advance coefficient

ρ = water density

D = propeller diameter

V_A = speed of advance

The advance coefficient for the standard operating condition of the vessel is now calculated and corresponding values of K_T and η_o taken from the open water characteristics to serve as basis for the calculations.

Having found the J value for the operating condition a series of J values less than the basis value are chosen and corresponding values of K_T and η_o are taken from the open water diagram. For each of these J values $(K_T/J^2)_1 / (K_T/J^2)_o$ can now be calculated, as well as the change in the open water efficiency $\Delta \eta_o$, and a diagram of:

$$1 + \frac{\Delta R}{R_o} \text{ against } \frac{1}{1 + \frac{\Delta \eta_o}{\eta_o}} \text{ can be constructed}$$

Figure (1.6) gives curves of added resistance against change in open water efficiency for a number of ship types, including the VLCC under consideration. The vessels are all single screw with 4 bladed propellers and of full form block coefficients between 0.75 and 0.84.

One word of warning in the practical use of these diagrams is required. The curve is only valid around the particular operating point (and therefore J value) for which it has been constructed. If speed is reduced the advance coefficient will increase, and this will generally decrease the slope of the curve.

1.3.1.5 THE COMBINED EFFECT OF HULL ROUGHNESS UPON PROPULSIVE EFFICIENCY

Having considered the separate effect of hull roughness as an added resistance upon the effective wake fraction and the open water efficiency, it is their combined effect upon the total propulsive efficiency which is of principal interest. This evaluation does not necessarily have to include roughness values. It will simply be sufficient to provide a range of increments $\Delta(\Delta C_F)$ to the viscous coefficient of resistance and calculate the resultant effect upon the effective wake fraction w_{TS} and the open water efficiency η_o.

Using the relationship for the total propulsive coefficient:

$$\underline{\eta_D = \eta_o \times \eta_H \times \eta_R}$$

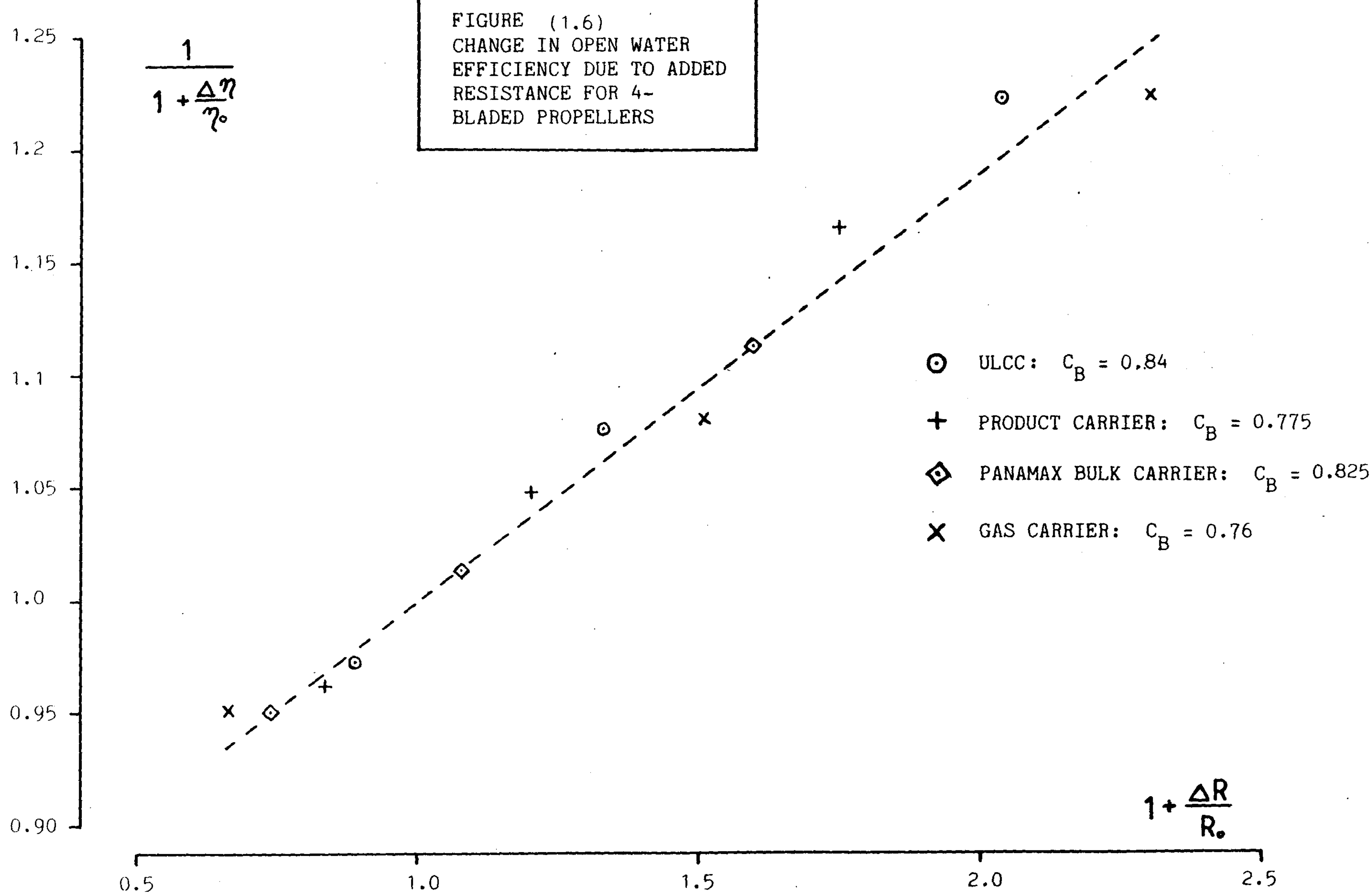


FIGURE (1.6)
CHANGE IN OPEN WATER EFFICIENCY DUE TO ADDED RESISTANCE FOR 4-BLADED PROPELLERS

or

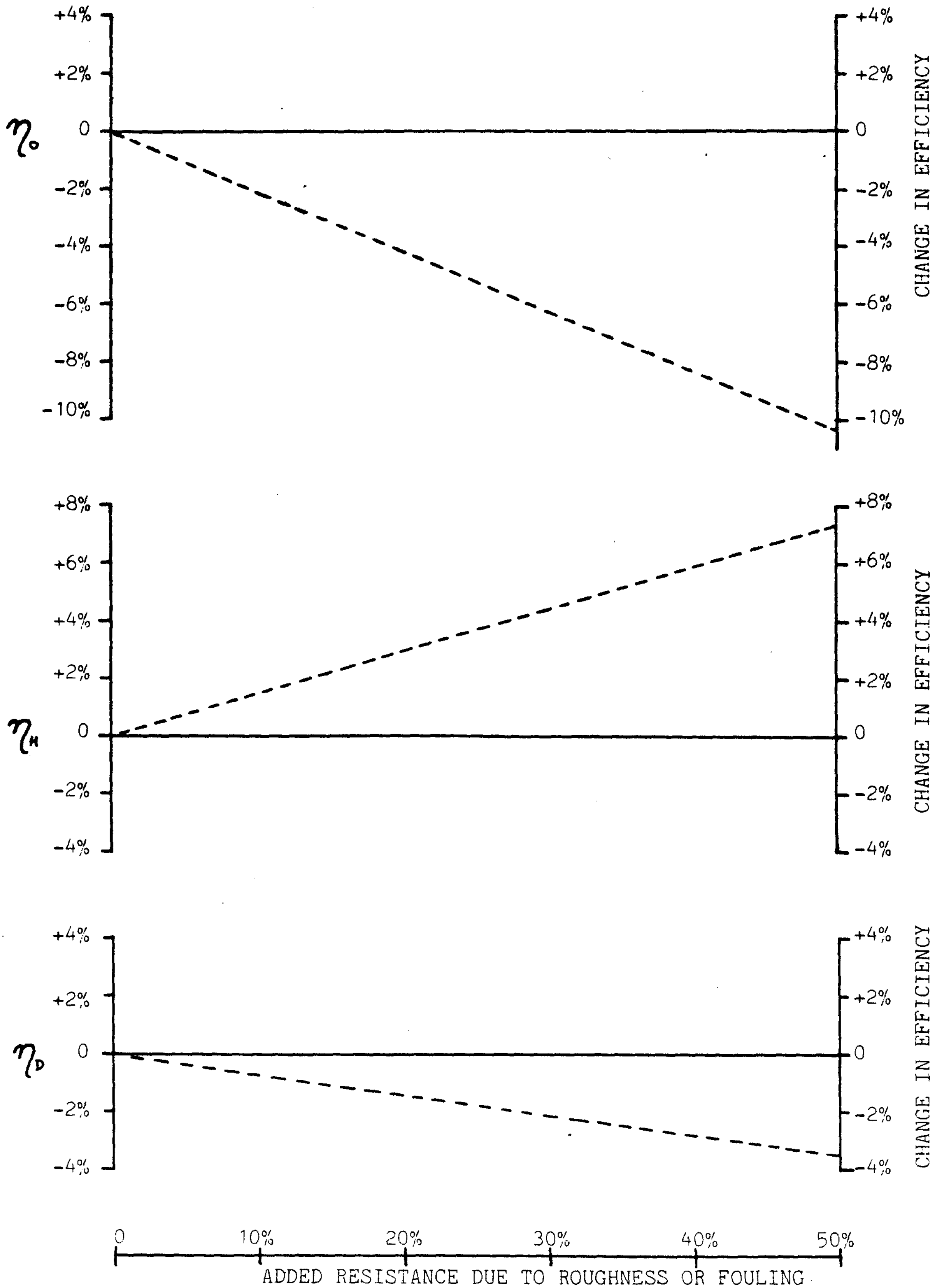
$$\eta_D = \eta_o \times \frac{(1-t)}{(1-w)} \times \eta_R \quad \text{where } \eta_R \text{ and t remain constant}$$

this resultant effect can be calculated.

Figure (1.7) illustrates the percentage changes in η_o and η_H and their combined effect upon the total propulsive efficiency η_D for a range of added resistance up to 50%.

The curves clearly demonstrate that although there is a significant decrease in the open water efficiency due to the increased loading on the propeller, the hull efficiency is increasing simultaneously due to the increase in the effective wake, and the net change in the efficiency is therefore minimal. For example, at an added resistance of 20% the change in total propulsive coefficient is just less than -1%. This small effect upon propulsive efficiency therefore does not justify the development of a correction procedure, and it is recommended that the quasi propulsive coefficient is kept constant in all practical calculations of added resistance due to hull roughness and fouling.

FIGURE (1.7)
THE EFFECT OF HULL ROUGHNESS UPON OPEN WATER, HULL AND PROPULSIVE EFFICIENCY FOR 4-BLADED PROPELLER FITTED TO A LARGE TANKER



CHAPTER 2

DESCRIPTION OF A PROPOSED DETERMINISTIC TECHNO-ECONOMIC MODEL

2.1 INTRODUCTORY REMARKS ON MODELS AND MODEL-BUILDING

The fundamental arguments behind the development of a techno-economic model of ship operation, with particular reference to hull and propeller maintenance have been presented in the introductory section. The purpose of the present Chapter is to describe the design philosophy behind the proposed deterministic model. This includes a general description as well as more detailed explanations of the working logic in principal modelling routines. Having introduced the word "model", it will first be necessary to present some of the basic concepts and definitions in model-building.

Models are simplified representations of real systems used to study or control the behaviour of the real system under various sets of conditions. Three principal types of model can be identified: (1) physical or geometric models; (2) analog models; and (3) symbolic models. It is the latter type which is implied in the present use of the word "model". A symbolic model consists of decision paths and mathematical equations giving a valid representation of the real system. Symbolic models can again be sub-divided into four groups depending on the nature of the variables and the relationship between them, and the method of solution. A model is said to be deterministic if the variables take single values only and the relationships between them are fixed. Alternatively, if at least one variable is random, then the model is called stochastic. Solution procedures for both model types can be analytical or numerical. The first describes a method in which the solution is obtained directly in the form of a mathematical formula. When analytical solutions are unobtainable, numerical solution procedures can be used instead. This is an approximate method in which numerical values are assigned to variables and parameters in the model. Numerical solution procedures which involve modelling the behaviour of real systems over extended periods of time are referred to as simulation models.

The advantages of using symbolic models for the analysis of the behaviour of real systems are discussed by Fishman in Reference (35) and can be summarised as follows:

1. Improve system understanding, including bringing into perspective the need for detail.

2. Expedite the analysis.

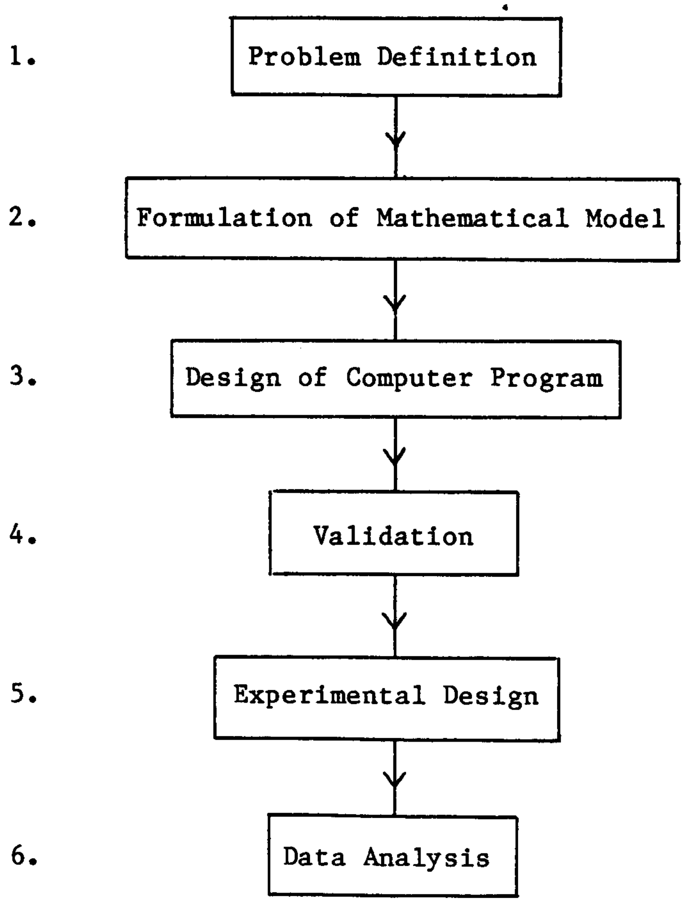
3. Provide a facility for testing the value of system modifications.

4. Permit more variation and easier manipulation than a direct study of the real system.

5. Higher cost effectiveness than experimenting with the real system.

The task of obtaining a valid representation of the real problem is critical in model building and will nearly always be related to the amount of detail included in the model. Detail is again given as a trade-off between accuracy and efficiency in the solution process. Improved detail usually also means more variables and therefore greater complexity, making the process of solution more difficult. A further consequence of improved detail may also be a change from an analytical solution procedure to a numerical one based on simulation. This will mean that the generality of the direct analytical solution is lost and will probably also increase the cost of the solution since computers will have to be used. Computer simulation, on the other hand, offers a number of advantages. First of all the ability to compress or expand time and therefore allows the analyst to move with time to examine the model in almost any possible state. It also results in fewer restrictions on the format of the model, permitting the inclusion of more detail to give a better representation of the real system. An important part of the facility for improved detail is the superior ability of computer simulation methods to provide algorithms for the efficient handling of partial correlations between variables. Furthermore, simulation methods using computers allow the replication of experiments with selected changes in variables. This is of particular importance in the development of stochastic models, where prior knowledge is required about the effect individual variables have on the final results. Finally, clear advantages are offered by computers in the statistical analysis of results.

Having discussed some of the general principles behind model building with particular reference to simulation methods, the next step is to provide in more detail a description of the methology behind the development of simulation models. Naylor in Reference (36) suggests a procedure divided into 6 steps:



The first step of formulating the problem primarily consists of defining the objectives of the analysis in the form of questions to be answered and hypotheses to be tested. This part has already been dealt with in the general introduction prece ding Chapter 1. The formulation of the new mathematical model itself consists of selecting variables and defining the relationships between them. At the same time, consideration must be given to the complexity of the model and the amount of computer programming required. The complexity is clearly related to how well the model represents the real system in any given situation, and the type of experiments that are going to be performed with it. The third step of designing the computer program, can in simple terms, be explained as the assembly of objectives and the mathematical model into a formal structure recognisable by the computer, supported by routines for the handling of data input and output. Chapter 1 has already established some of the principal relationships in the mathematical model. The remaining parts of step 2 will be discussed in the following subsections of the present Chapter in connection with the design of the computer program.

2.2 A BASIC MODEL DEVELOPED FOR THE COMPARATIVE EVALUATION OF TWO ALTERNATIVE HULL AND PROPELLER MAINTENANCE STRATEGIES

2.2.1 THE OVERALL STRUCTURE OF THE PROPOSED DETERMINISTIC TECHNO-ECONOMIC MODEL

The principal objectives behind the development of the proposed techno-economic model have been defined as providing a facility for the evaluation of alternative hull and propeller maintenance strategies for different ship types in the complete commercial context of vessel operation. Investment in improved hull or propeller maintenance involves the expenditure of additional capital, with the expectation of achieving a corresponding improvement in economic performance over some future period of time. Based on the assumption that a minimum amount of maintenance always has to take place when a vessel goes into drydock, the economic calculations take the form of comparing one alternative maintenance strategy with another, and calculating the economic return on the incremental investment corresponding to the more expensive alternative. As a result the model has been designed around the specific task of comparing two clearly defined maintenance strategies for the same vessel over a period of time using the principles of discounted cash flow. Following the arguments presented in Chapter 1, the results are calculated using several different measures of merit, leaving the final choice in any given situation to the analyst.

The requirement that the model should be suitable for any particular ship type with any reasonable trading pattern resulted in the development of methods for operational simulation based on constant speed as well as constant power. When the latter mode of operation is used a number of commercial factors will have to be specified. This resulted in the subsequent decision to develop the program as a complete operational model including all principal financial variables, except for capital charges.

A computer program normally consists of a main section and a set of procedures or subroutines. Each procedure is designed to perform a particular task in the calculation process and is called either by the main program or by another procedure. The procedures in the proposed deterministic techno-economic model can be subdivided into six groups according to the tasks they perform.

1. Data Input and Output

2. Data Preparation

3. Operational Simulation

4. Decision Analysis

5. Hull and Propeller Maintenance Evaluations

6. Cash Flow Calculations

Figure (2.1) illustrates the complete subroutine hierachy with names of the actual procedures. The following sections will give a description of the principal procedures and the tasks they perform, concluding with a description of the main program itself. Data input and output and data preparation procedures are considered trivial and will not be discussed.

2.2.2 PROCEDURE "ROUNDTRIPS" FOR OPERATIONAL MODELLING AT CONSTANT POWER

The principal function of this procedure is to perform the operational modelling of a vessel over a fixed period of time at constant power setting. In the absence of factors relating to deterioration in engine plant performance, this is identical to the condition of constant fuel consumption per unit time. The penalty due to roughness and fouling of hull and propeller is consequently a reduction in speed, which results in fewer roundtrips completed in the operational year, and therefore a loss of income. On a roundtrip basis the fuel consumption will also increase

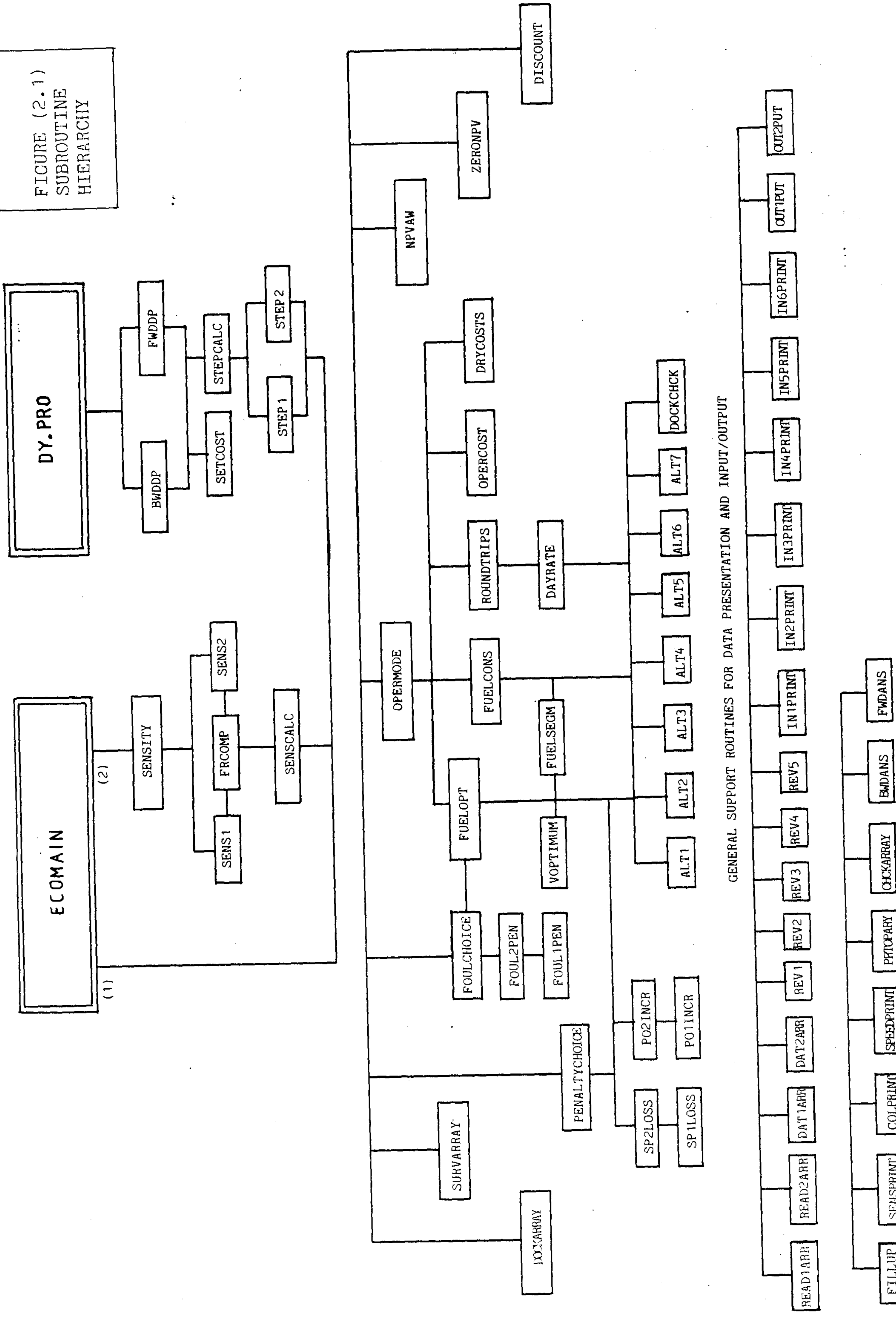


FIGURE (2.1) SUBROUTINE HIERARCHY

due to the longer time taken to complete each roundtrip voyage.

The speed-loss penalties due to roughness and fouling are supplied to the routine in the form of two dimensional arrays of dimension (N + 1) by 12. Each element contains the average speed penalty for the calendar month as identified by the array element numbering system where row number identifies the year and a column number the month of the year.

There are three basic sets of arrays containing speed-loss values supplied to the procedure, each set identified by the particular cause of the speed-loss. The first is the speedloss due to hull roughness as calculated by the procedures "SP1LOSS" and "SP2LOSS", secondly, speedloss due to fouling as calculated by procedures "FOUL1PEN" and "FOUL2PEN", and finally speedloss resulting from a loss in propulsion efficiency due to deterioration in blade surface condition, supplied to the program from an external datafile. In the case of hull roughness and fouling, individual arrays are supplied for the laden and the optional ballast or partly laden condition, where wetted surface areas and speed/power condition will be different.

The first step in the procedure is to combine the supplied arrays containing speed losses with the initial speed/power condition of the vessel to produce a final array of average operational speed for every month in the required period of calculation. This array serves as a basis for the operational modelling. The choice of this matrix framework for evaluating the speed/power characteristics at any given point in time was made primarily on the grounds of flexibility. With this fixed framework it is possible to combine a number of effects upon speed and power calculated separately by other procedures. It is also possible to include effects upon performance, which are calculated outside the program and simply read in as data items. The matrix structure also allows other factors affecting the speed/power performance to be added at a later stage with only minimal programming alterations, and without changing the logic structure of the operational routine in any way. The calendar month was selected as a unit for digitising the speed/power characteristics as a compromise between programming efficiency and accuracy of calculation. Only a very small improvement could be achieved by reducing the unit of time down to a week, or even a day, and at the same time the computing time required for program execution would increase to an unacceptable level when employing the procedure in the probabilistic cash flow simulation routine, which is explained in Chapter 4.

There are two potential sources of error with the use of this matrix of average speed/power characteristics on a monthly basis. The procedures for calculating speed/power characteristics according to the supplied hull maintenance scenarios have been designed so that the speed and power always correspond to the hull and propeller condition at the point of outdocking. With a totally flexible input of time in drydock and point of drydocking, this gives the possibility with short periods of time in drydock that the speed/power characteristics immediately after drydocking may also be applied to the final few days of the roundtrip prior to drydocking. Due to the procedure logic, in which the complete roundtrip is first modelled and subsequently checked against available time before the occurence of next drydocking or end of year condition, there is also a possbility of an "over-run" into the speed/power characteristics following the drydocking, if a new roundtrip is started immediately prior to a drydocking. The fractional roundtrip completed prior to drydocking is thus calculated partly on the basis of the speed/power characteristics after drydocking. This was found to introduce significant errors when there was a substantial change in hull condition taking place during drydocking. This problem was overcome by the use of procedures "DOCKCHCK" and "DAYRATE" calculating the exact point in time for every drydocking and maintaining a continuous check on the progress in time to prevent this "over-run" situation taking place.

The principle of first modelling a complete roundtrip voyage, and thereafter comparing the total time required for the roundtrip voyage with the time available before next drydocking or end of the year condition prior to accepting the complete or part roundtrip, was necessitated on the grounds that the penalties due to roughness and fouling are expressed in terms of speed-losses. The total time required, therefore, remains unknown until the roundtrip has been completed. When there is sufficient time available for the completion of a roundtrip the time, fuel consumption and roundtrip counters are incremented, and a new roundtrip is started. In the case when only a fractional roundtrip can be completed, one of six possible situations will occur. These are illustrated in Figure (2.6), and explained in Section (2.2.4). A completely new roundtrip is started after drydocking or end of year condition have been completed.

The roundtrip calculations are based upon a single representative voyage description giving the expected ratio between time spent at sea and time in port at the required speeds. Provision is made for part of this voyage to take place in part-laden or ballast condition at a different speed than that of the laden condition. As shown in the flow diagram, Figure (2.2), the laden part of the voyage is calculated first, followed by the optional ballast or part laden section and with the port days added at the end. In practice, the port time will be more evenly distributed over the roundtrip voyage, but the errors introduced by simply adding the total port time at the end of the voyage are insignificant, and no "cosmetic" change to provide a more flexible distribution of port time could be justified.

A simple power law, $P = k \times V^n$ and $SFC = j \cdot P^m$ with constant power exponents have been assumed to exist within a limited range for speed against power and power against fuel consumption, respectively. The same power exponent is used for the laden and the ballast condition, but the values of k are different as a result of P for the same V being different. For slow speed diesel main engines the exponent m is normally taken as zero. Upon completion of a roundtrip voyage these simplified formulae are used to calculate the main engine fuel consumption in laden and optional ballast condition. The auxiliary and port consumption are specified separately and added to the main engine consumption to give a total consumption figure for the roundtrip voyage. At the end of each operational year the fuel consumption for each roundtrip is added up to give a total amount for the year. Likewise, the number of fractional and complete roundtrips in the year are added up to give a total annual figure. These are the two principal results required from the operational modelling; the total number of roundtrips serving as basis for calculating the annual income, and the annual fuel consumption giving the magnitude of one of the principal items of expenditure.

FIGURE (2.2)
PROCEDURE
"ROUNDTRIPS"

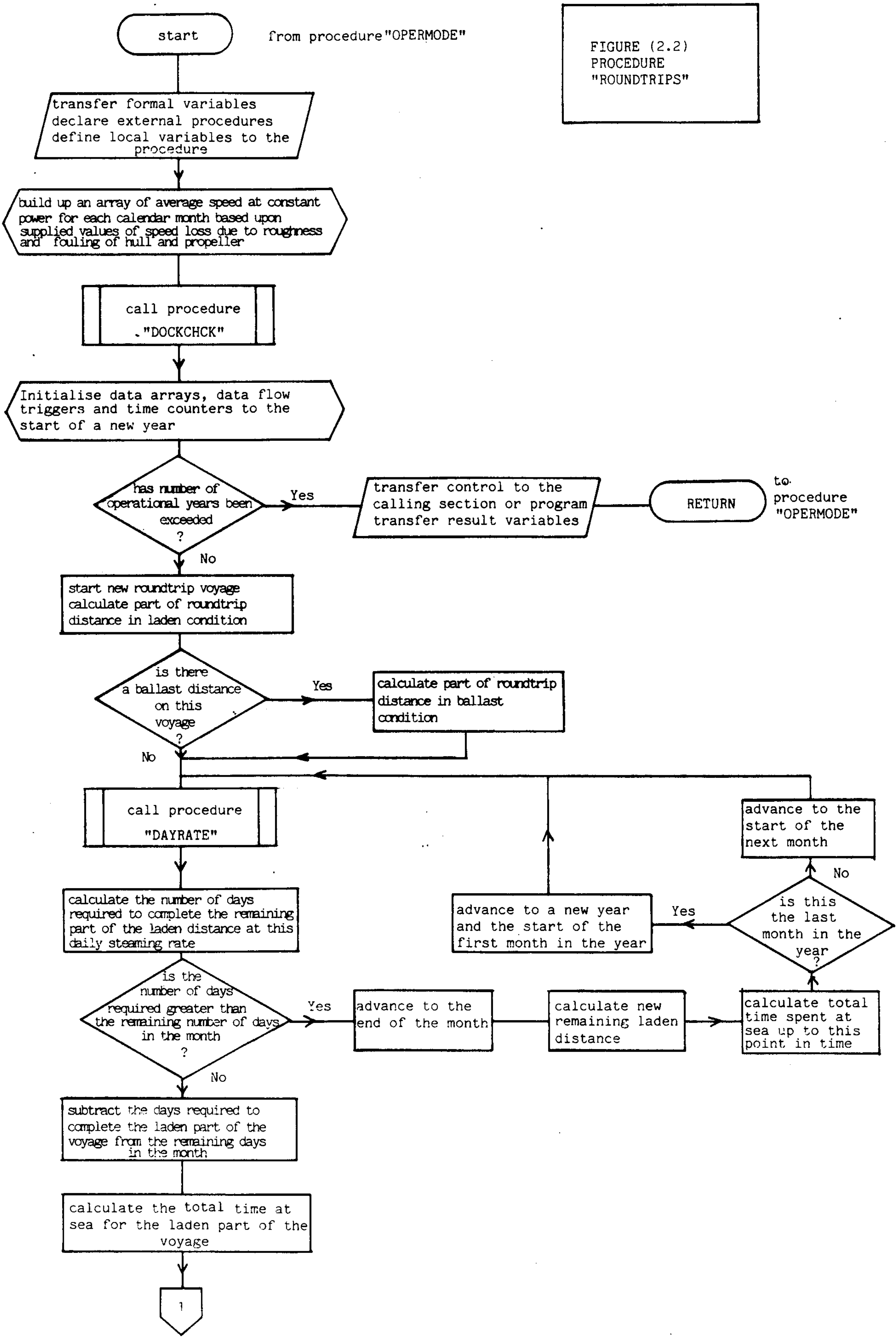


FIGURE (2.2) Contd.
PROCEDURE
"ROUNDTRIPS"

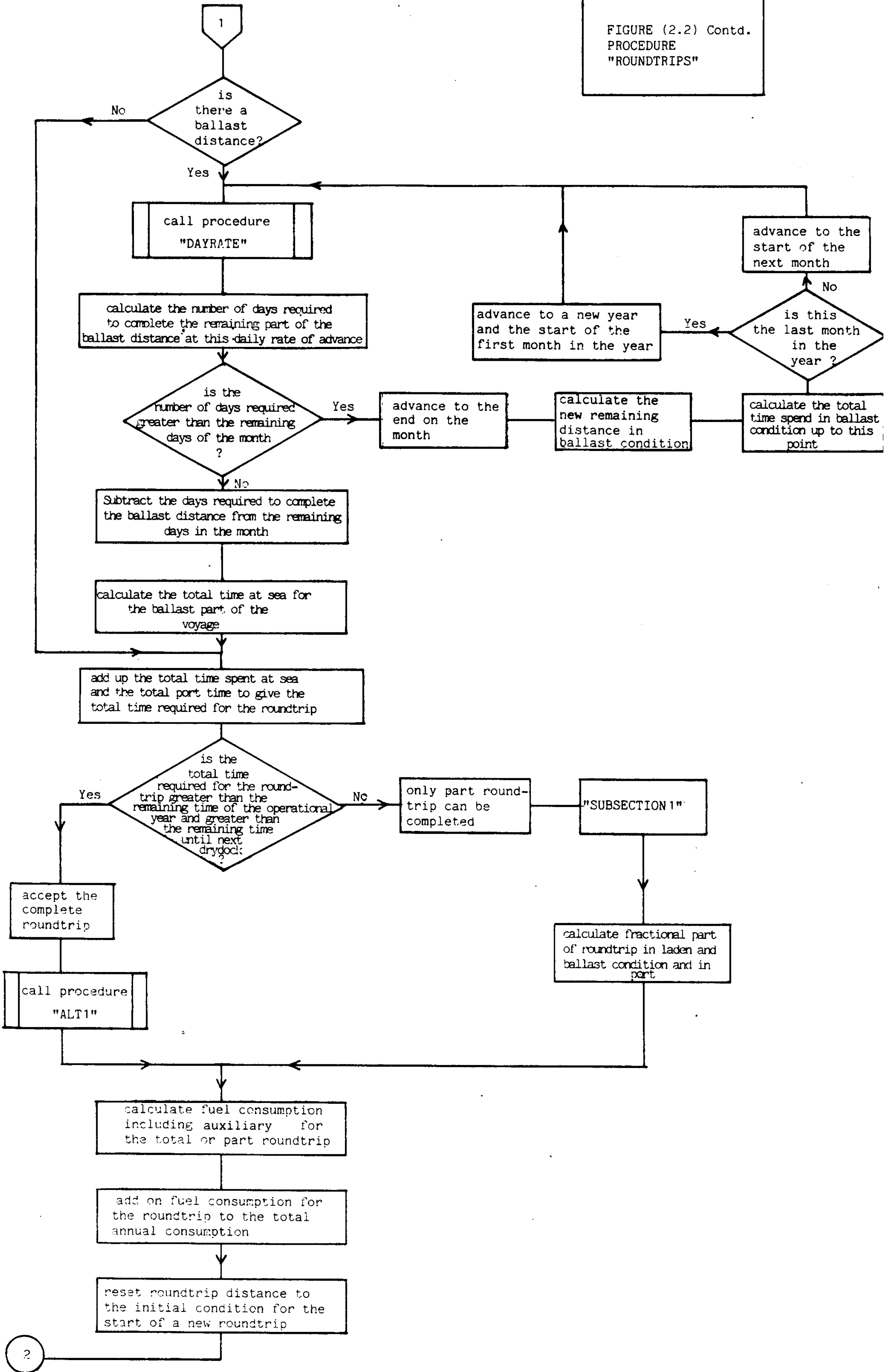
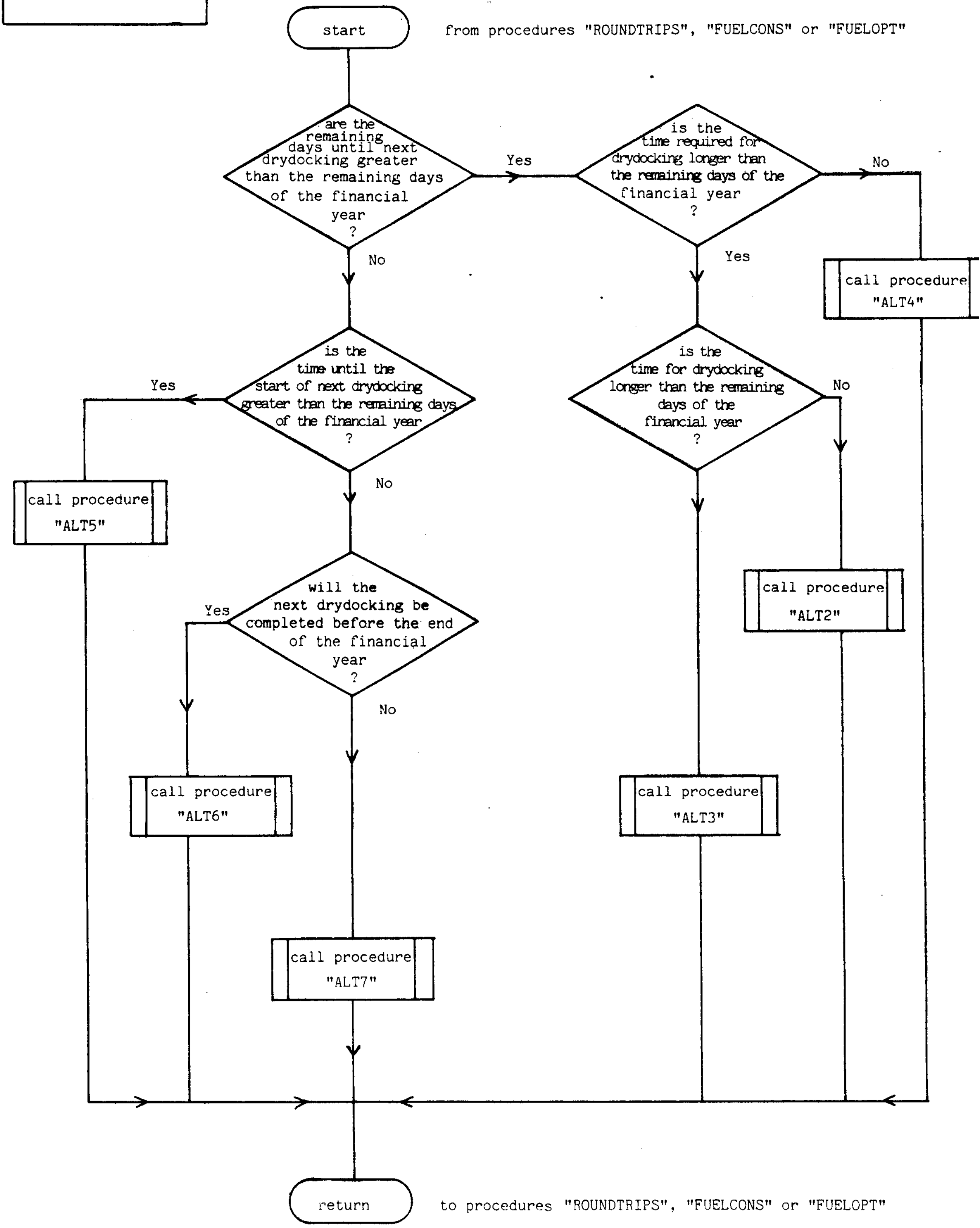


FIGURE (2.3)
"SUBSECTION1"



2.2.3 PROCEDURES "FUELCONS" AND FUELOPT FOR OPERATIONAL MODELLING AT CONSTANT SPEED

In the two procedures "FUELCONS" and "FUELOPT" constant speed is the basis for the operational modelling of the vessel. The penalty due to roughness and fouling of the hull and propeller is therefore an increased power requirement to maintain speed, with a resulting increase in fuel consumption. The two procedures have a logic structure very similar to "ROUNDTRIPS", where the penalty due to roughness and fouling is calculated as average monthly values, and the complete roundtrip is modelled in advance and examined against available time prior to acceptance. Only the points of difference are therefore described here. Increments to the power requirement at constant speed resulting from hull roughness are calculated by the procedures "PO1INCR" and "PO2INCR" and the corresponding increments due to fouling from the procedures "FOUL1PEN" and "FOUL2PEN". Power increments resulting from changes in propulsion efficiency are supplied from external sources as a datafile. With speed as a fixed parameter, the time required to complete each roundtrip is fixed, and the principal function of the procedure is to calculate the fuel consumption for each roundtrip on the basis of a power requirement which is changing from one month to the next. The simple relationship $SFC = j \times P^m$ is again assumed to be valid over the range of power values under consideration. Due to the use of a fixed matrix of average speed/power characteristics for each month and the advance modelling of roundtrip voyage results, potential sources of error similar to those in "ROUNDTRIPS" exist. The problem was overcome by the use of the procedure "DOCKCHCK" and by adding to the procedure "FUELSEGM" a program segment performing the same check on progress in time as "DAYRATE".

Although the two procedures "FUELCONS" and "FUELOPT" are both based upon constant speed operation and follow a similar logic structure, one or two major points of difference exist. In "FUELCONS" the speed in laden and optional ballast or part laden condition is fixed, and remain so over the total period of calculation. "FUELOPT", on the other hand, is linked with a procedure for optimum speed calculation, "VOPTIMUM", as shown in "SUBSECTION2". This procedure is called prior to the start of every roundtrip voyage and returns the optimum speed for the laden and the optional ballast part of the voyage. The roundtrip voyage is subsequently modelled at this optimum speed, after first having re-calculated the power penalties due to roughness and fouling at the new speed and power condition. When freight rates are sufficiently high, the optimum speed is identical to the maximum speed, and the two procedures "FUELCONS" and "FUELOPT" will yield identical results. Upon the first examination of the problem the application of an optimum speed calculation may appear to be unnecessary for the evaluation of different hull and propeller maintenance strategies. A more detailed investigation does, however, reveal that when the speed/power characteristics experience a change due to roughness and fouling, the optimum speed point will also be altered. When evaluating the economic difference between two maintenance alternatives at a constant speed setting, the principal difference will be due to roughness and fouling, but a small part will also be due to a displacement in the optimum speed point. This error is eliminated when the operating point, determined by the optimum speed calculation, is re-evaluated prior to the start of every roundtrip voyage, and the difference between the two alternatives will be due to hull and propeller condition only.

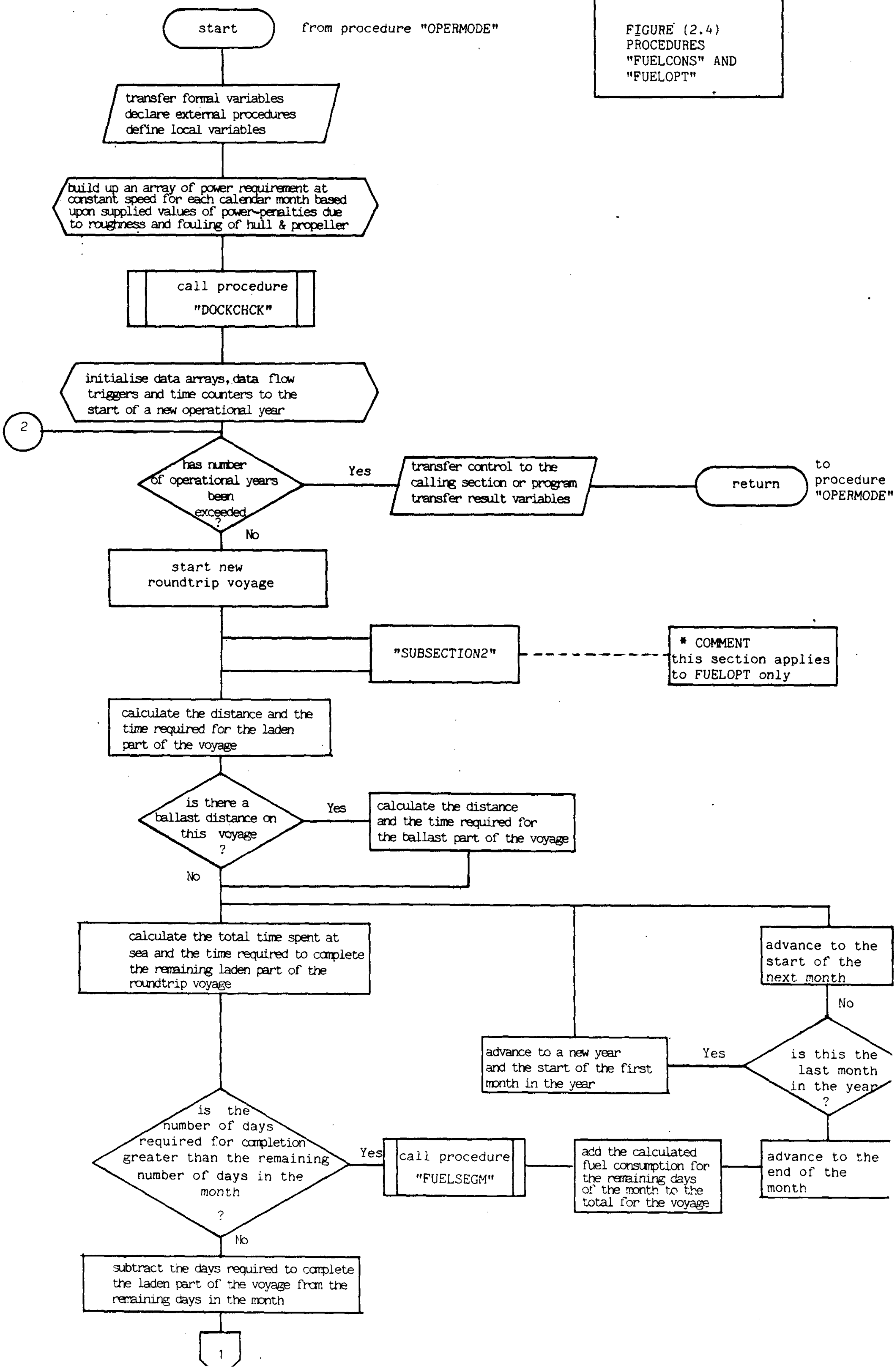


FIGURE (2.4)
PROCEDURES
"FUELCONS" AND
"FUELOPT"

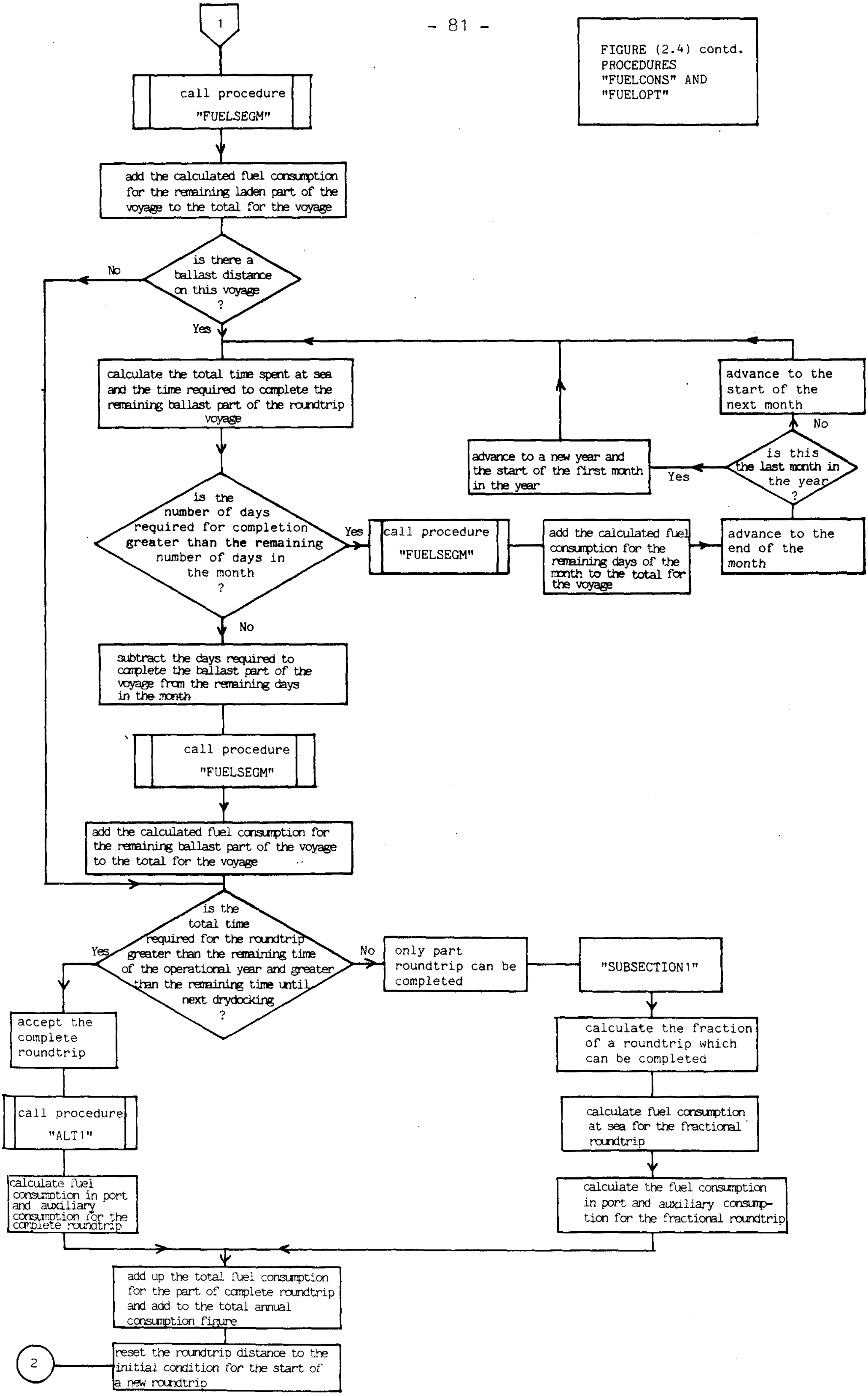
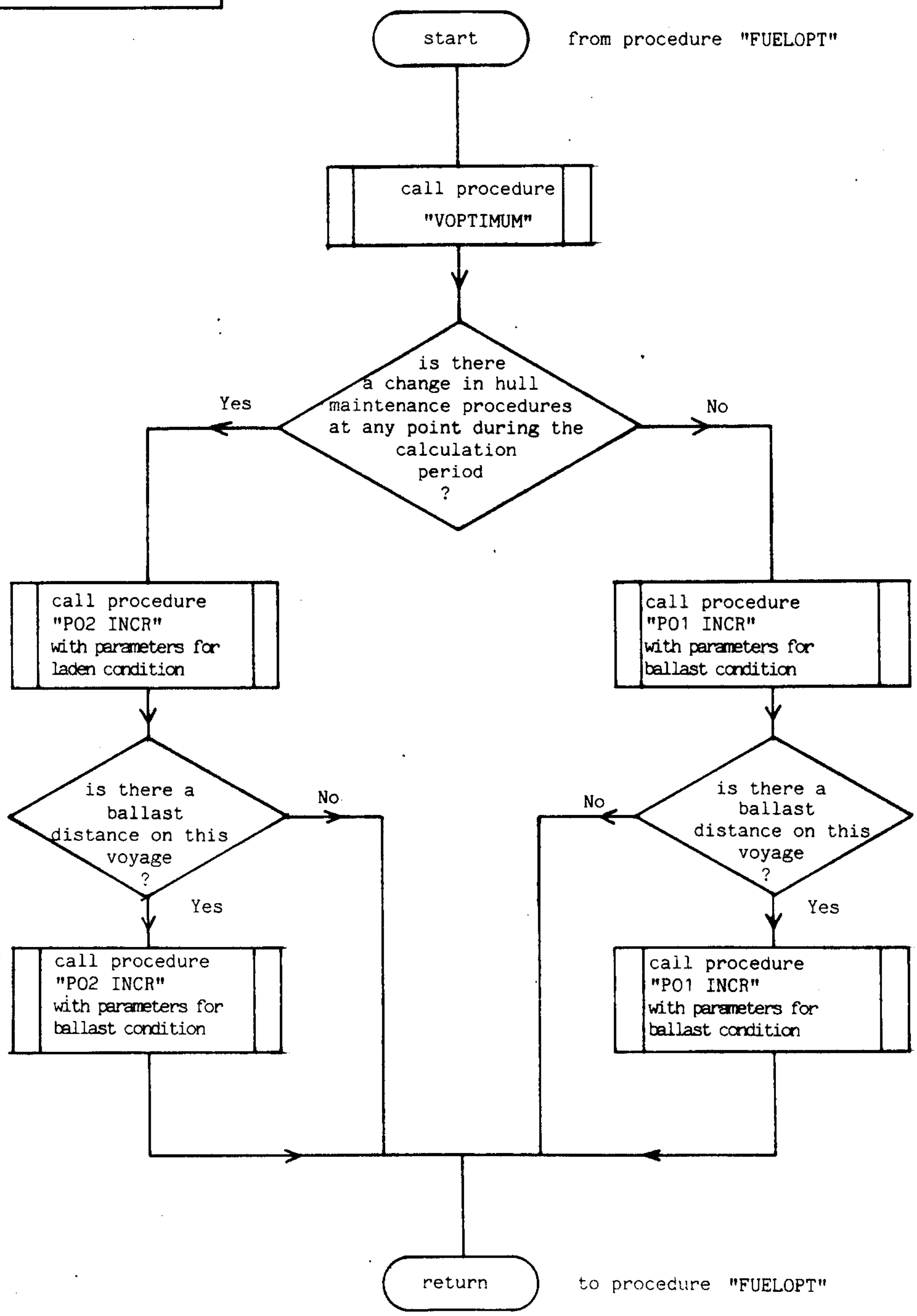


FIGURE (2.4) contd.
PROCEDURES "FUELCONS" AND "FUELOPT"

FIGURE 2.5
"SUBSECTION2""



Common to all three procedures, "ROUNDTRIPS", "FUELCONS" and "FUELOPT" is that they are designed for the specific purpose of modelling the operation of a vessel in an environment of changing hull and propeller condition.

For this reason the principal number of variables are related to hull and propeller maintenance strategies. However, since one of the principal objectives formulated in the initial stages of this work was to put the problems of hull and propeller maintenance into the total operational context of the ship, the procedures have been designed with sufficient flexibility and an adequate number of parameters, to allow their use in operational modelling outside the context of hull and propeller maintenance. This implies that the total techno-economic model can be used equally well for the analysis of other potential energy saving investments.

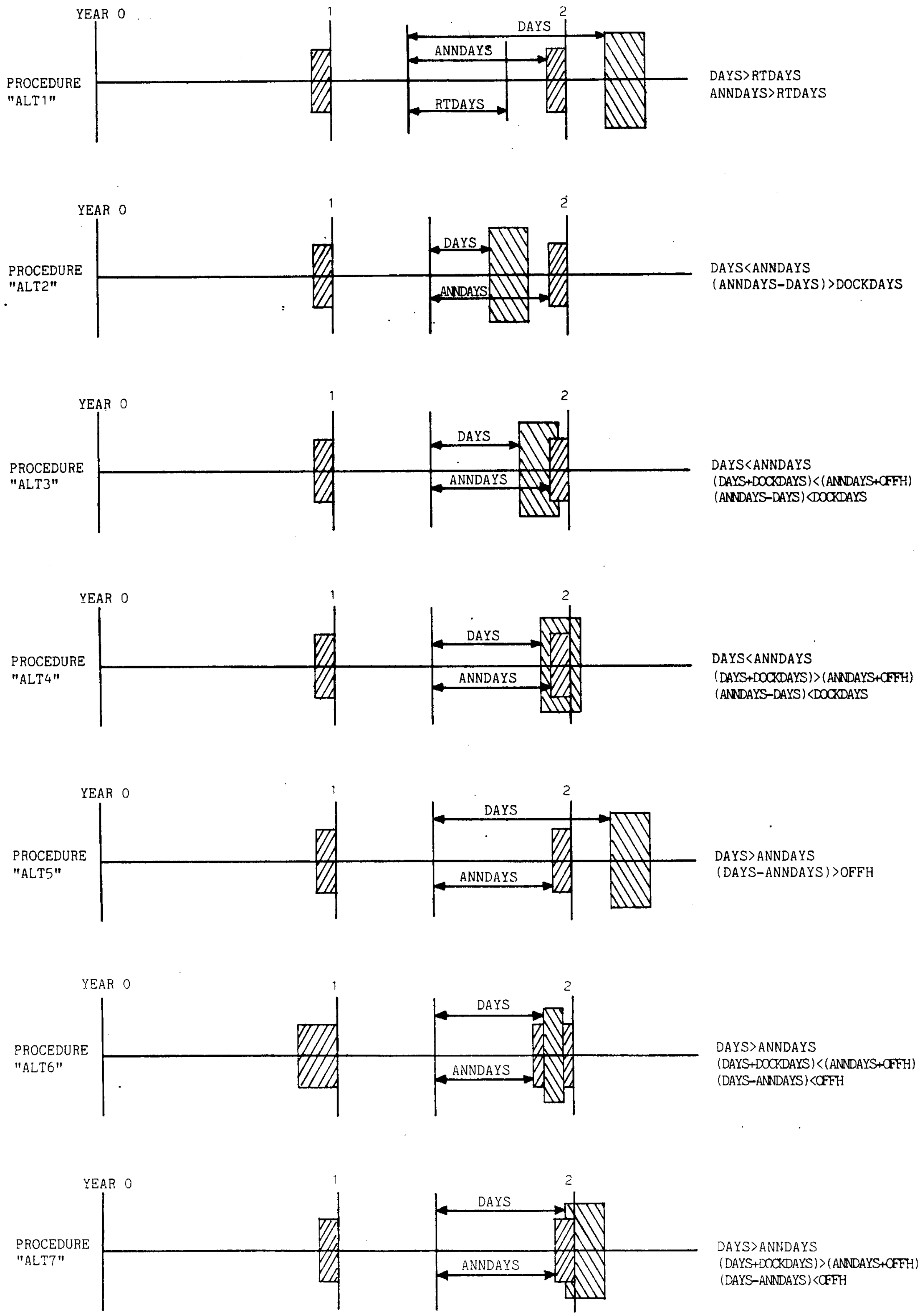
2.2.4 PROCEDURES "ALT1" TO "ALT7" FOR ALTERNATIVE COURSES OF ACTION AT END OF ROUNDTRIP VOYAGE

The set of 7 procedures "ALT1" to "ALT7" are concerned with the evaluation of alternative courses of action following the advance modelling of a roundtrip voyage. "ALT1" is called when sufficient time is available for the complete roundtrip to be accepted, while procedures "ALT2" to "ALT7" are designed to cover all possible situations when only a part roundtrip can be completed. "ALT2", "ALT3" and "ALT4" are called when the principal constraint is the available time prior to next drydocking, while the remaining procedures handle the situation when end of the year condition occurs first. The identification and the subsequent handling of these 7 possible situations are of primary importance for the accuracy of the calculations and are therefore described in some detail. "SUBSECTION1" has already demonstrated the criteria for the selection of alternative courses of action, and the present section will give a more detailed description of the steps in each alternative. A standard flow diagram does not give a good description of the various alternatives, and the 7 possible situations are instead illustrated along a time scale in Figure (2.6), supplemented by a short description in words.

The assumption is always made that the annual off-hire time takes place at the end of the financial year, and the length of an operational year is equal to the length of a financial year (365 days), minus the off-hire time. It is also assumed that drydocking can only take place during the operational year and not during off-hire time. In the situation when overlap occurs between drydocking and off-hire time, the drydocking period remains fixed while the overlapping part of the off-hire time is displaced backwards in time to a point immediately prior to drydocking. The term "off-hire" is used in this context as a general heading for any out of service time other than drydocking maintenance, (for example breakdown).

<u>"ALT1":</u> This is the simple situation where the available time prior to drydocking, represented by the variable DAYS, and end of year condition, represented by the variable ANNDAYS, are both greater than the total time required for the roundtrip voyage. The complete roundtrip is thus accepted, and the total time required for the roundtrip is subtracted from ANNDAYS and DAYS to give the starting condition for the next roundtrip voyage. Additional time counters are updated simultaneously to the start

FIGURE (2.6)
CONDITIONS FOR PROCEDURES ALT1 TO ALT7



DAYS = REMAINING DAYS UNTIL NEXT DRYDOCKING
ANNDAYS = REMAINING DAYS UNTIL END OF THE YEAR CONDITION
DOCKDAYS = DAYS IN DRYDOCK
OFFH = ANNUAL OFF-HIRE TIME

of a new roundtrip.

"ALT2": As illustrated in Figure (2.6), this represents the first of three possible situations when the principal reason for the completion of a part roundtrip only is the available time prior to drydocking. In this first case the drydocking does not interfere with the end of the year condition, and time is available upon completion of the drydocking for a further complete or part roundtrip prior to end of year condition. The fractional roundtrip is calculated as the ratio of DAYS, the available time prior to drydocking, to the total time required for the roundtrip. ANNDAYS is subsequently updated by subtracting the time required for the part roundtrip and the drydocking, and DAYS is assigned a value equal to the total time between drydockings for the particular maintenance system used at this last drydocking. The exact point in time for completion of drydocking is also calculated, and the remaining time counters are advanced to this point in time ready for the evaluation of a new roundtrip voyage.

"ALT3": Again only a part roundtrip can be completed due to the commencement of a drydocking, but because the drydocking takes place close to the end of the year condition, part of the time in drydock extends into the off-hire time. This implies that some of the time is accounted for twice and errors are introduced. The situation is corrected by keeping the drydocking period fixed and moving the overlapping part of the off-hire time to a position immediately prior to the start of the drydocking. The value of the variable DAYS is subsequently reduced by an amount equal to the displaced part of the off-hire time prior to the calculation of the fractional roundtrip. Although the time in drydock extends into the off-hire time, it does not extend beyond the end of the financial year. All time counters can, therefore, be advanced to the start of a new roundtrip as well as the start of a new operational and financial year. ANNDAYS is assigned a value equal to the length of the operational year and DAYS a value equal to the total time between drydockings for the particular maintenance system used at the last drydocking, minus the interval of time between end of drydocking and end of the financial year.

"ALT4": This alternative situation is similar to the one already accounted for by "ALT3", in that only a part roundtrip can be completed due to the commencement of a drydocking, and that the drydocking extends into the off-hire time. In addition, the time in drydock in this case also extends beyond the end of the financial year and into the new year. This has the implication that the complete off-hire time will have to be displaced back in time to the point immediately prior to drydocking, and the variable DAYS has to be adjusted accordingly before calculating the fractional roundtrip. The exact point in time for completion of drydocking is subsequently calculated and the various time counters advanced to be ready for a new roundtrip. The variable DAYS is given a value corresponding to the total time between drydockings for the maintenance system used at this last drydocking, and ANNDAYS is given a value equal to the length of the operational year, minus the amount of time by which the present drydocking has extended into the new year. In the procedure for calculating the cost of drydocking, the total cost will in this case be charged to the year in which the drydocking was completed.

"ALT5": As the first of the 3 possible situations where end of year condition is the principal reason for the completion of a part roundtrip, this particular alternative is similar to "ALT2", where drydocking does not interfere with end of year condition. The fractional roundtrip is calculated as the ratio of ANNDAYS to the total number of days required for the roundtrip. Since this is the end of the financial year, all time counters can be advanced to the start of a new roundtrip as well as the start of a new year. The variable ANNDAYS is assigned a value equal to the length of the operational year, and DAYS is updated by subtracting the time required for the part roundtrip and the time off-hire.

"ALT6": Again, only a part roundtrip can be completed due to end of the year condition, but in addition, drydocking is commenced and completed within the off-hire period. This double-accounting of time is not permitted, and the overlapping part of the off-hire time is therefore displaced backwards in time and appended prior to the original starting point of the off-hire. ANNDAYS is adjusted accordingly, prior to the calculation of the fractional roundtrip. All time counters are subsequently advanced to the start of a new roundtrip and a new year. The variable ANNDAYS is given a value equal to the length of the operational year and DAYS a value equal to the appropriate interval between drydockings , minus the difference in time between the end of drydocking and the end of the financial year.

"ALT7": This is the final possible situation. End of the year condition is again the reason for completion of a part roundtrip only, but drydocking is commenced during the off-hire time and extends beyond the end of the financial year. In order to remove the overlap between off-hire time and time in drydock, the complete off-hire period is in this case displaced backwards to a point where the completion of the off-hire corresponds to the starting point for the drydocking. ANNDAYS is adjusted accordingly prior to the calculation of the fractional roundtrip. Subsequent advancement of time counters and assignment of values to ANNDAYS and DAYS follows the steps outlined in the description of "ALT3".

2.2.5 PROCEDURE "VOPTIMUM" FOR CALCULATION OF OPTIMUM SPEED

This procedure estimates the optimum speed for a complete roundtrip based upon the criterion of maximising profits per unit time.

The method by which the optimum speed should be calculated depends entirely on the definition of the optimising problem and the constraints imposed. For an owner operated vessel where costs are calculated on a time basis and with an unlimited amount of cargo available, the optimising criterion will be to maximise profits per annum (or any other convenient unit of time). If, on the other hand, a cargo owner acquires a vessel on time charter to cover a fixed transportation requirement, the optimising criterion will be to minimise the transportation costs for each unit of cargo carried. The two principal factors in the calculation of optimum speeds are:

(1) the freight earned for each unit of cargo carried

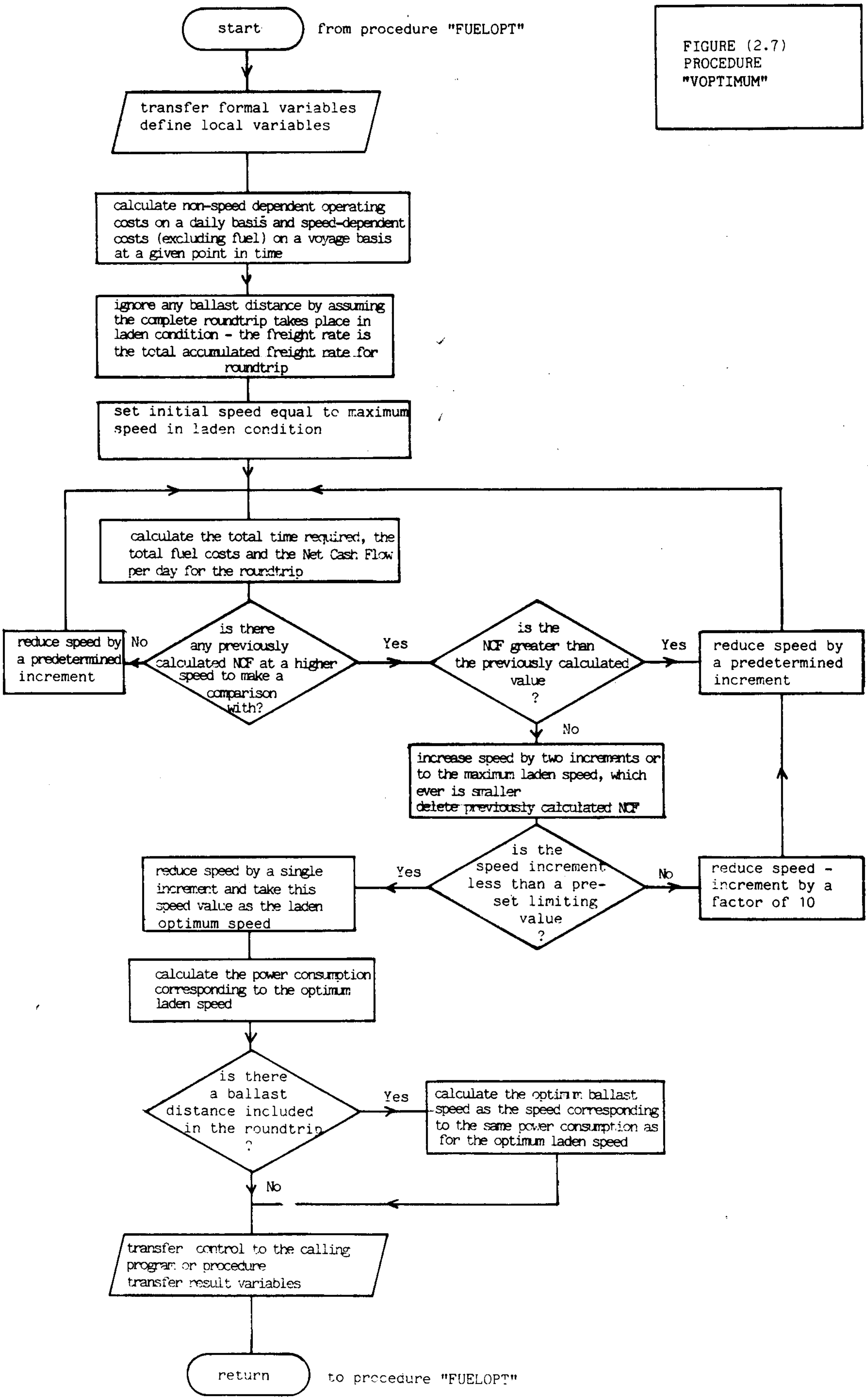
(2) the unit cost of fuel used for propulsion purposes

Other significant factors which may complicate the problem are inventory costs charged on the cargo and the influence of onward employment. When fuel price moves below or freight rate exceeds a particular limiting value, the optimising speed is the maximum speed, and the optimum speed calculations are no longer necessary.

The present techno-economic model has been designed for the primary purpose of evaluating alternative hull and propeller maintenance strategies. Improved maintenance procedures may involve considerable capital expenditures at present with a view to gaining substantial advantages in terms of reduced fuel consumption or increased speed in the future. Investments in improved hull and propeller maintenance therefore initially appeared to be directed towards owner-operated vessels, and a speed optimising routine based upon maximising profit per unit time was found best suited. Further consideration of chartered vessels has shown that vessels on long term charters may from the charterers's point of view be regarded as owned when evaluating the merits of alternative energy saving investments. The daily time charter hire may therefore be considered as the fixed part of the daily running costs, and the principle of optimising speed by maximising profit per unit time remains valid, except when the cargo is owned by the charterer.

The procedure "VOPTIMUM" is designed to be called at any point in time, and the first step in the calculation procedure is therefore to update all cost and price items to the particular point in time when it is being called. This step is particularly important when different escalation rates are used. The non-speed dependent costs are subsequently calculated on a daily basis. Prior to the calculation of the speed-dependent costs, the assumption is made that the complete roundtrip takes place in laden condition. This follows the recommendations for optimum speed

FIGURE (2.7)
PROCEDURE
"VOPTIMUM"



calculations set out in Reference (37). By the application of a simple search technique, the speed is gradually reduced until the speed where the maximum daily net cash flow occurs is found. The power consumption corresponding to the optimum laden speed is subsequently estimated from the speed/power curve, and if the voyage includes a ballast leg, the optimum ballast is calculated as the ballast speed with the same power consumption as the optimum laden speed.

2.2.6 PROCEDURES "PO1INCR" AND "SP1LOSS" FOR CALCULATION OF PENALTIES DUE TO HULL ROUGHNESS WITH SINGLE MAINTENANCE SYSTEM

The two procedures "PO1INCR" and "SP1LOSS" calculate the power increase or speed loss penalties due to hull roughness for a single hull maintenance alternative where there is no change in coating system or roughness specification during the period of calculation. "PO1INCR" is used for constant speed and "SP1LOSS" for constant power calculations. The penalties are calculated as average values for each calendar month as required by the operational routines, "ROUNDTRIPS", "FUELCONS" and "FUELOPT", and the resulting values are related to a basis value specified at the input stage. The calculated values are supplied to an array of size (N + 1) by 12 where N is the length of the period of calculation (in years), and the row element identifies the month of the year. Due to the advance modelling of each roundtrip the calculation has been extended for a period of 12 months beyond the end of this period. A totally flexible input of drydocking interval and time in drydock has resulted in out-and indocking taking place at any point in time and not necessarily at the start of a month. The principle used in the case of short drydockings, where in and out docking takes place within the same calendar month, has been to use the outdocking roughness as a basis for the complete month. Discrepancies at the point just prior to indocking are then corrected as explained in the procedure "ROUNDTRIPS". Further variables specified in the data file are the present AHR, average monthly increase in AHR, change in AHR during drydocking, interval between drydockings and the number of days required in drydock. A linear increase in AHR with time has been assumed on the grounds that no evidence could be found to support the use of a relationship of a different form, (Chapter 1). The change in roughness during conventional routine drydocking was found in Section (1.2.2), to be correlated to the indocking roughness, and the option is therefore given to express this change in roughness either as a linear function of the indocking AHR, or alternatively as a constant value. The ITTC correlation formula for hull roughness (Chapter 1) is used to transform values of hull roughness into corresponding increments ΔC_T to the total resistance coefficient C_T of the vessel. The values of ΔC_T are subsequently transformed into power increments and corresponding speed-losses (procedure "SP1LOSS") by maintaining a constant propulsive coefficient as recommended in Chapter 1. An optional facility for correcting the predicted power increment by a given percentage amount has been included in accordance with the conclusions of Chapter 1. The ITTC correlation formula is presently the only simplified method available for predicting the relationship between roughness and drag. Current and future research in this field may result in modifications to the ITTC formula, and the procedure logic is designed so that a new relationship can be introduced by simply altering one or two lines of program text in the source program, provided no additional variables are introduced to the existing datafile, (Appendix D).

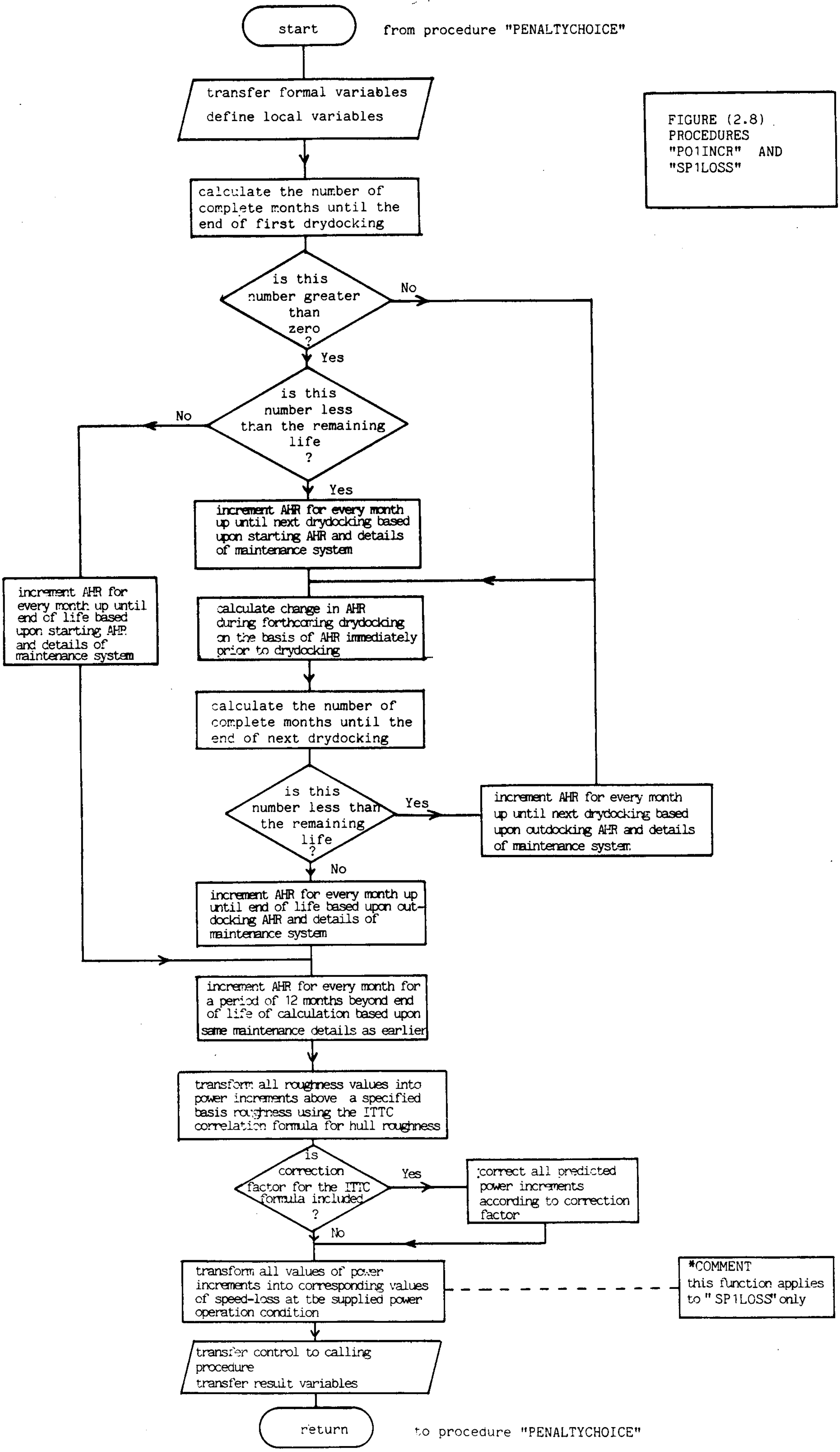


FIGURE (2.8)
PROCEDURES
"PO1INCR" AND
"SP1LOSS"

2.2.7 PROCEDURES "PO2INCR" AND "SP2LOSS" FOR CALCULATION OF PENALTIES DUE TO HULL ROUGHNESS WITH MULTIPLE MAINTENANCE SYSTEMS

The procedures "PO2INCR" and "SP2LOSS" for calculating power increase or speed loss penalties due to hull roughness both have the same function as the previously described set of procedures "PO1INCR" and "SP1LOSS". Identical functions and formats are used for transforming roughness increments into speed and power values, and the description of this part of the operation is not repeated. The principal difference between the two sets of procedures lies in the fact that "PO2INCR" and "SP2LOSS" are capable of handling a change from one maintenance alternative to a second alternative at any point in time within the specified period of calculation. This includes the change from one coating system to another, as well as changes in roughness specification, interval between drydockings, time in drydock and cost specifications. In practice, this "change" will normally mean a complete reblast with a change to a new coating system, and the option is also included for such a change to be repeated at regular intervals, i.e. reblast every second or third drydocking. Although the two sets of procedures perform the same task of building up an array of speed losses or power increases, the number of variables required and the complexity of the logic structure for this second set is substantially greater. In addition, one or two specific points in the procedure logic should be noted:

Drydockings take place principally due to Classification Society requirements, renewal of coating system, repairs or a combination of these 3 reasons. The specified drydocking periods have therefore been strictly adhered to irrespective of the remaining time of the predefined period of

FIGURE (2.9)
PROCEDURES
"PO2INCR" AND
"SP2LOSS"

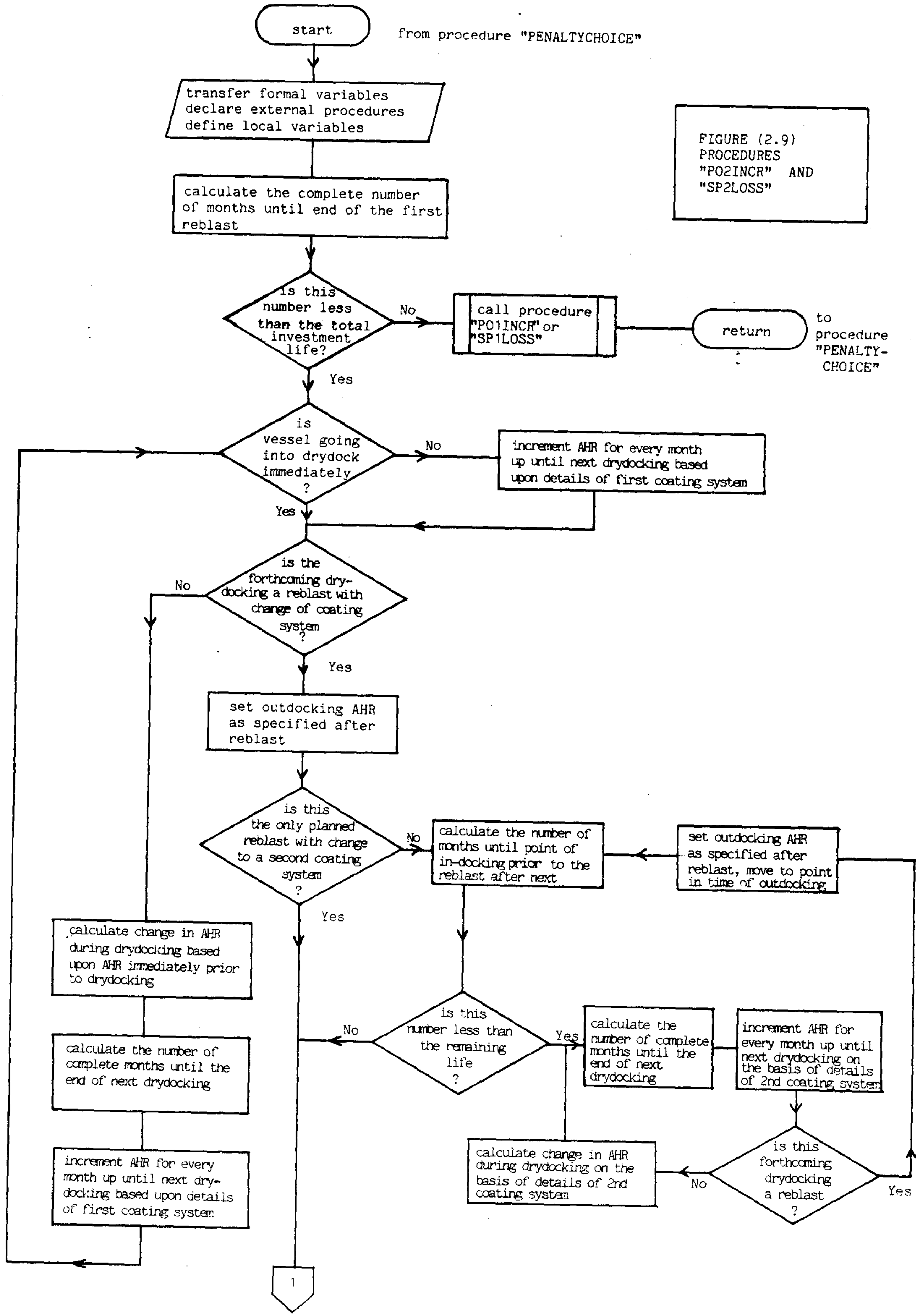
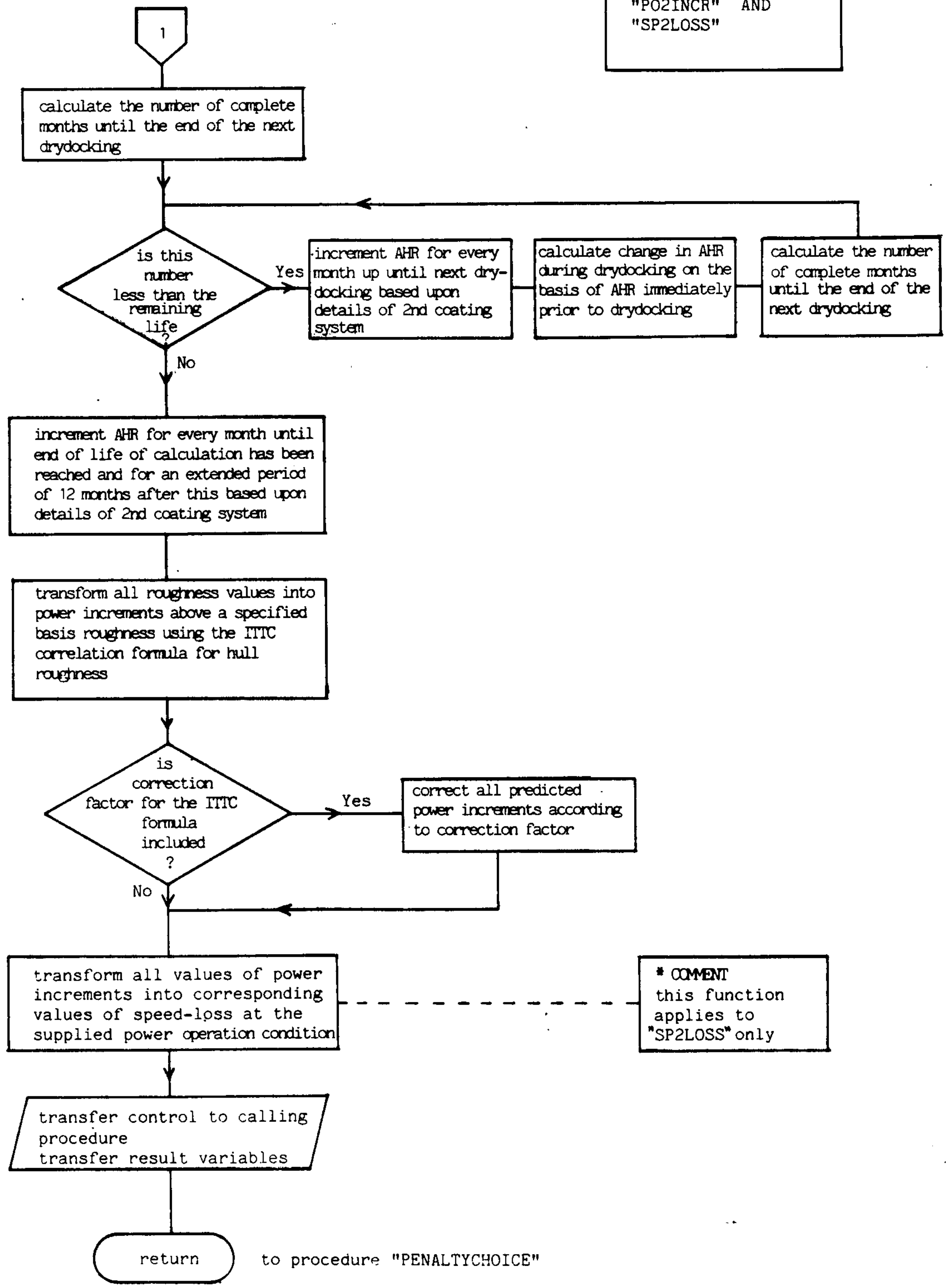


FIGURE (2.9) contd.
PROCEDURES
"PO2INCR" AND
"SP2LOSS"



calculation after every drydocking. Reblast or other changes in coating system involving capital expenditure can in most cases be regarded as investments made with the view to obtaining improvements over a future period of time. A complete reblast would therefore be of little value if the period of calculation comes to an end immediately afterwards. This possible situation has been accounted for by only allowing a reblast or change in coating system if sufficient operational time remains beyond the completion of this change. Sufficient time in this context has been defined as at least two-thirds of the originally specified time between reblasts. A flow diagram for the two procedures is provided in Figure (2.9).

2.2.8 OPTIONAL PROCEDURES "FOUL1PEN", "FOUL2PEN" AND "FOULCHOICE" FOR THE INCLUSION OF HULL FOULING

The optional facility of including the possible effects of hull fouling is accommodated by the call of procedures "FOUL1PEN" and "FOUL2PEN". The effects of fouling are calculated using a fixed model having an initial period without fouling, followed by the successful settlement of fouling with a corresponding reduction in operating speed over time modelled on a simple cosine curve. When saturation fouling growth has been reached, the speed loss is maintained at this constant value until drydocking takes place. Optionally, drydocking may take place at any intermediate point prior to the point in time when the maximum speed loss has been reached. If constant speed operation is assumed, the values of speed loss are transformed into corresponding power increments. The time period without fouling, the time period between initial fouling settlement and the saturation point where maximum speed loss is experienced and the absolute magnitude of the maximum speed loss may be specified as required in each case study without constraints. Selection between the two procedures "FOUL1PEN" and "FOUL2PEN" is performed by the procedure "FOULCHOICE", which is similar to the procedure "PENALTYCHOICE" explained below.

2.2.9 PRINCIPAL CONTROL PROCEDURES FOR OPERATIONAL MODELLING

Procedure "PENALTYCHOICE"

This procedure serves the simple function of selecting and calling with the appropriate parameters one out of the four procedures "SP1LOSS", "PO1INCR", "SP2LOSS" and "PO2INCR". The choice is determined entirely by the set of control triggers specified in the basic data file, and as shown in the flow diagram in Figure (2.10) the procedure logic consists only of a series of decision stages leading to the selection of the correct procedure.

Procedure "OPERMODE"

The procedure "OPERMODE" has a similar function to that of "PENALTYCHOICE" for the 3 alternative modes of operation "ROUNDTRIPS", "FUELCONS" and "FUELOPT". Again, the correct choice of procedure is determined by the values of the control triggers in the basic data file. In addition, after having completed the selection and call of the correct operational procedure, two alternative procedures "OPERCOST" and "DRYCOSTS" are called to complete the calculation of individual and total

FIGURE (2.10)
PROCEDURE
"PENALTYCHOICE"

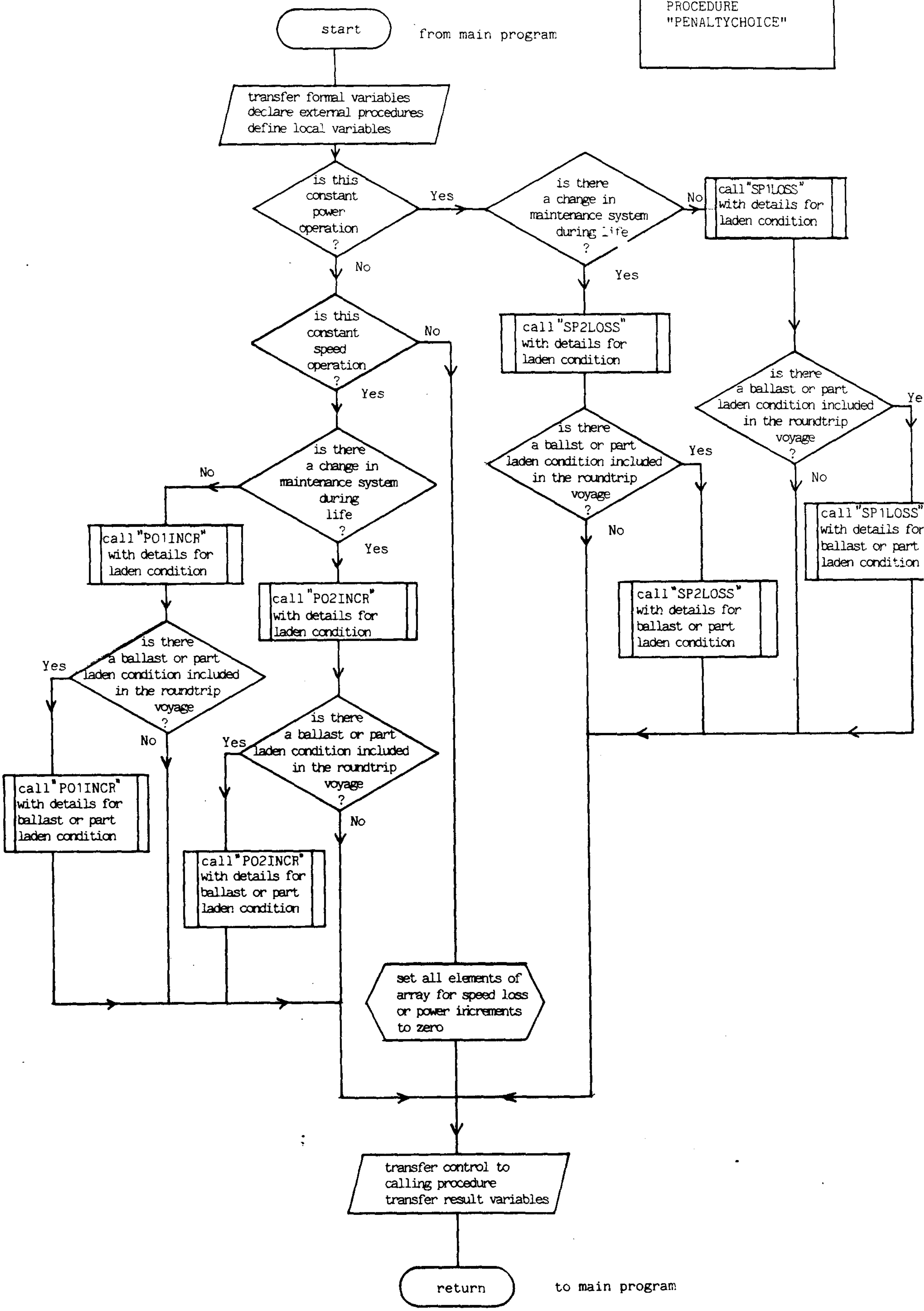
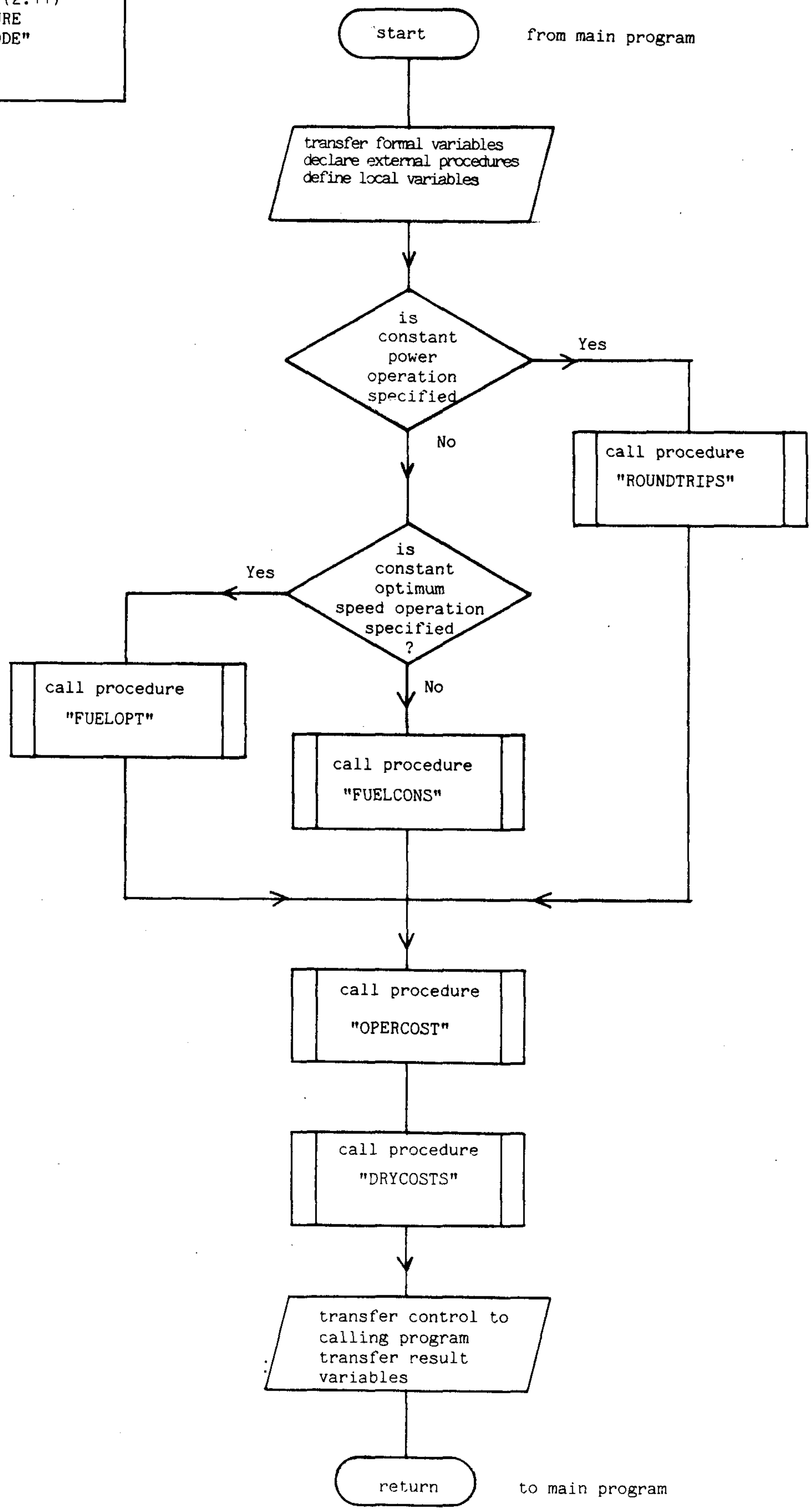


FIGURE (2.11)
PROCEDURE
"OPERMODE"



cash flows for each financial year.

2.2.10 PROCEDURES FOR CASH FLOW CALCULATIONS

"OPERCOST" calculates the principal income and expenditure items on an annual basis, including revenue, crew costs, upkeep costs, fixed costs, port charges and fuel costs, based upon supplied cost specifications, escalation rates and the results of the operational modelling performed by either of the procedures "ROUNDTRIPS", "FUELCONS" or "FUELOPT".

"DRYCOSTS" is a procedure specifically designed for the task of calculating costs associated with each drydocking and assigning the values to the appropriate year in the operating accounts. The costs are calculated by two different methods. First the actual cash expenditure on the hire of drydock, cost of preparation of hull surface and cost of coating system with application are estimated and added to the accumulated sum of negative cash flows for the appropriate year. The second method is used for calculating the true cost of the hull maintenance, including the cost of time out of service, but excluding the cost of hire of drydock and out of service charges for the number of days required for survey by classification society. If classification survey in drydock is not required then the total cost is allocated to the hull maintenance system. The results from this second method of calculating the cost of the hull maintenance system are not used directly in the cash flow calculation since the cost of the time out of service is implicitly taken into account in the operational modelling. As a result of an investigation into the levels of charges made for the hire of drydocks in different parts of the world, it was found that as a general rule a fixed amount according to ship size was charged for each day of the two first days in drydock, and approximately half this amount for each subsequent day. This relationship has been built into the model, and the value for hire of drydock supplied in the data file is the amount charged for each of the first two days.

"NPVAW" calculates the net present value and the equivalent annual worth of a series of annual cash flows for any specified rate of interest. The annual worth is calculated as a figure increasing in line with a predefined inflation rate, and just as a positive net present value can be described as an instantaneous cash gain, a positive annual worth is the same as a constant value additional profit available at the end of every year.

"ZERONPV" is an iterative procedure for calculating the interest rate for which the net present value of a series of annual cash flows becomes zero. In relation to investment calculations this particular interest rate is also known as the yield or the internal rate of return on the investment. Only internal rates of return between zero and 100 percent are calculated.

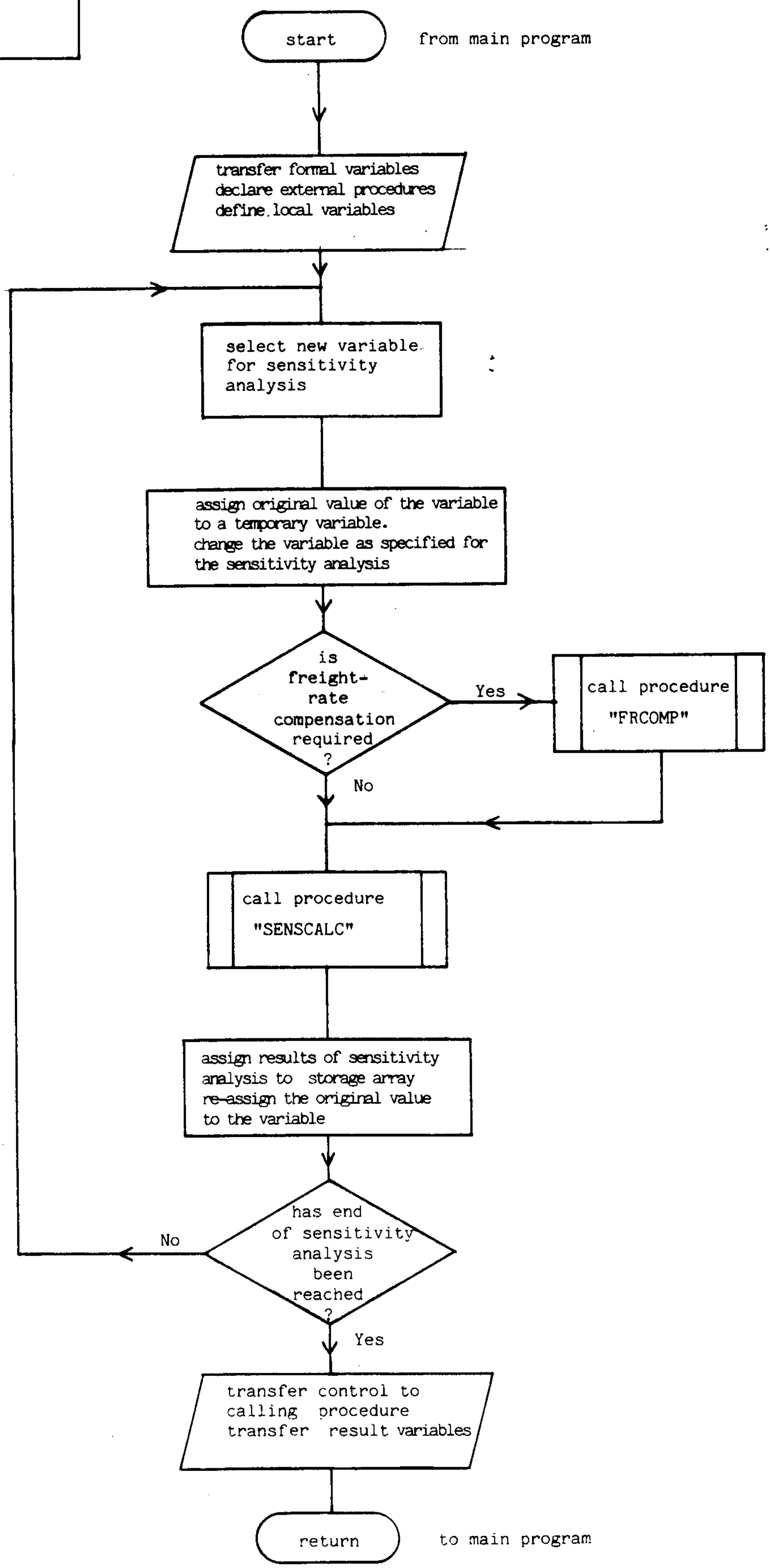
"DISCOUNT" is an optional procedure for calculating the net present value of a series of cash flows at various discount rates between zero and 75 percent. The procedure has been included as a tool for investigating the cash flow pattern of a project, when the procedure "ZERONPV" is unable to find a particular interest rate for which the net present value of the cash flows become zero. As discussed in Chapter 1, this situation may occur if the cash flow pattern is irregular, resulting in the net present value turning negative at some intermediate point in the life of the investment and then turning positive again.

2.2.11 PROCEDURES FOR SENSITIVITY ANALYSIS

"SENSITY" is the principal procedure for performing a sensitivity analysis on a selected number of variables. The correspondence between the flow diagram in Figure (2.12) and the actual logic of the procedure is not exact. This is because the sensitivity analysis for each variable essentially follows the same steps, and instead of repeating this nearly identical sequence a number of times a loop description is illustrated in the flow diagram. In the actual program, "SENSITY" is simply a procedure for calling two other procedures "SENS1" and "SENS2". These two procedures perform the actual calculations changing one variable at a time by a predetermined amount and calling the procedure "SENSCALC" prior to re-setting the variable to its initial value. The objective of a sensitivity analysis is to examine the effects upon the economic measure of merit of altering one variable at a time only. To avoid measuring the effects on more than one variable at a time, other variables will have to be compensated on occasion. In particular, this applies to the freight rate, and the procedure "FRCOMP" is called for this purpose.

"FRCOMP" serves the purpose of adjusting the freight in order to maintain a constant annual net cash flow. The compensation to freight rate is made on the basis of the speed and power characteristics with corresponding values of average hull roughness, as specified in the input file. A small error may be expected if the hull roughness characteristics

FIGURE (2.12)
PROCEDURE
"SENSITY"



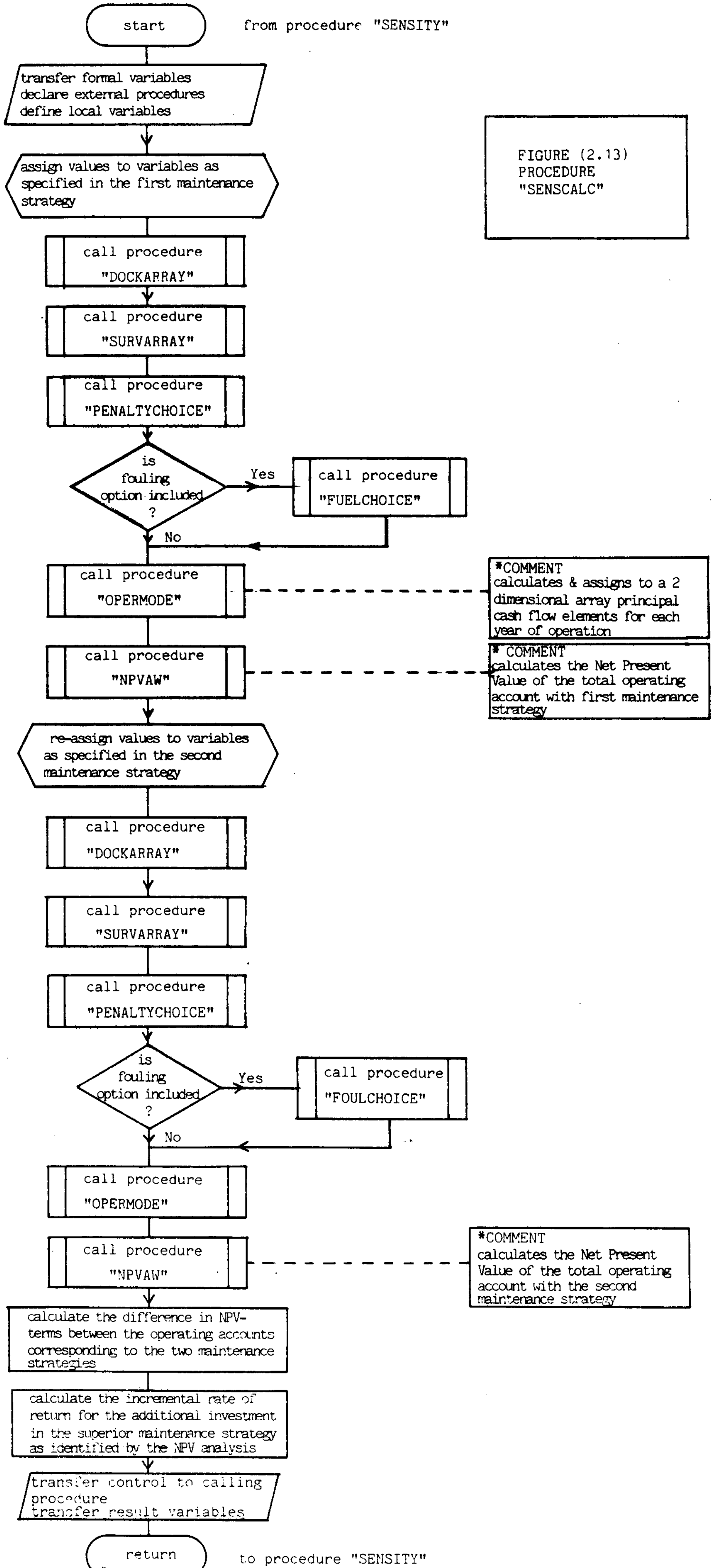


FIGURE (2.13)
PROCEDURE
"SENSCALC"

are significantly different from the initial specification over the period of calculation.

"SENSCALC" performs the actual deterministic comparison between two alternative maintenance strategies. The procedure is illustrated in Figure (2.13), and is essentially a simplified version of the main program "ECOMAIN".

2.2.12 MAIN PROGRAM "ECOMAIN"

The main program "ECOMAIN" serves the primary function of calling the various subroutines or procedures in the correct order. The calling sequence is determined by a set of integer triggers which are the first data items supplied to the program. In addition, the data triggers control the input of other data variables. Figure (2.14) illustrates the logic flow in the program. Detailed descriptions of individual data triggers and the optional values they can take are provided in Appendix D.

The analyst is given the option of performing a standard deterministic evaluation between two alternative maintenance strategies, or simply to calculate the annual net cash flows and discounted cash flows excluding capital charges for a vessel with a single maintenance alternative. This latter mode of calculation is used for other types of techno-economic calculations not directly related to the comparison between hull or propeller maintenance strategies. When the first mode of calculation is used, both maintenance alternatives are input simultaneously with other data variables. The data values associated with the second alternative

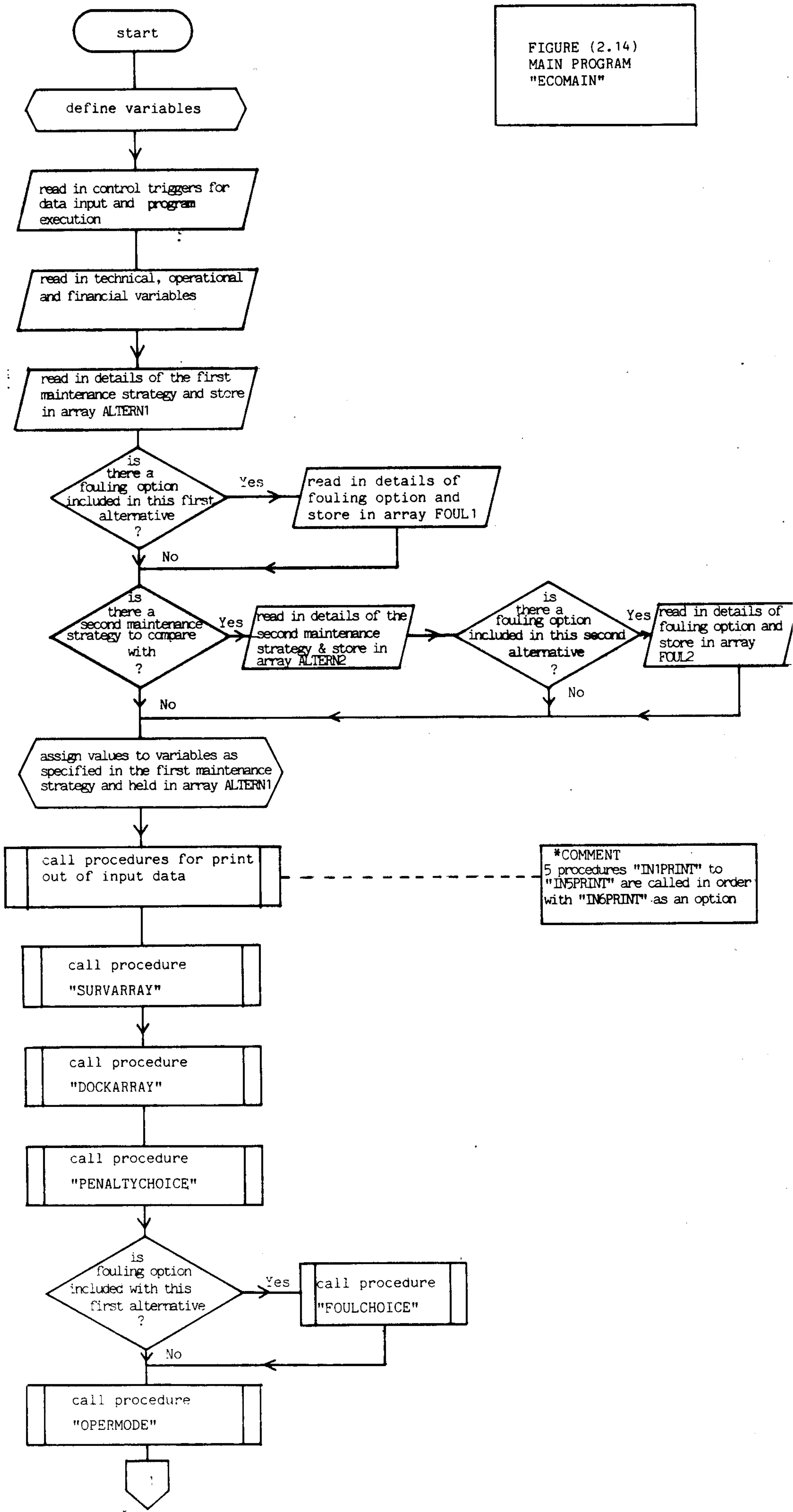
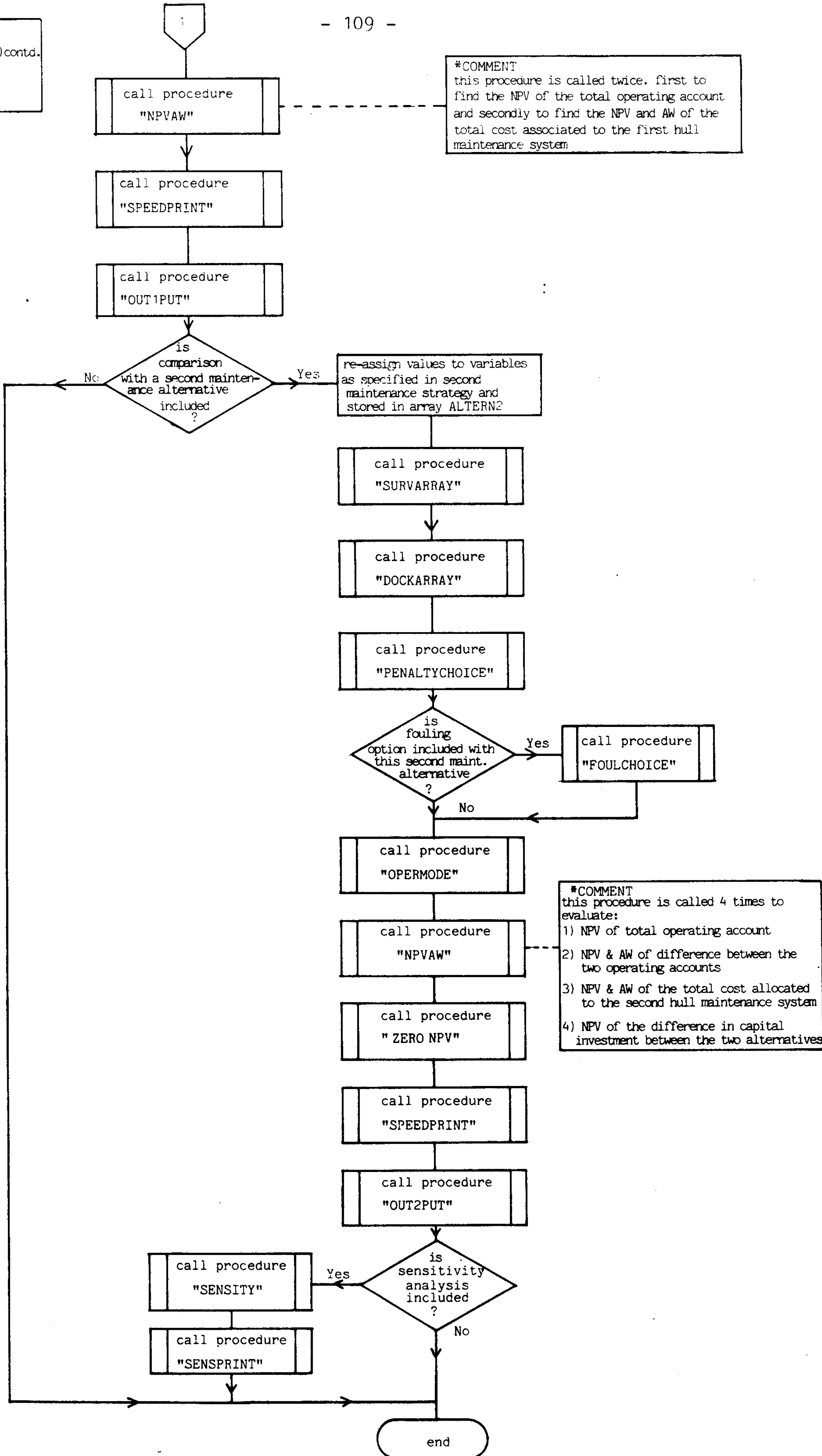


FIGURE (2.14)
MAIN PROGRAM
"ECOMAIN"
start
define variables
read in control triggers for data input and program execution
read in technical, operational and financial variables
read in details of the first maintenance strategy and store in array ALTERN1
is there a fouling option included in this first alternative ?
Yes
No
read in details of fouling option and store in array FOUL1
is there a second maintenance strategy to compare with ?
Yes
No
read in details of the second maintenance strategy & store in array ALTERN2
is there a fouling option included in this second alternative ?
Yes
No
read in details of fouling option and store in array FOUL2
assign values to variables as specified in the first maintenance strategy and held in array ALTERN1
call procedures for print out of input data
*COMMENT
5 procedures "IN1PRINT" to "IN5PRINT" are called in order with "IN6PRINT" as an option
call procedure "SURVARRAY"
call procedure "DOCKARRAY"
call procedure "PENALTYCHOICE"
is fouling option included with this first alternative ?
Yes
No
call procedure "FOULCHOICE"
call procedure "OPERMODE"

FIGURE (2.14)contd.
MAIN PROGRAM
"ECOMAIN"



are stored while the complete operational modelling on the basis of the first alternative takes place. Having calculated the net cash flows of each year for this first alternative, the variables related to hull or propeller maintenance are assigned the data values of the second system while all other technical, operational and financial variables remain unchanged, and the complete operational modelling is repeated. The differences in annual net cash flows between the two alternatives are subsequently calculated and the procedures "NPVAW" and "ZERONPV" called to obtain the discounted cash flows and rate of return on the incremental investment. Upon completion of printing the results the procedures for performing a sensitivity analysis are called if this option is specified, otherwise the execution of the program is terminated. A sample of printed output including sensitivity analysis is provided in Appendix D.

In the cash flow calculations the present point in time is defined as the end of year zero immediately before the start of year one. All cash flows for each year are accumulated and for the purpose of the discounting procedure are assumed to take place at the end of the year. Cost values are average values for the complete year. The discount factor supplied in the input data file is used to discount all end of the year cash flows, starting with year one. In order to accommodate investments which have just taken place immediately prior to the start of the calculations the variable ININVEST has been defined. The cash flow assigned to ININVEST is assumed to take place at the end of year zero and is subsequently not discounted during the calculations

Chapter 1 presented the discounted profit to investment ratio as a convenient measure of merit for incremental investments since the size of the investment is implicitly taken into account by the measurement of profit for each unit capital invested. This measure of merit can be calculated in two ways, either as the sum of the discounted profit and the discounted investment divided by the discounted investment, or simply as the discounted profit divided by the discounted investment. The latter method is used in the present model, giving a zero discounted profit to investment ratio when the net present value is zero.

Although the techno-economic model has been designed with a view to achieving maximum flexibility, some constraints exist. The life of the investment or period of calculation must be specified as an integer number of years with a minimum value of one. Likewise, the period between drydockings should be specified as an integer number of months to avoid errors being introduced. The specification of days spent in drydock and the annual off-hire time is flexible and can take any real value less than 365.

For further information about variable specifications and modelling constraints, reference is made to Appendix D, or the Program Manual in the Department of Naval Architecture and Shipbuilding, University of Newcastle upon Tyne.

2.3 A DYNAMIC PROGRAMMING EXTENSION TO THE BASIC MODEL FOR THE PURPOSE OF EVALUATING AN OPTIMUM MAINTENANCE STRATEGY

2.3.1 PROBLEM DEFINITION

The deterministic techno-economic model described in the previous section presents the opportunity for a detailed evaluation between two clearly defined hull or propeller maintenance alternatives, but has no facilities for finding optimum strategies. Clearly, an optimum could eventually be found by means of successive evaluations between two alternative strategies, but this would be a highly inefficient method. A more rational approach to the problem is to use a search method for finding the strategies of principal interest, with subsequent application of the complete deterministic model for a more detailed analysis. The practical solution to this proposed procedure first of all required a search method to be found.

Assuming that the interval between drydockings for a particular vessel is fixed, the operation of the vessel over a specified number of years can be divided into a series of subgroups extending from the point in time immediately before entering drydock to the point in time immediately before next drydocking. On entry to each subgroup a decision is made about the hull maintenance based upon the properties of the system at this particular point in time. Each drydocking is followed by a fixed period of vessel operation, during which no changes to the system in terms of hull maintenance are allowed.

The properties of the system on entry to the next subgroup are related to the decisions made on entry to the previous and earlier subgroups, but the actual decisions made on entry to every subgroup are always independent. An optimum hull maintenance strategy in other words is an optimised sequence of inter-related decisions. Each drydocking can be described as a decision stage, and depending on decisions made at earlier stages, the system can at any stage be represented by one out of a number of possible states. The situation is illustrated in Figure (2.15), where a time scale has been defined with a series of equally spaced states. Geometrically normal to the time scale is a second axis representing hull condition, or consequences of hull condition, in terms of speed loss or power increase. This second scale is used as a measure of the state of the system at any point in time, and joining the states between stages are the admissible paths the system can follow. The actual path followed from the present stage to the next is a function of the decision made at the present stage only and is unrelated to future decisions at following stages. An important consequence of this statement of independence between subgroups is that the initial problem can be divided into various subproblems, for which best solutions can be determined and subsequently used to optimise the whole problem.

Turning back to Figure (2.15a), this can be interpreted as illustrating the simple case of a vessel starting at stage A with a particular hull condition and having a linear increase in AHR with time. At stage B and all subsequent stages, a choice exists between two alternative courses of action; either recoat with the same coating system and allow the hull condition to deteriorate further at the same rate as before, or restore hull condition to the initial state by reblasting prior to recoating

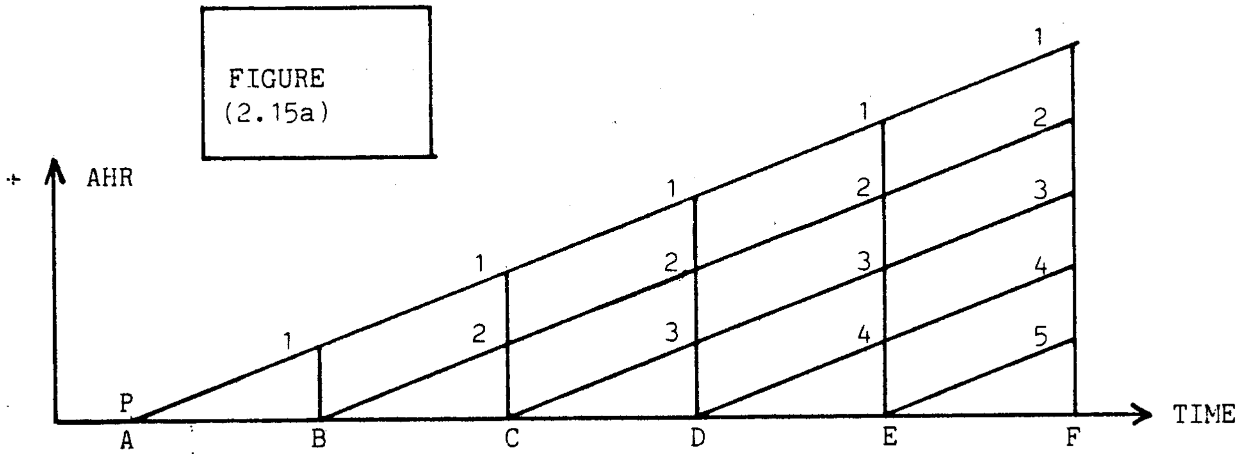


FIGURE (2.15a)

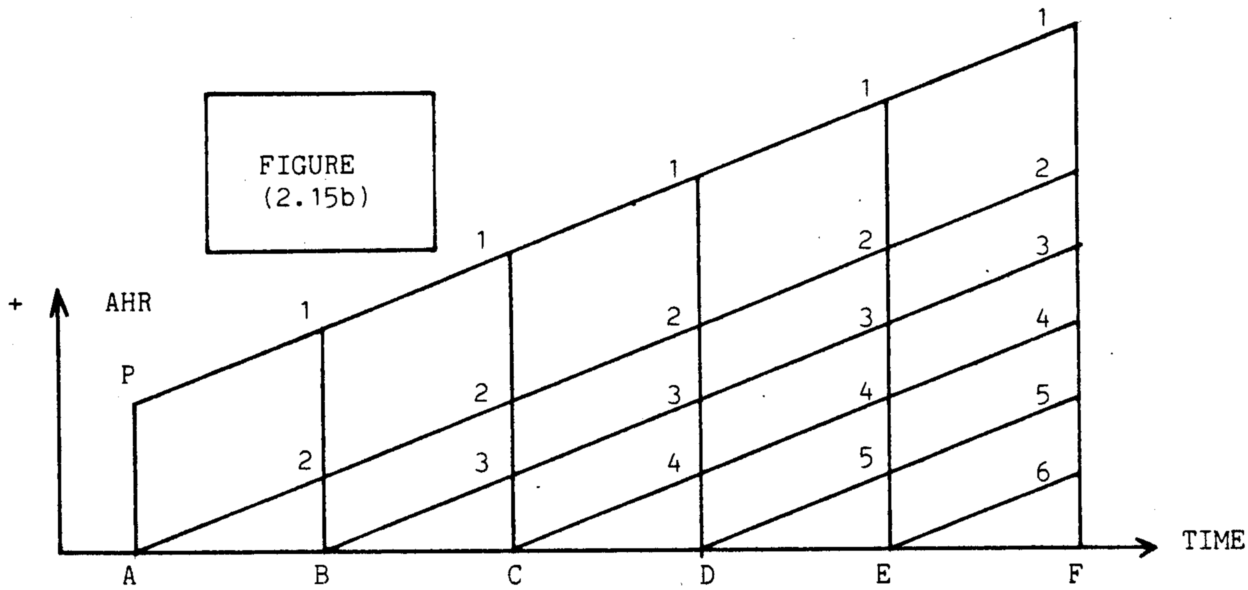


FIGURE (2.15b)

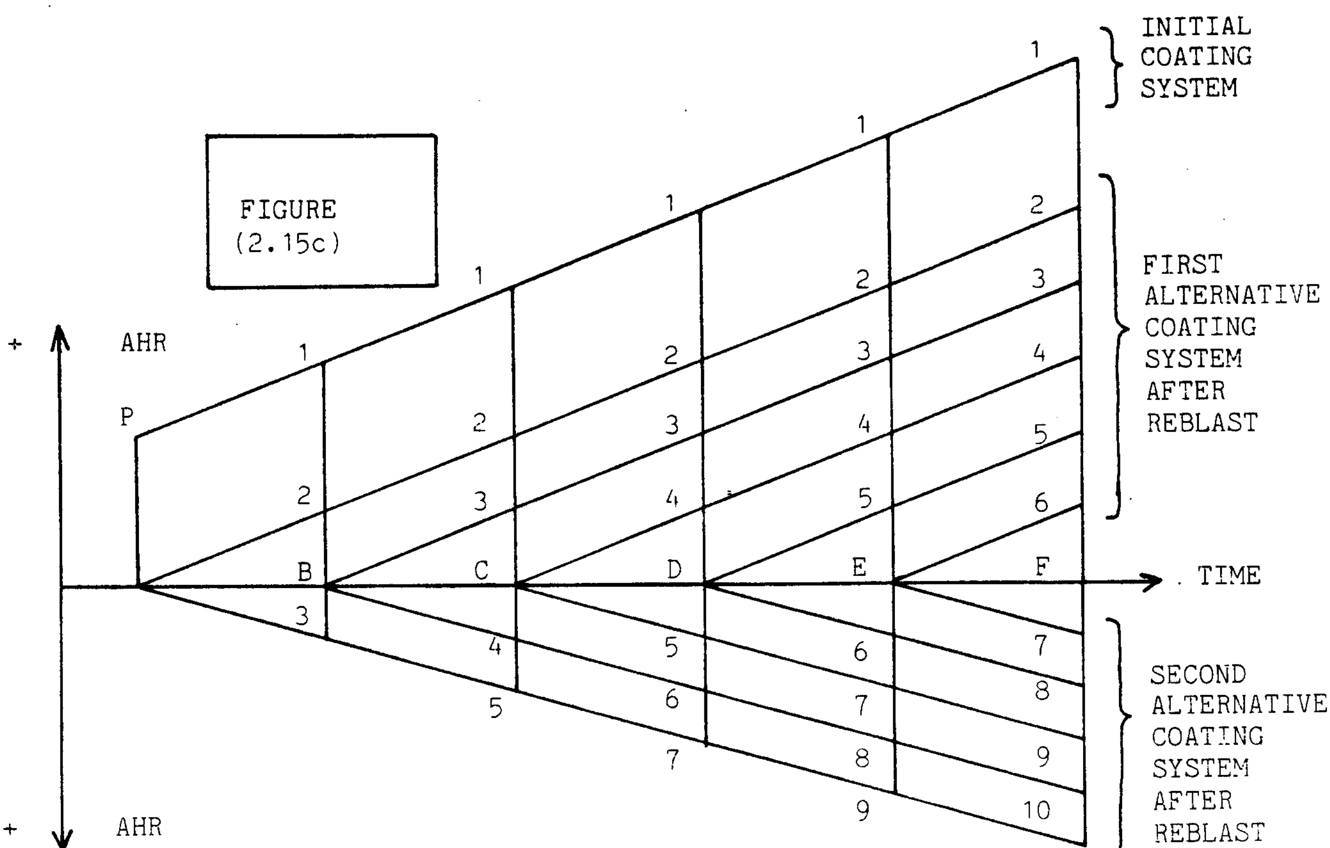


FIGURE (2.15c)

followed by subsequent deterioration at the same rate as before. Different costs will be associated with different courses of action.

In practice, this model represents an over simplified view of the problem; there is no provision for a choice between alternative coating systems, and the initial hull condition is assumed identical to the hull condition after reblast and recoating. Figure (2.15b) presents a first extension to the initial model in the form of a provision for the flexible input of initial hull condition. In addition, the coating system associated with the initial condition may be specified differently from the coating system after reblast with different rates of deterioration, if required. This extends the initial choice of maintenance system, but once the decision has been made to reblast and renew the coating system, the choice at subsequent stages is identical to that of the simple model illustrated in Figure (2.15a). A second and equally important extension is therefore to provide a choice between a minimum of two alternative coating systems in connection with a reblast. This situation is illustrated in Figure (2.15c), where the second alternative has been introduced on a new axis representing hull condition. The new axis is simply a mirror image of the already existing co-ordinate system, with the time axis as basis line. Theoretically, the same principle could be used to introduce any number of alternatives, but for the present study two alternatives are sufficient to achieve compatibility with the deterministic model. In the proposed model three alternative courses of action are made available at every drydocking (or stage).

(1) Simple re-application of the same coating system as used before.

(2) Reblast with application of first alternative coating system.

(3) Reblast with application of second alternative coating system.

For the network illustrated in Figure (2.15c), this gives a total of 81 permissible paths from stage A to E, with the remaining possible paths classified as invalid.

2.3.2 APPLICATION OF DYNAMIC PROGRAMMING TECHNIQUES TO THE CHOICE OF HULL MAINTENANCE STRATEGIES

A proposed method of solution to the optimisation problem described in the preceding section has been provided in the form of a dynamic programming model. Dynamic programming is an optimisation technique particularly suitable for problems consisting of a sequence of inter-related decisions. The principles of dynamic programming are described in detail in References (38) and (39). The method is founded on two elementary principles:

(1) By dividing the complete problem into a number of subproblems, the best solution for each subproblem can be obtained and subsequently used to find an optimum solution to the complete problem.

(2) Solutions to subproblems are obtained by starting the evaluations near the end of the complete problem where solutions are trivial.

In practice, the most difficult part of obtaining solutions to real problems using dynamic programming methods is related to the problem definition, including the identification of stages and states and selection of the correct optimising criterion. The solution procedure is simple and consists of no more than consecutive evaluations of subproblems, discarding non-optimum paths and building up an optimum path by moving stage by stage from one end of the problem to the other. Two methods of solution exist, forward and backward dynamic programming, where the names identify the direction in which the calculation takes place. The first method yields the optimum path from the initial stage to any selected later stage, while the latter method yields the optimum path from the initial or any intermediate stage to the terminal stage. A particular advantage of the application of dynamic programming methods to a series of inter-related investment decisions is that any combination of invalid paths can be accounted for without alteration of the dynamic programming algorithm, simply by assigning infinitely large cost values to the appropriate paths.

For the present problem illustrated in Figure (2.15c) computational efficiency has been substantially improved by the identification of similarity between subproblems. Three alternative courses of action are made available at every stage and state of the system, but since two out of the three alternatives involve a reblast, the costs and paths followed for these two alternatives are going to be the same irrespective of the state the system is in. The various invalid, valid and identical paths in moving between stages C and D are illustrated in matrix form in Figure (2.16a). From a total of 35 possible paths between stages C and D, the problem has been reduced to the separate evaluation of 7 different subgroups only.

In order to achieve the particular manipulation of the real system into the format described in this section a number of specific assumptions have been made. The drydocking interval has to be the same for all three

FIGURE (2.16a)
SUBGROUPS FROM
C TO D

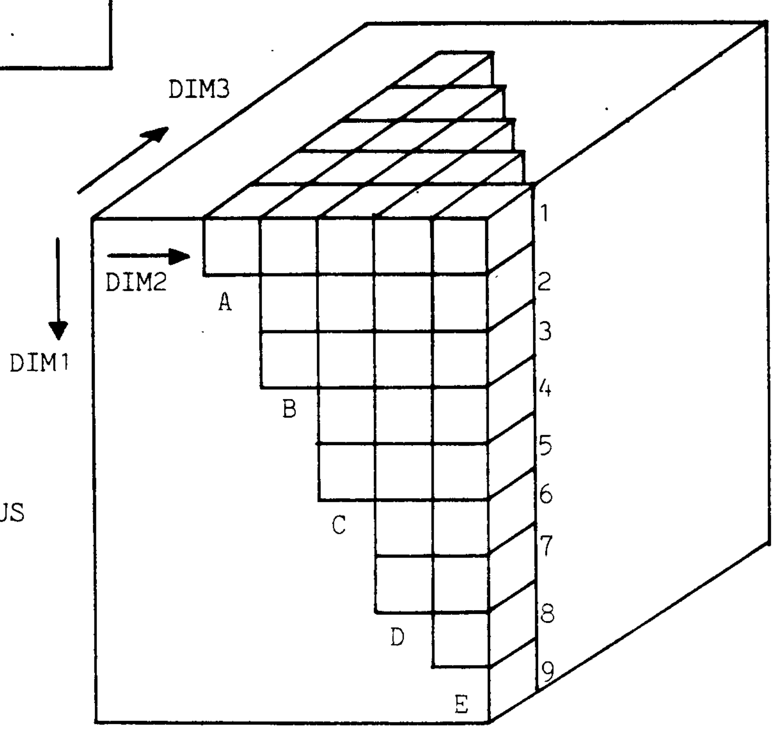
TO \ FROM	C1	C2	C3	C4	C5
D1	C_{11}	*	*	*	*
D2	*	C_{22}	*	*	*
D3	*	*	C_{33}	*	*
D4	C_{41}	C_{42}	C_{43}	C_{44}	C_{45}
D5	C_{51}	C_{52}	C_{53}	C_{54}	C_{55}
D6	*	*	*	C_{64}	*
D7	*	*	*	*	C_{75}

* = NON VALID PATHS

$C_{41} = C_{42} = C_{43} = C_{44} = C_{45}$

$C_{51} = C_{52} = C_{53} = C_{54} = C_{55}$

FIGURE (2.16b)
3-DIMENSIONAL
ARRAY "PATH"



D1M1=STATES

D1M2=STAGES

D1M3=PREVIOUS
STATES

systems under consideration, otherwise the network of paths illustrated in Figure (2.15c), and the method of solution using dynamic programming is no longer valid. In addition, the interval between drydockings must be specified as multiples of 12 months. This is to enable the existing deterministic model to be used for the evaluation of subgroups. The assumption is also made that the hull condition after reblast and recoat is the same irrespective of the coating system used or the hull condition prior to the reblast, and no change from one coating system to another is permitted without a complete reblast of the underwater hull. Reblast is here used as a general description for a method of roughness removal and adequate surface preparation applicable to all three alternative coating systems. Apart from this set of constraints, the flexibility in the specification of individual variables is the same as for the deterministic model.

Procedures for backward as well as forward dynamic programming have been designed. Intermediate optimal paths are presented in addition to the optimum path between the initial and terminal stages. A number of possible states exist at the terminal stage, and the particular state of the system at this point in time depends on decisions made at earlier stages. In other words, later stages are not independent of earlier ones, and the standard forward dynamic programming routine is invalid for this problem. As an alternative method of obtaining a forward solution, the optimum path between the initial stage and each possible state in the terminal stage has been calculated.

The optimising criterion used for both methods is net present value. From the three different measures of merit used in the deterministic model, only net present value is additive and can be used as a criterion to build up an optimum solution from the best solutions of a series of subproblems. Discounted profit to investment ratio and internal rate of return are more complicated to use, and the latter in particular requires an iterative solution procedure making it an impractical optimising criterion for a dynamic programming problem. The following section presents the algorithm of the dynamic programming procedures in more detail.

2.4 PROCEDURES FOR DYNAMIC PROGRAMMING OF OPTIMUM MAINTENANCE STRATEGIES

2.4.1 PROCEDURE "BWDDP" FOR OBTAINING BACKWARD SOLUTIONS

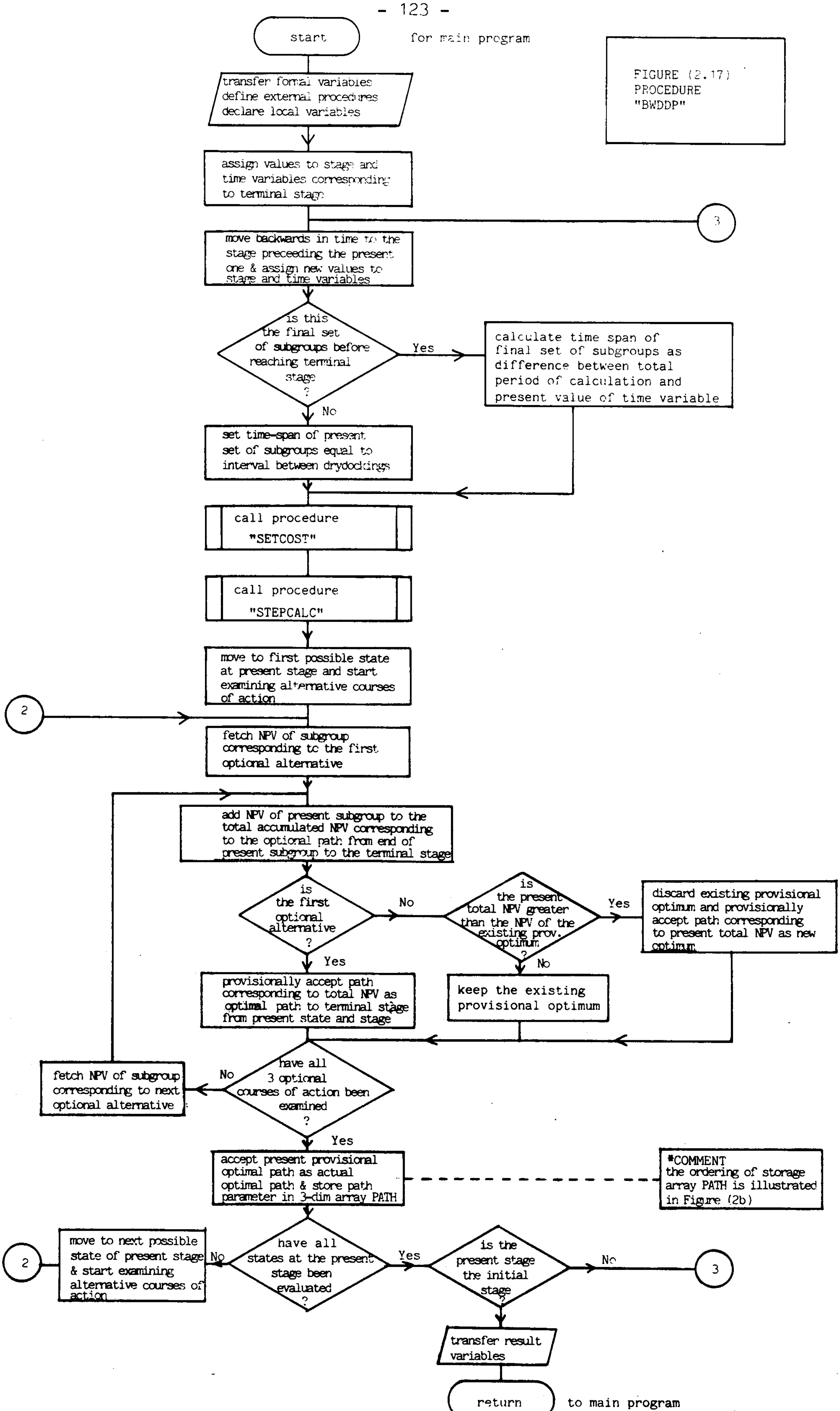
This procedure performs a backward dynamic programming on a network of the form illustrated in Figure (2.15c), starting with a single possible state at the intital stage and with a number of optional states at the terminal stage. From the earlier definition of states the terminal stage is in fact not a stage but the end point of the final set of subgroups extending in time from the start of the last drydocking to the end of the total calculation period. However, for this particular situation the labels stage and state are used slightly outside their original definition, in order to identify the terminal points of the various alternative paths in the problem. The time span of each set of subgroups is the same over the complete period of calculation, except for the final set of subgroups which are allowed to be shorter in time provided their lengths remain a multiple of 12 months.

The starting point of the calculations is the start of the final set of subgroups, or in other words, the stage preceeding the terminal stage. Time variables controlling the exact point in time and the advancement between stages respectively are assigned values corresponding to the starting point, and the procedure "SETCOST" is called to update all cost variables in accordance with the value of the time variable. The procedure "STEPCALC" is subsequently called to calculate the net present value of each valid subgroup corresponding to the present stage. As an example, the valid, identical and invalid paths between stages C and D of Figure (2.15c) are illustrated in Figure (2.16a). Having called "STEPCALC", the net present value of each subgroup now represents the cost of following the path associated with this particular subgroup between the present stage and the terminal stage.

Three alternative courses of action represented by three different subgroups are available at every state of the present stage. The analysis takes the form of comparing the net present value of the three alternatives in turn, and retaining the one with the highest net present value as the optimum decision path between the present state and stage and the terminal stage, while the remaining two alternatives are permanently discarded from the analysis. This procedure is repeated for every state of the present stage, yielding a single optimum path to be remembered for each state. Parameters for the identification of the optimum path are stored in the 3-dimensional array PATH illustrated in Figure (2.16b). Dimensions one and two represent states and stages respectively, while the third dimension is used to store in integer form the optimum path to the terminal stage, where each integer denotes states at subsequent stages.

Having completed the evaluation of states for the present stage, the calculations are subsequently moved backwards in time to the preceeding state, where time and state variables are first updated followed by a new call of the procedures "SETCOST" and "STEPCALC", to obtain net present values for all valid subgroups associated with the new present stage. Each state is again examined in turn, but now the new present value of each optional alternative is added to the total accumulated net present value corresponding to the optimum path from the end of the present subgroup to the terminal stage, and the optimum is judged on the basis of the total NPV. For every possible state a single optimum path to the terminal stage is remembered using the array PATH.

The same sequence of evaluations is repeated for every stage by moving backwards in time from one stage to the next. For every stage the number of possible states are reduced by two until the initial stage with only one possible state is reached, and the problem of evaluating an optimum maintenance strategy has reduced to a simple comparison between three alternative courses of action. Results are output using the procedure "BWDANS". Stages are labelled in alphabetical order, starting with A for the initial stage, and states at every stage are identified in numerical order as shown in Figure (2.15c). The logic flow of the procedure is illustrated in Figure (2.17).


start
for main program
FIGURE (2.17)
PROCEDURE
"BWDDP"
transfer formal variables
define external procedures
declare local variables
assign values to stage and
time variables corresponding
to terminal stage
3
move backwards in time to the
stage preceeding the present
one & assign new values to
stage and time variables
is this
the final set
of subgroups before
reaching terminal
stage
?
Yes
calculate time span of
final set of subgroups as
difference between total
period of calculation and
present value of time variable
No
set time-span of present
set of subgroups equal to
interval between drydockings
call procedure
"SETCOST"
call procedure
"STEPCALC"
move to first possible state
at present stage and start
examining alternative courses
of action
2
fetch NPV of subgroup
corresponding to the first
optional alternative
add NPV of present subgroup to the
total accumulated NPV corresponding
to the optional path from end of
present subgroup to the terminal stage
is
the first
optional
alternative
?
No
is
the present
total NPV greater
than the NPV of the
existing prov.
optimum
?
Yes
discard existing provisional
optimum and provisionally
accept path corresponding
to present total NPV as new
optimum
Yes
provisionally accept path
corresponding to total NPV as
optimal path to terminal stage
from present state and stage
No
keep the existing
provisional optimum
fetch NPV of subgroup
corresponding to next
optional alternative
No
have all
3 optional
courses of action been
examined
?
Yes
accept present provisional
optimal path as actual
optimal path & store path
parameter in 3-dim array PATH
*COMMENT
the ordering of storage
array PATH is illustrated
in Figure (2b)
2
move to next possible
state of present stage
& start examining
alternative courses of
action
No
have all
states at the present
stage been
evaluated
?
Yes
is the
present stage
the initial
stage
No
3
transfer result
variables
return
to main program

2.4.2 PROCEDURE "FWDDP" FOR OBTAINING FORWARD SOLUTIONS

This procedure provides an alternative dynamic programming solution to the network illustrated in Figure (2.15c). In principle, the two procedures "BWDDP" and "FWDDP" are similar. Both are based on the same principle of dividing the complete problem into a series of subgroups which are evaluated separately, and a complete solution is built up step by step starting from one end of the problem. The difference is in the direction in which an optimum solution is achieved.

In the procedure "FWDDP", the starting point of the calculations is the initial stage, and the objective is to find the optimum path between the initial and any future stage. As a result of later stages not being independent of earlier ones, this objective function has been modified to include the separate evaluation of optimum paths between the initial stage and all possible states at future stages. Backward dynamic programming therefore is the preferred method of obtaining a single optimum solution for the present problem, while forward dynamic programming is used to obtain quantitative information about alternative paths between the initial and terminal stage for comparison purposes.

A flow diagram of the procedure is presented in Figure (2.18). Evaluation in the forward direction takes the form of comparing alternative paths to all possible states at a particular stage. Only the alternative with the highest net present value is retained, while the remaining non-optimum paths are permanently discarded from the analysis. The number of valid paths to a particular state varies with the state as well as the stage. If the decision at the previous stage was to reblast

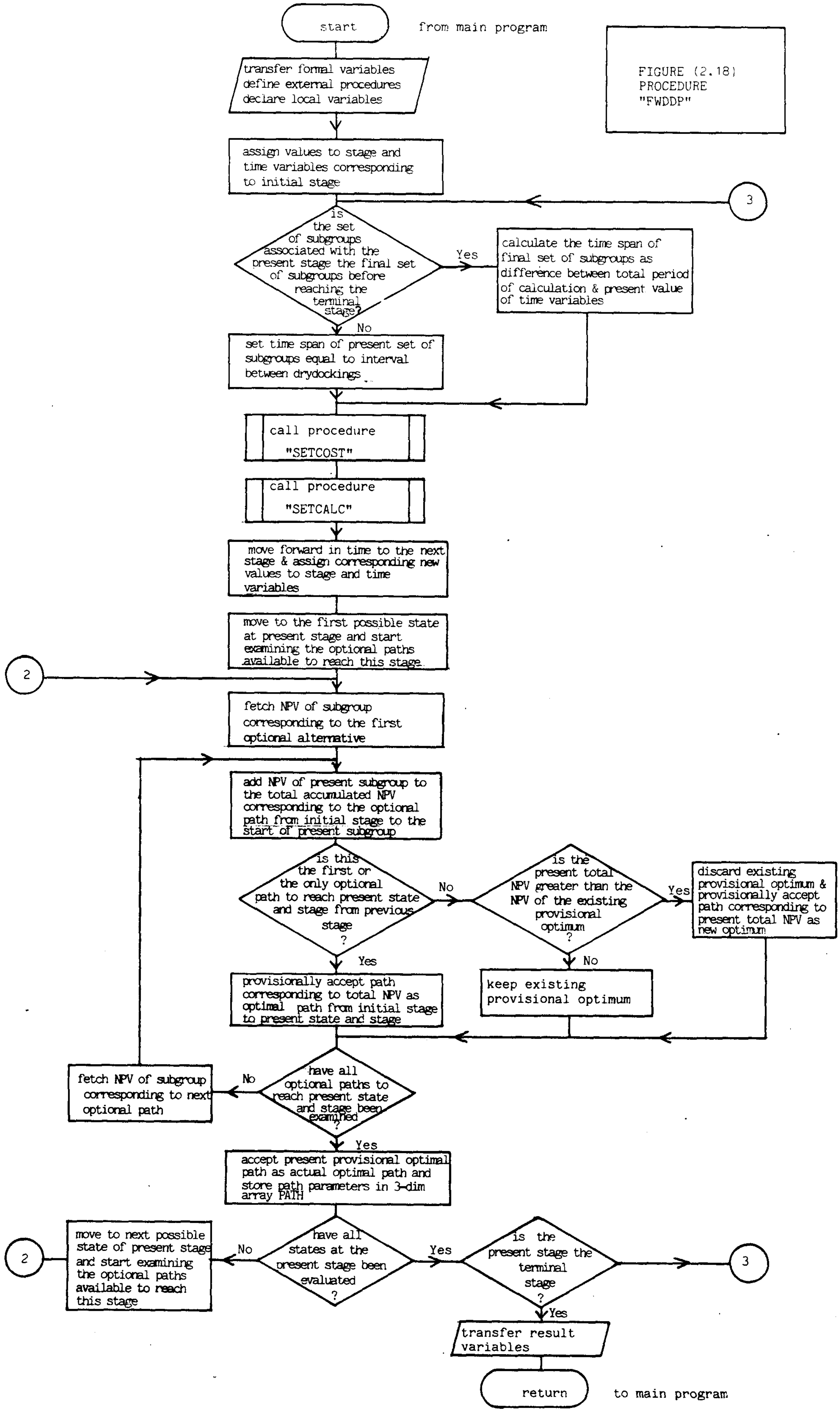


FIGURE (2.18)
PROCEDURE
"FWDDP"

and renew the coating system, then a number of possible paths to the present state and stage exist, otherwise only one valid path exists, and this by default becomes the optimum. The calculations are advanced forward stage by stage from the initial first stage until the terminal nth. stage is reached. At this point in time (2n-1) possible states exist, and the forward dynamic programming method yields a single optimum path to each one of these states. The best of the (2n-1) sub-optimum paths is identical to the single optimum path calculated using the procedure "BWDDP". Results are output using the procedure "FWDANS", where stages and states are identified in the same alphabetical and numerical order as used in connection with the forward dynamic programming method.

2.4.3 PROCEDURES "STEPCALC", "STEP1", "STEP2" AND "SETCOST"

The procedure "STEPCALC" has the function of calculating in net present value terms the economic results for all valid subgroups associated with a particular stage. For practical reasons the actual calculations are subdivided into two further procedures, "STEP1" AND "STEP2", which are both called from the procedure "STEPCALC".

Both procedures "STEP1" and "STEP2" are simple routines for performing a deterministic calculation of the total net present value, excluding capital charges, for a single alternative over the period of time covered by the subgroup. The two procedures are essentially a simplified version of the main economic program, "ECOMAIN", using the single alternative maintenance option only, and no flow diagram is therefore provided. A total of three different optional coating systems may be included, each with different specification of hull deterioration and cost of maintenance in drydock. The procedure "STEP1" is designed to handle subgroups associated with the initial system present at the starting point of the calculation and one optional system, while "STEP2" handles the subgroups associated with the remaining optional system. Results are output to a two dimensional array of the form illustrated in Figure (2.16a) for subsequent use in the two procedures "BWDDP" and "FWDDP".

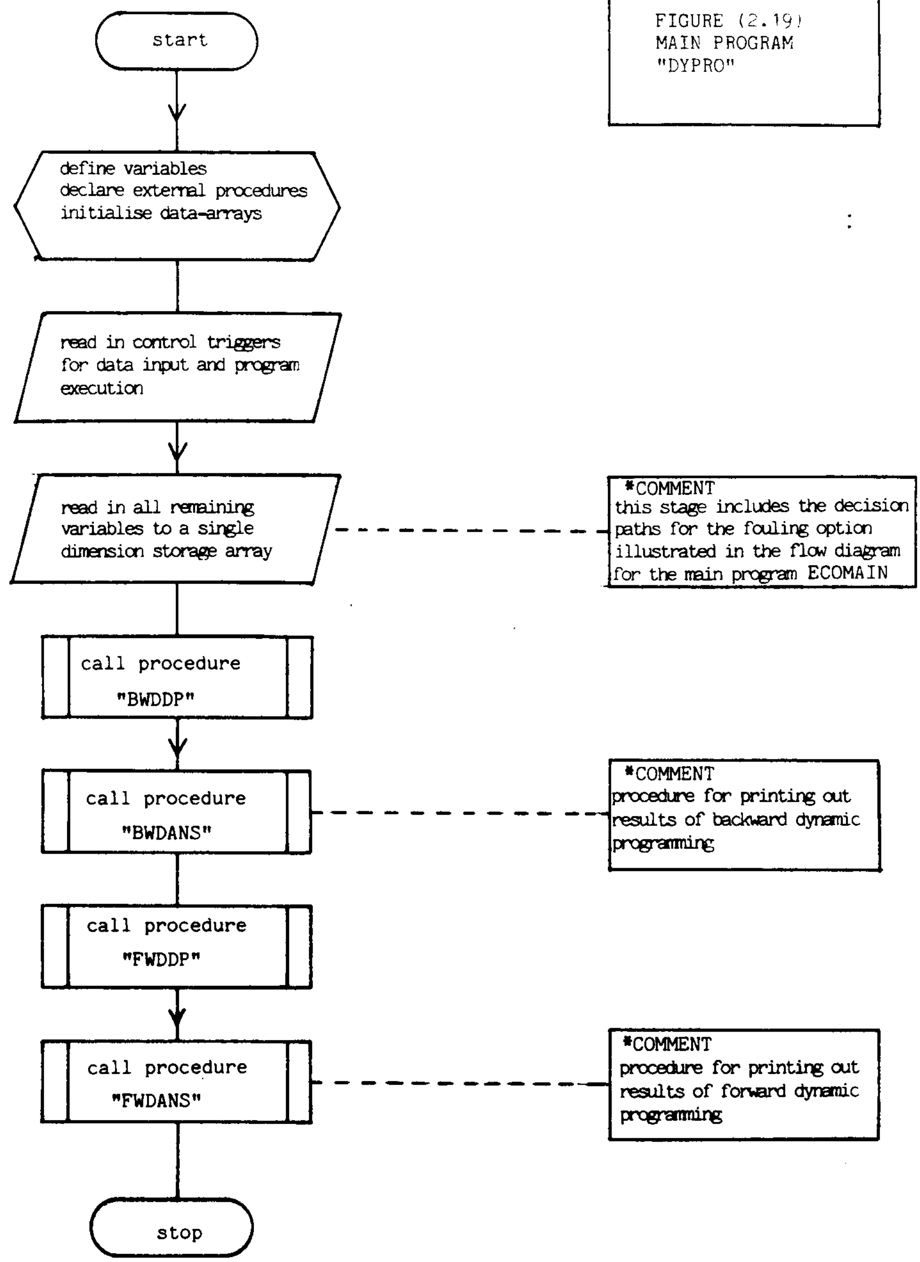
The procedure "SETCOST" is always called immediately before the call of "STEPCALC", and serves the function of updating all cost variables to the appropriate point in time corresponding to the start of the subgroups.

2.4.4 MAIN PROGRAM "DY.PRO"

The main program "DY.PRO" essentially consists of commands for reading in the required data, followed by calls of the various routines already described. A flow diagram of the program is provided in Figure (2.19). All data values are input directly into a one-dimensional array in order to simplify transfer and updates between stages in the dynamic programming algorithm. For practical reasons the input data file is maintained the same as for the deterministic techno-economic model, "ECOMAIN", with the result that some of the variables are redundant in the present model. Further details of variable descriptions are provided in Appendix D.

A total number of three alternative coatings and maintenance systems, including the system already in use at the starting point of the calculations, may be specified with each program run. Each system may be

FIGURE (2.19)
MAIN PROGRAM
"DYPRO"



associated with a different set of variable specifications including rates of deterioration in hull condition in service and in drydock, individual system costs, time periods required for drydocking and optional fouling specifications. The starting point of the calculations may correspond with a drydocking or any intermediate point in time between drydockings. Despite this high degree of flexibility with a selcted group of variables, constraints still exist as a result of the real system having been manipulated into a format, which is compatible with the dynamic programming algorithm. A principal restriction arises from the fact that intervals between drydockings can not be specified differently for alternative coating systems within the same program run. This problem can be overcome in practice by repeating the calculations for different drydocking intervals and assigning high cost values to coating systems for which longer drydocking intervals are not valid. A further minor point of difference exists between the deterministic model and the dynamic programming model in the definition of the interval between drydockings. This is defined as the period of time between the completion of one drydocking to the start of the next drydocking in the deterministic model, while in the dynamic programming model the manipulation of the real system into a formal structure for subsequent analysis, has required the drydocking interval to be re-defined to include the time spent in drydock to correspond with the definition of subgroups, as explained earlier. As a result the net present values from the two models may be different in absolute terms, but this is of no importance when comparing alternatives.

Despite the shortcomings mentioned, sufficient flexibility exists to provide a practical search method for finding maintenance strategies of principal interest based on a net present value optimising criterion.

Applications of the dynamic programming model to the evaluation of alternative maintenance strategies for different ship types are demonstrated in Chapter 3.

CHAPTER 3

CASE STUDIES OF MAINTENANCE

3.1 INTRODUCTION

During the early stages of this project, working contacts were established with a number of shipowners. The purpose of establishing these contacts was to obtain actual technical, operational and financial data for input to techno-economic case studies. Initial contact included selection of suitable vessels and collection of the basic data required for some preliminary case study evaluations. These first results served as a basis for the owner to re-examine the initial variable specifications, in particular, those relating to operational assumptions and alternative hull maintenance strategies. A dialogue was thus established and the data re-adjusted until a satisfactory representation of the actual vessel operation was achieved. With one owner in particular, this working relationship has extended beyond the initial areas of hull maintenance to include also other energy saving investments, and thereby provided a basis for demonstrating the versatility of the techno-economic model for evaluating investments other than hull and propeller maintenance. The results of some of these findings are presented in Reference (40). The principal contacts have included owners in Scandinavia, the United Kingdom and the United States with the European owners operating under national flags and the United States owner under a Liberian flag

During this search for suitable data for use in the techno-economic case studies, it was found that a surprisingly large number of owners were in possession of little or no basic technical information about their own ships, except for general machinery and equipment specifications. In the majority of cases, no model test reports were available, and new ship trials were found nearly always to have been performed in a partly laden condition, over an inadequate speed range and without appropriate corrections for external factors such as ocean currents and weather. The task of obtaining the required information for the series of case studies was therefore found to be very difficult and time consuming.

From the 8 to 10 ship types initially explored, a final group of 4 vessels were chosen for presentation in the formal analysis. These are:

Ship "A"	-	a 37000 tdw PARCEL TANKER
Ship "B"	-	a 3000 teu CONTAINER VESSEL
Ship "C"	-	a 350000 tdw OIL TANKER
Ship "D"	-	a PANAMAX BULK CARRIER

The choice was made primarily on the grounds of available information, but did also include considerations for obtaining a representative sample of the World's commercial deep-water fleet. The 350,000 tdw oil tanker represents a substantial part of the World fleet in deadweight terms.

Equally important is the fact that the large oil carriers represent a major part of the market for the advanced self polishing coating systems. The 37,000 tdw parcel tanker is a typical example of a small tanker, either as a parcel tanker for chemicals or the more common carrier of refined petroleum products. The Panamax bulk carrier represents the presently most popular size in the bulk carrier range, while the large container vessel has been chosen to represent an important, but completely different part of the commercial shipping fleet as a high speed volume carrier normally operating within the protected environment of a Liner Conference. In terms of operating speed, the 4 ship types cover a range of approximately 10 knots. The large oil carrier will, in the present market conditions, be operating at a laden speed in the region of 12 knots. The two remaining bulk vessels in the speed range 14-16 knots, and the container vessel at a speed of 20-22 knots. A further point of some importance is that the 3 deadweight carriers are operated at constant power, while the container ship essentially follows a constant speed operation, where the speed is determined from consideration of specified arrival times in each port. As discussed in Chapter 2, the definition of constant speed or constant power operations is important from the point of view of whether an added resistance due to, for example, hull roughness is going to be expressed in terms of an increase in the power requirement of the vessel or a decrease in the operating speed. An increase in the power requirement is simply transformed into an increased fuel consumption and can easily be directly measured in economic terms. The reduction in operating speed on the other hand results in fewer roundtrips per annum and therefore a loss in income. This can only be calculated with knowledge of the commercial factors involved. Most of the World's deep sea fleet can be classified as deadweight carriers, which are essentially operated at constant power. The need for evaluating the problems associated with alternative hull maintenance strategies within the full commercial context of the vessel operation is thus clearly demonstrated.

The principal objectives of performing a series of case studies have been defined as follows:

1. Demonstrate the use of the techno-economic model which has been developed.

2. Obtain some general conclusions with respect to the hull maintenance strategies which should be adopted for a selected set of ship types.

3. Identify the principal variables associated with the evaluation of optimum hull maintenance strategies.

4. Provide guidelines for the direction of further study of the techno-economic aspects of hull maintenance beyond the simple deterministic evaluation of selected alternatives.

5. To develop a simplified method based upon a set of general curves, which can be used by the shipowner or operator who is not in possession of advanced techno-economic tools, but with ships similar to those used in the present studies, for the purpose of evaluating in economic terms the principal alternatives available in a programme of improved hull maintenance.

As shown in Chapter 2 , the number of variables involved in a complete evaluation of two alternative hull maintenance strategies employing the present deterministic techno-economic model exceeds 100. Clearly, the majority of these variables will for each vessel type have to remain fixed throughout the series of case studies, and only a limited number of the parameters relating to the different alternative maintenance strategies can be allowed to vary. Each case study can, in other words, be regarded as a two-dimensional plane in the multi-dimensional space, and the conclusions drawn must be seen in relation to the constraints imposed by the fixed variables.

However, by carefully designing each case study so that only one alternative course of action is explored at a time, and by selecting a common basis of evaluation for all case studies, it is possible to build up a series of alternatives, which in economic terms are additive and from which a number of complete "strategies" can be explored. This will greatly extend the usefulness of a set of individual case studies.

From this background it was decided to investigate the following major courses of action:

1. Complete reblast, but no change in coating system

2. The economic effects of returning to different levels of average hull roughness after reblast (which will be independent of the coating system used).

3. The economic effects of delaying a complete reblast.

4. Comparison between conventional and advanced self polishing coating systems with different assumptions about roughness increase with time.

5. The economic effects of extending the time period between drydockings.

6. A general investigation into the economic effects of hull fouling.

All these alternative case studies are based upon the use of a paint system for the protection of the hull surface against corrosion and fouling. In certain industrial applications where painting of the steel surfaces is not possible, a steel clad with copper-nickel alloy has been used to provide a permanent protection. This method has recently also been presented as an alternative hull maintenance strategy, whereby the ship would be built with copper-nickel clad plating, and no further hull maintenance would be necessary over the lifetime of the vessel. From the economic point of view, this is an extreme alternative where a complete hull maintenance over the lifetime of the vessel is purchased with a single capital outlay at the start of the project. The few case studies which have hitherto been presented for this particular alternative have been deficient in several respects, both technically and in the economic methods employed. This alternative to hull maintenance is therefore included as a separate case study to investigate whether it is in fact a serious challenger to present day paint systems.

As a conclusion to the set of deterministic case studies, a sensitivity analysis is presented for each ship type under consideration. The various problems associated with the interpretation of results from a sensitivity analysis will be described in Chapter 4 . Despite these shortcomings, the sensitivity analysis has been found to be a useful method by which to investigate the effects upon the economic measure of merit of altering by a certain amount some of the parameters assumed fixed throughout the calculations. Furthermore, the sensitivity analysis will help to identify the most important variables associated with the selection of hull maintenance strategies, and which consequently will require the most accurate specification at the input stage. The sensitivity analysis will also provide a basis for the selection of variables which should be included in the more advanced analysis of uncertainty in Chapter 4.

3.1.1 CASE STUDY SPECIFICATIONS

This section summarises the basic technical, operational and financial information for each of the ship types chosen for the case study evaluations For reasons of confidentiality, some of the financial information can not be disclosed and is therefore presented in terms of ratio, where the initial figure has been divided by a standard "coding constant" number, known by the author only. A further precaution for maintaining confidentiality has been taken by adding together crew costs, upkeep costs (excludng costs associated with hull maintenance), and fixed costs (including insurance and administration). Specific costs related to hull maintenance are presented separately at the beginning of each case study. The costs associated with the various items in a maintenance specification are taken from Appendix B, in which the results of an up-to-date survey of hull maintenance costs are presented.

3.1.1.1 SHIP A: 3,000 teu CONTAINER VESSEL

Technical Data

Ship speed (laden condition)	=	21.0 knots
Ship speed (ballast or part laden) condition	=	(21.0 knots)
Main engine power corresponding to speed specifications	=	22,320 kw
Exponent to speed-power curve in the range 19-23 knots	=	2.990
AHR corresponding to speed-power data	=	125 μm
Specific fuel consumption of main engine	=	218 g/kWhr (H.V.F.)
Exponent to specific fuel consumption curve	=	0
Auxiliary fuel consumption at sea	=	14.0 t H.V.F. equivalent per day
Total fuel oil consumption in port	=	9.0 t H.V.F. equivalent per day
Quasi propulsive coefficient	=	0.65
Wetted surface area in laden condition	=	11,000 m^2
Wetted surface area in ballast condition	=	(11,000 m^2)
Ship length (between perpendiculars)	=	274.3 m

Operational Data

Maximum cargo carrying capacity	=	2,687 TEU
Loadfactor	=	confidential
Roundtrip distance		22,000 n. miles
Proportion of roundtrip distance spent in laden condition	=	100%
Number of portdays per roundtrip	=	18.0 days

Financial Data

Annual crew costs	=	$1,370,000* (crew, upkeep and fixed costs combined)	Annual escalation = 10%
Annual upkeep costs	=		Annual escalation = 10%
Annual fixed costs	=		Annual escalation = 10%
Fuel cost (per tonne)	=	$ 185	Annual escalation = 10%
Port charges (per roundtrip)	=	$ 460,000	Annual escalation = 10%
Cargo handling charges (per unit)	=	$ 369*	Annual escalation = 10%
Freight rate per unit	=	$ 777*	Annual escalation = 10%
Discount rate for economic calculations	=	17.5%	in money terms

(*) The true figure has been divided by a coding constant to protect confidential information.

Miscellaneous Data

Constant speed operation is assumed

Cargo payload remains constant throughout the roundtrip, hence constant draught condition.

The ITTC correlation formula for hull roughness is used to transform roughness values into power increments, but the values are discounted by 40% in accordance with the conclusions of Chapter 1.

3.1.1.2 SHIP B: 37,000 tdw PARCEL TANKER

Technical data

Ship speed (laden co dition)	=	15.72 knots
Ship speed (ballast or part laden condition)	=	17.03 knots
Main engine power corresponding to speed specifications	=	9000 kw
Exponent to the speed-power curve in the range of 14-17 knots	=	3.90

AHR corresponding to speed-power data	=	125 μm
Specific fuel consumption of main engine	=	218g/kWhr (H.V.F.)
Exponent to the specific fuel consumption curve	=	0
Auxiliary fuel consumption at sea	=	9.25 t H.V.F. equivalent per day
Total fuel oil consumption in port	=	14.0 t H.V.F. equivalent per day
Quasi propulsive coefficient	=	0.71
Wetted surface area in laden condition	=	7400 m^2
Wetted surface area in ballast or part laden condition	=	5650 m^2
Ship length (between perpendiculars)	=	169.0 m

Operational Data

Maximum cargo payload	=	34000 t
Loadfactor	=	0.5
Roundtrip distance	=	10664 n. miles
Proportion of roundtrip distance spent in laden condition	=	53.7%
Number of portdays per roundtrip	=	15.2 days

Financial Data

Annual crew costs	=	$1,178,000*	Annual escalation = 10%
Annual upkeep costs	=		Annual escalation = 10%
Annual fixed costs	=		Annual escalation = 10%
Fuel cost (per tonne)	=	$ 185	Annual escalation = 10%
Port charges (per roundtrip)	=	$ 80,000	Annual escalation = 10%
Cargo handling charges	=	0	

Accumulated freight rate per roundtrip	=	$ 14.80*	Annual escalation = 10%
Discount rate for economic calculations	=	17.5%	in money terms

(*) The true figure has been divided by a coding constant to protect confidential information.

Miscellaneous Data

Constant power operation is assumed (85% MCR)

The ITTC correlation formula for hull roughness is used to transform roughness values into power increments, but the values are discounted by 40% in accordance with the conclusions of Chapter 1 .

3.1.1.3 SHIP C: 350,000 tdw OIL TANKER

Technical Data

Ship speed	=	12.0 knots
Ship speed (ballast or part laden condition)	=	13.23 knots
Main engine power corresponding to speed specifications	=	12,848 kW
Exponent to the speed-power curve in the range 11-15 knots	=	2.910
AHR corresponding to speed-power data	=	125 μm
Specific fuel consumption of main engine	=	339g/kWhr
Exponent to the specific fuel consumption curve	=	-0.3873
Auxiliary fuel consumption at sea	=	0
Total fuel oil consumption in port	=	36 t H.V.F. per day
Quasi propulsive coefficient	=	0.64
Wetted surface area in laden condition	=	31,300 m^2

Wetted surface area in ballast or part laden condition	=	18,400 m^2
Ship length (between perpendiculars)	=	350 m

Operational Data

Maximum cargo payload	=	343,000 t
Loadfactor	=	0.5
Roundtrip distance	=	17,605 n. miles
Proportion of roundtrip distance spent in laden condition	=	63.44%
Number of portdays per roundtrip	=	6.0

Financial Costs

Annual crew costs	=	\$ 971,000*	Annual escalation = 10%
Annual upkeep costs	=		Annual escalation = 10%
Annual fixed costs	=		Annual escalation = 10%
Fuel cost (per tonne H.V.F.)	=	\$ 185	Annual escalation = 10%
Port charges	=	\$ 515,000	Annual escalation = 10%
Cargo handling charges (per tonne)	=	\$ 0.16	Annual escalation = 10%
Freight rate (per tonne)	=	\$ 6.309	Annual escalation = 10%
Discount rate for economic calculations	=	17.5%	in money terms

(*) The true figure has been divided by a coding constant to protect confidential information.

Miscellaneous Data

Constant power operation is assumed, slow steaming at 43.5% MCR

The ITTC correlation formula for hull roughness is used to transform roughness values into power increments, but the values are discounted by 40% in accordance with the conclusions of Chapter 1.

3.1.1.4 SHIP D: PANAMAX BULK CARRIER

Technical Data

Ship speed (laden condition)	=	15.0 knots
Ship speed (light ballast condition)	=	16.75 knots
Main engine power corresponding to speed specification	=	9,400 kW
Exponent to speed-power curve in the speed range 13-15.5 knots	=	3.216
AHR corresponding to speed-power specifications	=	125 μm
Specific fuel consumption of main engine	=	218g/kWhr
Exponent to the specific fuel consumption curve	=	0
Auxiliary fuel consumption at sea	=	4.0 t H.V.F. equivalent per day
Total oil consumption in port	=	5.0 t H.V.F. equivalent per day
Quasi propulsive coefficient	=	0.66
Wetted surface area in laden condition	=	10,500 m^2
Wetted surface area in ballast condition	=	7,660 m^2
Ship length (between perpendiculars)	=	214.50 m

Operational Data

Maximum cargo payload	=	60,000 t
Loadfactor	=	0.5
Roundtrip distance	=	16,380 n. miles
Proportion of roundtrip distance spent in laden condition	=	64.0%
Number of portdays per roundtrip	=	12.0

Financial Data

Crew costs	=	$1,000,000	Annual escalation = 10%
Upkeep costs	=	$ 500,000	Annual escalation = 10%
Fixed costs	=	$1,500,000	Annual escalation = 10%
Fuel cost (per tonne H.V.F.)	=	$ 185	Annual escalation = 10%
Port charges	=	$ 45,000	Annual escalation = 10%
Cargo handling charges	=	0	
Accumulated freight rate (per tonne)	=	$ 18.00	Annual escalation = 10%
Discount rate for economic calculations	=	17.5% in money terms	

Miscellaneous Data

Constant power operation is assumed (85%MCR)

The ITTC correlation formula for hull roughness is used to transform roughness values into power increments, but values are discounted by 40% in accordance with the conclusions of Chapter 1.

3.1.1.5 STAN DARD HULL MAINTENANCE SPECIFICATION

Paint system cost on a square metre basis are given in Appendix (B)

Annual escalation of paint system costs = 10%

Drydocking charges:	Ship A:	\$20,000 per day for the first two days and \$10,000 per day for subsequent days
	Ship B:	\$ 6,000 per day for the first two days and \$ 3,000 per day for subsequent days
	Ship C:	\$40,000 per day for the first two days and \$20,000 per day for subsequent days
	Ship D:	\$12,000 per day for the first two days and \$ 6,000 per day for subsequent days

Annual escalation in drydocking charges	=	10%
New ship roughness	=	125 μm AHR
Average increase in service	=	1.85 μm per month
Average increase in drydock	=	-0.094 AHR + 37 (μm)
Outdocking roughness after complete reblast	=	125 μm AHR
Standard interval between drydockings	=	24 months
Number of days in drydock for routine	=	Ship A: 10 days
		Ship B: 14 days (*)
		Ship C: 5 days
		Ship D: 7 days

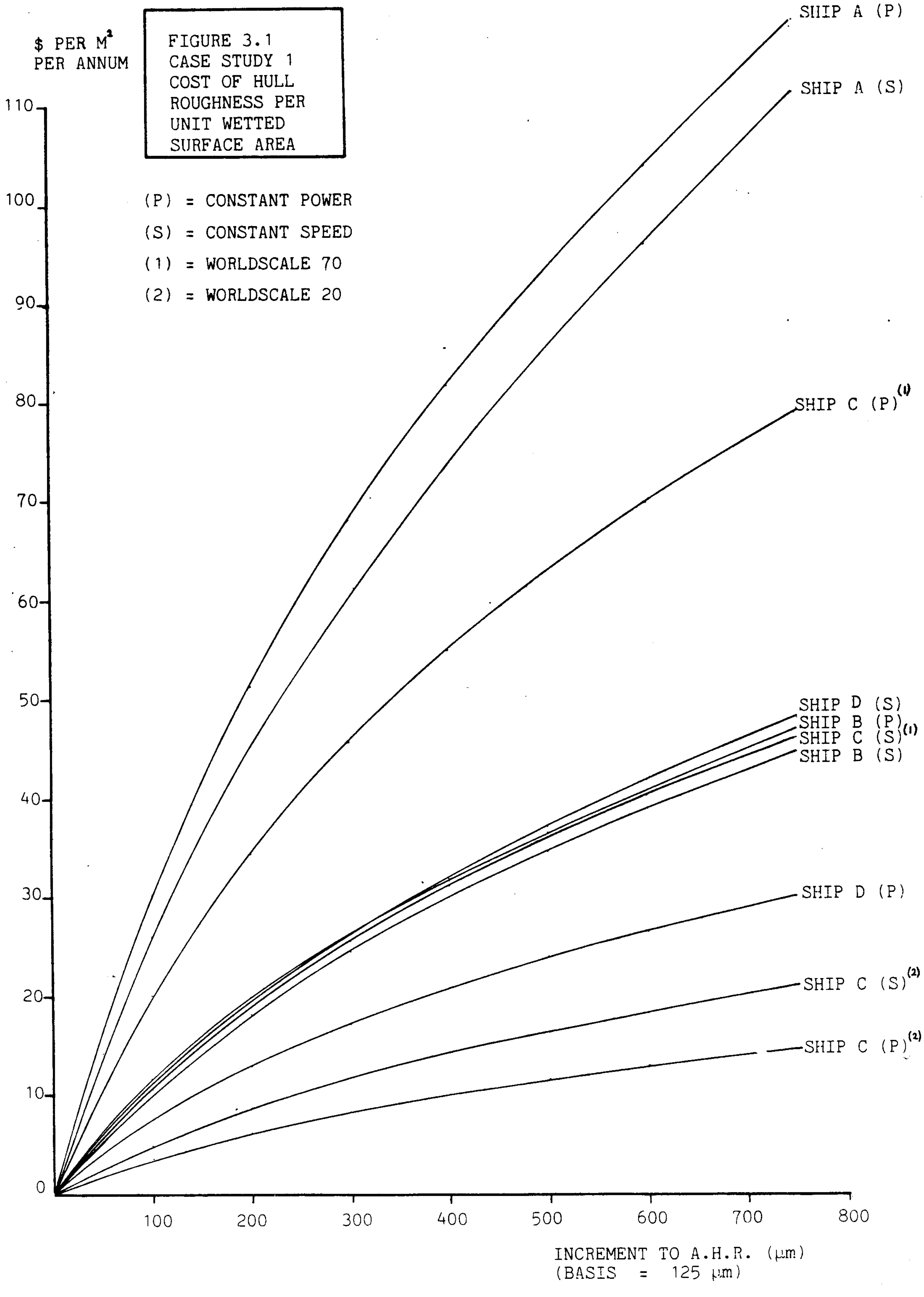
Additional number of days required for complete reblast and renewal system = 5 days

Classification survey is the principal reason for drydocking with drydocking intervals of 24 months or more.
(*) 4 days in drydock, 10 alongside for tank repairs.

3.2 PRINCIPAL HULL MAINTENANCE ALTERNATIVES EXAMINED FOR FOUR SHIP TYPES

3.2.1 CASE STUDY 1: AN EXAMINATION OF THE COST OF ADDITIONAL ROUGHNESS

An introductory study into the evaluation of alternative hull maintenance strategies may be provided by excluding details of maintenance specifications altogether, and simply calculate in net present value terms the cost of additional roughness above a typical new ship AHR of 125 μm for each operational year. Presented as a cost per unit of wetted surface area, this figure will provide a guidance to the maximum annual expenditure which can be justified in economic terms on maintaining the hull surface in the "new" condition. Results of this particular study for the 4 ship types, and based upon the technical, operational and financial information given in Section 3.1.1, are provided in Figure (3.1). To further illustrate the difference between constant speed and constant power operation as discussed in Chapter 2 , the calculations have been performed for both conditions. Figure (3.1) clearly demonstrates the substantial difference in results between different ship types with different operating profiles, and as shown the amount available per unit of wetted surface area for Ship A exceeds that of ship C by a factor of eight at the present levels of fuel price and freight rates. In Figure (3.2) curves of percentage increase in power against increase in roughness above a value of 125 μm AHR are presented for each of the 4 ship types. A simple comparison between the curves presented in Figure (3.1) and those in Figure (3.2), clearly demonstrates the point that the simple calculation of increased power with increasing hull roughness provides



$ PER M²
PER ANNUM
FIGURE 3.1
CASE STUDY 1
COST OF HULL
ROUGHNESS PER
UNIT WETTED
SURFACE AREA
(P) = CONSTANT POWER
(S) = CONSTANT SPEED
(1) = WORLDSCALE 70
(2) = WORLDSCALE 20
SHIP A (P)
SHIP A (S)
SHIP C (P)(1)
SHIP D (S)
SHIP B (P)
SHIP C (S)(1)
SHIP B (S)
SHIP D (P)
SHIP C (S)(2)
SHIP C (P)(2)
0
10
20
30
40
50
60
70
80
90
100
110
100
200
300
400
500
600
700
800
INCREMENT TO A.H.R. (μm)
(BASIS = 125 μm)

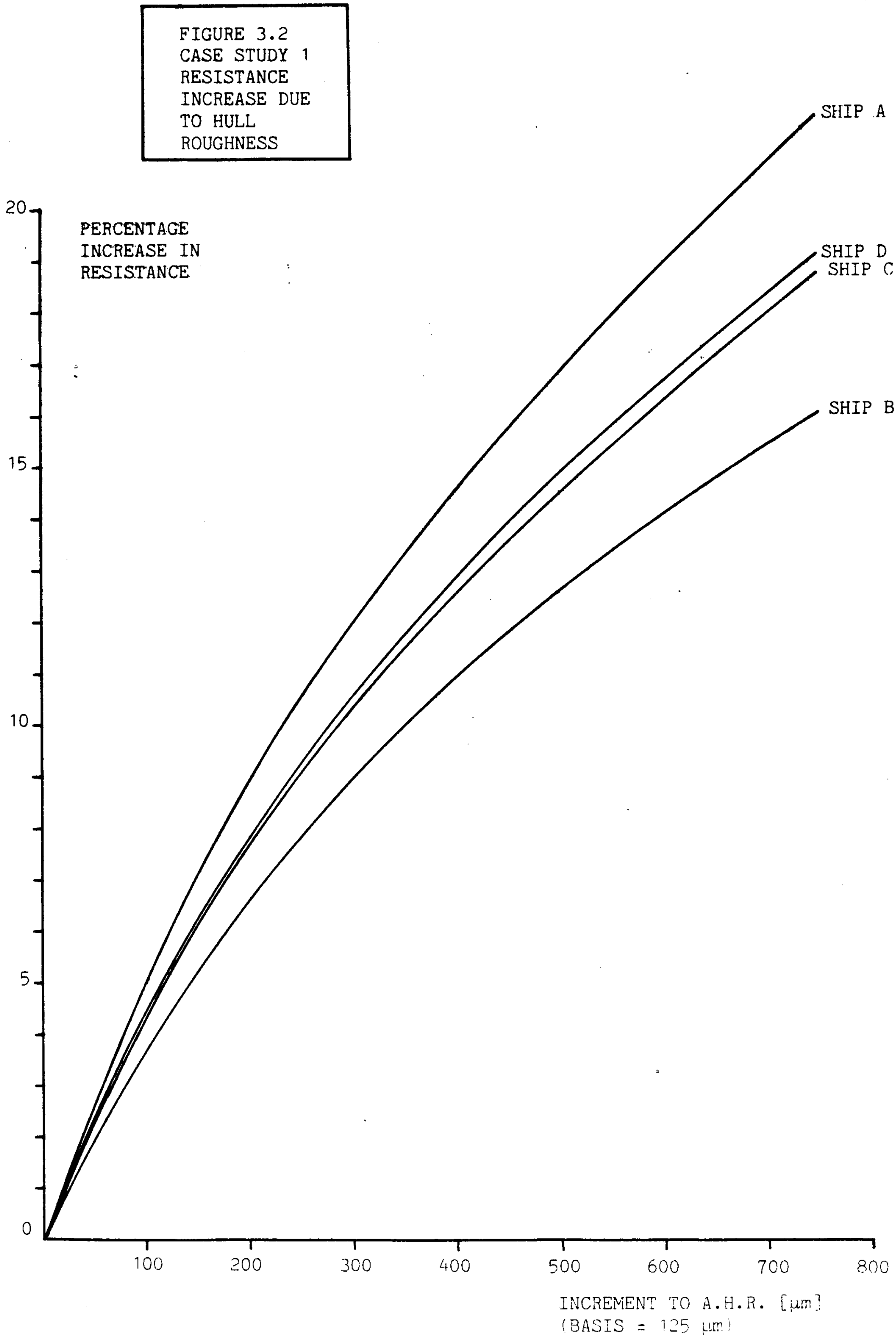


FIGURE 3.2
CASE STUDY 1
RESISTANCE
INCREASE DUE
TO HULL
ROUGHNESS
PERCENTAGE
INCREASE IN
RESISTANCE
SHIP A
SHIP D
SHIP C
SHIP B
20
15
10
5
0
100
200
300
400
500
600
700
800
INCREMENT TO A.H.R. [μm]
(BASIS = 125 μm)

little or no guidance to the problem of estimating the size of the investment which can be justified in economic terms for avoiding this additional roughness.

In the results based upon constant speed operation, the power penalties due to hull roughness have been transformed directly into increased fuel consumption, while in the case of constant power operation, increments in hull roughness results in a loss of speed and consequently a reduction in freight income due to the reduced number of roundtrips in each operational year. This assumption completely ignores any contractual obligations and assumes a free market condition, where the lost annual volume of cargo is taken over by a competitor. If the assumption is made that the loss in revenue due to a reduction in speed can be compensated by increasing the amount of cargo carried on each roundtrip, this indicates that the vessel is already operating at a speed which is too high. In practice, of course, the rigid assumptions imposed in this case study do not always hold. The choice of operating speed, in particular for container vessels, will also be decided from the commercial consideration of providing an efficient service as demanded by the customers. A further observation to be made from Figure (3.1) is the difference in results between constant speed and constant power assumption for the 4 vessels. For Ship A and Ship B, the curves based upon constant speed and constant power are substantially the same. The operation of both vessels is modelled on the basis of a voyage description and freight rate level, giving a moderate operating profit. In the case of Ship C, slow steaming and with freight income at the Worldscale 20 level, and Ship D operating at full speed, but in a depressed freight market with low rates, the cost of hull roughness at constant speed is twice that of the constant power case. The difference can be attributed to the fact that when freight rates are low, the cost of ship's time is also low compared with the cost of fuel for main engine propulsion. The opposite situation can be observed in the curves representing Ship C at full speed and more than adequate freight income at the Worldscale 70 level. Time is now expensive due to the high income which can be earned, and the cost of hull roughness at constant power is therefore substantially higher than for constant speed operation. Having explained the reasons for the difference observed in Figure (3.1), the principal variables which contribute to creating these differences can easily be identified.

They are:

- Annual fuel costs
- Annual net income after deductions for port charges and cargo handling costs
- Seatime ratio (the proportion of the total operating year which is spent at the specified operating speed)

Further analysis resulted in the following approximate formula:

$$\frac{\text{Cost of hull roughness at constant Speed}}{\text{Cost of hull roughness at constant Power}} = 3.1 \times \frac{\text{Daily fuel costs at sea}}{\text{Daily average income after deductions for cargo handling and port charges}}$$

As discussed in Chapter 1, as well as earlier in the present Chapter, most commercial ships are operated at constant power and consequently, for the purpose of calculating the economic effects of hull roughness (and fouling), the more complex method of calculation will be required, whereby the principal commercial factors are also taken into account. Alternatively, if only an approximate answer is required, the above formula provides the basis for a new method in which the economic penalties can first be calculated using the constant speed assumption, and subsequently be transformed into equivalent values at constant power. This calculation procedure incorporates a minimum number of commercial and operational variables.

The results from this first case study of course only provide one side of the equation and a complete evaluation of alternative hull maintenance strategies in economic terms will also have to include the various maintenance options and their associated costs.

3.2.2 JUSTIFICATION FOR THE USE OF A SIMPLIFIED FORMULA FOR CALCULATING THE RATIO BETWEEN THE COST OF AN EXTERNALLY ADDED RESISTANCE AT CONSTANT SPEED AND AT CONSTANT-POWER OPERATION

The proposed simplified formula for calculating the ratio between the cost of additional hull roughness at constant speed and constant power could equally well be expressed as a formula for calculating the ratio between cost of added resistance at constant speed and constant power. Extending the definition from "additional hull roughness" to "added resistance" means that the formula can serve as a tool in the economic evaluation of several types of added resistance.

The proposed formula has been suggested as a simplified method of transforming calculations at constant speed to a basis of constant power, but so far has not been justified. Results are therefore presented of a detailed techno-economic modelling at constant speed and constant power to allow a comparison to be made with the values calculated from the proposed simplified formula. The four different ship types previously selected for the case study evaluations are used, and Ship C is shown under two different operating conditions, first at Worldscale 70 and full speed, and secondly at Worldscale 20 and slow-steaming. This is to demonstrate that the formula works equally well for both conditions. The results are presented in Table(3.1).

TABLE (3.1)

	Ratio from economic modelling (Case Study 1)	Ratio from simplified formula	% Deviation
Ship A	0.90	1.06	+ 17.8%
Ship B	0.93	0.91	- 1.7%
Ship C W20	1.40 (*)	1.47	+ 4.8%
Ship C W70	0.56 (*)	0.58	+ 2.7%
Ship D	1.53	1.64	+ 7.5%

(*) Constant 3.1 modified for steam turbine installations

The formula:

$$\frac{\text{Cost of added resistance at constant speed}}{\text{Cost of added resistance at constant power}} = 3.1 \times \frac{\text{Daily fuel costs at sea}}{\text{Daily average income after deductions}}$$

is restricted to vessels with diesel machinery installations only where main engine power and fuel consumption are roughly proportional. For steam turbine installations the constant 3.1 will have to be multiplied by the absolute value of the ratio between the percentage change in fuel consumption for a given change in power and the corresponding percentage change in power. This ratio will for most steam turbine installations take a value between 0.6 and 0.75 depending on the machinery loading.

3.2.3 CASE STUDY 2.1 : THE COST EFFECTIVENESS OF REBLAST AND RENEWAL OF COATING SYSTEM

Having estimated the cost of additional hull roughness, the first and most obvious case study is to examine the cost effectiveness of removing this additional roughness by means of reblast and complete renewal of the coating system. As discussed in the introduction to this Chapter, one of the principal objectives of performing a series of case studies is to build up a series of maintenance alternatives, which in economic terms are additive, and which therefore can form the basis of a simplified method of evaluating complete maintenance strategies for different ship types. Consequently, only one principal course of action can be explored at a time. In this particular case study of the economic effects of removing hull roughness, the assumption is made that the same coating system with the same average roughness increase in service is used before and after reblast. The two alternatives to be explored are therefore:

<u>ALTERNATIVE 1:</u> complete reblast of underwater hull, build up a new anticorrosive system and recoat with a conventional high performance antifouling paint, according to specification in Table (B-6), Appendix B. The same antifouling paint is also used at subsequent drydockings which take place at 24 month intervals. Outdocking roughness after reblast and recoat = 125 µm AHR

<u>ALTERNATIVE 2:</u> no reblast, reapplication of the same conventional high performance antifouling paint, as used in Alternative 1. Roughness development over future years follows the average specification in Chapter 1.

Technical, operational and financial data for each ship type are specified in Section (3.1.1).

The coating system costs are taken from Table (B-6), Appendix B, and are:

Cost of complete reblast and renewal of conventional coating system	=	\$20.81 per m^2
Cost of conventional re-application	=	\$ 8.17 per m^2

Otherwise the standard hull maintenance specification in Section 3.1.1 applies to all 4 vessels. The same number of additional days required in drydock for a complete reblast and renewal of coating system is used for all ship types. This is because the time required is not principally dependent on ship size, but instead determined by the time required between coats of paint. The operational specifications for Ship B are different from the 3 remaining vessels, in that the additional time out of service at every drydocking for repair of tank coatings exceeds the additional time required for a complete reblast, and no additional out-of-service cost is therefore incurred in Alternative 1. In order to allow a comparison between the 4 vessel types, on an identical basis, an additional calculation was performed for Ship B with a drydocking specification identical to that of Ship D.

The period of calculation covered ranges from 2 to 10 years and the range of present indocking roughness (AHR) is 200 to 800 µm in steps of 100 µm. From discussions with ship owners, clear indications were obtained that investments of this type would normally be considered over a time period of 4 to 6 years, and the range up 10 years is only included for completeness. The results for the 4 different ship types are presented in Figures (3.3) to (3.7) and Tables (C-1) to (C-5) of Appendix C, in terms of difference in net present value between Alternatives 1 and

FIGURE 3.3
CASE STUDY 2.1
SHIP A

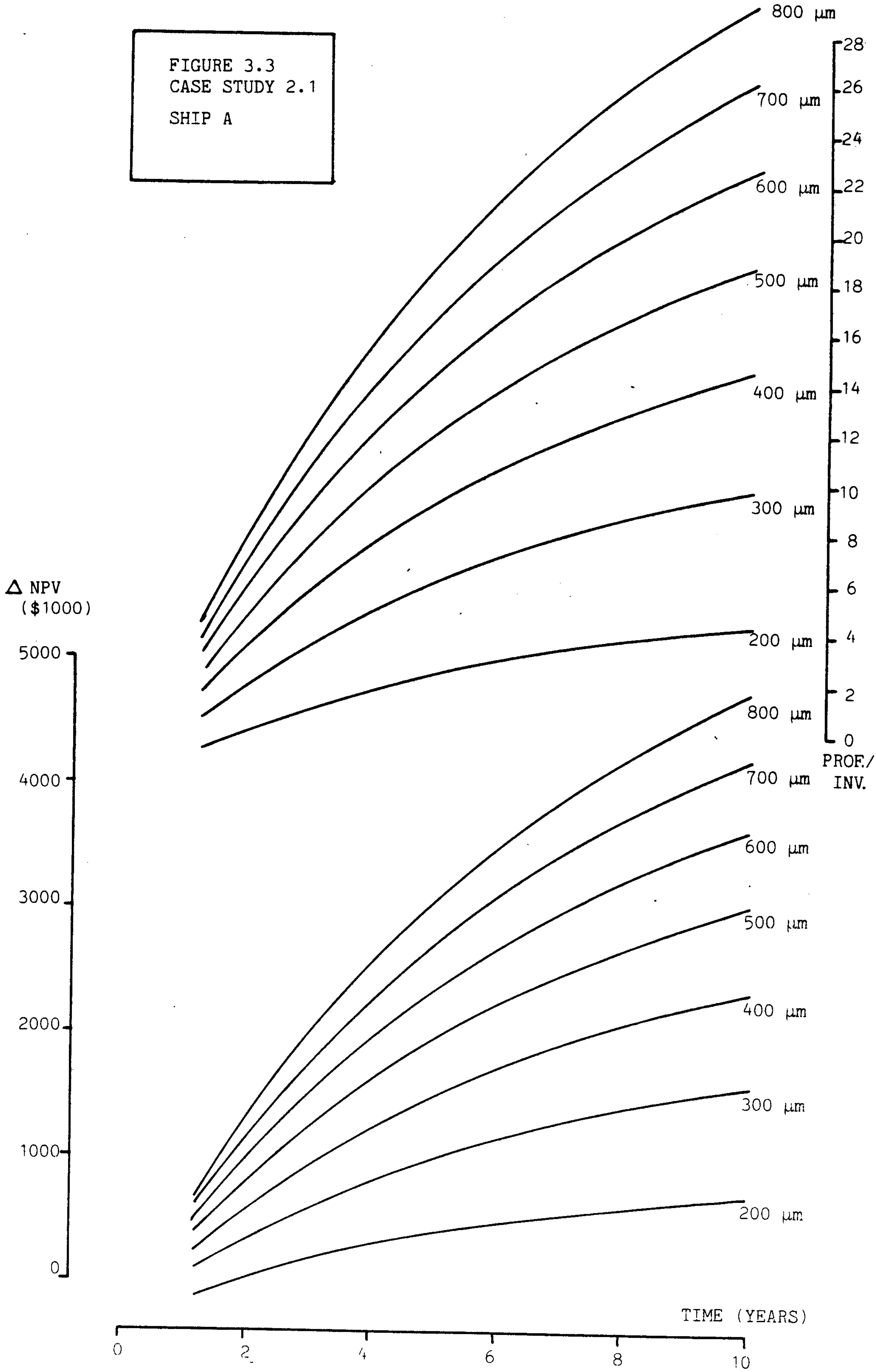


FIGURE 3.4
CASE STUDY 2.1
SHIP B (1)

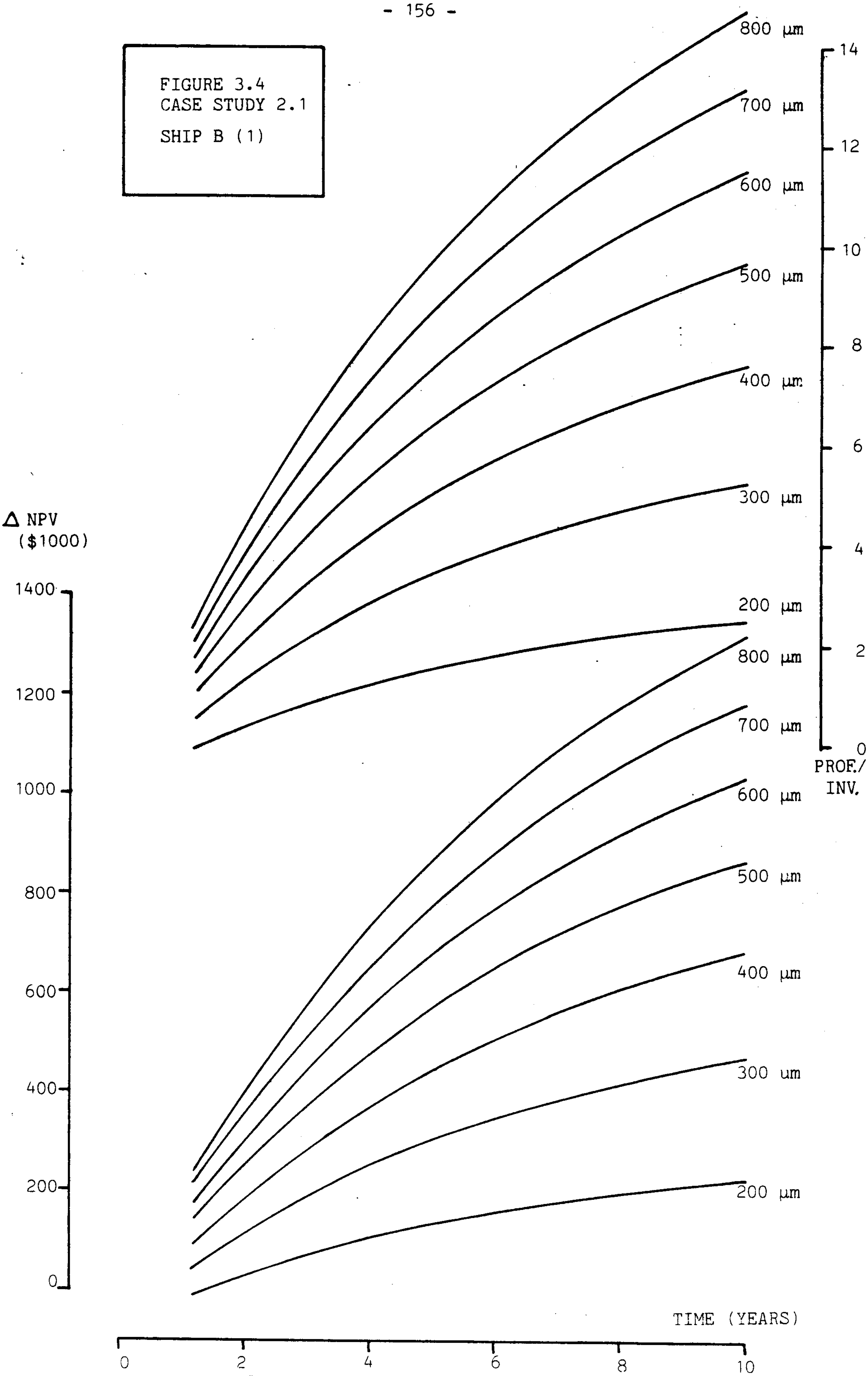
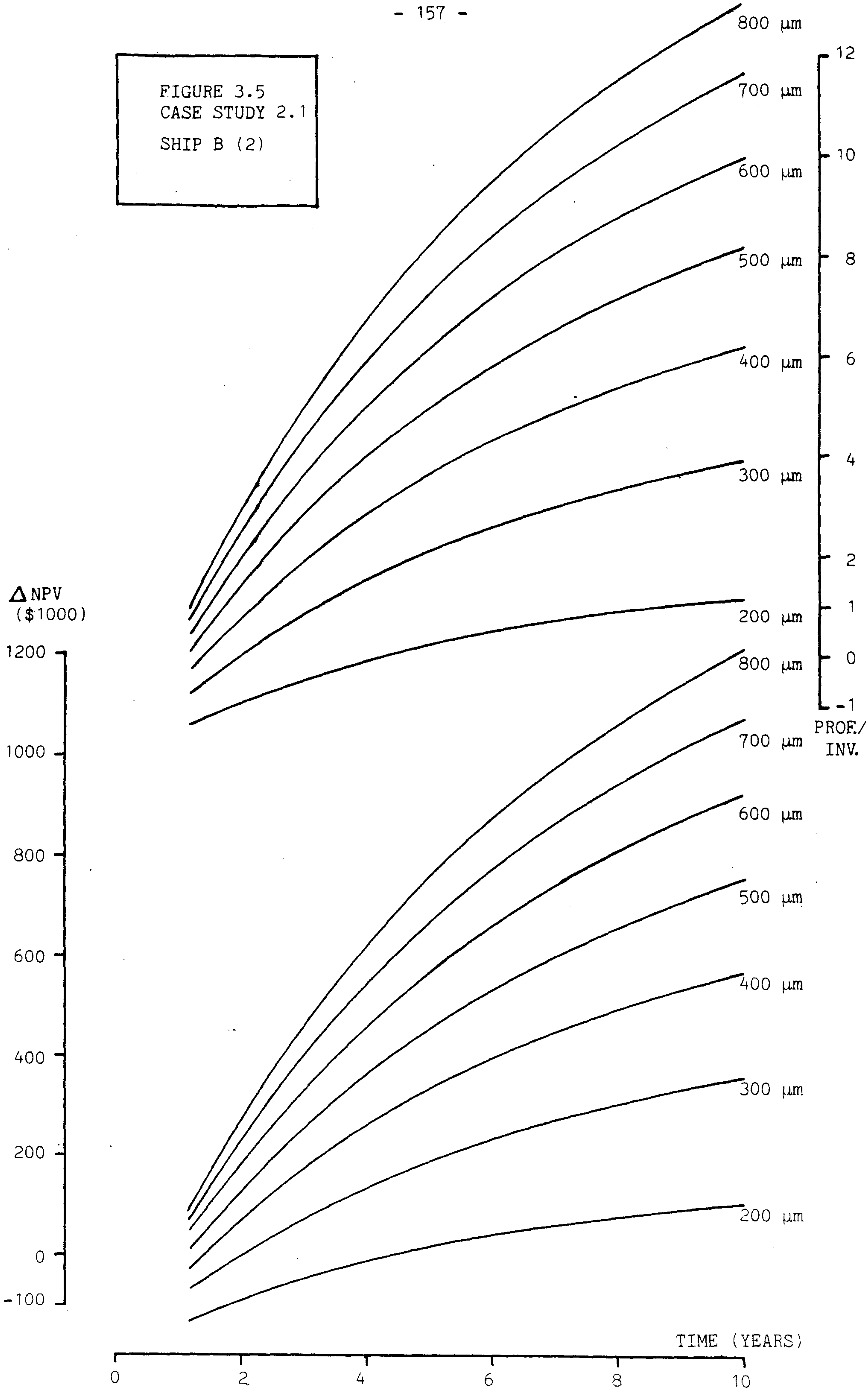


FIGURE 3.5
CASE STUDY 2.1
SHIP B (2)



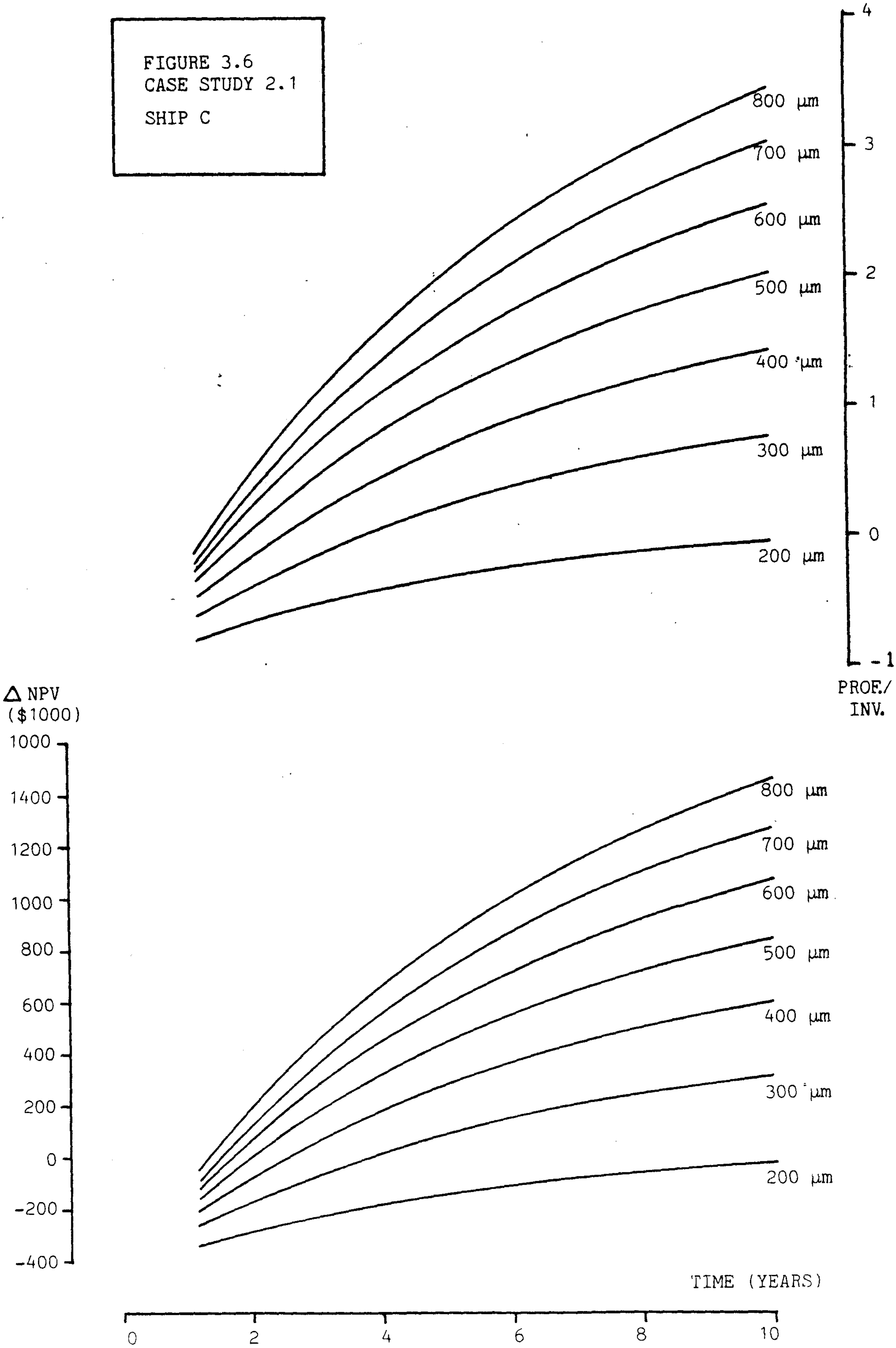


FIGURE 3.6
CASE STUDY 2.1
SHIP C
800 μm
700 μm
600 μm
500 μm
400 μm
300 μm
200 μm
4
3
2
1
0
-1
PROF./
INV.
Δ NPV
($1000)
1000
1400
1200
1000
800
600
400
200
0
-200
-400
800 μm
700 μm
600 μm
500 μm
400 μm
300 μm
200 μm
TIME (YEARS)
0
2
4
6
8
10

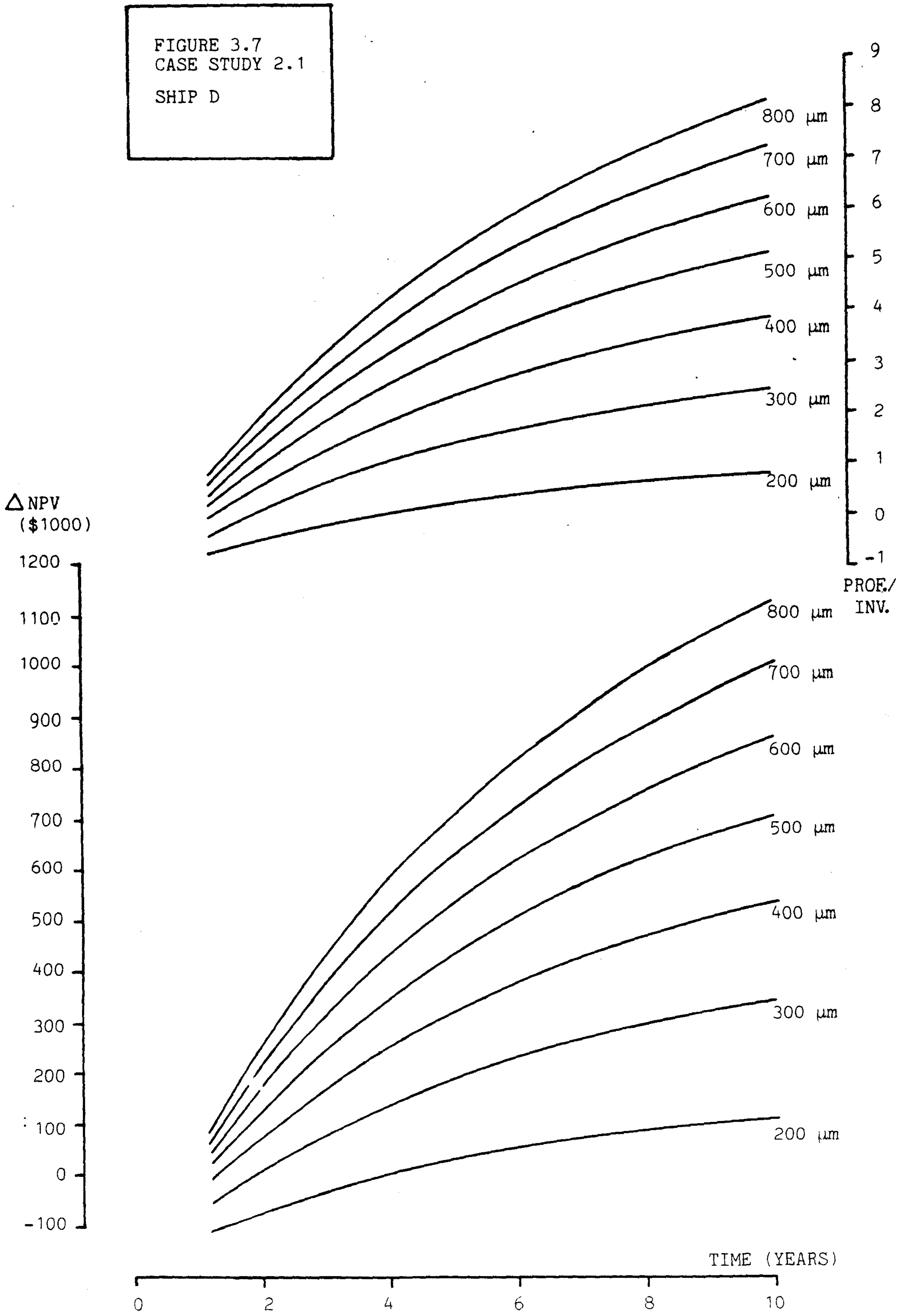


FIGURE 3.7
CASE STUDY 2.1
SHIP D
800 µm
700 µm
600 µm
500 µm
400 µm
300 µm
200 µm
9
8
7
6
5
4
3
2
1
0
-1
PROF./
INV.
ΔNPV
($1000)
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
-100
TIME (YEARS)
0
2
4
6
8
10

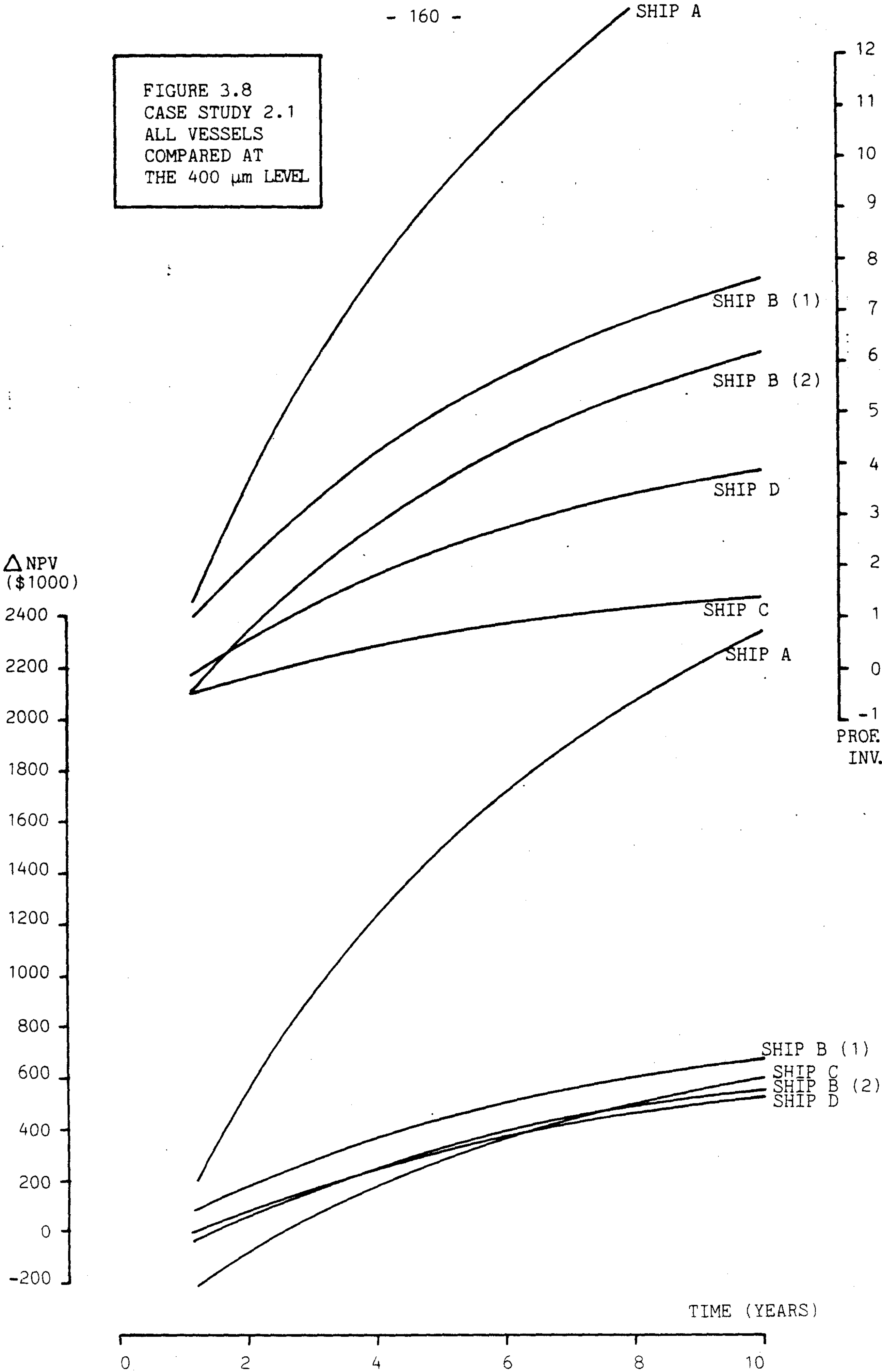


FIGURE 3.8
CASE STUDY 2.1
ALL VESSELS
COMPARED AT
THE 400 μm LEVEL
SHIP A
SHIP B (1)
SHIP B (2)
SHIP D
SHIP C
SHIP A
ΔNPV
($1000)
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
-200
SHIP B (1)
SHIP C
SHIP B (2)
SHIP D
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
PROF./
INV.
TIME (YEARS)
0
2
4
6
8
10

2, and as a discounted profit to investment ratio for the additional investment in Alternative 1. A detailed comparison between Figure (3.8) and Figure (3.1) reveals similar trends, but the magnitude of the difference between ship types is significantly reduced when the actual cost of hull maintenance is taken into account. In case study 1, the cost of hull roughness on Ship A was found to be greater than that of Ship C by a factor of 8, while the return in net present value terms on the proposed investment for removing hull roughness if found to be greater for Ship A than Ship C by a factor of only 3. If discounted profit to investment ratio is used as a measure of merit, the investment outcome for Ship A is again greater than that of Ship C by a factor of 8 or 9.

3.2.4 CASE STUDY 2.2 : THE ECONOMIC CONSEQUENCES OF RETURNING TO DIFFERENT LEVELS OF HULL ROUGHNESS AFTER REBLAST AND RECOAT

The previous case study (2.1) made the assumption that an outdocking roughness value equal to the new ship average of 125 μm AHR could always be achieved after a complete reblast and renewal of the coating system. In practice however, the hull roughness after reblast is determined by a number of factors, such as the condition of the steelwork, the quality of workmanship during paint application and also weather conditions. It is therefore important to explore in economic terms the effect of not returning to an AHR of 125 μm. For the 4 ship types used in this series of case studies, a range of outdocking AHR from 125 μm to 250 μm was explored while all other variables remained fixed as specified in Case Study 2.1. The results are presented in Figures (3.9) to (3.12) and Tables (C-6) to (C-9) of Appendix C, in terms of changes in the difference

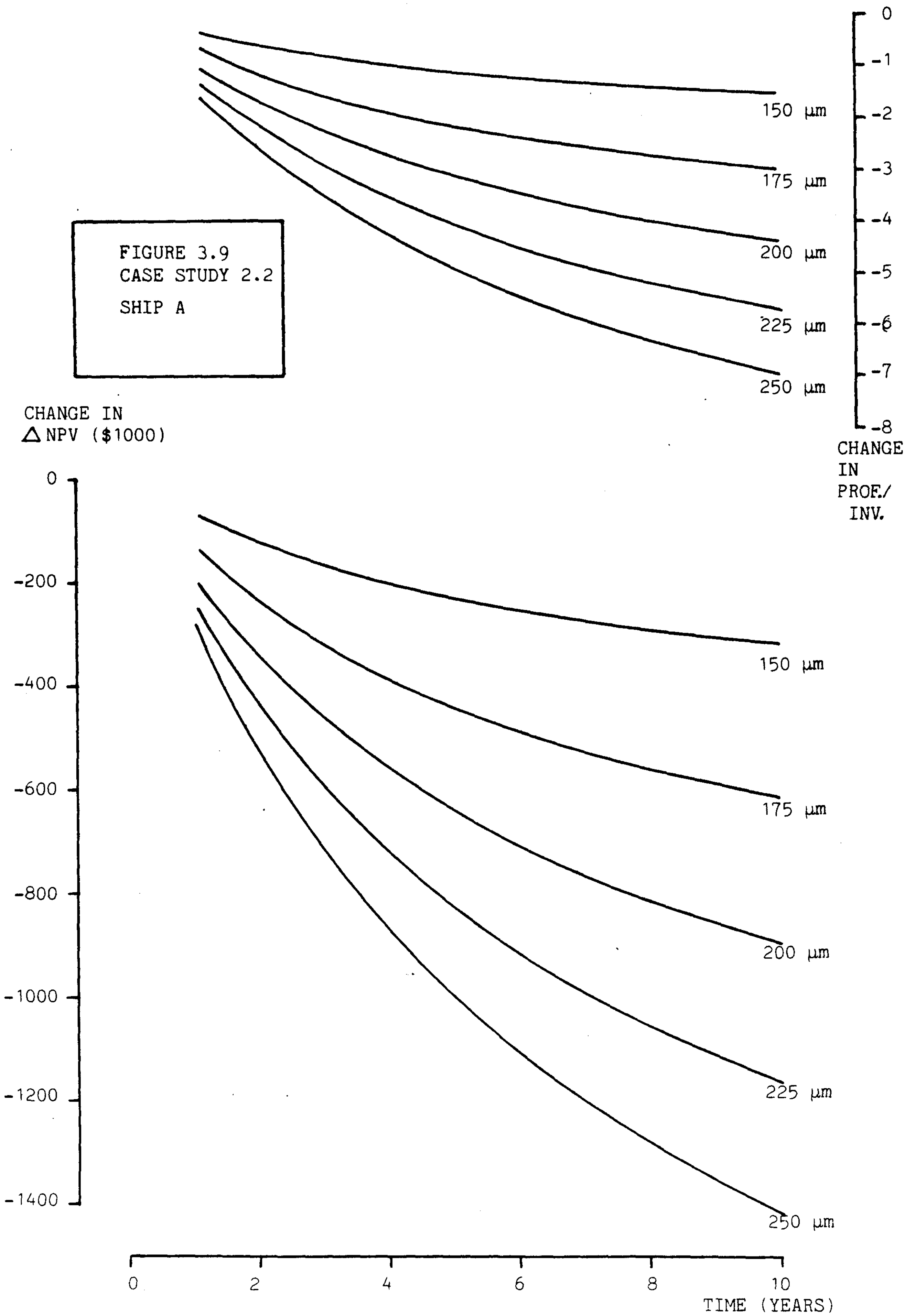
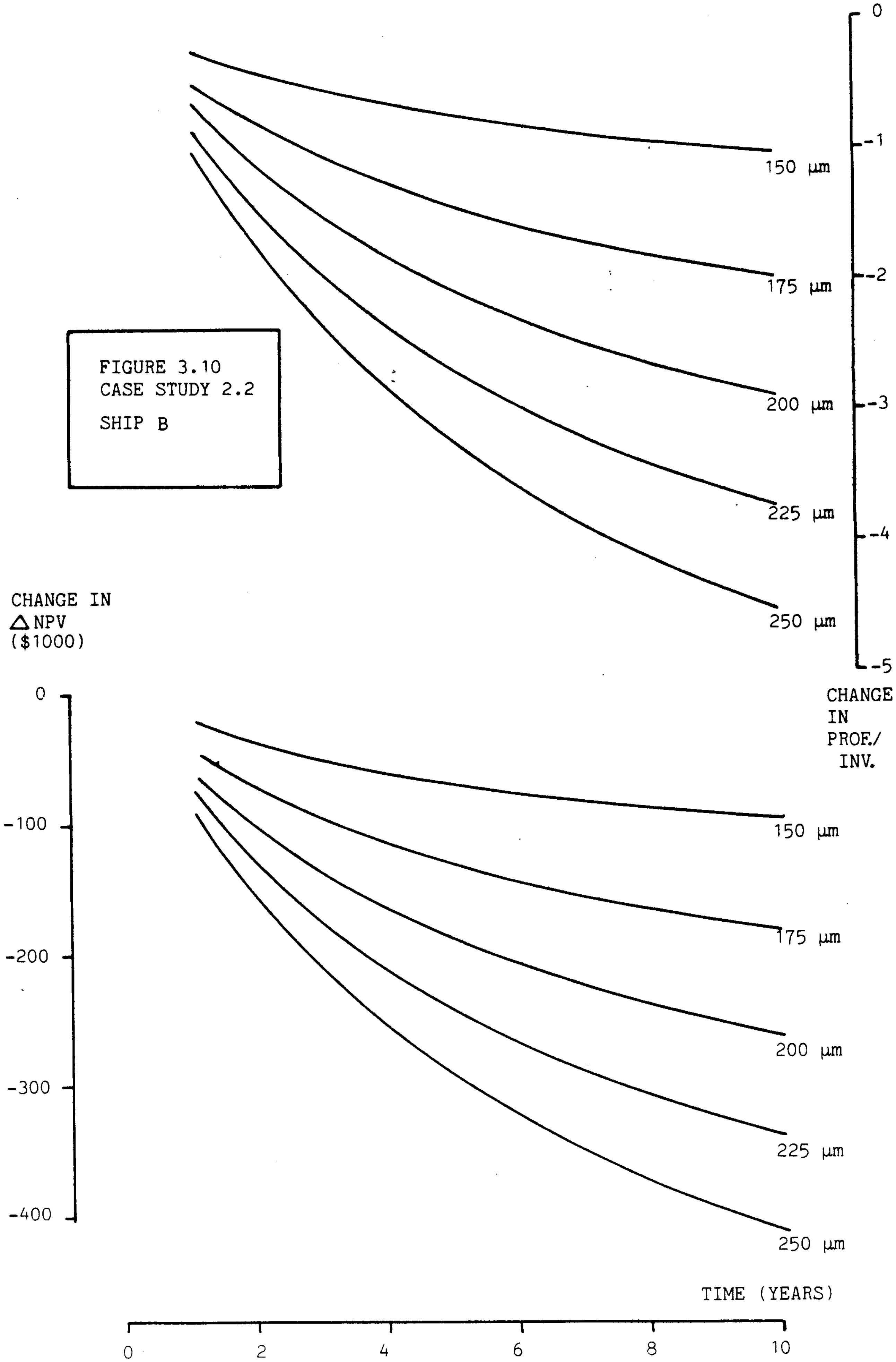
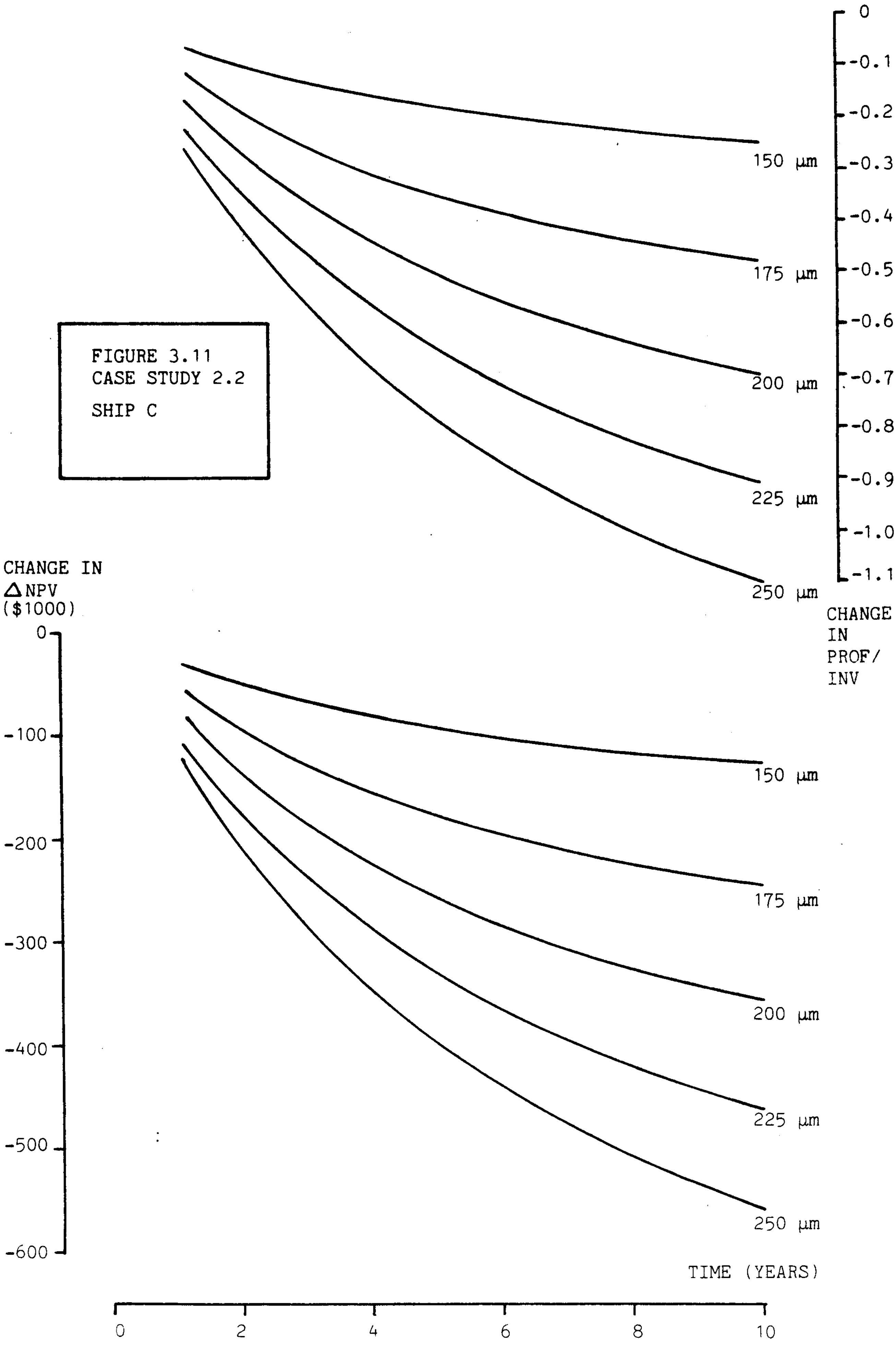


FIGURE 3.9
CASE STUDY 2.2
SHIP A
CHANGE IN
Δ NPV ($1000)
0
-200
-400
-600
-800
-1000
-1200
-1400
150 µm
175 µm
200 µm
225 µm
250 µm
0
-1
-2
-3
-4
-5
-6
-7
-8
CHANGE
IN
PROF./
INV.
0
2
4
6
8
10
TIME (YEARS)

FIGURE 3.10
CASE STUDY 2.2

SHIP B




0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
-1.1
150 µm
175 µm
200 µm
225 µm
250 µm
FIGURE 3.11
CASE STUDY 2.2
SHIP C
CHANGE IN
△NPV
($1000)
0
-100
-200
-300
-400
-500
-600
CHANGE
IN
PROF/
INV
150 µm
175 µm
200 µm
225 µm
250 µm
TIME (YEARS)
0
2
4
6
8
10

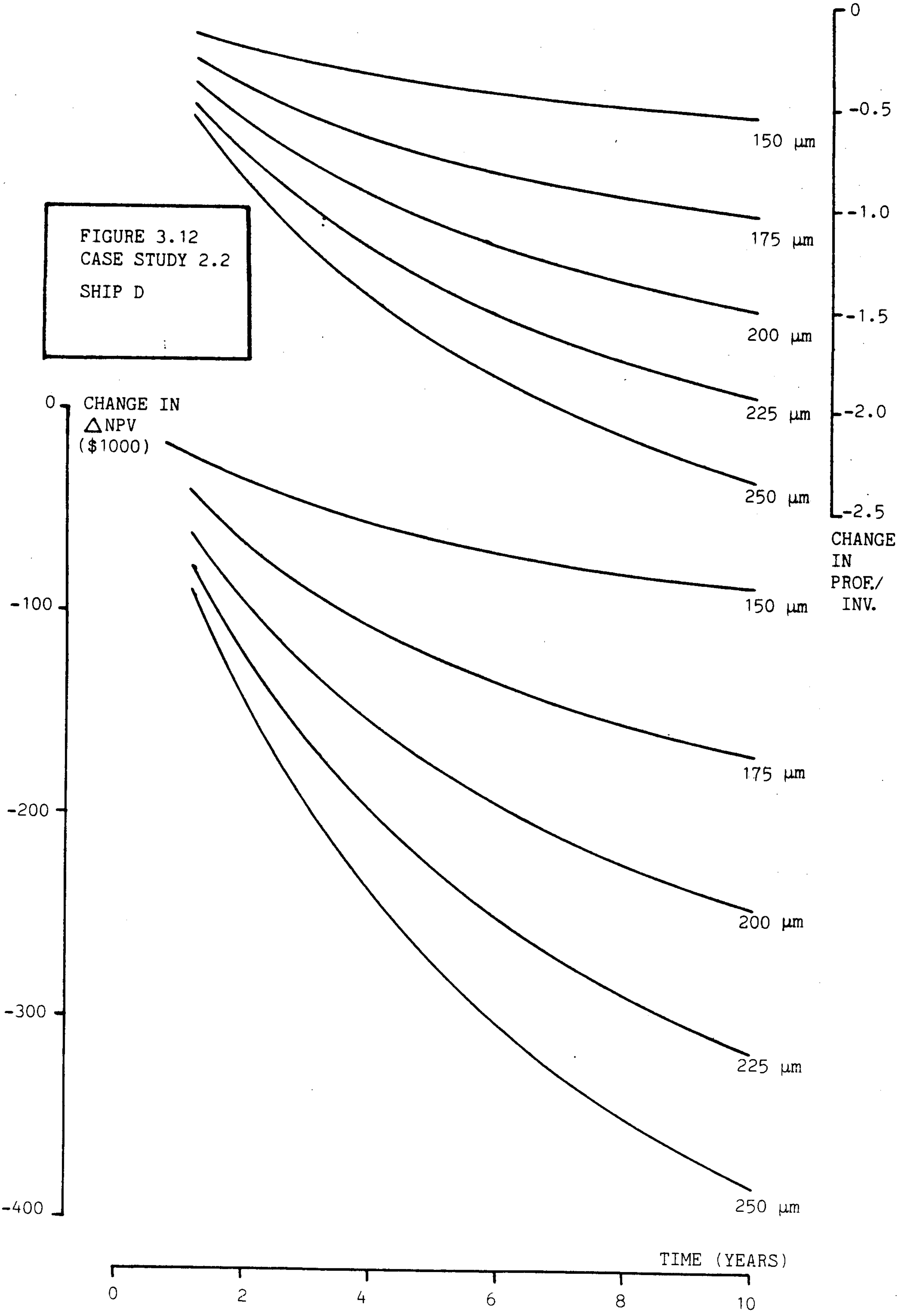


FIGURE 3.12
CASE STUDY 2.2
SHIP D
0
-0.5
-1.0
-1.5
-2.0
-2.5
CHANGE IN PROF./ INV.
150 µm
175 µm
200 µm
225 µm
250 µm
0
-100
-200
-300
-400
CHANGE IN △NPV ($1000)
150 µm
175 µm
200 µm
225 µm
250 µm
TIME (YEARS)
0
2
4
6
8
10

in NPV between the two alternatives as well as changes in the profit to investment ratio.

This particular case study can also serve as a basis for the economic assessment of a recently developed method of mechanically polishing the paint surface under-water, using divers equipped with high speed rotating power tools. The process is designed to remove only a small part of the total paint thickness using fine abrasive materials. Due to the mechanical abrasion this method should only be used on sound paint systems where good adhesion exists between coats of paint in order to avoid serious detachment. It is therefore a process ideally suited for vessels which have undergone a complete reblast and renewal of coating system, but with a higher than expected outdocking hull roughness due to bad paint application.

3.2.5 CASE STUDY 2.3 : THE ECONOMIC CONSEQUENCES OF DELAYING REBLAST AND RECOAT

Case study 2.1 has demonstrated that even the reblast of a vessel with an AHR of less than 300 μm can be justified in economic terms, provided a low outdocking AHR can be achieved. Some ship owners may argue that the present depressed freight market situation does not permit additional expenditure on hull mantenance. As a further supplement to the basic reblast Case Study 2.1, the economic effects of delaying reblast by one drydocking (24 months) or two drydockings (48 months) may be explored. The hull maintenance specifications used are all the same as in Case Study 2.1, except in the first instance the reblast specified in Alternative 1 is delayed until next drydocking , in the second set of calculations the delay is two complete docking intervals. The maintenance delayed by a further complete drydocking interval. The maintenance specifications for Alternative 1 prior to the reblast are identical to those specified for Alternative 2. Results of the calculation are presented in Figures (3.13) to (3.16) and Table (C-10) of Appendix C, and clearly indicate that a delay of 24 or 48 months may be very costly indeed.

For Ships B,C and D, the cost of delaying the reblast and renewal of the paint system is of the same order of magnitude in net present value terms for most of the roughness levels. At a roughness level of 200 μm AHR there is in fact a small benefit to be gained from delaying the reblast by 24 months, provided the reason for reblasting is purely to remove roughness and get back to a new ship AHR of 125 μm, and the same coating system following an average increase in AHR with time is used before and after the reblast. In practice, few owners would even contemplate reblasting a vessel with an AHR of 200 μm and otherwise in good condition, unless the reason for reblast is to apply a new and more advanced paint system which is incompatible with the present system. When the indocking roughness exceeds 300 μm AHR, the cost of delaying reblast until next drydocking becomes significant for all ships, but only if an outdocking AHR of 125 μm can be achieved after reblast. The results presented in the previous Case Study, 2.2, clearly indicate that the benefits of a reblast are quickly reduced if bad workmanship in the drydock results in a higher than expected outdocking AHR For Ship A the costs in net present value terms of delaying reblast are 3 to 4 times higher than the values obtained for the 3 deadweight carriers, confirming the preliminary results in Case Study 1.

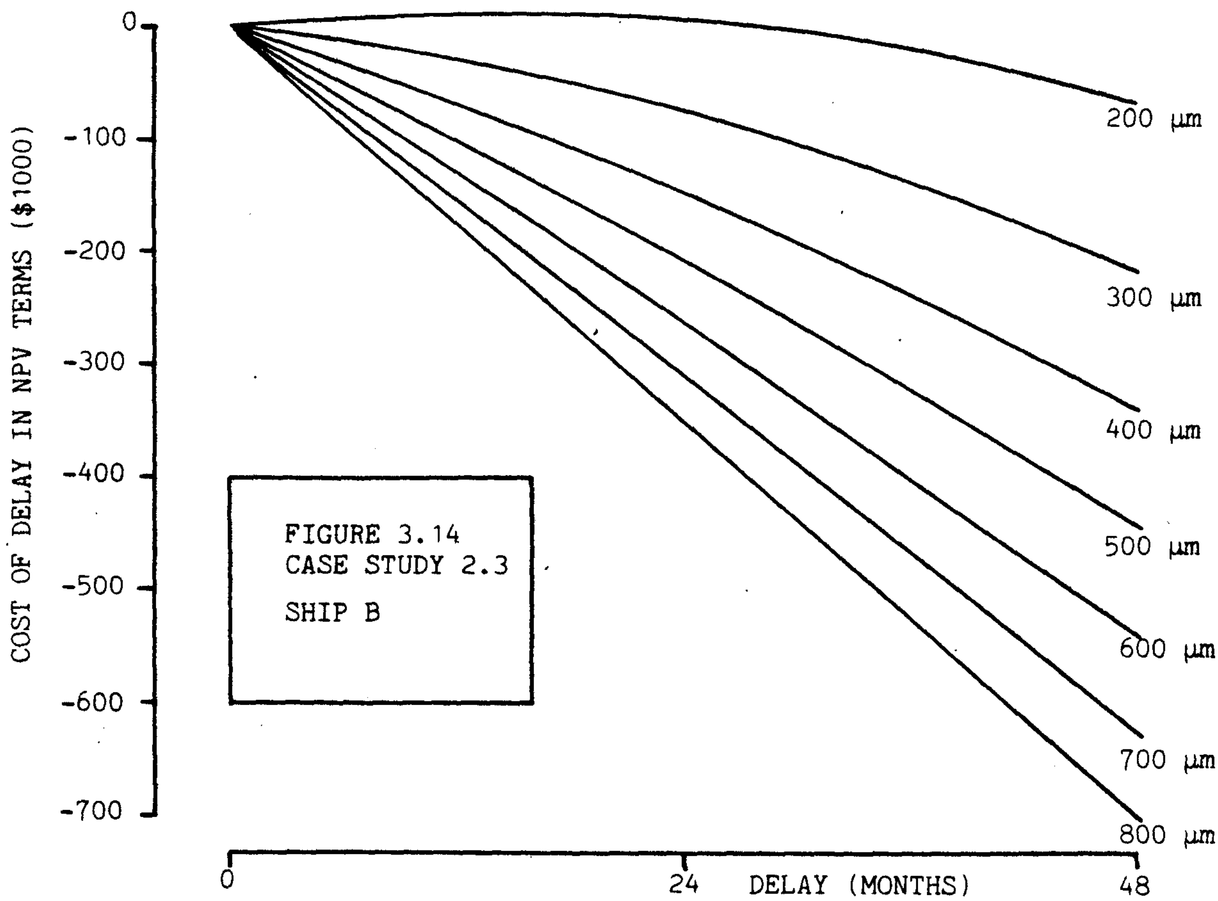


FIGURE 3.14
CASE STUDY 2.3
SHIP B

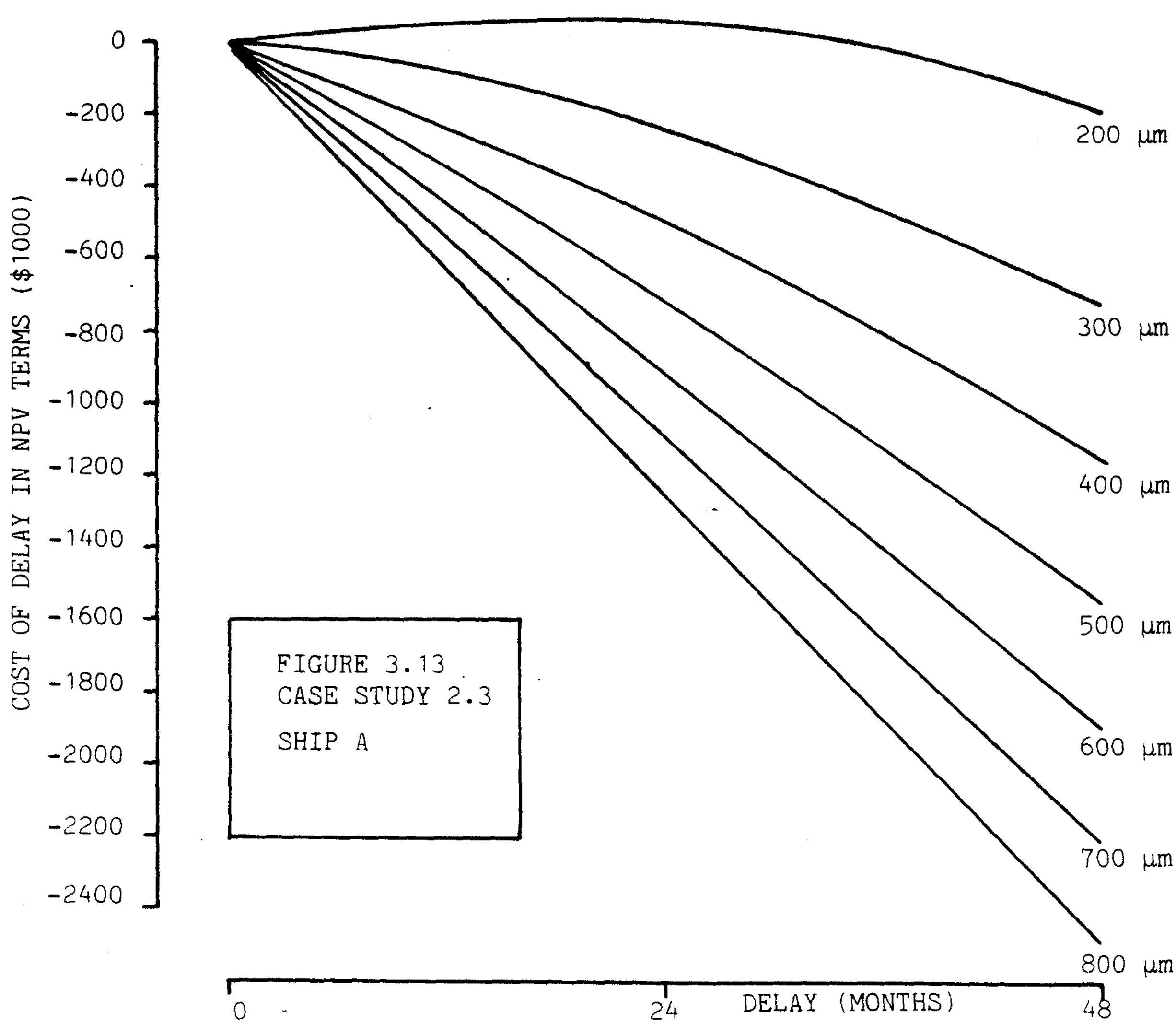


FIGURE 3.13
CASE STUDY 2.3
SHIP A

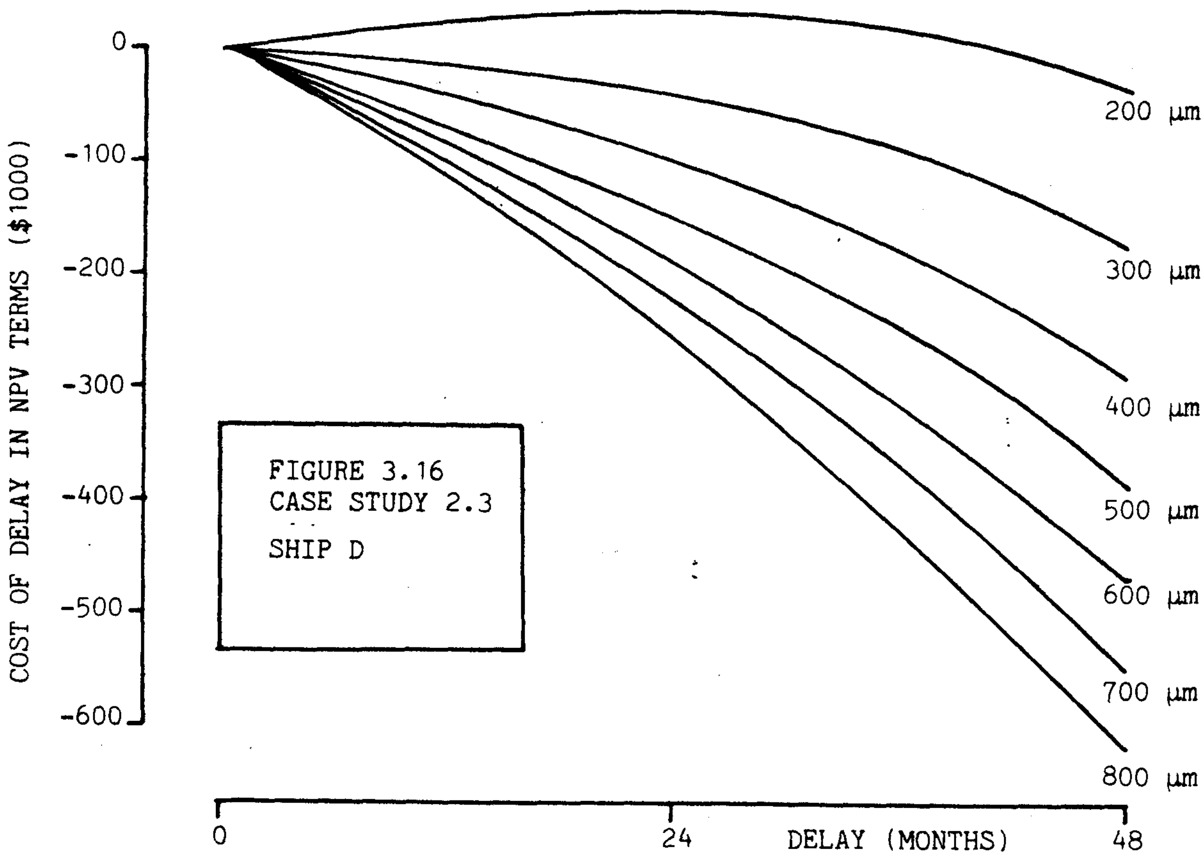


FIGURE 3.16
CASE STUDY 2.3
SHIP D

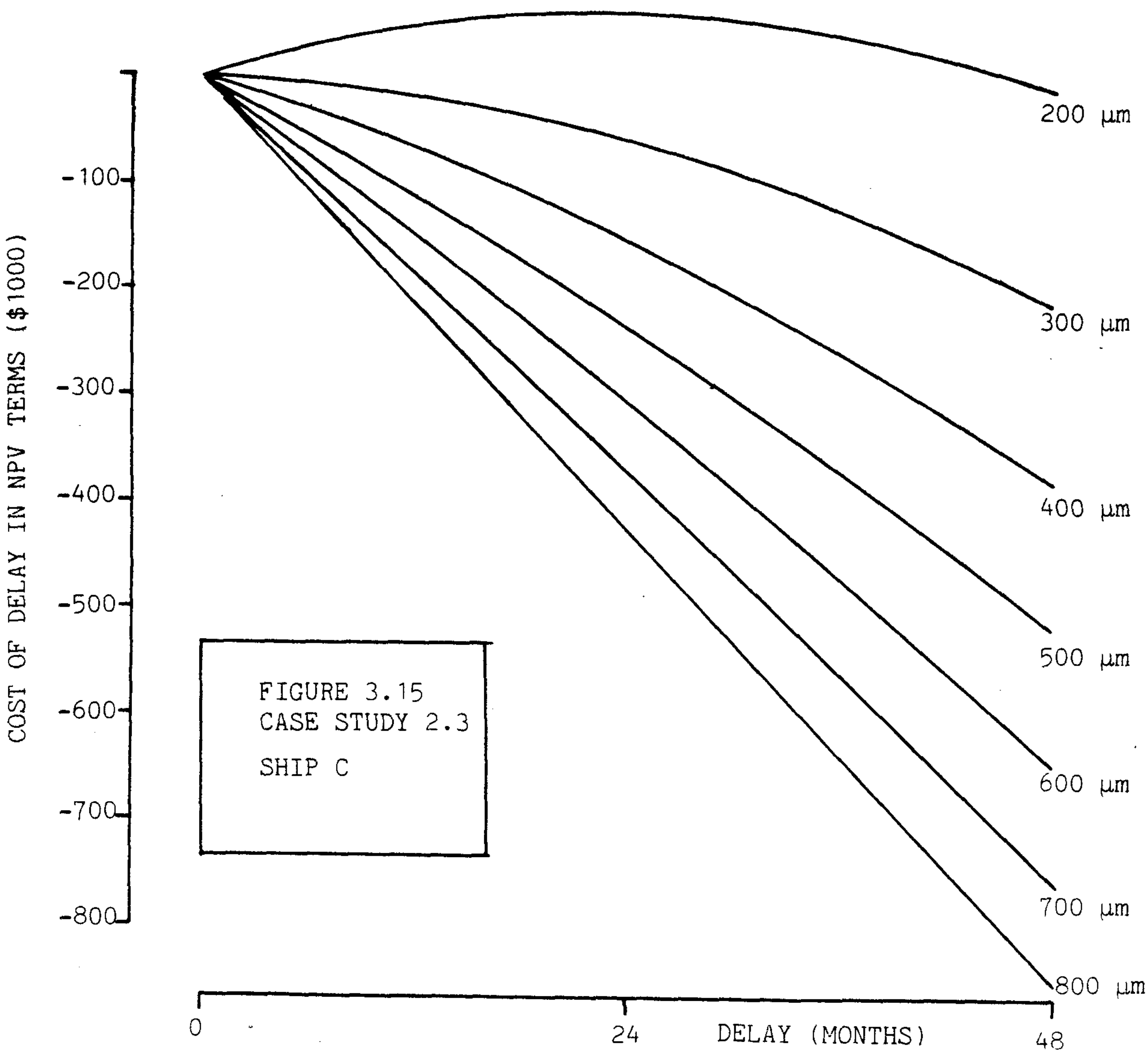


FIGURE 3.15
CASE STUDY 2.3
SHIP C

3.2.6 CASE STUDY 3.1 : SELF-POLISHING ANTIFOULINGS EXAMINED AGAINST CONVENTIONAL ANTIFOULINGS FROM THE HULL ROUGHNESS ASPECT ONLY

In Case Study 2 the various economic effects of reblasting and removing roughness have been explored, but a standard conventional paint system with a standard average development of roughness with time has been used to provide a common basis for comparison. This following case study will build on the previous work, and explore in economic terms the introduction of a self polishing co-polymer type of paint as a principal alternative to a conventional high performance system. As discussed in Chapter 1, insufficient information exists to provide in statistical terms an average value and corresponding probability distribution of roughness development with time in service for this type of system. Indications from a limited number of repeated measurements on a few ships are that this type of coating system will deteriorate less rapidly than a conventional system, mainly due to the prevention of a build up of old coatings, and also due to a small smoothing effect on some types of roughness, for example overspray particles from application in drydock. Significant reductions in roughness would not be expected for vessels which are already quite smooth, and the large reductions in roughness due to polishing reported in Reference (10). were primarily due to the high polishing rates of early co-polymer systems. Present systems have considerably lower polishing rates, and the reduction of hull roughness due to polishing is not a realistic scenario in techno-economic calculations. Ships also suffer mechanical damage to the coating system in service, and in this respect there will be no substantial difference in the behaviour of a self polishing system compared with the conventional system investigated previously. Faced with this uncertainty about the development of roughness with time for a self polishing system, it was decided to present 4 different roughness scenarios for comparison with the standard conventional system used in the previous case study. The 4 scenarios are:

Scenario 1: no increase in AHR with time in service; no increase in AHR in drydock.

Scenario 2: no increase in AHR with time in service; average increase in AHR in drydock as defined in Chapter 1

Scenario 3: increase in AHR with time in service is 50% of the average value for conventional paint systems, as defined in Chapter 1 ; average increase in AHR in drydock

Scenario 4: increase in AHR with time in service is the same as the average value for conventional systems; average increase in AHR in drydock

The four different scenarios are illustrated in Figure (3.21).

In practice, a realistic scenario is expected to be somewhere between Scenario 2 and 3 above. The assumption of no increase in roughness above the new level of 125 μm AHR presented in Scenario 1 is unrealistic, because commercial vessels will always suffer some mechanical damage in service. Similarly, Scenario 4 is expected to be an overestimate compared with a conventional system, because it does not include the benefits obtained from avoiding the build up of old coatings and the associated problems of paint detachment. The two principal alternatives to be explored are therefore:

ALTERNATIVE 1: complete reblast of underwater hull, build up of new anticorrosive system and recoat with a self polishing co-polymer type paint according to specifications in Table (B-6), Appendix B . The same antifouling paint is also used at subsequent drydockings which take place at 24 month intervals. Outdocking roughness after reblast and recoat = 125 μm AHR. Roughness development over future years follows the above specified scenarios.

ALTERNATIVE 2: complete reblast of underwater hull, build up of new anti-corrosive system and recoat with a conventional high performance antifouling paint according to specifications in Table (B-6), Appendix B. The same antifouling paint is also used at subsequent drydockings which take place at 24 month intervals. Outdocking roughness after reblast and recoat = 125 μm AHR. Roughness development over future years follows the average specification in Chapter 1.

Technical, operational and financial data for each ship type are as specified in Section 3.1.1.

The paint system costs are taken from Table (B-6), Appendix B , and the standard hull maintenance specification in Section 3.1.1 applies to all four vessels.

Results for the four ship types in terms of differences in net present value between the two alternative maintenance strategies and discounted profit to investment ratio for the additional investment in the more expensive alternative are presented in Figures (3.17) to (3.20) and Table (C-11) of Appendix C .

It is intuitively obvious that maintenance Alternative 1 with roughness Scenario 4 is going to be an unattractive proposition in economic terms. Both alternative maintenance strategies have the same drydocking intervals and the same roughness scenarios with the assumption that the conventional system in Alternative 2 remains free from fouling. The only difference is that Alternative 1 requires a higher expenditure without giving any economic benefits. With Scenarios 1, 2 and 3 the benefit in economic terms is due to a lower increase in roughness, and as expected, the results differ quite considerably between the four ship types.

In the case of Ship A, Figure (3.17) clearly demonstrates that hull maintenance Alternative 1 using a self polishing type of paint is highly attractive in economic terms under roughness Scenarios 1 and 2. Using

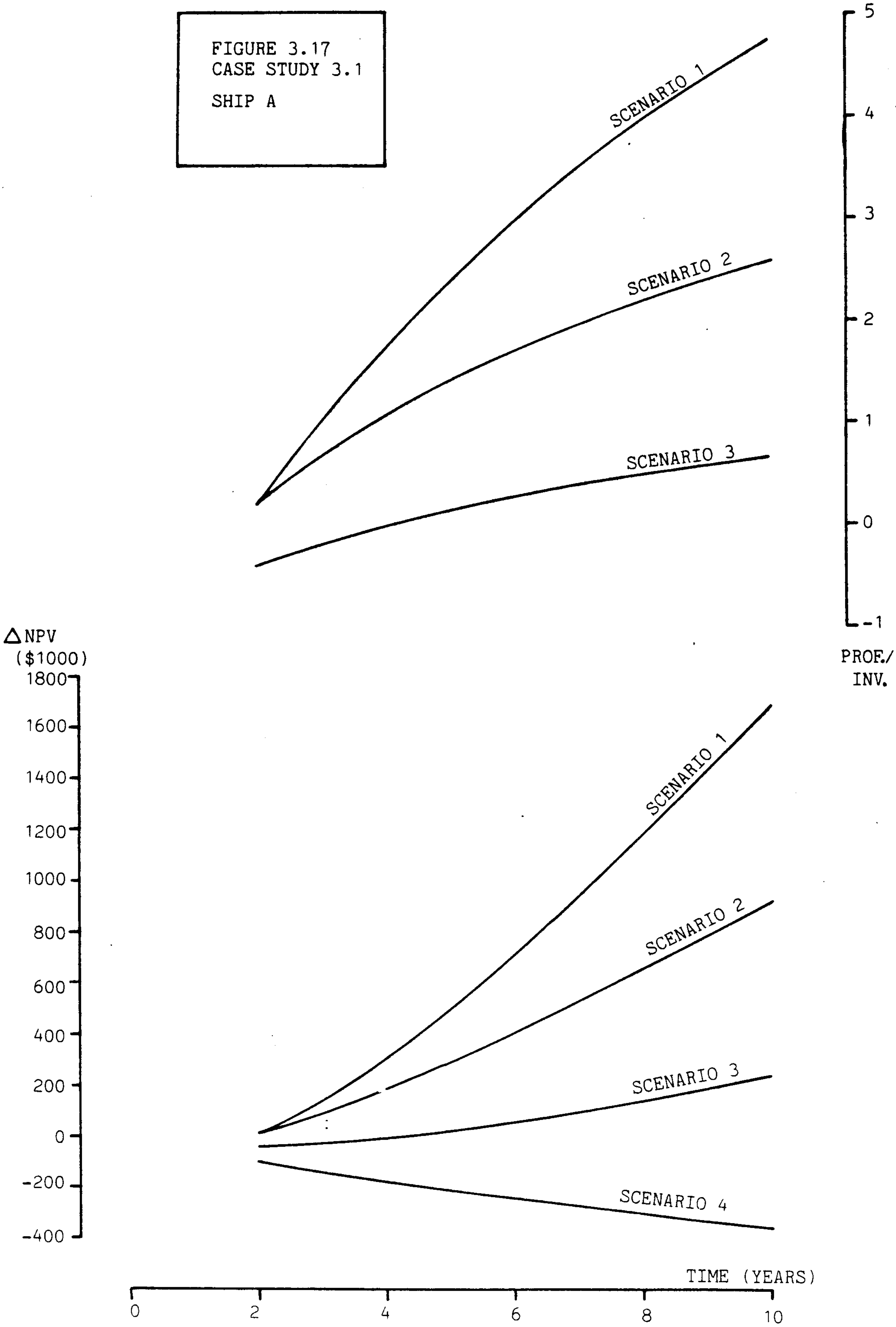


FIGURE 3.17
CASE STUDY 3.1
SHIP A
SCENARIO 1
SCENARIO 2
SCENARIO 3
SCENARIO 4
5
4
3
2
1
0
-1
PROF./
INV.
ΔNPV
($1000)
1800
1600
1400
1200
1000
800
600
400
200
0
-200
-400
TIME (YEARS)
0
2
4
6
8
10

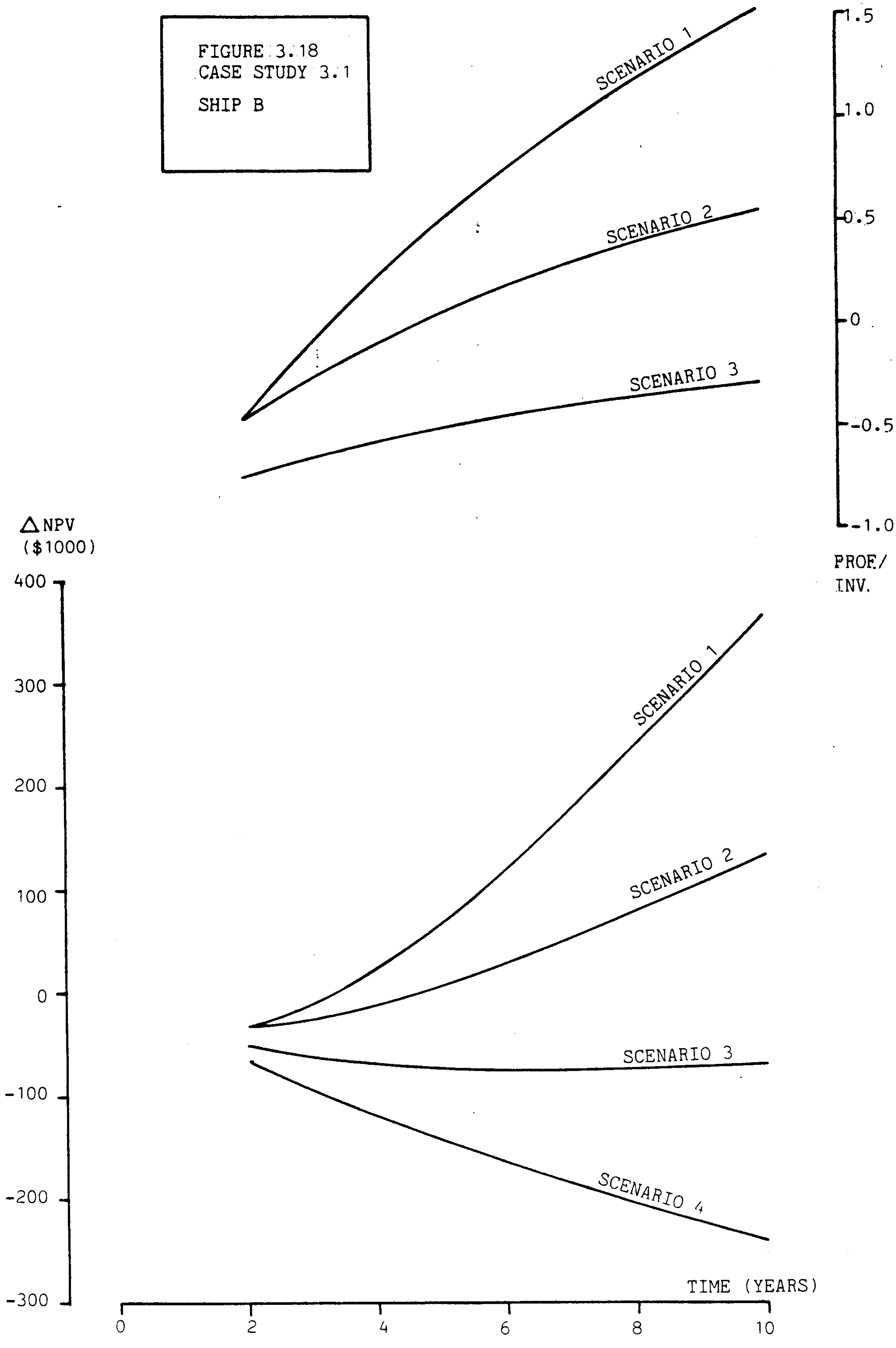


FIGURE 3.18
CASE STUDY 3.1
SHIP B
SCENARIO 1
SCENARIO 2
SCENARIO 3
1.5
1.0
0.5
0
-0.5
-1.0
PROF./
INV.
△NPV
($1000)
400
300
200
100
0
-100
-200
-300
SCENARIO 1
SCENARIO 2
SCENARIO 3
SCENARIO 4
TIME (YEARS)
0
2
4
6
8
10

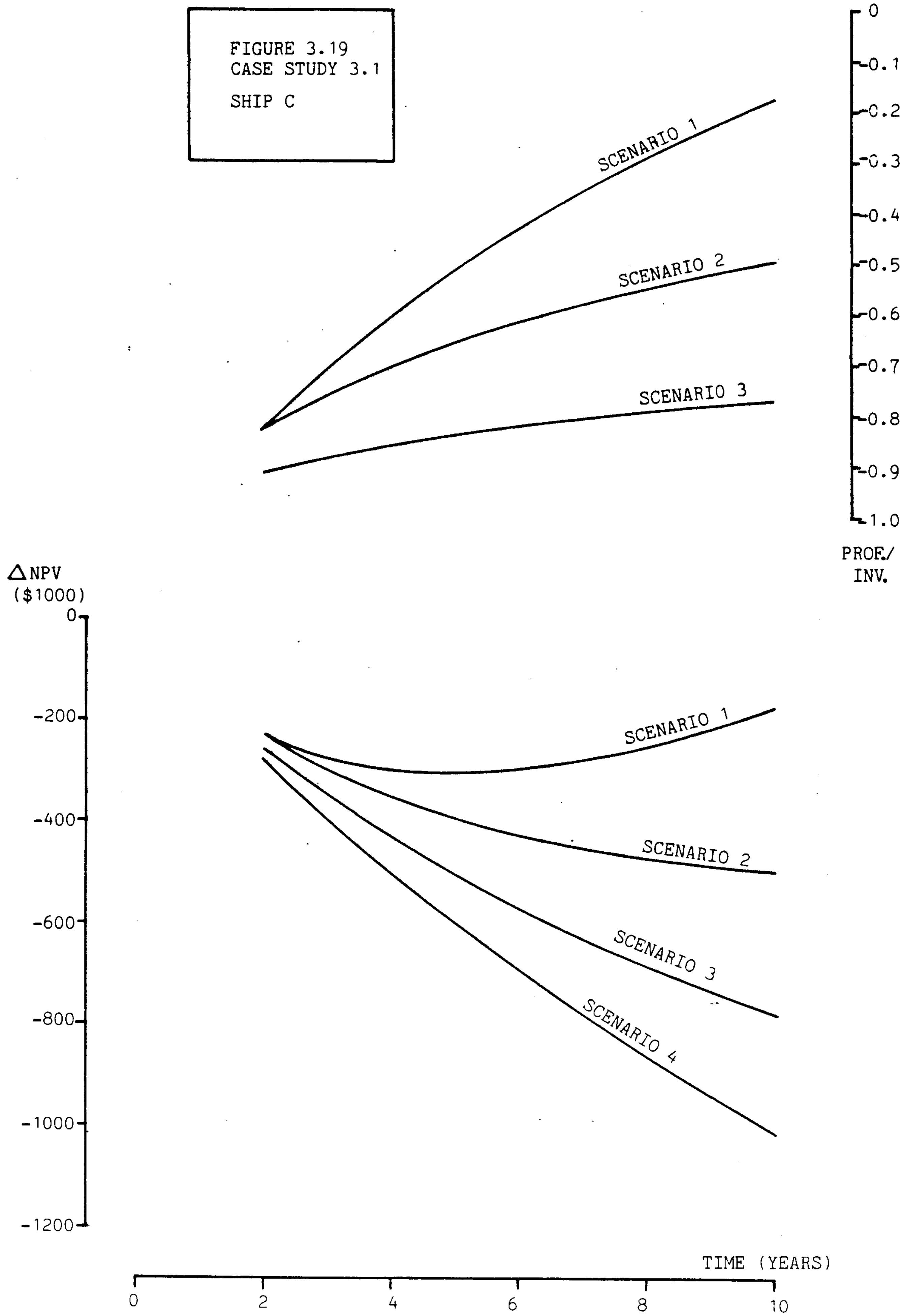


FIGURE 3.19
CASE STUDY 3.1
SHIP C
SCENARIO 1
SCENARIO 2
SCENARIO 3
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
PROF./
INV.
ΔNPV
($1000)
0
-200
-400
-600
-800
-1000
-1200
SCENARIO 1
SCENARIO 2
SCENARIO 3
SCENARIO 4
TIME (YEARS)
0
2
4
6
8
10

FIGURE 3.20
CASE STUDY 3.1
SHIP D

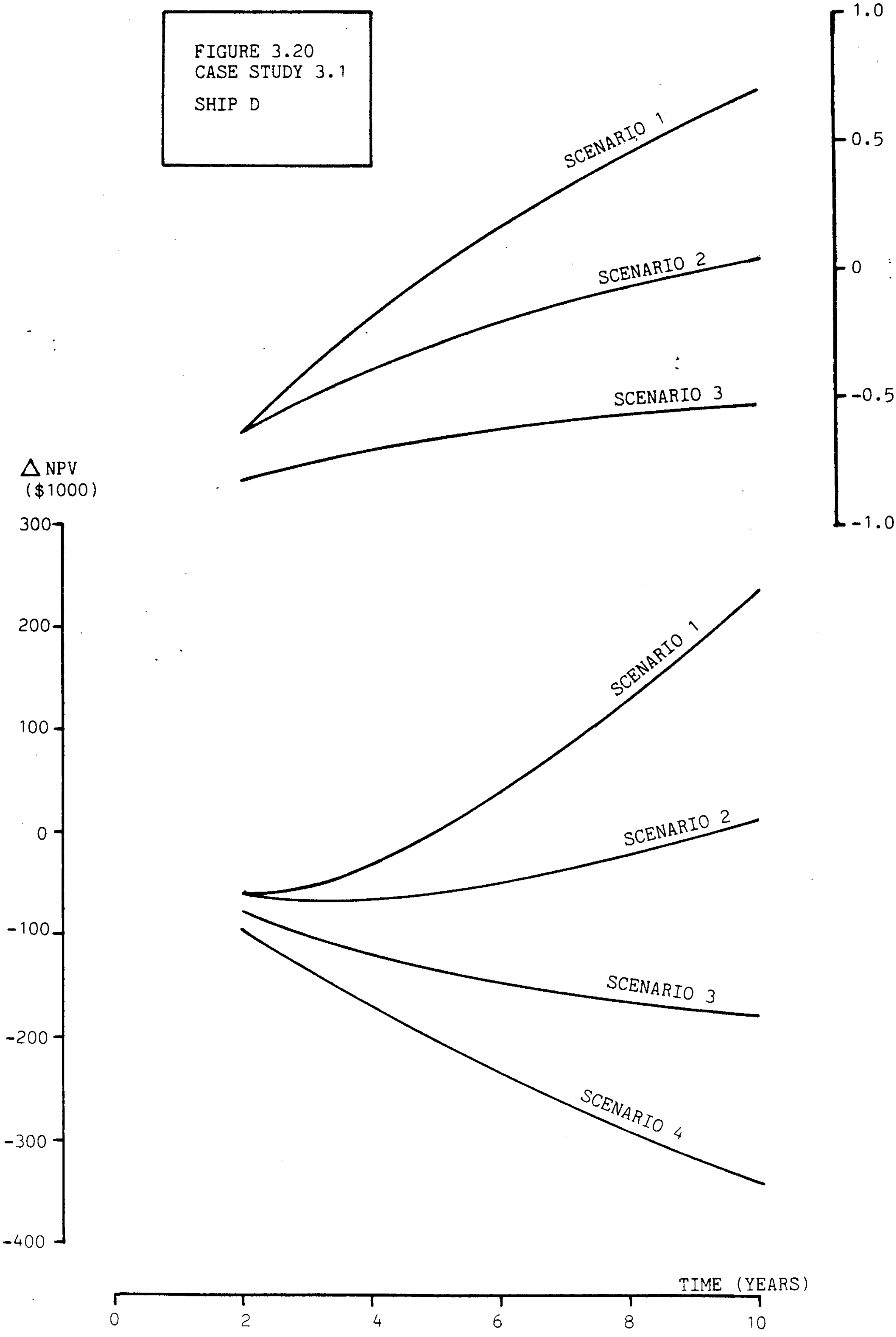
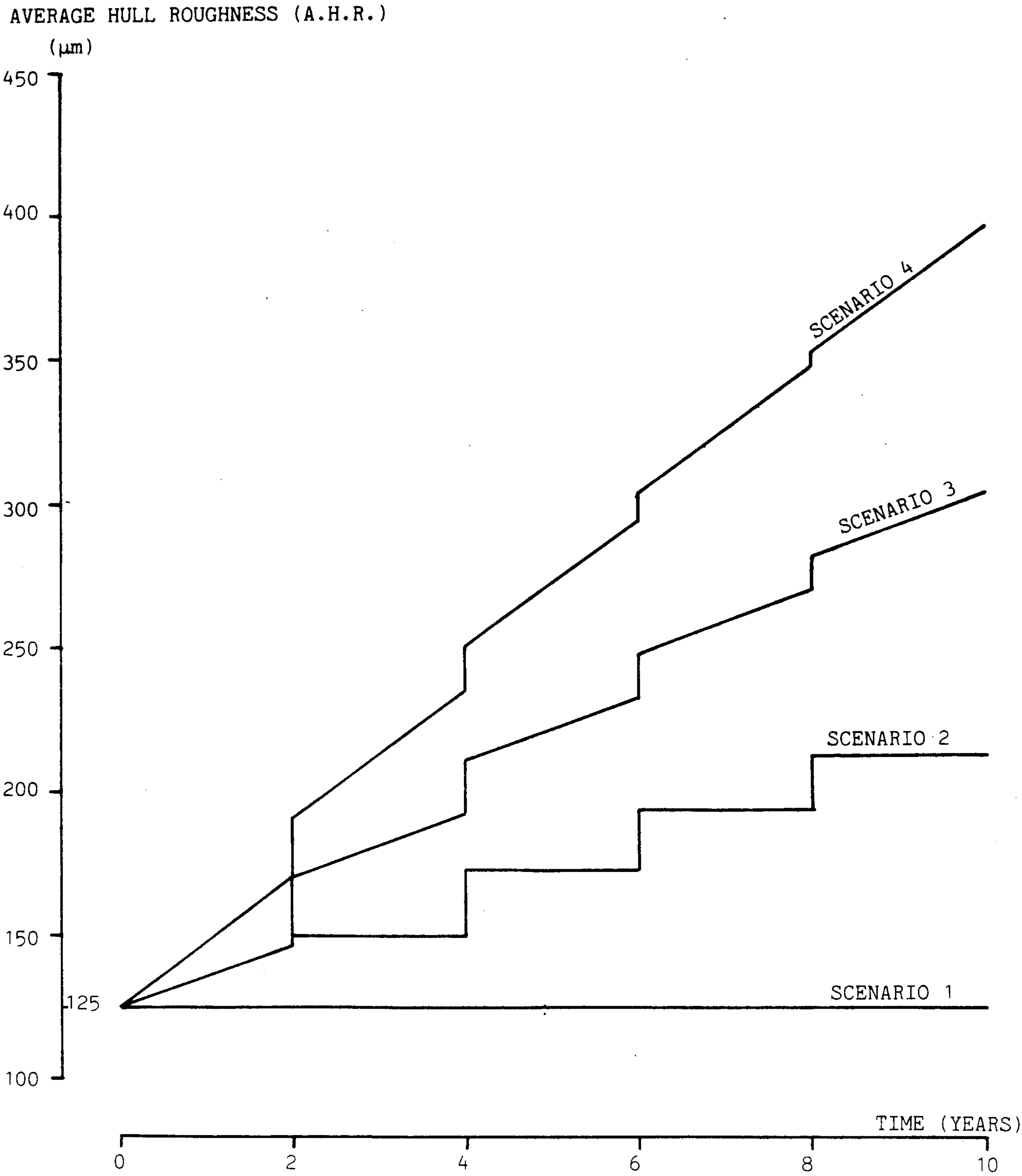


FIGURE 3.21
GRAPHICAL PRESENTATION OF
PRINCIPAL ROUGHNESS SCENARIOS



Scenario 3, the break-even point for Alternative 1 is 4 years or 2 drydockings. The self polishing type of paint system is therefore justified on the grounds of roughness alone for most realistic roughness scenarios for this type of ship when compared with a conventional paint system having an average increase in roughness with time.

For Ship B the conclusions are less favourable with respect to Alternative 1 than for Ship A. As shown in Figure (3.18), the self polishing type of paint is unattractive in economic terms when using roughness Scenario 3, irrespective of the period of calculation used, and with Scenarios 1 and 2 the break-even points are 3.5 and 4.5 years, respectively.

The more expensive Alternative 1 can therefore not be justified in economic terms on account of reduced hull roughness alone, unless the underwater hull surface experiences only small amounts of mechanical damage, and the self polishing system can be maintained in a "nearly new" condition over a number of years. This difference in conclusions between different ship types is demonstrated even more clearly for Ship C in Figure (3.19). For this type of vessel, operating at slow speed in a poor freight market, the loss of time becomes less important in economic terms, and the more expensive self polishing system can not be justified, even under the most favourable set of assumptions about hull roughness provided in Scenario 1.

A similar, although not completely as dramatic situation, is shown for Ship D in Figure (3.20). The operation of this vessel is also modelled in a presently typical situation of low freight income, where the revenue is sufficient to cover daily running costs and fuel costs, but insufficient to repay completely all capital charges or provide an operating profit. The loss of time and the corresponding reduction in freight income is therefore less important than for high freight rates, and the capital available for investment in preventing speed loss due to hull roughness is less. Consequently, the more expensive self polishing paint alternative is only marginally attractive on account of reduction in hull roughness using Scenario 1, and for any other roughness scenario would be rejected as an investment proposal.

In conclusion, having considered four different ship types under identical assumptions with respect to the development of hull roughness with time and the cost of alternative paint systems, it is clear that only for Ship A can the alternative of using a more expensive self polishing type of paint be justified on the basis of reduced hull roughness alone when using the most realistic set of roughness scenarios. In the case of Ship B the decision is marginal with a likelihood of reaching no more than a break-even point for the additional investment. For Ships C and D there is little chance of even reaching a break-even point, and the additional investment in a self polishing type of paint system can not be justified in economic terms on account of reduction in hull roughness alone.

The above set of case studies are, of course, only a set of hypothetical calculations, subject to the many assumptions made in defining a series of roughness scenarios. Consequently, the results are only intended as a set of guidelines and not for drawing absolute conclusions. Furthermore, only the roughness aspects associated with the use of more advanced self polishing types of paint have been included in the above analysis, and the economic effects of fouling prevention and the possible extension of time between drydockings will have to be included before any final conclusions can be drawn. In economic terms the prevention of fouling settlement is possibly the most important single factor, and this will be examined in more detail in the following case studies.

3.2.7 CASE STUDY 3.2 : SELF-POLISHING ANTIFOULINGS EXAMINED AGAINST CONVENTIONAL ANTIFOULINGS FROM THE ASPECT OF EXTENDING INTERVALS BETWEEN DRYDOCKINGS

The lifetime of a self polishing co-polymer type of coating system is proportional to the dry-film paint thickness. Compared with a conventional high performance system of the contact diffusion type, where the leaching rate of the toxin follows an exponential decay curve limiting the lifetime of the best system to between 18 and 24 months, the self polishing type can offer the clear advantage in economic terms of extending intervals between drydockings beyond the traditional 24 month limit. The purpose of this particular case study is to evaluate the magnitude of the economic benefits obtained from extending the interval between drydockings, and to examine if this alone can justify the use of the more expensive self polishing type of paint system.

Again the differences between two alternative maintenance strategies are evaluated in terms of net present value and discounted profit to investment ratio. Both alternatives have the same maintenance specifications as for the self polishing system and roughness Scenario 4 in the previous case study, except for drydocking interval and paint system costs which are gradually increased for Alternative 1, while maintaining the drydocking interval fixed at 24 months for Alternative 2. The increase in paint system cost with extended time between drydockings is based upon the assumption that every increase in the drydocking interval by a period of 12 months will require one additional coat of antifouling paint. A further assumption made is that every additional coat of paint will require the vessel to remain for another day in drydock, resulting in a loss of earnings, and therefore to some extent reducing the benefits obtained from extending the interval between drydockings. In a discounted cash flow calculation over a specified number of complete financial years the economic benefits of extending the time between drydockings can only be measured in terms of every complete number of reduced drydockings over the calculation period. Consequently, for an extension of the drydocking interval of 6 months, a 10 year period of calculation is required. Corresponding figures for 12 months are 6 years and for 24 months 4 or 8 years.

Results for the 4 different ship types are presented in Figure (3.22) and Table (C-12) of Appendix C. In Figure (3.22) the basic difference in NPV between the two alternatives in Case Study 3.1 is given using roughness Scenario 4, and the appropriate period of calculation corresponding to the required extension of drydocking interval. To this figure is added the change in NPV resulting from extension of the drydocking interval to give a total NPV which, if positive, demonstrates that the more expensive self polishing system can be justified on the grounds of extending the time between drydockings alone.

FIGURE 3.22
CASE STUDY 3.2
THE ECONOMIC
CONSEQUENCES OF
EXTENDED TIME
BETWEEN DOCKINGS

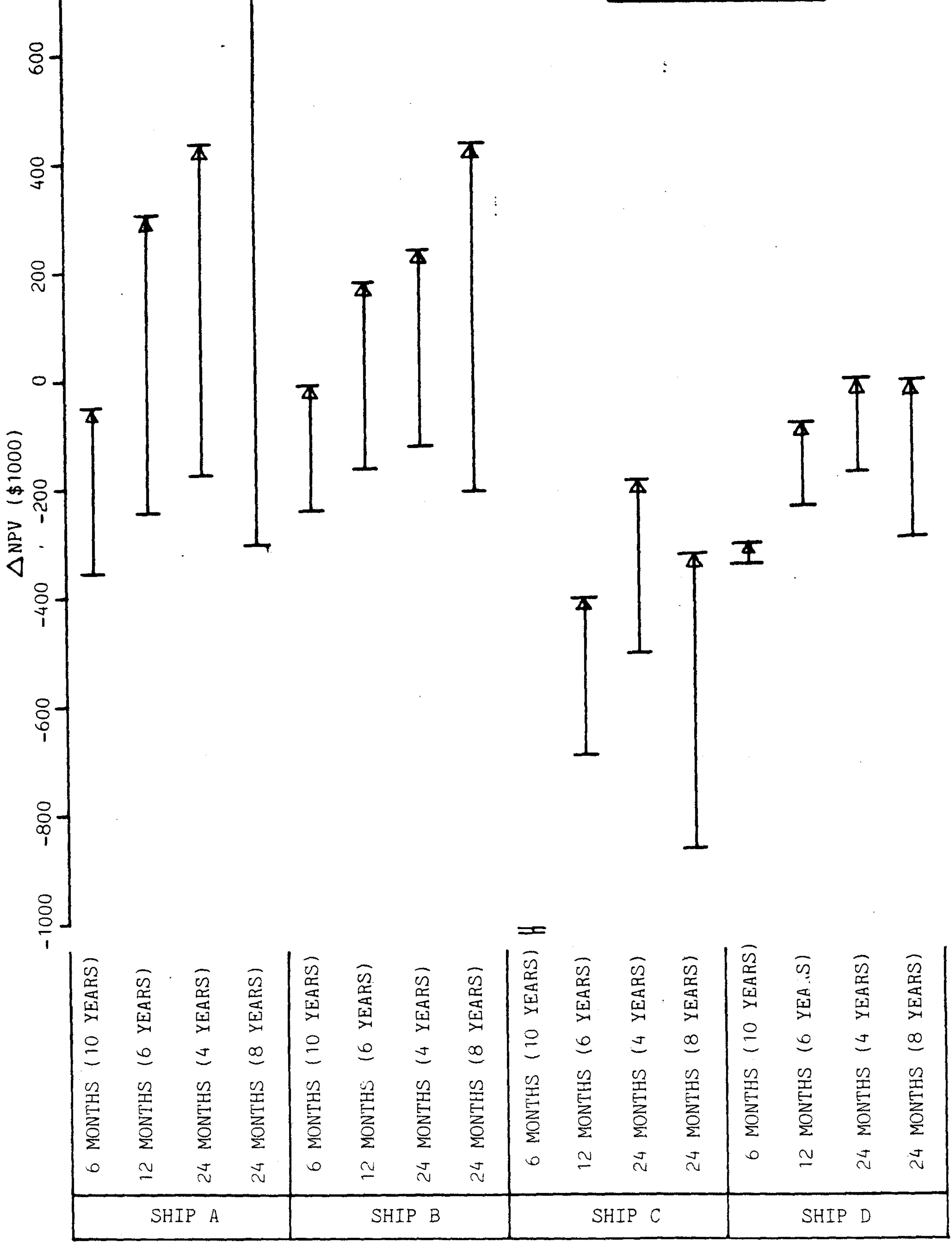


Figure (3.22) clearly indicates that for Ships A and B the self polishing system is justified, provided the drydocking interval is extended by more than 6 months. In the case of Ship C, extension of the drydocking interval by up to 24 months does not provide sufficient reason in economic terms, and for Ship D the break-even point is just reached with an extension of 24 months.

Negligible changes in NPV are obtained for Ships C and D from extending the drydocking interval by only 6 months, and this is explained by the fact that most of the economic benefits achieved by saving a complete drydocking over the 10 year period are used to pay for the additional day required for paint application at every drydocking. The various projected extensions to the time required between drydockings are, of course, subject to approval by Classification Societies. Present rules state that all vessels classified 1A1 in the rules of Det norske Veritas or 100A1 in the rules of Lloyds will have to be drydocked at intervals of 2.5 years, [References (41) and (42)]. A further extension of 6 months will be granted under the rules of DnV if required, giving a total maximum of 3 years between drydockings. In the rules of Lloyds, extensions may be granted on an individual basis if satisfactory reason can be provided by the owner. Vessels classified as "built for in-water survey", (B.I.S.), need only be drydocked every 5 years, but only a small number of VLCC's have this classification. The general rule which can be applied for most ocean going commercial vessels is therefore a maximum drydocking interval of 36 months. The 24 month extension presented in the present case study is intended simply to demonstrate the further economic benefits which may be obtained from changing the Classification Rules currently in force. In the case of the self polishing co-polymer system, no allowance has been made for slower polishing rates at lower operating speeds, and no attempt has been made to differentiate between polishing rates in cold water and temperate waters. These factors have to be examined in more detail for individual vessels with their own particular operating profiles.

3.2.8 CASE STUDY 4: AN INVESTIGATION INTO OPTIMUM HULL MAINTENANCE STRATEGIES FOR 4 SHIP TYPES

In Case Studies 2 and 3, principal maintenance alternatives have been investigated for 4 different ship types. The results have, in each case, been presented as a series of generalised diagrams, serving as basis for a simplified approximate method of evaluating alternative hull maintenance strategies for vessels of similar type and operating profile. The analysis has also allowed conclusions to be drawn with respect to the relative merit of alternative courses of action for decisions on hull maintenance between different ship types, clearly pointing towards different optimum maintenance strategies for different ship types. The method of analysis used, by which the difference in economic terms between two clearly defined alternatives is calculated, has allowed only a limited number of principal maintenance alternatives to be investigated, and the method is clearly unsuited for the task of searching for optimum maintenance strategies.

In Chapter 2, a model for finding optimum hull maintenance strategies based upon the principles of dynamic programming was proposed. This model is intended for use at a preliminary stage in the calculation process as a method of selecting maintenance strategies of principal interest, and which should be investigated further in a more detailed analysis. A basic requirement for the application of dynamic programming techniques is that the optimising criterion is independent of later stages, otherwise non optimum partial paths can not be discarded from the analysis. This requirement , combined with the initial assumption that the problem can be subdivided into finite stages and states, has resulted in the practical constraint that only maintenance strategies with equal intervals between drydockings can be included in the same analysis. Extending the interval between drydockings will require a separate analysis, and the results of the dynamic programming analysis should always be interpreted with this in mind.

As already mentioned , the dynamic programming model would normally be used at a preliminary stage in the evaluation process for the purpose of selecting provisional optimum maintenance strategies. In the present series of case studies a more detailed analysis for a limited number of alternatives has already been performed, and the dynamic programming model will therefore be used instead to re-examine maintenance strategies for the 4 ship types in the light of the already existing results. The dynamic programming model permits a total of 3 independent alternative courses of action at every drydocking. In order to achieve compatibility with the previous case studies, these 3 alternatives are specified as follows for an existing vessel already in service:

(1) <u>Reblast Alternative 1:</u> Complete reblast of underwater hull, build-up of a new anticorrosive system and recoat with a conventional high performance antifouling paint according to specifications in Table (B-6), Appendix B. Outdocking roughness after reblast and recoat = 125 μm AHR. Roughness development over the period until next drydocking follows the average specification in Chapter 1.

(2) Reblast Alternative 2: Complete reblast of underwater hull, build-up of a new anticorrosive system and recoat with a self polishing co-polymer type of paint according to specifications in Table (B-6), Appendix B. Outdocking roughness after reblast and recoat = 125 μm AHR. Roughness development over the period until next drydocking follows one of the four scenarios specified in Case Study 3.1

(3) Standard Drydocking: Recoat with the same system as used on previous drydocking. Roughness development and paint system costs follow the specifications of the already existing system.

Drydocking interval = 24 months, irrespective of the paint system used.

Extra time required for reblast = 5 days in drydock for all vessels and coating systems.

Technical, operational and financial data for each ship type are as specified in Section 3.1.1, and the standard hull maintenance specification in the same section applies to all four vessels.

Case Studies 2 and 3 have provided firm guidelines with respect to the roughness levels at which a complete reblast and renewal of the coating system is justified in economic terms, but only a few principal strategies have been explored, none of which may necessarily be the optimum. The problem for which the dynamic programming model may be able to provide some guidance is therefore, first of all, in the specification of a maintenance strategy following the initial decision to reblast.

To ensure that the optimum first decision is to reblast immediately, all four vessels are assumed to be coated with a conventional high performance antifouling paint following a roughness scenario as described in (1) above, and having a present hull roughness of 400 μm AHR measured at indocking.

Results for the four ship types in terms of indicated optimum maintenance strategy and net present value of operating account, excluding capital charges, are given in Tables (C-14) to (C-29) of Appendix C . A 10 year calculation period has been used to comply with the results of the earlier case studies, but some care should be taken in the interpretation of drastic changes in maintenance system towards the end of this period due to the adverse effect of the discounting factor on distant cash flows.

For Ship A, the optimum strategy is clearly to reblast and apply the self polishing type of paint with re-application of the same at subsequent drydockings when roughness Scenario 1 is assumed. The same conclusions are obtained under Scenario 2, but in this case a further reblast to remove roughness would be recommended after 4 or 6 years. Under Scenarios 3 and 4 the optimum maintenance strategy is found to be a high performance conventional system, with complete reblast every 48 months if drydocking intervals are restricted to 24 months, and the conventional system is assumed to remain free from fouling. A separate analysis, assuming drydocking intervals can be extended by 12 months to a total of 36 months for the self polishing system, resulted in a complete change in the recommended maintenance procedure under roughness Scenarios 3 and 4. In both cases the optimum strategy is now to use the self polishing type of coating with a complete reblast every 36 or 72 months under Scenario 3, and every 36 months under Scenario 4. The benefits in net present value terms obtained from this change in strategy are $360,000 and $575,000 for Scenarios 3 and 4 respectively, over 6 years.

For Ship B, the optimum maintenance strategy under Scenario 1 is identical to that of Ship A, with reblast and application of a self polishing type of paint and reapplication of the same at subsequent drydockings. Under any of the remaining scenarios, however, the optimum maintenance strategy is found to be a high performance conventional system with reblast every 48 months if drydocking intervals are restricted to 24 months. A separate analysis, assuming drydocking intervals can be extended by 12 months for the self polishing system, results in changes in optimum strategies under all three Scenarios 2, 3 and 4. The recommended maintenance procedure for Scenario 2 is to use the self polishing type of coating with a complete reblast every 72 months. For Scenarios 3 and 4 the recommended paint system is the same, but with reblasts at every drydocking, or 36 months.

In the case of Ship C, the optimum maintenance strategy is found to be a complete reblast and application of a high performance conventional system with reapplication of the same at subsequent drydockings, irrespective of the roughness scenario used for the self polishing system, when drydocking intervals are restricted to 24 months. As shown in Case Study 3.2, the use of the self polishing type of paint can not be justified on the grounds of extending the drydocking interval from 24 to 36 months alone. The advanced system is in fact only marginally justified in economic terms on the basis of extended drydocking interval combined with a zero increase in roughness as described in Scenario 1. Further analysis assuming drydocking intervals can be extended by 12 months for the self polishing system results in no changes in the optimum maintenance strategies under Scenarios 2, 3 and 4. In other words, the use of a high performance conventional system remains the optimum strategy under the most realistic roughness scenarios for this type of vessel in the present economic climate, provided the conventional system remains free from fouling over the 24 month period between drydockings.

For Ship D, the optimum maintenance strategy under roughness Scenario 1 is found to be the same as for Ships A and B. Under Scenarios 2, 3 and 4 the optimum is found to he a high performance conventional system with reblast every 48 or 72 months, if drydocking intervals are restricted to 24 months. With a drydocking interval of 36 months for the self polishing system, this is found to be the optimum maintenance strategy under roughness Scenarios 2 and 3, but in the case of Scenario 3 the change in optimum strategy is only marginally justified in economic terms. Under Scenario 4 there is no change in the optimum and the conventional high performance system with reblast every 48 or 72 months remains the recommended maintenance strategy, again assuming no fouling.

Having already drawn conclusions for individual ship types, only some general comments are required about the results obtained in this case study. The objectives were identified at the start as being two-fold; first to test the use of the dynamic programming model; secondly to demonstrate that investigation of principal maintenance strategies may not necessarily yield the required optimum, and that a rational search method provides a more efficient tool for identifying areas of principal interest. This second point has clearly been demonstrated; only for Ship C is the optimum strategy unchanged, while for Ships A,B and D, the optimum is different from any of the principal strategies examined in Case Studies 2 and 3 under the most realistic set of roughness scenarios. The results have confirmed the observations made in the earlier case studies that for some types of ships, in particular Ship A, the economic penalty of increasing hull roughness is high. For vessels similar to Ship A and coated with a self polishing type of coating,economic justification can be found for complete reblast and renewal of the coating system at regular intervals, if the hull is subject to a less than half the average deterioration in surface condition with time experienced with conventional antifouling systems. It is important in this particular case to be aware that the optimising criterion in the dynamic programming model is net present value, and as discussed in Chapter 1 , this economic measure of merit is not related to the actual size of the investment, effectively encouraging large investments. Since the application of a self-polishing type of coating requires a higher capital investment, the optimum strategy with respect to a NPV criterion may therefore not necessarily remain the optimum when using the criterion of maximising profits for each unit of captial invested.

3.2.9 CASE STUDY 5: THE POSSIBLE ECONOMIC PENALTIES ASSOCIATED WITH HULL FOULING

Throughout the preceeding case studies the assumption has been made that a high performance conventional paint system will remain free from fouling for a period of 24 months, and that the occurrence of hull fouling is in economic terms a disaster, which can not under any circumstances be tolerated. The results of an investigation into the amount of fouling settlement after various periods of time in service presented in Chapter 1 clearly indicate that this assumption of no fouling is not true in the great majority of cases. A substantial number of vessels coated with a high performance conventional antifouling system were found to have acquired significant levels of fouling after less than 24 months in service, and an assumed period of 18 months prior to fouling settlement would probably be a better estimate. The settlement of fouling depends principally on the effectiveness of the antifouling paint, but also on a number of variables outside the direct control of the ship owner or operator, for example, water temperature, location and season, tidal conditions and time spent in stationary condition or at slow speed.

Even more uncertain is the increase in resistance associated with various degrees of fouling settlement, and few reliable sources of information are readily available. Reference (43) reports on an in-service performance monitoring programme on a fleet of tankers. For two of the vessels reported on in this work, continuous performance records were available over a period of nearly 2 years, and the speed loss was calculated to be 9% over 19 months and 11% over 22 months, respectively, for each vessel. A similar vessel was put into service after drydocking without any antifouling paint and the performance monitored over a period in excess of 12 months, [Reference (44)]. The intital rate of deterioration in speed performance was found to be 4% per month for the first 3 months, and thereafter levelling out to reach a total speed loss of approximately 16.5% after 12 months. These results should be interpreted with some care because of the numerous sources of errors associated with a staff operated performance monitoring system, but indications are that speed losses of between 5% and 10% due to fouling are plausible, and for heavily fouled vessels this figure could be substantially greater. A further source of uncertainty is the time period between the initial settlement of fouling larvae or spores and the fully saturated state of fouling. In the case of barnacles, the rate of growth will always be slow, and a saturated state will take several months to develop. Having settled on the hull surface the barnacles are also less influenced by surrounding conditions than weed fouling. Under favourable conditions weed fouling can reach a fully grown state over a period of only 4 weeks, while under different conditions can take 6 months to reach the same state. An average time period of 3 months from initial settlement to a fully saturated state is therefore taken as a realistic assumption in an economic case study where a single number representation is required.

On the basis of the above information the following fouling scenario was formulated for a conventional high performance type of paint system, to be investigated for the four ship types used in the case study.

(i) Time period from outdocking to intitial settlement of fouling = 18 months.

(ii) Time period from initial settlement of fouling to a fully saturated state = 3 months, where speed loss during this period of time follows a cosine curve, as described in Chapter 2.

(iii) Speed loss in the fully saturated state = 5% or 10% of normal operating speed.

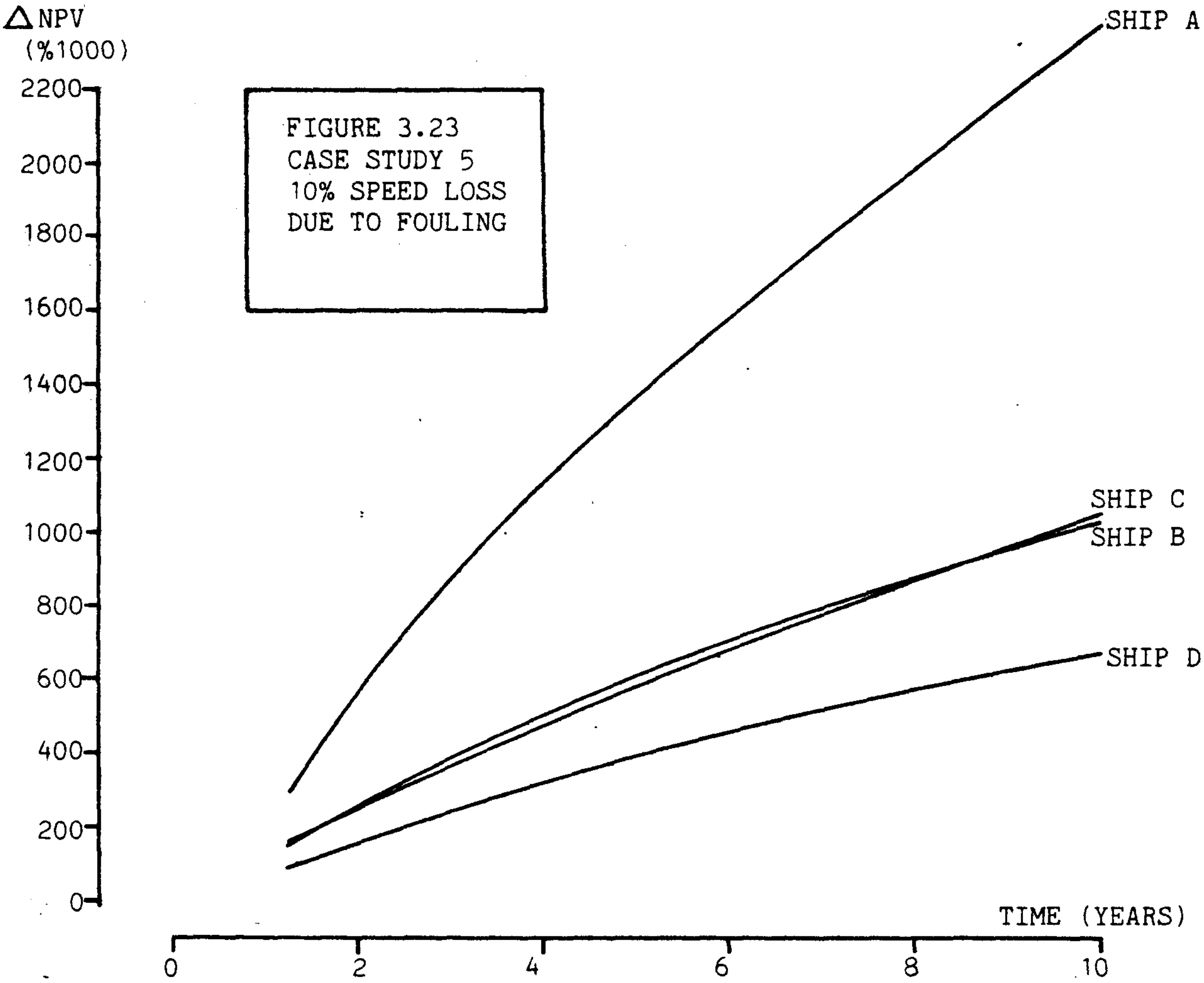
It should be emphasised that this is a hypothetical scenario based upon a set of bold assumptions, and is intended to demonstrate simply the possible economic consequences of hull fouling. No further conclusions should be drawn from the results. Technical, operational and financial data for each ship type are as specified in Section 3.1.1.

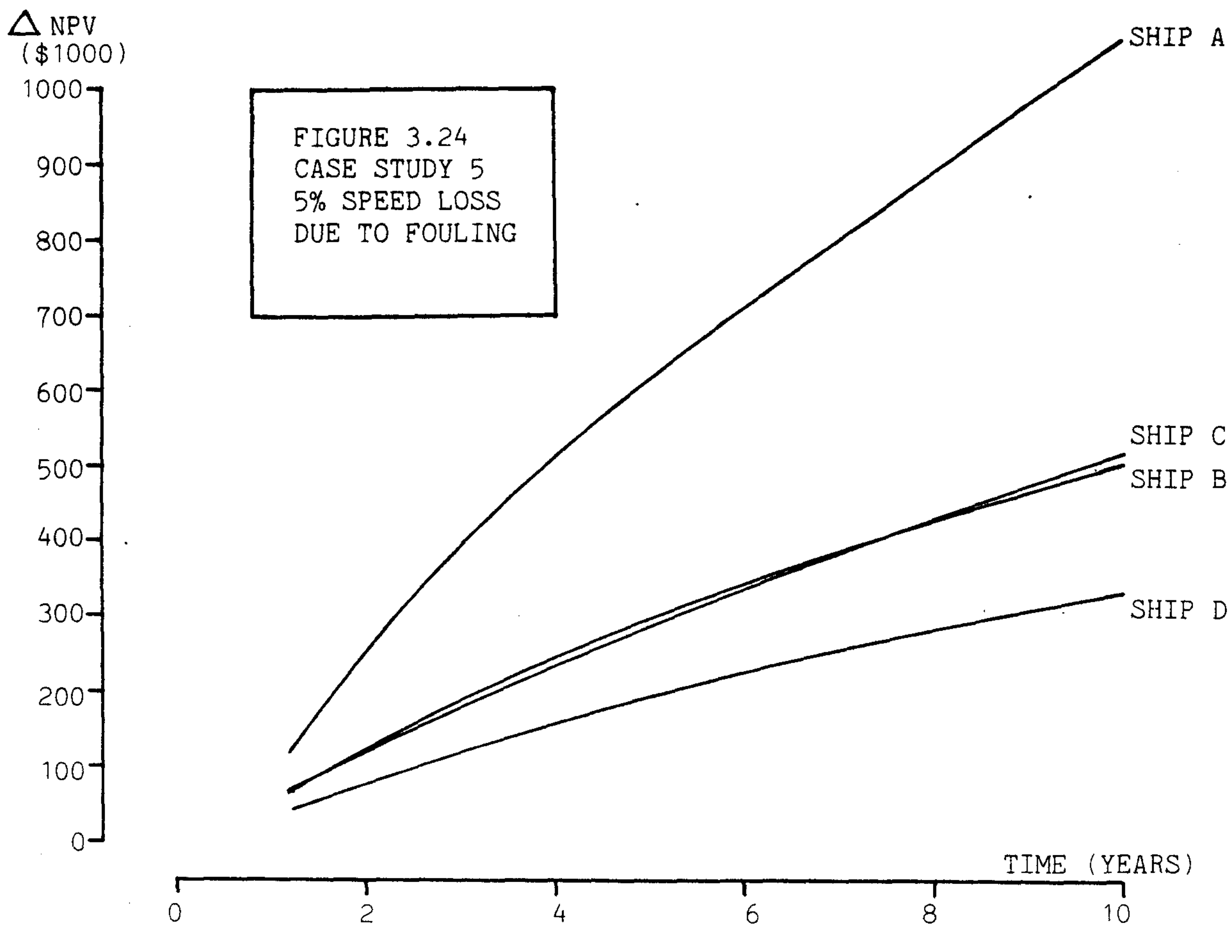
In each case the difference is calculated in net present value terms between a conventional system remaining free from fouling over the 24 month period between drydockings and a similar system following the above fouling scenario. Results are presented in Table (C-13) of Appendix C and

Figures (3.23) and (3.24), for a calculation period between 2 and 10 years. For Ship A constant speed operation is assumed and the predicted values have been transformed into an increase in power requirement, while for Ships B, C and D, the values of speed loss have been used as specified.

As initially predicted, the loss of speed due to fouling towards the end of the drydocking cycle has a potentially disastrous effect upon the operating profits and is in economic terms totally unacceptable. A comparison with the results obtained in Case Study 3.1 demonstrate that for Ships A, B and D the more expensive self polishing system would be justified on the grounds of preventing this speed loss due to fouling alone using the low projection of only 5% loss of speed in the saturated condition. In the case of Ship C, the speed loss projection would have to be 10% in order to justify the self polishing system under the same set of conditions.

As a temporary measure, the economic consequences of hull fouling may be reduced by the use of underwater scrubbing techniques, but it should be emphasised that this is only a temporary solution. Reference (45) has shown that the process of underwater scrubbing to remove weed fouling leaves a sufficient amount of basal parts to promote renewed and intensified growth within a few weeks. In some cases the repeated use of hull scrubbing equipment may also result in damage to the coating system with corresponding problems of corrosion and increases in hull roughness.


△NPV
(%1000)
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
FIGURE 3.23
CASE STUDY 5
10% SPEED LOSS
DUE TO FOULING
SHIP A
SHIP C
SHIP B
SHIP D
TIME (YEARS)
0
2
4
6
8
10


△NPV
($1000)
1000
900
800
700
600
500
400
300
200
100
0
FIGURE 3.24
CASE STUDY 5
5% SPEED LOSS
DUE TO FOULING
SHIP A
SHIP C
SHIP B
SHIP D
TIME (YEARS)
0
2
4
6
8
10

3.2.10 SENSITIVITY ANALYSIS FOR 4 SHIP TYPES

As a supplement to the series of case studies, a sensitivity analysis has been performed on principal variables for the four ship types. This allows variations in some of the previously fixed variables to be explored, as well as identification of principal variables for further investigation in the following analysis of uncertainty.

Ideally, a sensitivity analysis should have been performed for each ship type in every case study, but for practical purposes sufficient accuracy was found to be achieved by exploring two selected maintenance strategies over time periods of 2 and 6 years.

The two maintenance alternatives examined are the same as those used in Case Study 2.3, and where roughness Scenario 1 is used in connection with Alternative 1.

Technical, operational and financial data for each ship type are specified in Section 3.1.1, the paint system costs are taken from Table (B-6), Appendix B, and the standard hull maintenance specification in Section 3.1.1 applies to all four vessels.

Results of the sensitivity analysis for each vessel are presented in net present value terms in Tables (3.2) to (3.5). The change in the total NPV of the operating account is provided for each maintenance alternative, as well as the change in the difference between the two alternatives.

TABLE (3.2) SENSITIVITY ANALYSIS FOR SHIP A

	CALCULATION PERIOD: 2 YEARS			CALCULATION PERIOD: 6 YEARS		
	CHANGE IN NPV OF ALTERNATIVE 1	CHANGE IN NPV OF ALTERNATIVE 2	CHANGE IN DIFFERENCE IN NPV BETWEEN ALTERNATIVES	CHANGE IN NPV OF ALTERNATIVE 1	CHANGE IN NPV OF ALTERNATIVE 2	CHANGE IN DIFFERENCE IN NPV BETWEEN ALTERNATIVES
BASIS CONDITION (TOTAL NPV GIVEN)	+23755	+23738	+17	+63474	+62762	+712
1. Improve propulsion efficiency by 10%	+900	+911	-11	+2392	+2479	-87
2. Specific fuel consumption decreased by 10%	+900	+912	-12	+2392	+2488	-96
3. Voyage distance doubled (freight rate adjusted)	0	-21	+21	0	-165	+165
4. Fuel price increased by 10% (freight rate adjusted)	0	-12	+12	0	-96	+96
5. Fuel price increased by 10% (no freight rate adjustment)	-1037	-1049	+12	-2755	-2850	+96
6. Fuel price escalation increased by 10% (freight rate adjusted)	0	-8	+8	-160	-490	+330
7. Fuel price escalation increased by 10% (no freight rate adjustment)	-466	-473	+8	-6538	-6868	+330
8. Freight rate increased by 10%	+8772	+8772	0	+23301	+23301	0
9. Freight rate escalation increased by 10%	+3939	+3939	0	+55303	+55303	0
10. Paint system costs increased by 10%	-16	-8	-8	-44	-20	-24
11. Hire of drydock increased by 10%	-14	-14	0	-31	-31	0
12. Cost of reblast increased by 10%	-13	-13	0	-13	-13	0
13. Docking interval of Alternative 1 increased by 12 months	0	0	0	+593	0	+593
14. All docking intervals increased by 12 months	0	0	0	+593	+600	-8
15. Days in drydock increased by 2 for Alternative 1	-108	0	-125	-284	0	-284
16. Days in drydock increased by 2 for both Alternatives	-108	-108	0	-284	-281	-3
17. Extra days in drydock for reblast increased by 2	-108	-108	0	-108	-108	0
18. Hydrodynamic importance of hull roughness decreased by 10%	0	+12	-12	0	+96	-96
19. Rate of roughness increase in service doubled	0	-103	+103	0	-530	+530
20. Discount rate halved in real terms	+1193	+1189	+4	+7363	+7242	+122

All figures are expressed in terms of ($1000)

Values given for basis condition are absolute values, while for items 1 to 20 the values given are relative to the basis condition

TABLE (3.3) SENSITIVITY ANALYSIS FOR SHIP B

	CALCULATION PERIOD: 2 YEARS			CALCULATION PERIOD: 6 YEARS		
	CHANGE IN NPV OF ALTERNATIVE 1	CHANGE IN NPV OF ALTERNATIVE 2	CHANGE IN DIFFERENCE IN NPV BETWEEN ALTERNATIVES	CHANGE IN NPV OF ALTERNATIVE 1	CHANGE IN NPV OF ALTERNATIVE 2	CHANGE IN DIFFERENCE IN NPV BETWEEN ALTERNATIVES
BASIS CONDITION (TOTAL NPV GIVEN)	+10032	+10063	-31	+26688	+26568	+120
1. Improve propulsion efficiency by 10%	+392	+392	0	+1036	+1038	-2
2. Specific fuel consumption decreased by 10%	+330	+330	0	+872	+874	-2
3. Voyage distance doubled (freight rate adjusted)	0	-8	+8	0	-62	+62
4. Fuel price increased by 10% (freight rate adjusted)	0	-1	+1	0	-8	+8
5. Fuel price increased by 10% (no freight rate adjustment)	-449	-449	0	-1188	-1190	+2
6. Fuel price escalation increased by 10% (freight rate adjusted)	0	-1	1	-62	-88	+26
7. Fuel price escalation increased by 10% (no freight rate adjustment)	-201	-202	0	-2815	-2822	+7
8. Freight rate increased by 10%	+2195	+2192	+3	+5805	+5777	+28
9. Freight rate escalation increased by 10%	+984	+982	+2	+13758	+13663	+95
10. Paint system costs increased by 10%	-11	-5	-6	-29	-14	-16
11. Hire of drydock increased by 10%	-1	-1	0	-4	-4	0
12. Cost of reblast increased by 10%	-10	-9	-1	-10	-9	-1
13. Docking interval of Alternative 1 increased by 12 months	0	0	0	+375	0	+375
14. All docking intervals increased by 12 months	0	0	0	+375	+349	+26
15. Days in drydock increased by 2 for Alternative 1	-49	0	51	-129	0	-134
16. Days in drydock increased by 2 for both Alternatives	-49	-49	0	-129	-128	-1
17. Extra days in drydock for reblast increased by 2	-49	-49	0	-49	-49	0
18. Hydrodynamic importance of hull roughness decreased by 10%	0	3	-3	0	+28	-28
19. Rate of roughness increase in service doubled	0	-31	+31	0	-154	+154
20. Discount rate halved in real terms	+505	+505	0	+3097	+3070	+27

All figures expressed in terms of ($1000)

Values given for basis condition are absolute values, while for items 1 to 20 the values given are relative to the basis condition

TABLE (3.4) SENSITIVITY ANALYSIS FOR SHIP C

	CALCULATION PERIOD: 2 YEARS			CALCULATION PERIOD: 6 YEARS		
	CHANGE IN NPV OF ALTERNATIVE 1	CHANGE IN NPV OF ALTERNATIVE 2	CHANGE IN DIFFERENCE IN NPV BETWEEN ALTERNATIVES	CHANGE IN NPV OF ALTERNATIVE 1	CHANGE IN NPV OF ALTERNATIVE 2	CHANGE IN DIFFERENCE IN NPV BETWEEN ALTERNATIVES
BASIS CONDITION	-2309	-2077	-232	-5320	-5020	-300
1. Improve propulsion efficiency by 10%	+508	+506	+2	+1349	+1332	+17
2. Specific fuel consumption decreased by 10%	+1041	+1041	0	+2765	+2768	-3
3. Voyage distance doubled (freight rate adjusted)	0	-2	+2	0	-19	+19
4. Fuel price increased by 10% (freight rate adjusted)	0	-4	+4	0	-30	+30
5. Fuel price increased by 10% (no freight rate adjustment)	-1077	-1077	0	-2862	-2864	+2
6. Fuel price escalation increased by 10% (freight rate adjusted)	0	-2	2	-85	-185	+100
7. Fuel price escalation increased by 10% (no freight rate adjustment)	-480	-480	0	-6781	-6787	+6
8. Freight rate increased by 10%	+1972	+1966	+6	+5239	+5188	+51
9. Freight rate escalation increased by 10%	+879	+875	+4	+12416	+12241	+175
10. Paint system costs increased by 10%	-47	-22	-25	-124	-58	-66
11. Hire of drydock increased by 10%	-20	-20	0	-40	-40	0
12. Cost of reblast increased by 10%	-37	-34	-3	-37	-34	-3
13. Docking interval of Alternative 1 increased by 12 months	0	0	0	+507	0	+507
14. All docking intervals increased by 12 months	0	0	0	+507	+333	+174
15. Days in drydock increased by 2 for Alternative 1	-45	0	-45	-119	0	-209
16. Days in drydock increased by 2 for both Alternatives	-45	-45	0	-119	-117	-2
17. Extra days in drydock for reblast increased by 2	-45	-45	0	-45	-45	0
18. Hydrodynamic importance of hull roughness decreased by 10%	0	5	-5	0	+38	-38
19. Rate of roughness increase in service doubled	0	-43	+43	0	-210	+210
20. Discount rate halved in real terms	-96	-90	-6	-544	-538	-6

All figures are expressed in terms of ($1000)

Values given for basis condition are absolute values, while for items 1 to 20 the values given are relative to the basis condition

TABLE (3.5) SENSITIVITY ANALYSIS FOR SHIP D

	CALCULATION PERIOD: 2 YEARS			CALCULATION PERIOD: 6 YEARS		
	CHANGE IN NPV OF ALTERNATIVE 1	CHANGE IN NPV OF ALTERNATIVE 2	CHANGE IN DIFFERENCE IN NPV BETWEEN ALTERNATIVES	CHANGE IN NPV OF ALTERNATIVE 1	CHANGE IN NPV OF ALTERNATIVE 2	CHANGE IN DIFFERENCE IN NPV BETWEEN ALTERNATIVES
BASIS CONDITION	+991	+1051	-61	+2938	+2899	38
1. Improve propulsion efficiency by 10%	+314	+313	+1	+834	+834	+6
2. Specific fuel consumption decreased by 10%	+422	+422	0	+1122	+1125	-3
3. Voyage distance doubled (freight rate adjusted)	0	-4	+4	0	-33	+33
4. Fuel price increased by 10% (freight rate adjusted)	0	-2	+2	0	-13	+13
5. Fuel price increased by 10% (no freight rate adjustment).	-468	-468	0	-1244	-1247	+3
6. Fuel price escalation increased by 10% (freight rate adjusted)	0	-1	+1	-48	-92	+44
7. Fuel price escalation increased by 10% (no freight rate adjustment)	-209	-209	0	-2950	-2959	+9
8. Freight rate increased by 10%	+1145	+1141	+4	+3040	+3015	+26
9. Freight rate escalation increased by 10%	+512	+510	+2	+7209	+7121	+88
10. Paint system costs increased by 10%	-16	-7	-8	-42	-19	-22
11. Hire of drydock increased by 10%	-7	-7	0	-15	-15	0
12. Cost of reblast increased by 10%	-12	-12	0	-12	-12	0
13. Docking interval of Alternative 1 increased by 12 months	0	0	0	+220	0	+220
14. All docking intervals increased by 12 months	0	0	0	+220	+.73	+47
15. Days in drydock increased by 2 for Alternative 1	-28	0	-28	-75	0	-75
16. Days in drydock increased by 2 for both Alternatives	-28	-28	0	-75	-75	0
17. Extra days in drydock for reblast increased by 2	-28	-28	0	-28	-28	0
18. Hydrodynamic importance of hull roughness decreased by 10%	0	+3	-3	0	+27	-27
19. Rate of roughness increase in service doubled	0	-29	+29	0	-144	+144
20. Discount rate halved in real terms	+56	+58	-2	+366	+348	+19

All figures are expressed in terms of ($1000)

Values given for basis condition are absolute values, while for items 1 to 20 the values given are relative to the basis condition

3.2.11 CASE STUDY 6: COPPER-NICKEL CLADDING OF THE UNDERWATER HULL EXAMINED AS AN ALTERNATIVE TO CONVENTIONAL HULL PAINTING PROCEDURES

3.2.11.1 INTRODUCTION

The "ideal" hull surface is a permanently smooth surface which remains free from biological fouling, does not corrode and which requires no maintenance throughout the lifetime of the vessel. Of the hull surface materials presently available, the (80-20) or (90-10) Copper-Nickel Alloy probably comes nearest to meeting these requirements, but at a cost. Both copper and nickel are substantially more expensive than the conventional steel used for shell-plating, and the principal problem is therefore to find a solution which is feasible both in technical as well as in economic terms. At present 3 different methods of covering the hull surface with a copper nickel alloy are commercially available.

1. A composite material consisting of a copper alloy mesh embedded in glass-reinforced polyester in such a way that the knuckles of the mesh are exposed regularly over the flat surface. The material is manufactured in the form of sheets and are applied to steel using an epoxy adhesive.

2. A copper-nickel alloy sheeting manufactured as a thick foil and applied to the steel surface using an adhesive.

3. Cladding the shell plating over the complete underwater area with a

2-3mm thick copper-nickel alloy. The cladding process is performed in the steel mill using a hot rolling process creating a metallic bond between the two materials.

The first two alternatives can be used on existing vessels, while the third alternative will have to be incorporated from the design stage and is therefore only suitable for new ships.

All 3 methods have been tested in various other applications under mostly static conditions. The manufacturers of the wire mesh have produced evidence of good antifouling properties, but in the Author's view doubts exist about the ability of the copper alloy mesh to provide antifouling protection under dynamic conditions. Tests with antifouling paints have shown that the bioligical fouling accumulates on inert areas of a size smaller than pin-heads under dynamic conditions, suggesting that non-toxic areas are not protected by surrounding areas of high toxicity. Some of the antifouling properties observed may also be due to the initial smoothness of the surface, creating a type of "physical effect" antifouling material.

Doubt also exists about the ability of alternatives (1) and (2) to withstand the impact of mechanical damage, and repair procedures have not been thoroughly investigated and tested out to provide sufficient confidence in the systems. For commercial ocean going vessels, only the third alternative of constructing the underwater hull area from copper-nickel clad shell plating appears to be technically feasible, and this is the only solution investigated in this case study.

3.2.11.2 ADDITIONAL NEW BUILDING COSTS ASSOCIATED WITH A COPPER-NICKEL CLAD HULL

ADDITIONAL COST OF FABRICATION :

Due to lack of experience with this type of work, no reliable data are available from shipyards. A private feasibility study on the various aspects associated with the use of copper-nickel clad steel shell plating for ships has been carried out by a group of independent consultants on behalf of a major manufacturer of copper-nickel alloys. This study, which includes a detailed investigation into the production aspects of copper-nickel clad vessels, was generously made available as a source of information for the present case study evaluation, [Reference (46)]. From this source, an additional fabrication cost of DM58.00 per square metre was estimated for vessels with a wetted surface area in the region of 5000 to 15000 square metres (in 1978 prices). Assuming an annual escalation of 15%, the cost in 1981 prices will be DM88.00 per square metre or $38.30 per square metre using DM2.30 = $1.00.

COST OF COPPER-NICKEL CLAD STEEL PLATING :

From price data, the cost of copper-nickel clad steel plating in May, 1980 was DM6.30 per kg. for a plating thickness of 15mm steel and 2mm copper-nickel alloy. This gives an additional cost per square metre for copper-nickel materials amounting to DM/37.50. According to the manufacturers, the price remains the same for 1981, and hence using a $ to DM conversion factor of 2.3 gives an additional cost of $320.70 per square metre in 1981 prices.

Ideally, only the wetted surface to the deep load line will require cladding, but since the possible problems of corrosion at the edge of the plating have not been thoroughly examined, a safety margin is included by also cladding an area above the waterline amounting to 10% of the total wetted surface area. In addition, a cutting margin of 10% will be required in the production process. Hence the cost of materials are increased by 20% to give a value of $384.80 per square metre. Adding the additional cost of fabrication gives an estimated total cost of $423.10 per square metre of wetted surface area.

Due to the uncertainty in the additional cost of fabrication, this is increased by 100% to give a second estimate of $461.40 per square metre. This is the total additional cost per square metre of wetted surface area which will have to be paid for a new building with a copper-nickel clad steel shell plating.

3.2.11.3 ECONOMIC EVALUATIONS OF COPPER-NICKEL CLADDING FOR A LARGE CONTAINERSHIP

The substantial cost of copper-nickel clad steel plating implies that not all ship types are likely candidates for this alternative hull maintenance strategy. Case study 1 clearly points out the differences in the amounts of capital available on a square metre basis to reduce hull roughness for different ship types. Clearly, the fast containership is the most obvious candidate, and Ship A has therefore been chosen for this particular case study evaluation. The results obtained for Ship A will indicate whether calculations are also required for the remaining 3 vessels.

The two alternative hull maintenance strategies to be examined are therefore copper-nickel cladding against conventional hull painting procedures. In economic terms, the benefits of a copper-nickel system are going to be obtained from a smoother surface condition, less time required in drydocking because no hull maintenance is required and from the ability to extend the time between drydockings. This last benefit of extending the time between drydockings can also be achieved using a self polishing type of antifouling paint, and should therefore not be counted as an exclusive benefit of the copper-nickel system. The average hull roughness of a copper-nickel clad vessel can only be estimated from roughness measurement on samples of plating, since no full scale experience is available. Indications are that the surface roughness of the plating will be in the range 40-60 μm and an average hull roughness in the range 75-100 μm over the lifetime of the vessel should therefore be achievable after allowing for some deterioration. The paint system alternative is assumed to start with a roughness of 125 μm, and for this particular case study is assumed to deteriorate at the average level of a conventional system, as described in Chapter 1. Paint system costs are given in Appendix B. With a 24 month standard drydocking interval, a 3 coat self polishing system will be required. Extending this drydocking interval by 12 months will require one additional coat of paint, and extending it by 24 months will require two additional coats of paint. Based upon the lowest estimated unit cost of $423.10 per square metres for the copper-nickel system, the total additional new-building cost for Ship A becomes:

+ $4,441,000 compared with a 3 coat self polishing paint system

+ $4,389,000 compared with a 4 coat self polishing paint system

+ $4,337,000 compared with a 5 coat self polishing paint system

Some of this high capital expenditure may possibly be recovered when the vessel is scrapped after a service life of 15 to 20 years, but the uncertain prospect of a small additional cash flow at some distant point in time is not a realistic assumption to include in the present set of calculations.

All other technical, operational and financial information are given in Section 3.1.1. Although the copper-nickel system would be expected to last for the lifetime of the vessel, say 15 to 20 years, it is unlikely that a shipowner would be willing to consider the investment over more than 8 to 10 years, which is the normal period of repayment for shipbuilding loans. A 10 year calculation period is therefore used with a discount rate of 17.5% in money terms. The copper-nickel alternative is based upon a number of assumptions, and the following 4 alternative situations are therefore presented:

CASE A: AHR of copper-nickel alternative = 75 μm throughout the period of calculation.
AHR of self polishing system = 125 μm at new building, increasing at average rate (Chapter 1)
Time in drydocking is 10 days for both systems.
Fuel price escalation in line with other cost escalations at 10%.

CASE B: Roughness specifications as for Case A.
Time in drydock for copper-nickel system is 5 days and for paint system 10 days.
Fuel price escalation as for Case A.

CASE C: Roughness specifications as for Ship A.
Time required in drydock is the same as for Case B.
Fuel price escalation = 15% per annum or 5% in real terms.

CASE D: AHR of copper-nickel alternative = 100 μm throughout the period of calculation.
AHR of self polishing system = 125 μm at new building, increasing at average rate.(Scenario 4, Case Study 3.1)
Time required in drydock is the same as for Case B.
Fuel price escalation as for Case C.

Results from a 10 year economic modelling are presented in Table (3.6) in terms of differences in the net present value between the two alternatives, yield of the additional investment and discounted profit to investment ratio for the additional capital invested.

TABLE (3.6) ECONOMIC EVALUATIONS OF COPPER-NICKEL CLADDING AGAINST SELF POLISHING COPOLYMER PAINT SYSTEM.

DRYDOCKING INTERVAL	MEASURE OF MERIT	CASE A	CASE B	CASE C	CASE D
24 MONTHS	NPV($)	-587,000	201,300	1008,800	142,300
	YIELD	14.8%	18.3%	21.5%	18.0%
	PROF/INV	-0.148	0.052	0.203	0.037
36 MONTHS	NPV($)	-722,100	-167,300	611,100	-256,700
	YIELD	14.1%	16.8%	19.9%	16.5%
	PROF/INV	-0.182	-0.043	0.158	-0.066
48 MONTHS	NPV($)	-820,000	-452,200	322,900	-546,000
	YIELD	13.6%	15.5%	18.8%	15.2%
	PROF/INV	-0.205	-0.115	0.082	-0.139

Table (3.6) clearly demonstrates that under no circumstances can the copper-nickel alternative give any substantial return on the invested capital. A good rate of return is only achieved with the shorter drydocking interval. This result appears at first to be somewhat unexpected, but is explained by the fact that when the drydocking interval is extended, the benefits from the shorter time required in drydocking are gradually reduced, because fewer drydockings will be required over the 10 year period.

The question also remains whether in fact the paint system used for comparison is the optimum paint system alternative for all the cases presented in Table (3.6). A search for the optimum maintenance strategy in each case can easily be performed using the dynamic programming extension to the deterministic economic model, as explained in Chapter 2. Application of the dynamic programming procedure to CASE C with a 24 month drydocking interval points towards a conventional high performance antifouling with complete reblast every 48 months as the optimum maintenance strategy, when using average rates of increase in roughness for all paint systems, and assuming that the conventional system will remain free from fouling over the 24 month period. The difference in Net Present Value over the 10 year period between the self polishing paint system alternative presented in CASE C, and the optimum paint system alternative from the dynamic programming analysis is in fact $1,300,000. Hence, the apparent good return on the copper-nickel investment presented in CASE C is subsequently reduced to a loss of $300,000, when the minimum required rate of return is 17.5% in money terms, (approximately 7.5% in real terms). In CASE D the sensitivity of the economic results for the copper-nickel alternative to changes in the assumption about surface roughness are clearly demonstrated with an increase of 25 μm in the AHR, giving a further reduction in the Net Present Value of nearly $900,000 over the 10 year period.

In conclusion, therefore, it appears that irrespective of how the copper-nickel alternative is presented, it can only be classified as marginally attractive in economic terms under the most favourable set of assumptions for the containership used in this example. Since the capital investment required is substantially greater than for any other maintenance procedure, and the system is hitherto untried on a full scale, it is therefore unlikely to attract serious interest from commercial shipowners. The fact that the copper-nickel alternative under the most favourable set of circumstances can only be marginally attractive for a fast containership also implies that, for most other commercial ocean going vessels, it is going to be an unattractive investment proposal. In addition, some doubt exists about the ability of the (90-10) copper-nickel alloy to keep the hull completely free from fouling. Certainly all animal fouling and most weed fouling will be prevented, but it is expected that stunted weed fouling and accumulation of slime will take place.

Unless some dramatic changes to the initial assumptions in this case study take place, shipowners will therefore be advised from the economic point of view to search for optimum hull maintenance strategies using paint systems.

3.3 A METHOD FOR THE RAPID ECONOMIC EVALUATION OF HULL MAINTENANCE STRATEGIES FOR PRINCIPAL SHIP TYPES

The preceeding case studies have demonstrated the detailed level to which the economic analysis of hull maintenance strategies can be taken, given that the appropriate techno-economic model is available. Although the problem itself is not new, the rational techno-economic approach to providing solutions is, and the present model is believed to be the first attempt which has been made to put the hull maintenance problem into the complete commercial context of ship operation, without prejudging the results by making a large number of prior assumptions about the relationships between individual variables [see especially Reference (47)].

The present model has been developed primarily as a research tool and has only been made available to a limited number of selected shipowners and operators. Similar models may become generally available at some future point in time, but even if the tools were readily available a large number of shipowners and operators would, in practice, be unable to find the necessary time and data information for this same type of detailed calculation. From the practical point of view, the need therefore clearly exists for a simple method of obtaining approximate solutions to the problems.

The preceeding case studies have identified two different alternatives for a simplified method for the rapid economic evaluation of hull maintenance strategies:

1. A step by step method of building up economic results for alternative strategies based upon the general diagrams from the preceeding case studies.

2. A tabular method where annual cash flows are calculated for each alternative based upon constant speed operation, and the results are transformed to a constant power basis using the proposed simplified formula.

For the purpose of using the first method, no detailed knowledge is required about the application of economic methods and measures of merit to investment calculations, other than the ability to interpret the diagrams provided. In the second method, a simplified techno-economic modelling is performed and an elementary understanding of discounted cash flow methods is necessary, combined with a knowledge of how to transform measures of deteriorating hull condition into economic terms. The following sections provide a more detailed explanation of the two proposed methods.

3.3.1 (1) A STEP BY STEP METHOD BASED UPON DIAGRAMS OF RESULTS FROM A SET OF CASE STUDIES

The preceeding case studies have been performed with the additional objective of establishing a basis for a simplified method of evaluating alternative hull maintenance strategies. Each case study evaluation has been designed so that only one alternative course of action is explored at a time. By selecting a common basis of evaluation for all the case studies it has been possible to provide a series of alternatives which, in economic terms, are additive when net present value is used as a measure of merit. Complete strategies can therefore be explored simply by adding together the results from the individually explored alternatives. The results from the sensitivity analysis are used to make approximate corrections, if any of the principal variables are different from the standard values used in the case studies.

The obvious advantage of this particular method is that a series of calculations is performed once only, and later case studies simply consist of assembling results with a minimum of input data, effort or understanding of the economic principles required. Simplicity, however, comes at the expense of accuracy and flexibility in application. Only a limited number of principal alternative courses of action have been explored, and unless the maintenance strategies under investigation involve the same alternatives, the method is of little use. Furthermore, the case studies have been performed for four principal ship types only, and practical applications of the method are limited to similar ship types. This point has been clearly demonstrated in the individual case studies where the results from different ship types have been shown to vary considerably.

Despite the various shortcomings mentioned, the procedure can serve as a useful method for the rapid evaluation of hull maintenance strategies, particularly at a preliminary stage. The following example demonstrates the use of the step by step method of evaluation for a particular vessel and a particular set of alternative hull maintenance strategies.

Example: A similar vessel to Ship D in the preceeding case studies with the same technical and operational specifications is assumed. The present average hull roughness immediately before drydocking is 350 μm, increasing at average rate in service and in drydock according to the standard specifications in Section 3.1.1. The present coating system in use is a high performance conventional system with a corresponding drydocking interval of 24 months. Two alternative maintenance strategies are available; recoat with the same conventional coating system and assume hull deterioration continues at the present rate, or reblast the complete underwater hull area and apply a modern self polishing system. Outdocking roughness with this second alternative is assumed to be 150 μm, and the average rate of increase in roughness in service is assumed to be half of the average rate (Scenario 3, Case Study 3.1). In addition, the assumption is made that the interval between drydockings can be extended from 24 to 36 months with the self polishing system. Further deviations from the standard specification used in the earlier set of case studies are:

(i) Cost of self polishing paint is 10% less.

(ii) Freight rate is 25% higher.

(iii) Number of additional days required in drydock for reblast and recoat is reduced by one.

Period of calculation is 6 years, and discount rate is 17.5% in money terms.

The effects of hull fouling are ignored in this example.

From Figures (3.7), (3.12), (3.20) and Table (3.5) the difference in net present vaue between the two alternatives can be assembled step by step as follows:

(1)	Reblast and recoat of underwater hull	+ \$310,000
	(1.1) Correction for freight rate	+ \$112,500
(2)	Effect of returning to 150 μm instead of 125 μm AHR	- \$ 70,000
	(2.1) Correction for freight rate	- \$ 17,500
(3)	Difference between self polishing and conventional system	- \$145,000
	(3.1) Approximate correction for freight rate	+ \$ 32,000
(4)	Benefit of extended drydocking interval	+ \$154,000
(5)	Correction for paint cost	+ \$ 42,000
(6)	Correction for days in drydock	+ \$ 14,000
	(6.1) Approximate correction for freight rate	+ \$ 4,000
	DIFFERENCE IN NPV BETWEEN ALTERNATIVES:	+ \$436,000

Constant power operation is assumed for the vessel used in the present example. The benefit of reduced hull roughness is therefore increased speed and more revenue is earned. If the level of revenue does not correspond with the standard value used in the set of case studies, corrections are required when penalties or benefits associated with variations in levels of roughness are explored. In the present example the freight rate has been increased 25% above the standard value. Item (1) calculates the economic effects of reblasting only with results taken from Case Study 2.1 . The net present value is \$310,000 with a discounted profit to investment ratio of 2.2, giving a total investment value of \$140,000 in present value terms. Hence, a gross economic benefit of \$310,000 + \$140,000 = \$450,000 is derived entirely from more freight income as a result of the higher speed. Increasing freight rate by 25% results in an additional benefit in present value terms of 0.25 x \$450,000 = \$112,500 and this is the correction provided under item (1.1). From the similar argument, the economic penalty of not returning to the specified outdocking roughness is directly proportional to the freight rate, and item (2.1) is calculated as 25% of item (2). The first two items are obtained from Case Studies 2.1 and 2.2, and are based on a high performance conventional coating system. Item (3) introduces the difference in economic terms between the conventional and the self polishing coating system as calculated in Case Study 3.1 , and where roughness Scenario 3 corresponds to the specifications of the present example. A correction is again required for freight rate and since roughness Scenario 3 is used this correction is taken as approximately half the value provided in Table (3.5) for every 10% increase in freight rate. Item (4) is obtained from Case Study 3.2 , and includes the benefits obtained from less frequent drydockings and therefore longer periods of continuous trading. The value of item (4) is also affected by changes in the freight rate and corrections should, in theory, be made for a 25% increase from the standard value in the present example. However, this correction is not easily obtained from the existing set of case studies and has therefore not been included. The final two items (5) and (6) are obtained from Table (3.5). For most practical purposes the small correction provided in item (6.1) can be ignored.

3.3.2 (2) A SIMPLIFIED TABULAR METHOD BASED UPON DIFFERENCES IN ANNUAL CASH FLOW

The proposed simplified method for the evaluation of alternative maintenance strategies using generalised diagrams for a series of case studies has the serious limitation of restricting the applications of the method to similar ship types, and does not permit substantial deviations from the standard variable specifications used in the case studies. A more flexible, simplified approach is therefore required for situations outside the pre-defined limits of the first method, and this is provided in the form of a tabular calculation procedure.

The difference between calculations based on constant speed and constant power operation has already been discussed. Most commercial ocean going vessels are essentially constant power operated and the more complex method of evaluation is required. In Section (3.2) a method for tranforming the cost of added resistance at constant speed into cost of added resistance at constant power was presented, and this formula forms the basis for the proposed simplified tabular method. The calculation procedure is best illustrated by an example, and the two alternative maintenance strategies from the prece ding section are therefore re-evaluated using the new tabular method. From the standard case study specifications in Section 3.1.1, the following variables are calculated for Ship D:

Daily fuel costs at sea	\$ 9,840
Daily average income after deductions	\$23,390

$$\text{Ratio: } \frac{\text{Cost of added resistance at constant speed}}{\text{Cost of added resistance at constant power}} = 3.1 \times \frac{9,840}{23,390} = \underline{1.304}$$

Cost of one day out of service = \$23,390 - \$9,840 = <u>\$13,550</u>

In tabular form the example is evaluated as follows:

Table (3.7) SIMPLIFIED TABULAR METHOD FOR EVALUATING HULL MAINTENANCE ALTERNATIVES

	ALTERNATIVE 1				
Year	Operating Days In The Year	Average Hull Roughness [um]	Annual Fuel Consumption At Constant Speed	Annual Fuel Costs At Constant Speed	Dry Docking Costs
1	358	365	16551	3062	140
2	365	384	16916	3442	0
3	358	403	16689	3736	169
4	365	422	17053	4199	0
5	358	438	16810	4553	205
6	365	456	17169	5115	0

Table (3.7) contd.

	ALTERNATIVE 2				
Year	Operating Days In The Year	Average Hull Roughness [um]	Annual Fuel Consumption At Constant Speed	Annual Fuel Costs At Constant Speed	Dry Docking Costs
1	358	155	15523	2872	433
2	365	164	15856	3227	0
3	358	195	15770	3530	0
4	365	204	16100	3964	353
5	358	231	15965	4324	0
6	365	240	16288	4853	0

Year	Diff In Fuel Costs	Diff At Const Power	Diff In Dryd Costs	Comp. For Out Of Service Time	Net Cash Flow	Disc. Factor	Disc. Cash Flow
1	190	145.7	-293	-54.2	-201.5	0.851	-171.5
2	215	164.9	0	0	164.9	0.724	119.4
3	206	158.0	+169	+114.8	441.8	0.616	272.1
4	235	180.2	-353	-144.3	-317.1	0.525	-166.5
5	229	175.6	+205	+138.9	519.5	0.446	231.7
6	262	200.9	0	0	200.9	0.380	76.3

Net Present Value = 361.5

(Monetary values are expressed in $1000, and fuel consumption figures are metric tonnes)

The roughness values used are the average values for each year calculated from the scenarios provided. Values of average hull roughness are transformed into power increments, and subsequently into values of increased fuel consumption using the ITTC correlation formula for hull roughness. Taking the difference between two levels of roughness this can be written:

$$100\% \times \frac{\Delta P}{P} = \frac{105\left[\left(\frac{h_2}{L}\right)^{1/3} - \left(\frac{h_1}{L}\right)^{1/3}\right] \times 10^{-3}}{C_T}$$

and reducing the values predicted by this formula by 40% as recommended in Chapter 1 gives:

$$100\% \times \frac{\Delta P}{P} = \frac{1}{C_T}\frac{63}{(L)^{1/3}}\left[(h_2)^{1/3} - (h_1)^{1/3}\right] \times 10^{-3}$$

P = power corresponding to roughness level h_1

Δ P = difference in power between the two roughness levels h_1 and h_2

and the remaining symbols are as explained in the nomenclature.

For the vessel under consideration C_T is calculated from the case study specifications in Section 3.1.1. :

$$C_T = 2.509 \times 10^{-3}$$

An alternative formula from Reference (10),

$$100\% \times \frac{\Delta P}{P} = 0.60 \times 5.8\left[(h_2)^{1/3} - (h_1)^{1/3}\right]$$

may be used for transforming values of hull roughness into power increments, but this formula is less accurate due to the fixed relationship between L and C_T, and is only valid for the laden design condition.

In the first part of the tabular calculation an equal number of operating days is assumed for both alternatives. This is necessary to avoid a reduced fuel consumption due to less operating days per annum being transformed into an economic benefit assumed due to reduced hull roughness. Correction for a difference in the number of operating days between the two alternatives is subsequently made by using the estimated net cost out of service time. The remaining part of the evaluation procedure is a simple discounted cash flow calculation, giving a final result expressed in net present value terms. If required, the discounted value of the investment can be obtained from the column representing the difference in drydocking costs, and the discounted profit to investment ratio may be calculated as an alternative measure of merit.

Principal sources of error in the tabular method are due to the simplified assumption of an average hull roughness for each operational year and the empirical transformation of economic penalties due to hull roughness from constant speed to constant power basis. A check on the accuracy of both simplified methods has been made by repeating the evaluation of the two alternative maintenance strategies in the preceeding example using the computer based techno-economic model ECOMAIN. The result obtained from this complete economic modelling is a net present value of $420,000, compared with $436,000 using the first simplified method and $362,000 using the second method.

In conclusion, the two proposed simplified methods are in good agreement with the more advanced techno-economic modelling, and they are both recommended for use in the rapid evaluation of alternative hull maintenance strategies, provided the above described limitations are observed.

3.4 A CASE STUDY OF PROPELLER MAINTENANCE

3.4.1 INTRODUCTION

Rough ships sometimes also have rough propellers, although the reasons for the surface deterioration after a period of time in service are not the same. Unlike the hull, the propeller blades are not painted with a protective coating, and most propellers will therefore suffer corrosion due to electro-chemical action. If controlled correctly this process could result in reduced surface roughness by a process called electro-chemical polishing, but in practice the effect of the electro chemical action is to cause an increase in blade surface roughness. In addition, surface deterioration will also be caused by erosion due to the adverse pressure effects over the most heavily loaded parts of the blade.

The measurement of propeller roughness and its effect upon propulsion efficiency have occasionally attracted the interest of research institutions, but until recently no significant progress had been made in this field. Most notable are the efforts of BSRA some 20 to 25 years ago, in which a special stylus instrument for the measurement of propeller roughness was built and measurements carried out on a large number of propellers over a period of several years. Unfortunately this work did not result in a standard measurement procedure for propeller roughness in the same way as for hull roughness, where a standard measure of roughness is obtained using a standard instrument and a standard measurement procedure. An early, but in retrospect unfortunate, conclusion drawn by

BSRA was that the surface roughness of propeller blades is similar in nature to that of a surface uniformly covered with sand. This resulted in stylus measurements being related directly to sand grain size, and section drag increments due to roughness could then be calculated from Schlichting's flat plate formula for sand roughened surfaces [Reference (48)]. Until recently this sand grain analogy was the only method available for estimating the effects of blade surface roughness upon propulsion efficiency.

Grigson in Reference (49) pointed out that sand grain roughness is not an adequate way of describing the surface topography of a rough propeller blade, and he postulated that propeller roughness is similar to other types of irregularly rough "engineering" surfaces, including hull roughness, which are commonly referred to as "Colebrook-White roughness". This implied that the work of Musker and Lewkowicz, [References (50) and (51)], on a range of ship surfaces could be used to relate stylus instrument measures of propeller surface roughness to actual section drag increments, avoiding the incorrect use of a sand grain analogy. The behaviour of Colebrook-White type surfaces in fluid flow is not adequately described by a single roughness height parameter, and an additional measure of surface texture is also required. Grigson in his work unfortunately only used subjective estimates of a texture parameter, without supporting his values by actual measurements. Furthermore, the accuracy of his procedure for transforming roughness drag increments into changes in torque and thrust characteristics, using a set of approximate formulae proposed by the 1978 ITTC for corrections due to scale effects on drag, is open to discussion. It was therefore decided that a different approach was required for the transformation of drag increments into changes in propulsion characteristics, serving as a basis for subsequent economic evaluations of propeller maintenance.

3.4.2 CALCULATION OF PROPELLER CHARACTERISTICS FOR ROUGHENED PROPELLERS

The method used for calculating the propeller characteristics for smooth as well as a series of roughened conditions is the well established Burrill's vortex analysis method, a design procedure for moderately loaded propellers, [References (52) and (53)]. This is a strip-theory method used for calculating the characteristics of marine propellers in real flow conditions behind a ship's hull. Briefly, the method consists of dividing the propeller blade into a number of two dimensional sections, for which the basic lift and drag characteristics are calculated from NACA aerofoil data, [Reference (54)]. The values of the lift and drag are subsequently transformed into elemental torque and thrust using vortex theory, and are integrated to give total torque and thrust characteristics for the blade, after first undergoing corrections for cascade effects and the fact that the propeller has a small finite number of blades. The NACA data are based upon experiments on smooth aerofoil sections with a turbulence stimulator on the leading edge, and the estimated propeller characteristics are therefore valid only for a smooth propeller. Since the present problem is to estimate changes in propeller characteristics from roughened conditions, the strip theory method has been modified to take account of blade surface roughness. For each section the increments to the drag coefficient due to roughness are calculated and added to the total drag coefficient for the smooth section at a point in the calculation procedure immediately before estimating the modification to the lift coefficient due to contraction of the slip stream. The lift coefficient will also be affected by a change in blade circulation due to surface roughness. Model experiments on an artificially roughened propeller presented in the procedings of the 1978 ITTC, [Reference (17)], indicate the following relationship between incremental values to the lift and drag coefficients:

$$\Delta C_L = -1.1 \, \Delta C_D$$

Since C_L is normally of a magnitude 20 to 30 times greater than C_D, and the absolute magnitude of changes to C_L is small, the effects of changes in C_L upon the propeller characteristics can be assumed negligible for moderate values of blade surface roughness.

The turbulent skin friction drag for each section has been calculated using a version of the boundary layer integration method described in Section 1.2.3.3, Chapter 1, simplified for use in 2-dimensional flow over a thin aerofoil, by assuming each section to be an aerofoil of infinite width with no convergence of streamlines and zero cross-flow. The three equations of mean motion are identical to Grigson's B1,B2 and B3 in Reference (49). It is normally assumed that the flow in the wake of a ship is fully turbulent, and the flow over the propeller blade sections are therefore taken as fully turbulent from the leading edge. Having integrated the boundary layer and obtained a coefficient of turbulent skin friction, the drag coefficient is calculated from the formula:

$$C_D = C_f \, (1-1.16 \; t/c)$$

which is based upon the work of Squire and Young, [Reference (55)].

Since the work of Musker and Lewkowicz was to be used for relating measures of propeller roughness to section drag increments, it was decided also to use Musker's method of accounting for variations in surface texture. The roughness parameter h′ proposed by Musker is a combined height and texture parameter defined as:

$$h' = R_q(1+aS_p)(1+bS_k K_u)$$

where:

S_p = average slope based on a sampling interval of length equal to the phase lag over which the Autocorrelation Coefficient decays from 1.0 to 0.5

S_k = skewness of the height distribution of the surface profile based on a sampling interval of 50 μm

K_u = kurtosis of the height distribution of the surface profile based on a sampling interval of 50 μm

a = constant = 0.5

b = constant = 0.2

and where all parameters are measured using a stylus instrument with a long wavelength cut-off of 2mm. It should be emphasised that h′ has been derived on the basis of experimental work on five different ship surfaces only, and is therefore only valid as a combined height and texture parameter for values of R_q, S_p, S_k and K_u within the ranges covered in the original work.

The Author is indebted to Mr. J. S. Medhurst for performing the boundary layer integration calculations.

Having calculated the thrust and torque characteristics for the same propeller with various degrees of blade surface roughness measured in terms of h′, the next step is to transform these values into penalties in terms of power and speed. The torque characteristics of the propeller for each roughness condition can be expressed as a linear equation in the operating range, hence:

$$K_T = aJ + b$$ where a and b are constants.

Fortunately, a remains constant for increasing values of roughness, and only b will change. Substituting values for K_T and J, the above equation can be expressed as:

$$\frac{T}{D^4} = \frac{a\ V_A}{D} N + b\ N^2$$

Based upon the assumption of thrust identity, this equation can be used to calculate the rpm for each roughened condition. From the torque characteristics and the relationship:

$$P_D = \frac{K_Q}{95.1} \times N^3 \times \left(\frac{D}{10}\right)^5$$

the power increments for the various roughened conditions can be calculated.

As an additional feature, the strip theory method of calculation has also been modified to allow the effects of different degrees of roughness on various parts of the blade to be explored. This may be of interest if only limited time is available for maintenance, or if propellers are found to experience varying amounts of surface deterioration over different parts of the blade.

The vessel chosen to demonstrate the effects of propeller roughness upon speed and power performance and for subsequent economic evaluations is Ship B, one of the 4 vessels used in the preceeding case studies of hull maintenance. This vessel has a propeller of fixed pitch type with 4 blades and is designed to absorb 10600kW at 126 rpm on trial (122 rpm in service). Additional details are:

Diameter	=	6.0m
Pitch ratio at 0.7R	=	0.768
Expanded area/Disc area	=	0.576
Hub diameter	=	1.147m

Detailed propeller drawings were supplied by the owners of the vessel for input to the vortex analysis method. In addition, model tests with wake measurements and full scale trials data were obtained, and this allowed the construction of an approximate radial distribution of the full scale effective wake, from which local values of wake fraction for each radial section could be taken for input to the Burrill method of calculation.

Results of the calculation are presented in Table (3.8) and Figure (3.25), in terms of percentage increase in power for a range of h′ between 0 and 300 μm, and for the two alternative situations when the whole or only the outer half of the blade is affected. The results clearly demonstrate that the outer half of the blade is most important, accounting for approximately 85% of the total penalty of that for the complete blade. In Figure (3.26), the results from Table (3.8) have been re-drawn to a scale of h′ to the one third power exponent. The straight line relationship obtained indicates that a one third power law exists between the percentage increase in power at constant speed and the combined roughness height and texture parameter h′. For the 4-bladed propeller

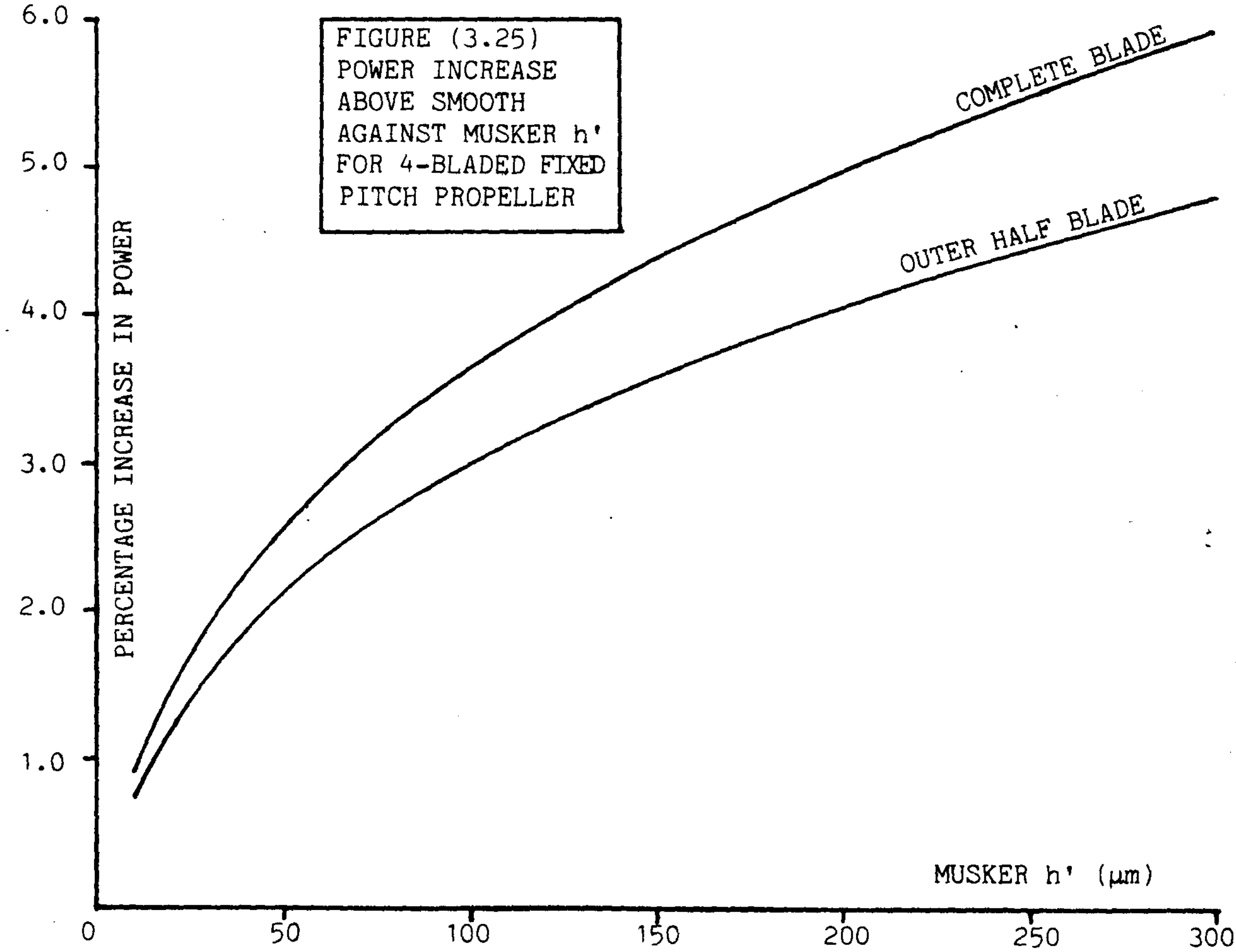


FIGURE (3.25)
POWER INCREASE
ABOVE SMOOTH
AGAINST MUSKER h'
FOR 4-BLADED FIXED
PITCH PROPELLER

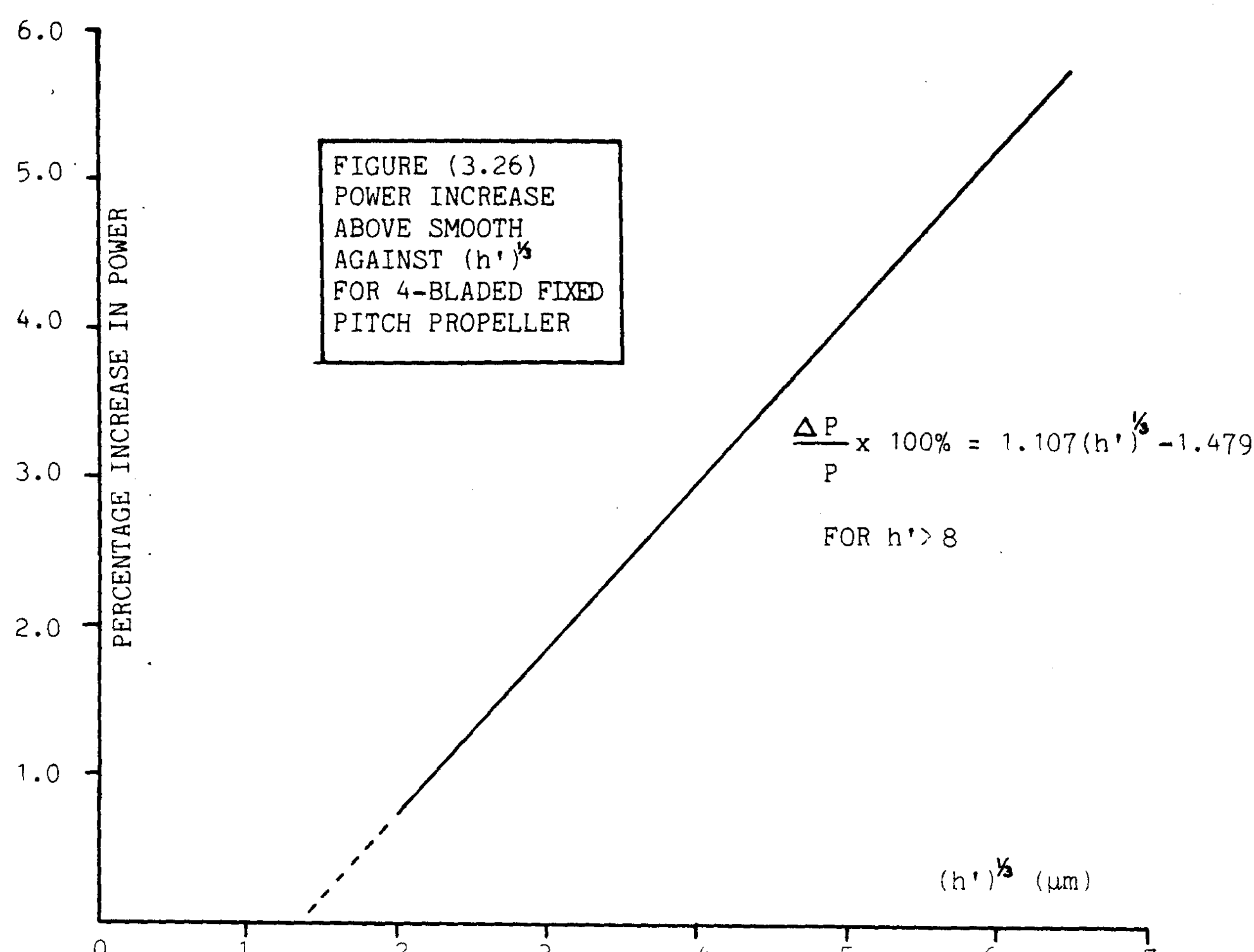


FIGURE (3.26)
POWER INCREASE
ABOVE SMOOTH
AGAINST $(h')^{1/3}$
FOR 4-BLADED FIXED
PITCH PROPELLER

used in this example the following relationship was obtained:

$$\frac{\Delta P}{P} \times 100\% = 1.107 (h') - 1.479 \qquad \text{for } h' > 8$$

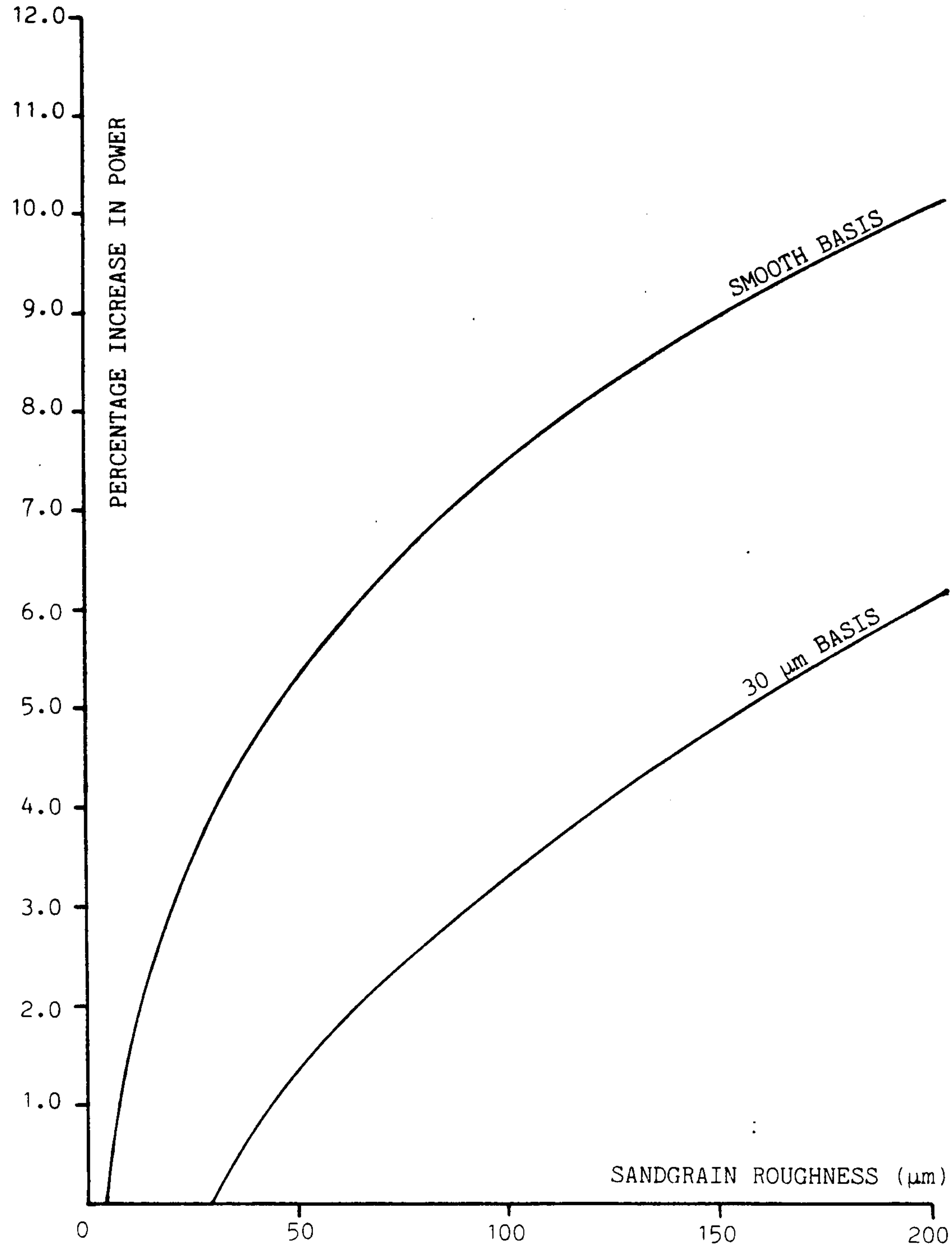
Further investigation is required to establish the limits of application of a 'one third power law' for propellers, and it should be emphasised again that these calculations are for one particular propeller and ship's wake.

TABLE (3.8) POWER INCREASE WITH ROUGHNESS (MUSKER h')

Musker h' (μm)	Complete blade affected		Outer half blade affected	
	RPM	% Increase in power	RPM	% Increase in power
0	128.000	0	128.000	0
10	128.065	0.92	128.043	0.76
20	128.106	1.50	128.073	1.25
50	128.185	2.60	128.125	2.14
100	128.262	3.67	128.174	3.02
150	128.320	4.42	128.210	3.61
200	128.396	5.48	128.259	4.45

For the purpose of comparison results are presented in Figure (3.27) for the same propeller using a sand grain analogy. Although the measure of roughness in this case is sand grain diameter k_s, which is not directly compatible with the combined height and texture parameter h', it is quite obvious from the shape of the curves that a sand grain analogy greatly over-estimates the power penalty due to the presence of surface roughness

FIGURE (3.27)
POWER INCREASE AGAINST SANDGRAIN ROUGHNESS FOR 4-BLADED FIXED PITCH PROPELLER



on the propeller blades.

Before any economic analysis can be made for alternative propeller maintenance strategies, some knowledge is required about the magnitudes of propeller roughness found in practice, both in the new condition as well as after periods of time in service. Compared with the substantial amount of knowledge now available about development of hull roughness with time in service, surprisingly little is known about propeller roughness. Occasional measurements have been published in the technical literature, but mostly without stating the type of measuring instrument or the high and low wavelength cut-off values used. Comparison between measurements is therefore difficult because no common basis can be found. As a result BSRA is the only source of information for data about the roughness of propellers after various periods of time in service. Byrne et.al. have recently re-analysed the original data collected by BSRA 20-25 years ago, in addition to a series of more recent measurements performed on propellers of various ages, [Reference (56)]. The results are presented as separate height and texture parameters, using a long wavelength cut-off value of 2.5mm, for a total of 130 propellers.

Unfortunately, the separate height and texture parameters from this survey cannot be transformed directly into the combined height and texture parameters used in the present calculations.

A simpler, but less accurate method of estimating the roughness of a propeller is to use a set of comparator gauges. Rubert & Co. have manufactured a comparator based upon replicas of 6 different grades of propeller roughness. Grade A represents a new propeller, grade B a reconditioned propeller and grades C to F a series of gradually increasing values of surface roughness. To enable the 6 different grades of surface roughness on the comparators to be related to the previously calculated power penalties for various values of h′, the surface topography of each replica was measured using a bench stylus instrument linked to a microprocessor. Values R_q (2.0) and R_{tm} (2.0) were obtained and h′ calculated for a long wavelength cut-off of 2.0mm. (Measurements carried out by Mr. J.S. Medhurst with instrument provided by International Paint Company). The results are presented in Table(3.9).

TABLE (3.9) ROUGHNESS MEASUREMENTS FOR RUPERT PROPELLER GAUGES

GAUGE CODE	R_{tm}(2.5) ACCORDING TO MANUFACTURER	R_{tm}(2.0) PRESENT STUDY	h′
A	6.7 μm	4.7 μm	1.4 μm
B	14.2 μm	8.3 μm	2.8 μm
C	31.7 μm	33.4 μm	35.6 μm
D	50.8 μm	44.5 μm	91.1 μm
E	97.2 μm	93.4 μm	296.7 μm
F	153.6 μm	165.8 μm	438.6 μm

For surfaces A to D the parameters required for the calculation of h′ are all within the valid range, while in the case of surfaces E and F the slope S_p exceeds the valid range by a factor of 3 to 4, and the calculated values for h′ are only approximate.

Comparing the 6 Rubert gauge replicas with the roughness measurements on 130 propellers analysed in Reference (56), demonstrates the fact that no propellers were found to have a surface condition as bad as grade F, and only 25% could be classified as Grade D or worse. The data in Reference (56) have not been plotted on a scale of roughness versus age, and no average rate of deterioration can therefore be calculated. However, since more than 50% of the 130 propellers are re-analysed data from Reference (57), in which it is stated that half the measurements are on new propellers and the remaining half on propellers no more than 6 years old, it is believed that the total sample in Reference (56) will have a bias towards relatively new propellers. An average annual rate of deterioration in surface condition between 10 and 20 µm measured in terms of h′ is therefore thought to be a reasonable estimate, although it should be emphasised that this is only an assumption, and further measurements are required.

3.4.3 ECONOMIC EVALUATIONS OF PROPELLER MAINTENANCE

To demonstrate the economic effects of propeller roughness, the results of the prece ding section have been transformed into economic terms using the basic deterministic techno-economic model, "ECOMAIN". Technical, operational and financial variables are the standard values specified for Ship B in Section 3.1.1. Hull roughness is assumed constant at a new ship value of 125 µm throughout the calculations.

Two different economic studies are presented

1. Using the Rubert roughness comparators as basis the cost of excessive roughness relative to Grade A or B condition is calculated in annual terms.

2. Assuming a grade A (smooth) starting point, the annual amount available in net present value terms at every biennial drydocking for refurbishing the propeller to Grade A condition is calculated using different values for annual rate of deterioration.

In both cases constant power operation is assumed so that increasing propeller roughness results in a loss of speed, and consequently a reduction in freight income due to the reduced number of roundtrips in each operational year.

Results of Study (1) are presented in Table (3.10).

TABLE (3.10) ECONOMIC PENALTY OF EXCESSIVE PROPELLER ROUGHNESS

RUBERT GRADE (COMPLETE BLADE)	ANNUAL COST OF ROUGHNESS RELATIVE TO GRADE A	ANNUAL COST OF ROUGHNESS PER M^2 RELATIVE TO GRADE A
C	$42,000	$1380
D	$68,000	$2230
E	$116,000	$3800
F	$144.000	$4720

It is worth noting that for Grade D condition the economic penalty due to propeller roughness over an operating period of 2 years is equal to the cost of a new propeller for this type of vessel.

The total cost of reconditioning for a propeller of the size used in this example to Grade A or B condition may be between $3000 and $6000, depending on location and the amount of work involved. Table (3.10) therefore clearly indicates that the potential benefits are of a magnitude several times greater than the costs involved.

A further point to note is the specification for surface roughness in the ISO 484/1-1981 "Standards of finish for propellers". The Class 1 condition normally used for commercial ships' propellers specify a roughness value $R_a(0.8)$ not greater than 6 μm. Using an approximate scale of transformation provided in Reference (56), this could be equivalent to a value of $R_{tm}(2.5)$ in the range 35-40 μm, or similar to Grade C on the Rubert gauges. Even with a new propeller an owner could therefore be suffering an economic penalty of $40,000 per annum because standards of surface finish for new propellers are not sufficiently high from the economic point of view.

Table (3.11) presents the results of the second study:

TABLE (3.11) CAPITAL AVAILABLE AT EVERY DRYDOCKING FOR PROPELLER MAINTENANCE

ANNUAL RATE OF INCREASE IN h' (SMOOTH CONDITION AS BASIS)	MAXIMUM AMOUNT AVAILABLE AT EVERY BIENNUAL DRYDOCKING IN NET PRESENT VALUE TERMS	MAXIMUM AMOUNT AVAILABLE AT EVERY BIENNUAL DRYDOCKING PER M^2 OF PROPELLER SURFACE AREA
10 μm	$23,900	$784
20 μm	$38,600	$1266

Again the economic argument is obvious; even with the lower rate of deterioration the economic penalty due to roughness is of a magnitude several times greater than the cost of refurbishing the propeller to a smooth condition, and further arguments should not be required to convince shipowners that a high quality of propeller maintenance at every drydocking is money well spent.

3.4.4 CONCLUDING REMARKS TO THE STUDY OF PROPELLER MAINTENANCE

A few questions remain unanswered following the calculation of propeller characteristics for a series of roughened conditions. Little is known about the surface topography of rough propellers and how this changes with time, and more work is required before being entirely confident about the relationship between roughness and drag. The assumption that the basic lift characteristics are unaffected by the presence of roughness will also have to be investigated, especially for the higher levels of roughness. Furthermore, a rough propeller is usually accompanied by a rough hull, with corresponding changes in resistance and wake characteristics,and the combined effect of these factors upon efficiency needs to be examined.

It has been suggested in Reference (58) that the power penalty due to propeller roughness may be comparable with that due to poor hull surface condition. On the basis of the present calculations this statement is clearly not correct. Even for the most badly deteriorated propellers, the power penalty due to blade surface roughness will not exceed 5 to 6 percent, while severe hull roughening can result in a power penalty of magnitude 3 times greater than this value. On the other hand, the surface area of the propeller is small compared with the underwater hull, and the economic calculations have demonstrated that the return on capital invested in high quality propeller maintenance will give a rate of return for each unit of capital invested substantially greater than for any known hull maintenance alternative. The fact that the estimated power penalties due to roughness in Table (3.10) could be reduced by 50% without affecting the conclusions drawn clearly indicates that the calculation procedure is more than sufficiently accurate from the practical point of view, and the questions which remain unanswered are mainly of academic interest. No further time and effort have therefore been spent on the economic evaluation of propeller maintenance strategies.

CHAPTER 4

UNCERTAINTY IN SHIP-ECONOMIC CALCULATIONS

4.1 INTRODUCTION TO THE CONCEPTS OF UNCERTAINTY

In the previous Chapters a deterministic model has been developed and used to examine the financial return on a series of alternative hull and propeller maintenance strategies for different ship types. The design and subsequent use of this particular model for the evaluation of investment alternatives has been based on the simplified assumption that all variables are known with absolute certainty. Selection between alternative strategies is then simply a matter of selecting between single value numerical representations of investment outcomes. This assumption is convenient, but unfortunately does not hold in practice. The present economic environment will not be known with absolute certainty, technical and operational variables may be associated with some degree of uncertainty and predictions about the future always contain a high degree of uncertainty. Allowing for the fact that some variables may take on more than a single value immediately throws the use of existing methods and measures of merit into confusion. Some clarification may be provided by reverting back to the principal objective behind the techno-economic analysis of investment alternatives, which was identified as providing guidance in the decision making process. In the deterministic case this guidance consists simply of selecting the alternative giving the maximum value of the economic criterion in use. Under conditions of uncertainty the guidance will be directed towards finding the investment alternative which remains acceptable, even when variables assume values different from those expected. The existing deterministic model is clearly incapable of accommodating this latter type of analysis in its present form, and other methods of analysis have to be investigated.

First of all, it may be of some use to explain the difference between risk and uncertainty, because the difference will influence the method of analysis to be adopted.

Risk is a situation where the probabilities of a discrete set of outcomes or alternatives are known and also the values of the possible outcomes. This is therefore a case where the experiment or situation has been repeated a sufficient number of times so that a statistically objective probability distribution of possible outcomes has been obtained.

Uncertainty is where the situation or experiment has not previously taken place or can not be repeated due to its particular nature. In this case the range and possible outcomes may be known but their associated objective probabilities can not be assessed. Subjective probabilities will therefore have to replace the objective probabilities in the risk case.

It immediately becomes apparent that the risk situation is typical for insurance companies, where a large amount of statistical information will enable accurate and objective probability distributions to be constructed for most situations. Uncertainty is typical for economic calculations where the economic environment experiences continuous changes and experiments are not repeatable.

In a commercial context a capital investment can normally be defined as a commitment of capital to a specific project with the expectation of recovering the principal as well as one or more interest payments at some future point in time. This definition brings to attention two important factors in the analysis of capital investments, future and expectation. If investments could be made retrospectively, the outcome of the investment would be known with absolute certainty, and the owner of the capital would not be subjected to the risk of losing the principal or the interest payments, simply because non profitable investments would never be undertaken. In practice, however, investments are made at present, and the economic evaluation of investment alternatives will inevitably have to be based upon predictions about the future. Forecasting techniques have been developed to assist with this particular part of the problem, and numerous methods are available to the analyst, but however advanced the forecasting techniques, a forecast can be no more than a forecast and is therefore no substitute for absolute certainty. As a result the investor will have an expectation of a rate of return on a particular investment, but in the majority of cases cannot be certain of achieving this. In fact, only fixed interest bank deposits and some types of government stock give a guaranteed return, and all remaining types of investment are associated with some degree of risk or uncertainty. This degree of uncertainty will vary between different projects depending upon the variables involved. Analytical or other tools are therefore required by the analyst in the evaluation procedure to enable a quantification of the uncertainty in the final economic measure of merit to be made. Otherwise a rational basis for decision making cannot be established.

Classical economic theory has not provided the methods required for handling the problems associated with uncertainty in investment calculations. Either the methods have been too theoretical in nature to be of any use in practical applications, or they have been based on a simplified approach to the problem and as a consequence have only provided one part of the required answer. The first major improvement in dealing with uncertainty in economic calculations came with the development of modern utility theory, principally due to von Neumann and Morgenstern, [Reference (59)], but also due to Marschak, [Reference (60)], and Savage, [Reference (61)], among a number of others.

The basis for modern utility theory had in fact been established more than 200 years earlier by Daniel Bernoulli, [Reference (62)]. He suggested that the principle of maximising mathematical expectation was an inadequate and under certain circumstances a wrong basis for decision making under uncertainty, and he illustrated his arguments in the form of a number of examples of which "The St. Petersburg Paradox" is probably the most famous. Instead he proposed the maximisation of expected utility as a hypothesis to explain how rational people would make decisions under uncertainty. Economists accepted Bernoulli's idea of using utility as a measure of choice between consequences, but quickly discarded the probability part of the theory and continued the development of a probability-less utility theory, now generally known by the name of "classical" utility theory. When this particular idea of probability-less utility was later demonstrated to be of no practical value in providing solutions to economic problems under uncertainty, it also resulted in discrediting the complete utility hypothesis, and a revival did not take place until von Neumann and Morgenstern re-introduced the theory in 1947. Modern utility theory also has some significant shortcomings which will be discussed later in this Chapter, but it does provide a workable method which can be of assistance in the decision making process.

A further step forward came with the introduction of more advanced probability theory to economic calculations. Although the use of probability theory was first introduced by Bernoulli and more recently advocated by a number of authors, Hillier, [References (63) and (64)], was among the first to put the ideas into an analytical framework, by which the probability distribution of the economic criterion and the expected utility could be calculated for more complex economic problems. Hillier's work is somewhat theoretically orientated, and other authors have later modified his work to provide more practical methods of calculation,

The introduction of electronic computers in the late 50's and early 60's opened up a new dimension to the analysis of uncertainty. The ability of computers to provide efficient handling of large numerical problems enabled approximate solutions to complex problems in statistics to be obtained using simulation techniques based upon a method of stochastic sampling, now generally known under the name of "Monte Carlo analysis".

The technique of sampling from probability distributions had been known from the early 1900 by statisticians who, for example, used model sampling methods to investigate the effect of non-normality on statistical test procedures. Mathematicians in the late 40's discovered that random sampling methods could be used to solve determinate mathematical problems, and the technique was extensively developed in this connection. After the novelty had worn off in the area of theoretical interest, it was discovered that the technique could have a much wider applied use than first realised. First in areas of operations analysis where the problems had become so complicated that conventional numerical or analytical methods could no longer be employed in a satisfactory manner, and later in areas as far apart as nuclear research on the one hand and economics on the other.

No particular person can be given the credit for introducing Monte Carlo techniques to economic calculations. A number of economists seem to have hit upon the idea simultaneously in the early part of the 60's. The first published account of the technique in investment calculations came with Hess & Quigley in 1963, [Reference (65)], and Herz in 1964, [Reference (66)], and it became accepted as a valuable method for evaluating the uncertainty in investments with a complex cash flow pattern and where analytical methods could not be used.

The first attempted use of the method in the analysis of marine investmemts was presented by Klausner in 1969, [Reference (67)], where he briefly described the various steps involved in obtaining simple estimates of the probability distributions for the principal variables and the probability distribution of the economic measure of merit for a single ship investment, using a Monte Carlo simulation. Similar ideas have also been applied to the marine environment by Norman and Lorange, [Reference (68)], but their work has been centred more around the problems of portfolio selection in the shipping industry and risk preference patterns among shipowners. No further reference to the application of these simulation techniques in the evaluation of marine investments can be found in the literature, and conversations with a number of shipowners and operators has confirmed for the Author that no advanced methods are used for the purpose of assessing the effects of uncertainty in investment decisions.

In the following sections a description will be given of the development of a Monte Carlo simulation model for the evaluation of the uncertainty in marine investment calculations, with particular reference to investments in hull and propeller maintenance. However, on the grounds that there are a number of methods available for the evaluation of uncertainty in investment calculations, it has been found necessary to present these briefly together with the assumptions involved and therefore also their shortcomings, and on this basis present the arguments for selecting a Monte Carlo approach to the particular case of investment in hull and propeller maintenance.

The first four methods described are all deterministic with minor modifications to take account of uncertainty, but without actually quantifying the uncertainty. The remaining methods are based on a more advanced approach, where the concepts of utility or probability theory are utilised, not only to take account of, but also to quantify the effects of uncertainty in the economic calculations.

4.2 METHODS AVAILABLE FOR THE EVALUATION OF UNCERTAINTY IN INVESTMENT CALCULATIONS

4.2.1 DETERMINISTIC METHODS FOR THE ESTIMATION OF UNCERTAINTY

4.2.1.1 ADJUSTING VARIABLES TO REFLECT UNCERTAINTY

This is the simplest possible method of examining uncertainty. The analyst produces conservative adjustments to the variables in the calculation as a way of reflecting his subjective assessment of uncertainty. The result is a single value based on a deterministic calculation which reflects the analyst's subjective assessment of uncertainty, but in no way clarifies the investment picture. If anything, it will have become more obscure by the fact that it reflects the opinion of the analyst only, and has no statistical basis. In addition, the variable estimates may have passed through a number of management levels which have all applied adjustments for uncertainty. The result is an "over pessimistic" calculation which may lead to potentially good investment opportunities being missed altogether. The problem of subjective estimates will be addressed in a later section.

4.2.1.2 HIGH/LOW ESTIMATES TO GIVE A RANGE OF POSSIBLE OUTCOMES

This approach will consist of three simple deterministic calculations, the first based on the expected values of the individual variables followed by two calculations based on high and low estimates which are meant to represent optimistic and pessimistic cases, respectively. This is probably the best of the simple methods of dealing with uncertainty, as it gives an expected outcome and an associated range of possible outcomes. The principal objections to the method are again that the calculated range reflects the subjective view of the analyst with all the associated problems, and secondly that the "range" will appear greater than it will be in reality, due to the very small likelihood that all variables will take "high" or "low" values at the same time.

4.2.1.3 ADJUSTING THE DISCOUNT RATE TO TAKE ACCOUNT OF UNCERTAINTY

The choice of discount rates or minimum acceptable rates of return on projects is a decision that normally rests with top management. This process of deciding on discount rates for individual projects is frequently used as a method of allowing for uncertainty. Management will make subjective adjustments (increases) to the discount rate, which is intended to reflect their view on the amount of uncertainty involved in the investment project, or, in other words, to include a margin against uncertainty.

The single value answer obtained from the deterministic calculation using the modified discount rate is subsequently taken as including the effects of uncertainty. Apart from the obvious objections on the grounds of subjectivity and the non-statistical basis of the modification of the discount rate, the principal shortcoming of the method is that it does not in fact take account of uncertainty at all. Increasing the discount rate to allow for uncertainty has quite the opposite effect to that intended. By discounting the most distant cash flows which will be known with less certainty, the effect is to suppress uncertain elements instead of including them. The method should therefore not be used.

4.2.1.4 SENSITIVITY ANALYSIS ON THE PRINCIPAL VARIABLES

A sensitivity analysis consists of applying a specified amount of variation to each one of a number of selected variables in turn and each time recording the effect this variation has on the economic measure of merit. This method is excellent for estimating the accuracy to which individual variables in the analysis should be specified, and it is therefore also a useful tool in the process of selecting variables which should be included in a more advanced approach to analysing uncertainty.

A sensitivity analysis on its own does not however produce an answer to quantifying problems of uncertainty. Only one variable is altered at a time and the remaining ones are kept constant; in reality a number of variables may be subject to variations. As the variations in the economic measure of merit due to variation in the individual variables are not additive, it is not possible to estimate a range of outcomes reflecting uncertainty. The presence of correlation will complicate this problem further and this topic will be addressed in a later section.

4.2.2 PROBABILITY THEORY AS A TOOL FOR QUANTIFYING UNCERTAINTY

4.2.2.1 PROBABILITY BASED ON ANALYTICAL METHODS

Hillier, [Reference (63)], first introduced probability theory into an analytical framework for the purpose of analysing the effects of risk and quantifying the effects of uncertainty upon the measure of merit, instead of merely identifying it. Hillier assumed that the Net Cash Flow in each year, Y_j , was made up of m separate cash flows X_{jx}, each with a finite mean μ_{jx} and a variance σ_{jx}^2 so that:

$$Y_j = X_{j1} + X_{j2} + X_{j3} + \ldots\ldots + X_{jm}$$

Therefore the expected value becomes:

$$E[Y_j] = \sum_{x=1}^{m} \mu_{jx}$$

and the variance $\quad \text{var}\,[Y_j] = \sum_{x=1}^{m} \sigma_{jx}^2 + 2 \sum_{x \neq y} \text{cov}(X_{jx}, X_{jy})$

The covariance term becomes zero if all cash flows X_{jx} are mutually independent.

The present value over an investment life of n years becomes:

$$Z_n = \sum_{j=0}^{n} \left[\frac{R_j}{(1+i)^j} \right]$$

where i is the opportunity cost of capital

and since Z_n is in fact a random variable the expected value becomes:

$$E[Z_n] = \mu_p = \sum_{j=0}^{n} \left[\frac{\sum_{x=1}^{m} \mu_{jx}}{(1+i)^j} \right]$$

and the variance: $$var[Z_n] = \sum_{j=0}^{n} \frac{var(R_j)}{(1+i)^{2j}} + 2 \sum_{j \neq j^*} \frac{cov(R_j, R_{j^*})}{(1+i)^{j+j^*}}$$

where j and j* is a notation to signify different time periods (in this case different years).

If there is no correlation between cash flows in different years, then the covariance term becomes zero.

Having calculated the expected value and the variance of the net present value, the analyst can now provide a quantitative assessment of the uncertainty in the investment proposal. Hillier built further on this work to include the case where the life of the investment, n, itself has a probability distribution. He also proposed a method of deriving the proability distribution of the internal rate of return of the investment project on the basis of the distribution of the net present value.

The principal starting point in Hillier's analysis is that the means and variances of the individual elements which make up the annual net cash flows are known and the implicit assumption is made that a simple relationship exists between the individual elements. Secondly, the assumption is made that a sufficient set of conditions exists for the Central Limit Theorem to apply so that the probability distribution of the economic criterion is uniformly normal. In practice, the relationship between the individual cash flow elements may not be as simple as suggested by Hillier. Wolfram, [Reference (70)], among others, extended Hillier's analytical approach to allow for more complex cash flow patterns with skewed distributions. This method is in fact identical to that used by Farrar in developing a model based on a utility approach to decision making under uncertainty 20 years earlier, [Reference (69)]. The fundamental assumption employed is that the economic criterion can be expressed as a single function:

$$Z = f(X_1, X_2, X_3 \ldots\ldots X_n)$$

and since the variables X_1, $X_2 \ldots\ldots X_n$ are stochastic variables the function can be expanded as a Taylor Series, provided all the variables are independent and uncorrelated.

Taking expected values and neglecting second order terms we get :

$$E[Z] = E[f(\mu_1, \mu_2, \mu_3 \ldots\ldots \mu_n)] = \mu_z$$

and the variance can be derived from basic statistical textbooks :

$$\sigma_z^2 \approx \sum_{j=1}^{n} \left(\frac{\partial Z}{\partial X_j}\right)_{\mu_j}^2 \times \sigma_j^2$$

Strictly speaking this expression for the variances is only valid for linear functions, but it can also be used with reasonable accuracy for products and quotients, provided the coefficient of variation of the individual variables is less than 15%. If some of the individual variables are represented by skewed distributions, this is taken into account by calculating the third moment about the mean, μ_{3z}, to give the coefficient of skewness of the measure of merit :

$$\frac{\mu_{3z}}{\sigma_z^2} = \frac{\sum_{j=1}^{n} \left(\frac{\partial Z}{\partial X_j}\right)_{\mu_j}^3 \times \mu_{3j}}{\left[\sum_{j=1}^{n} \left(\frac{\partial Z}{\partial X_j}\right)_{\mu_j}^2 \times \sigma_j^2\right]^{2/3}}$$

There are two principal shortcomings in this Taylor series approach to analysing risk and uncertainty. First of all it requires the economic measure of merit to be expressed as a single function. For investment situations with complex cash flow pattern this may be a difficult requirement to fulfil.

Secondly there is no provision for including correlation between variables. The absence of correlation is a basic requirement for the Taylor series expansion to be valid, and in practice it will therefore only be possible to include correlation if this is 100%, and the dependent variable can be completely defined in terms of the independent variable. Most practical investment situations will include variables which are only partially correlated, and the Taylor series approach then becomes difficult to use. Despite the criticism, the Taylor series method is a simple analytical model which may be used with excellent results for relatively simple investment proposals, provided the analyst is aware of the restrictions and limitations which the method imposes.

4.2.2.2 PROBABILITY BASED ON SIMULATION METHODS

Probabilistic cash flow simulation methods are usually referred to under the general heading of Monte Carlo methods. A Monte Carlo simulation can be described as a method of controlled sampling from a given probability distribution function, using random numbers. If the sampling is repeated a sufficient number of times, the variable which is being sampled will be selected with a frequency which corresponds to the initial given probability. The method was first developed as a procedure for studying the behaviour of certain statistical parameters of the parent distribution (or population). Subsequently, the technique has been extended to allow the resultant distribution and corresponding statistical parameters to be obtained from practically any combination of an unlimited number of individual distributions.

In the analysis of risk and uncertainty in investment decisions, the general flow diagram in Figure (4.1) illustrates the steps in probabilistic cash flow simulation.

The model consists in principle of three distinct parts, (1) a sampling routine, (2) a main calculation routine which is identical to that used for the deterministic model and (3) a data analysis routine. The starting point is to identify the variables associated with uncertainty and obtain probability distribution functions for these. The choice of type of function and the evaluation of function parameters will be discussed in the next section. The remaining variables are defined deterministically by their expected value. The main calculation is repeated a predefined number of times, each repetition based on a new dataset consisting of a fixed part of supplied expected values and a variable part obtained by sampling a single value from each of the probability distribution functions. The results from each single calculation are stored until the total specified number of simulations has been completed. At this point the data analysis routine takes control and produces a frequency distribution curve of the economic measure of merit with relevant statistical parameters such as expected value, variance and skewness. The process of controlled sampling of a single number from a frequency distribution takes the form illustrated in Figure (4.2).

A major advantage with probabilistic cash flow simulation methods is that almost any degree of correlation between variables can be incorporated in the analysis. There are a number of methods which can be used to take account of correlations, but probably the simplest and most flexible approach is to make use of the basic linear regression equation:

FIGURE (4.1)
FLOW DIAGRAM FOR
PROBABLISTIC CASH
FLOW SIMULATION

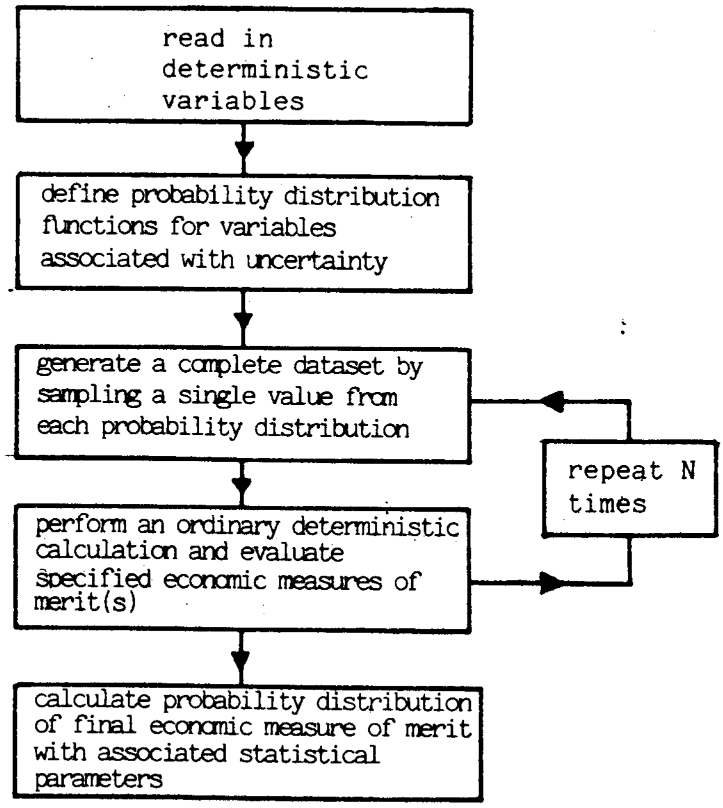
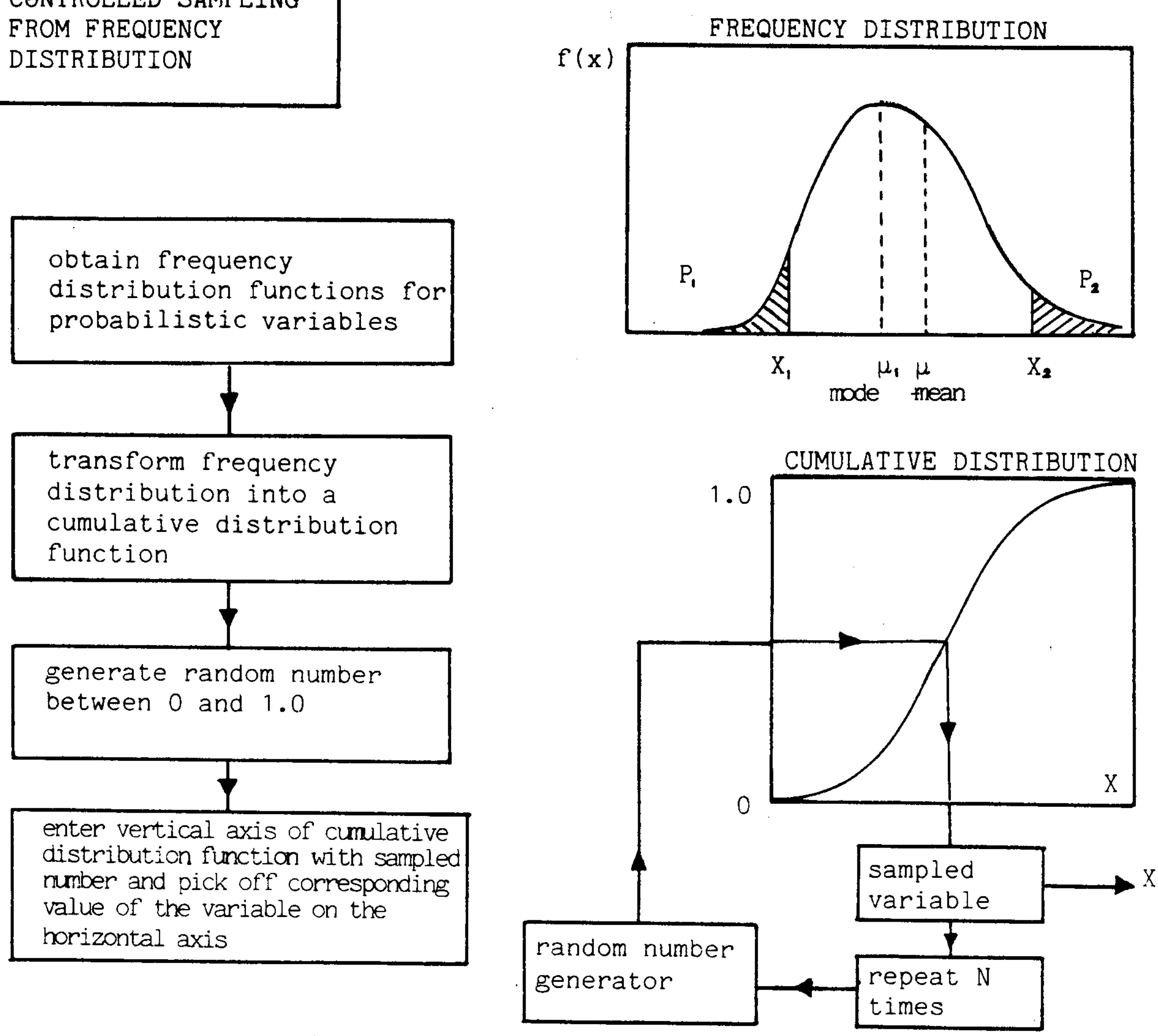


FIGURE (4.2)
CONTROLLED SAMPLING
FROM FREQUENCY
DISTRIBUTION



$$y = ax + b + e$$

where a and b are constants, and e is the error term which follows a distribution with expected value zero.

If the variance of the error distribution is zero then y = ax + b, which defines the situation where x and y are fully correlated. Putting a=0 gives y=b, or in other words y simply takes a constant value. When e has a finite variance, then the situation of no correlation between x and y is defined by a=0. Intermediate degrees of correlation are defined by a≠0 and e with a finite variance. Correlation is increased by reducing the variance of e. Figure (4.3) gives a visual interpretation of the procedure for describing correlations.

Principal arguments against the use of simulation methods have been that they are computer dependent, require specialist programs and are expensive in computer time. This argument is well founded for simple problems where analytical methods can produce sufficiently accurate results. In the case of more complex investment problems with a number of inter-related variables and various degrees of correlation, these arguments no longer hold. If a deterministic investment model already exists, then the amount of computation required for adding a sampling routine and an additional data analysis routine is quite small.

The objections on the grounds of computer costs and availability are rapidly being made redundant with the introduction of powerful and relatively inexpensive machines within most companies.

FIGURE (4.3)
PROCEDURE FOR
DESCRIBING
PARTIAL
CORRELATIONS

x = independent variable
y = correlated variable
ε = error distribution
a & b = constants

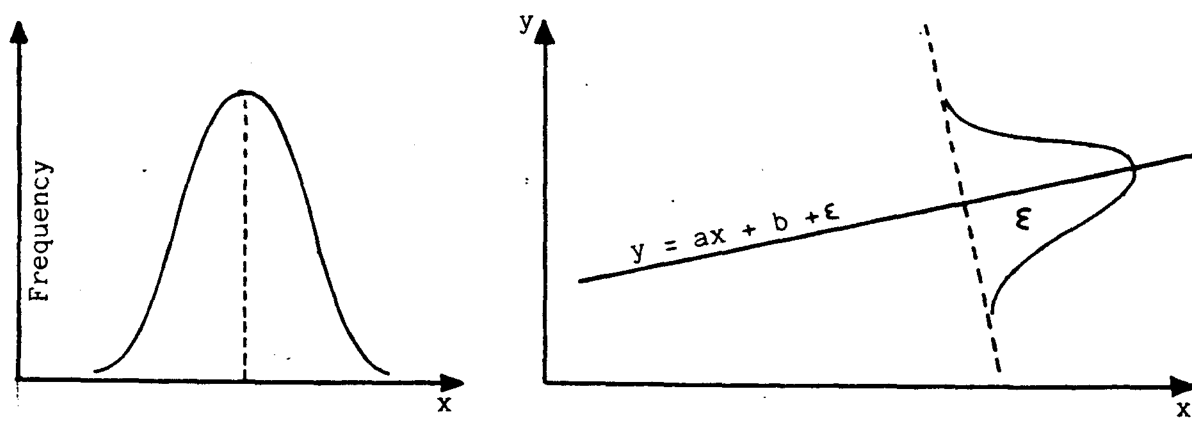
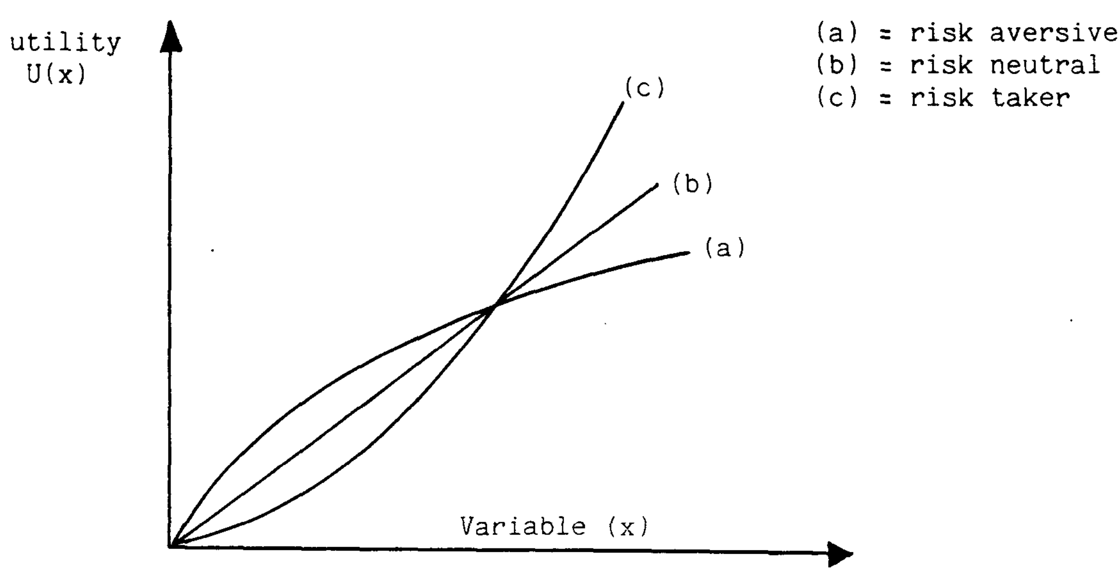


FIGURE (4.4)
PRINCIPAL FORMS
OF THE UTILITY
FUNCTION



A second type of argument against advanced simulation methods has been that when analysing uncertainty, most of the probabilities will be subjective, and the use of advanced computer simulation will not do anything to improve the quality of the data. This is quite true and Keynes in Reference (71) does in fact warn against treating subjective probabilities as if they were objective probabilities proven by repeated tests, but he also continues by saying that subjective probabilities are better than nothing. The range and absolute values of subjective estimates will reflect the degree of confidence the analyst has in his assessments, and therefore provides information about what is known as well as what is unknown about the variables.

A large number of variables represented by subjective probabilities will naturally increase the amount of uncertainty surrounding the investment, and this should be reflected in the decision maker's attitude towards risk-taking in a decision making process. The use of probabilistic cash flow simulation methods is intended to quantify the uncertainties in the investment decision in terms of range and probabilities, but is one step removed from actually specifying a decision. This one step is defined by the attitude towards uncertainty held by the individual or corporate decision makers.

The probabilistic information about a potential investment, combined with the decision maker's attitude towards risk and uncertainty is described within the general framework of utility theory. The following section briefly introduces the concepts of the modern utility theory.

4.2.3 UTILITY THEORY AS A TOOL FOR DECISION MAKING UNDER UNCERTAINTY

Utility is an attempt to put a numerical value to a consequence. In the context of investment decisions, utility can be defined as the relative usefulness or desirability of the investment outcome to the decision maker. The absolute magnitude of the numerical scale is unimportant since the objective of the utility function is to provide an ordering between possible outcomes or consequences. In mathematical language this is the same as saying that the utility function is unique up to a positive linear transformation.

When Bernoulli first introduced the concept of utility as a measure of consequences, [Reference (62)], he suggested that a rational person would always attempt to maximise the expected utility in a decision making process. This theorem has become known as "The Expected Utility Hypothesis", and has played an important part in the development of modern economic theory. The general rule proposed by Bernoulli was to multiply the utility of each possible outcome by the number of ways in which it could occur, and then divide by the total number of cases to give a mean utility; the profit corresponding to this mean utility would be equal to the value of the risk in question. This latter cash flow value is also called "The Certainty Equivalent". Bernoulli went on to deduce a general form for the utility function itself, suggesting that an increase in wealth from x to x+dx would give an increase in utility which is:

a) proportional to the increase in wealth dx

and

b) inversely proportional to the initial wealth x

This is equivalent to postulating that the utility is equal to the logarithm of the initial wealth, and is an assumption which is more rigid than the law of diminishing marginal utility. However, to the present day no better universal representation of the utility function has been suggested, and experimental work has in fact shown that the logarithmic law can be a good approximation to the actual behaviour of decision makers under conditions of uncertainty, [Reference (72)].

Bernoulli's derivations are unsatisfactory in the eyes of present day economists, and von Neumann and Morgenstern, [Reference (59)], developed a different approach which has later been improved by Marschak, [Reference (60)], Savage, [Reference (61)], Luce and Raiffa, [Reference (73)], and others. One of the more satisfactory aspects of modern derivations of the utility theory is that they say nothing about the shape of the utility function, except that a positive increase in wealth or consequences must give a positive increase in utility, or in other words, the first derivative of the utility function must be positive or zero. Figure (4.4) illustrates the 3 principal forms the utility function can take.

Curve (a) is a concave function and represents the risk aversive decision maker whose attitude towards risk and uncertainty follows the law of diminishing marginal utility. A person having this characteristic utility function will never accept a fair gamble. In practice, the investors aversion to further risk is an increasing function of the amount of risk already being carried, and hence the concave function is generally a good representation.

The opposite attitude towards risk and uncertainty is illustrated in curve (c), which is a convex function, and represents a typical risk taker who is willing to gamble, even when the terms are not quite fair. Curve (b) represents the risk neutral decision maker. In this case there is no preference towards risk, and the outcome with the greater expected value will be chosen without considering the risk of deviation from this expected value. This particular attitude towards risk and uncertainty may be valid over a limited range of possible outcomes, but is intuitively wrong when wealth becomes large. (Otherwise there would always be a prize which would make a gamble more attractive than a sum of cash payable with certainty).

In practice, the utility function may not necessarily take any one of the 3 different forms shown in Figure (4.4), but may instead be represented by a function which combines the 3 principal shapes.

A number of references can be found in the literature where attempts have been made to define the utility curves for individuals or groups of decision makers. True utility functions can only be obtained using an experimental procedure in which the individual decision maker is asked a series of questions relating to risk preference or indifference patterns. One simple and efficient method is to present one or more investment alternatives with a number of possible probabilistic outcomes and ask the decision maker to assign an equivalent certain cash value to each probabilistic outcome. This method was used by Spetzeler in a large experiment in which 36 executives from the same corporation were subjected to repeated interviews in an attempt to define a corporate utility function, [Reference (72)]. The results were first analysed using a general logarithmic utility model, but Spetzeler later rejected this in favour of a more complicated logarithmic model involving power exponents of investment outcomes. Re-examination of Spetzeler's work has confirmed that a better correspondence with the actual data collected was obtained using the more complicated logarithmic model, but at the same time has suggested that the initial simpler model was perfectly adequate when taking into consideration the fact that this is intended to be a universal utility model. Rubinstein in Reference (74) provides further support for the use of the same general utility model in portfolio selection. Although the utility function is unique to a particular decision maker and company at a particular point in time, and can take a number of different forms, clear intuitive as well as practical evidence exists that the logarithmic utility function is an acceptable approximation to a universal utility function. This conclusion has also been drawn by Rose in Reference (75). Acceptance of the general logarithmic utility model in addition simplifies the calculation of the certainty equivalent in a stochastic simulation model. This can be shown as follows:

Bernoulli suggested a utility function of the form:

$$U(x) = A + B \ln(x)$$

which can be expressed more generally as:

$$\underline{U(x) = A + B \ln(x + C)}$$

when $x \leq -C$, U(x) becomes infinite. This point can be defined as the minimum acceptable return on the investment.

The certainty equivalent is calculated from the expected value of the Utility, E[U(x)]. If the probability distribution of the return on the investment is given as a discrete distribution over n intervals, each with probability p_i, then the expected utility is given as:

$$E[U(x)] = \sum_{i=1}^{n} p_i [A + B \ln(x_i + C)]$$
$$E[U(x)] = A \sum_{i=1}^{n} p_i + B \sum_{i=1}^{n} p_i \ln(x_i + C]$$
$$E[U(x)] = A + B \sum_{i=1}^{n} p_i \ln(x_i + C]$$

The certainty equivalent $X_{\bar{U}}$ is now defined from the following relationship:

$$U(X_{\bar{U}}) = \bar{U}(x) = A + B \ln(X_{\bar{U}} + C)$$

hence:

$$\ln(X_{\bar{U}} + C) = [\bar{U}(x) - A]/B$$

and by substituting for $\bar{U}(x)$:

$$\ln(X_{\bar{U}} + C) = \sum_{i=1}^{n} p_i \ln(x_i + C)$$

or

$$X_{\bar{U}} = \prod_{i=1}^{n} (x_i + C)^{p_i} - C$$

Constants A and B only determine the zero crossing and the scale of the utility function. The choice of values for A and B are quite arbitrary, and as a result have been eliminated from the equation. The only variable which requires specification in this simplified utility function is therefore the minimum tolerable return on the investment, as defined by the constant C.

Objections against the use of utility theory have principally been raised on a practical level. A true utility function can only be established on the basis of interviewing the decision makers using a pre-established standard technique. In the case of an individual decision maker this method is straightforward, but in most medium to large companies major investment decisions are taken by a senior management team, and the individual members will have different attitudes towards risk the task of obtaining a single utility function representing company policy becomes difficult.

Assuming that a utility function has been established implies that a constant attitude towards risk and uncertainty in investment decisions has been defined, and investment alternatives can be compared on an identical basis. This may, however, not necessarily be the correct approach to the problem. The potential failure of a project and its implications on the prosperity of the company should also be included when defining a utility function. Clearly the potential risk of bankruptcy will result in a much higher degree of risk aversion. Two further parameters have therefore entered the calculation, the magnitude of the investment relative to the total company wealth and the vulnerability of the company. The two can be incorporated into the utility function as a ratio of expected project earnings to total company earnings and as the level of gearing, both of which are easily definable. Vulnerability will also depend on whether or not the investment proposal implies a diversification of the company's interest, a quantity of which is not easily definable.

We therefore reach the conclusion that ideally a practicable utility function should go beyond considering the attitude towards individual investments and include variables which reflect the complete company structure. These additional variables will not remain constant with time, and the utility function will have to be re-defined at frequent intervals.

In conclusion, therefore, utility theory does not provide a universal answer to the problems of decision making under uncertainty, and in general is not a practical management tool. However, as has already been shown, a simplified utility approach may be developed for use in certain situations to supplement the other methods in the decision making process, and this application will be demonstrated further in the following sections.

4.3 THE DEVELOPMENT OF A PARTICULAR METHOD OF DESCRIBING UNCERTAINTY IN VARIABLES

4.3.1 PRIOR CONSIDERATION OF METHOD AND DESCRIPTION VARIABLES

4.3.1.1 THE CHOICE OF METHOD FOR DEALING WITH UNCERTAINTY

Having discussed the various methods available for dealing with uncertainty in economic calculations and their advantages and disadvantages, the next step is to select the most appropriate method for our particular type of investment decision. The simplified methods of allowing for uncertainty without quantifying it are excluded from the start, as they will not provide a rational method of comparison between alternatives. The choice therefore remains between an analytical model and a simulation model based upon the use of probability theory. The earlier description of the deterministic techno-economic model clearly demonstrates the impossibility of expressing one or more of the final economic measures of merit as a single functional relationship in terms of the input variables. Additionally, the limitations in allowing for correlation between variables using a Taylor series approach weighs heavily against the use of an analytical model. Furthermore, a deterministic techno-economic model has already been developed and extensively tested, and the development of a probabilistic cash flow simulation routine around the existing model will consequently be the most efficient approach.

Based upon the above arguments, it was decided to proceed with the development of a probabilistic cash flow simulation model based upon the well established principles of the Monte Carlo method of controlled sampling from given probability distribution functions. First of all, this required a decision on the type of probability distribution to be adopted.

4.3.1.2 A CRITICAL COMMENT ON THE CHOICE OF A PROBABILITY DISTRIBUTION

A fundamental requirement for the use of a Monte Carlo sampling technique is that the probabilistic information is presented in the form of a probability distribution function. This does not imply finding the true distribution for each variable. Instead the aim is to obtain a distribution which, as far as possible, provides the best representation of the variables in terms of range and associated probabilities.

Earlier approaches to the use of probabilistic cash flow simulation techniques [References, (66) and (67)], have been based upon physically drawing a probability distribution function from subjective probability estimates followed by a digitizing process to transform the frequency curve into a cumulative probability distribution function for use in the sampling process. This method is time consuming, it relies heavily on the estimation of the mode of the distribution, and the method also requires a minimum of three probability estimates to provide a reasonable curve. The use of the modal value or most likely value as a parameter for defining the probability curve will be discussed separately in the following section.

An alternative solution to the problem of defining a probability curve for each variable is to use a standard type of distribution with known statistical properties. The manual process of drawing the curves is thus avoided, and by using a standard type of distribution the number of subjective estimates required will be fewer. A principal disadvantage is the constraints imposed upon flexibility. No universal type of distribution exists which is capable of describing every possible combination of probability estimate, and a compromise must be reached by selecting a distribution which generally provides the best fit for the variables involved in the calculation. A variety of distributions is available, most of them serving special purposes in statistical theory as a result of their particular properties. The choice of distribution type for the simulation process considered here will therefore have to be based upon the following three factors.

1. Flexibility in use
2. Accuracy of description
3. Simplicity and efficiency in use

Although these three criteria provide a framework for the various options available, the final choice of distribution type will have to be based upon subjective assessment. The available distributions which will be considered can be divided into two classes; continuous and non-continuous. Figure (4.5) gives a graphical description of the types of distribution which have been investigated and their most relevant form for the problem under consideration.

The Uniform or Rectangular Distribution is based upon estimating the upper and lower limits of the range of probable outcomes, and subsequently assigning equal probabilities to all possible outcomes in this range. Although the definition of this distribution requires a minimum of information it is highly unlikely that any investment project in practice will have an equal probability of any outcome within the range, but absolutely no chance of being greater or less than the limits of the range. The use of this distribution will therefore normally add to the confusion around an investment.

The Triangular Distribution is defined by three parameters; the upper and lower limits of the range and the modal or most likely value. The distribution therefore simply reflects the decreasing probability of outcomes further away from the most likely value. The linearly decreasing probability on either side of the mode makes sampling from this distribution a simple operation, although the assumption of linearity is probably an over-simplification for most variables. A major objection against its use is that it relies too heavily on the modal value, without considering the mean or expected value at all. Secondly, the distribution becomes inflexible in situations of extreme skewness, where the mode coincides with one of the limits of the range, and the ratio between upper and lower limits and the mean value becomes fixed.

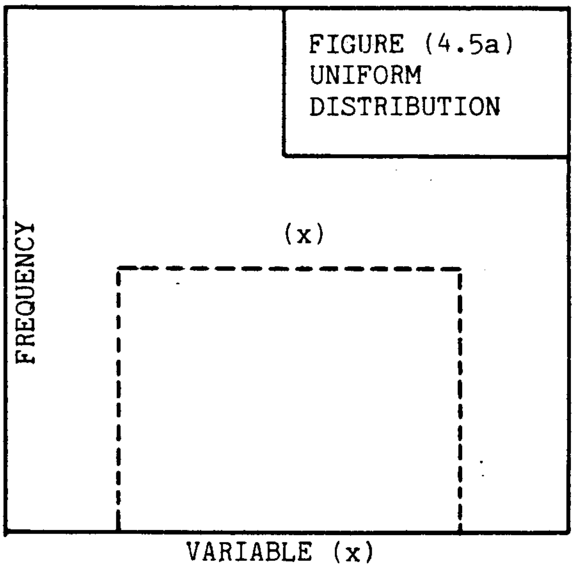


FIGURE (4.5a)
UNIFORM
DISTRIBUTION

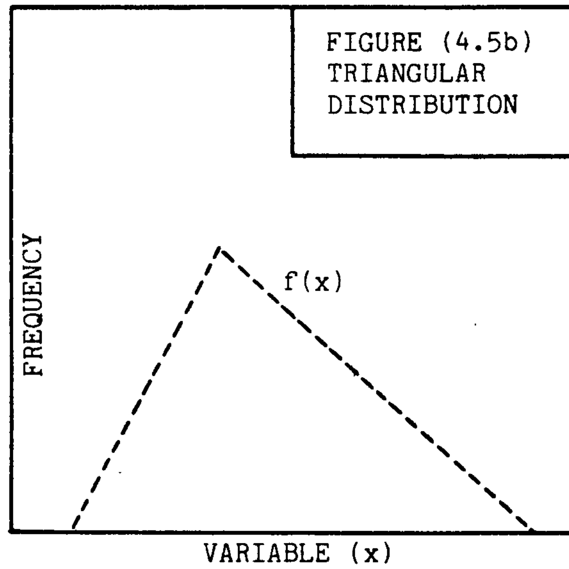


FIGURE (4.5b)
TRIANGULAR
DISTRIBUTION

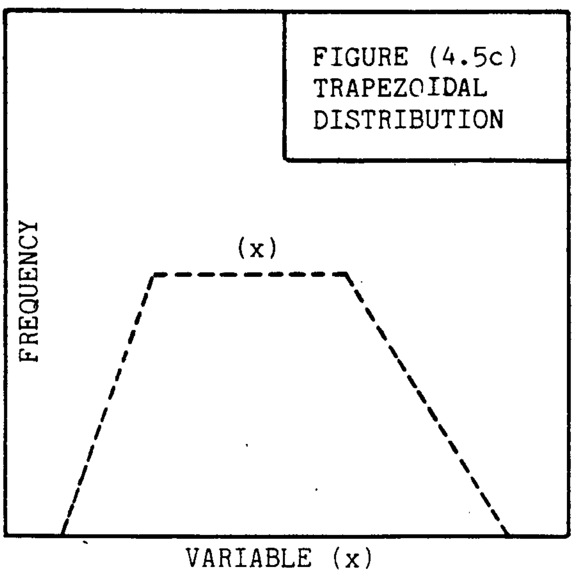


FIGURE (4.5c)
TRAPEZOIDAL
DISTRIBUTION

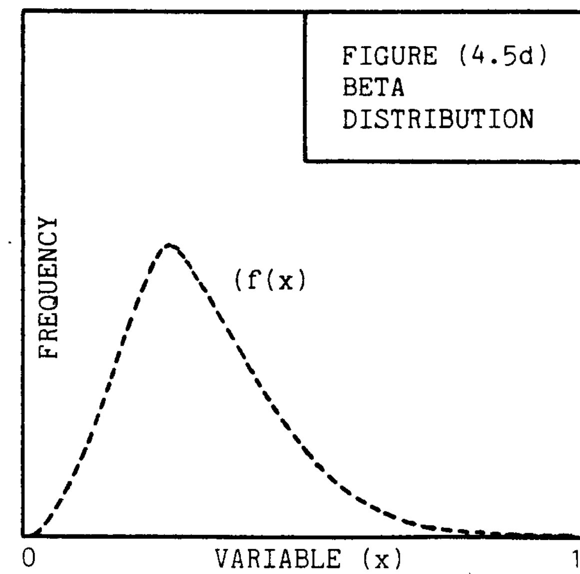


FIGURE (4.5d)
BETA
DISTRIBUTION

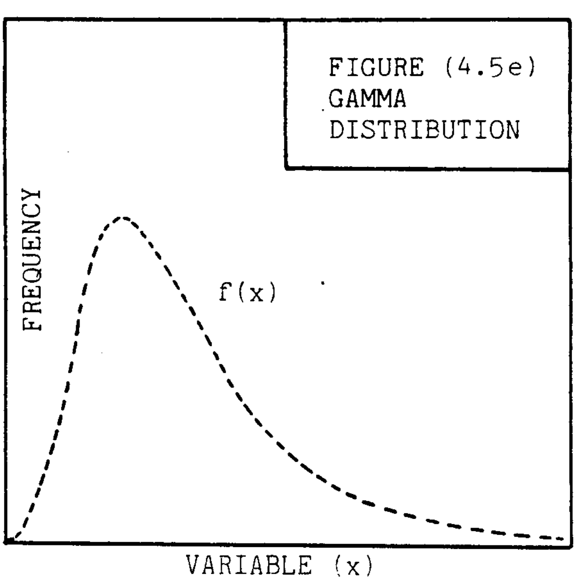


FIGURE (4.5e)
GAMMA
DISTRIBUTION

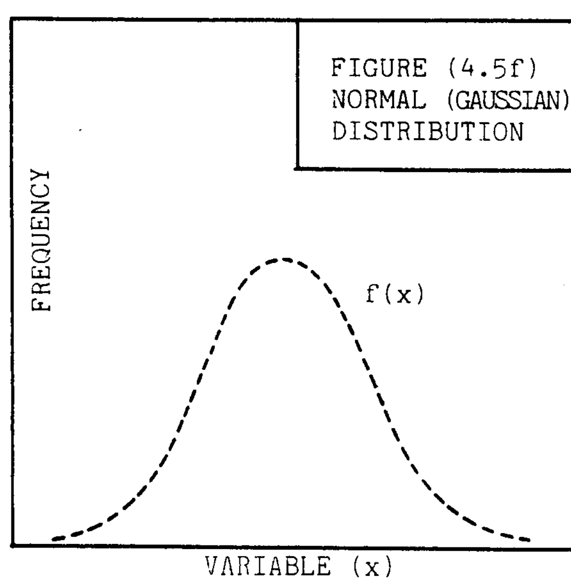


FIGURE (4.5f)
NORMAL (GAUSSIAN)
DISTRIBUTION

The Trapezodial Distribution is simply a combination of the Rectangular and the Triangular distributions, where an inner range of equal probability will have to be defined in addition to the upper and lower limits of the total range. The distribution corrects some of the shortcomings pointed out in the uniform and the triangular disribution and is substantially more flexible. Pouliquen of the World Bank, [Reference (76)], found that this distribution could fit a large class of subjective judgements, and he therefore recommends its use. It should be remembered, however, that in situations of extreme skewness, the trapezodial distribution becomes triangular, and the problems described above will apply.

The Beta Distribution is defined in the range 0 to 1.0 only. Different ranges of definition can only be allowed on the basis of a linear transformation of the scales. The distribution can be defined by two parameters only and therefore appears to be inflexible if more than two parameters are provided. Pouliquen claims that the Beta distribution puts too much emphasis on the most likely value, and he found in his work that this distribution was a bad choice.

The Gamma Distribution is an exponential distribution and is therefore continuous on one end and non-continuous on the other. Within certain choices of constants it approximates closely to the beta distribution. It does, however, have the serious limitation that it can only be positively skewed, and is therefore a bad choice for representing a series of variables which may be skewed in either direction. The Chi-square distribution has also been suggested as an alternative, but is in reality only a special case of the gamma distribution and therefore also has the same limitations.

The Normal Distribution is probably the most commonly used distribution in statistical applications. The distribution has been found to provide an adequate description of any random process, and by virtue of the central limit theorem also to represent the resultant sum of a number of individual distributions which are not themselves normal. The basic normal distribution is symmetrical about the mean value, continuous at both ends and is completely defined by the mean value and the standard deviation. Skewness can be introduced by the coefficient of skewness which is the third moment of the distribution about the mean. This parameter can be calculated from a data sample, but is in practice more difficult to quantify numerically in a subjective estimate, and is therefore an undesirable parameter on which to base the analysis. Pouliquen argues that the normal distribution is a bad choice because the variations we are trying to describe are generally neither statistical errors nor random variables, but on the basis of this argument of identity between the statistical properties of the variable and the type of distribution adopted, it would be impossible to obtain any distribution at all. The fact that the normal distribution is continuous at both ends has also been pointed out as an argument against its use on the grounds that most variables will physically have an upper or lower limit, or both. This problem can be overcome by ensuring that the probabilities at these limits are so small that the distribution can effectively be terminated at these points without significant error. Admittedly, the basic uniform normal distribution is inadequate on the grounds that it cannot effectively take account of skewness.

On the basis of this brief introduction to the available options, the trapezodial distribution therefore appears to be the best suited with the beta distribution as a possible alternative, although both have their limitations.

Considering the trapezodial distribution as a combination of the rectangular and the triangular distribution this particular idea of combining distributions may be extended to the normal distribution as indicated in Figure (4.6) by combining 2 halves of separate normal distributions. The resultant distribution has the advantage of being able to incorporate a great variety of skewness and does not become as inflexible as the trapezodial distribution in cases of extreme skewness. Compared with the beta distribution it has the advantage of being less reliant upon the modal value. It also has the obvious visual advantage of not having a linear decrease in probability towards the extreme limits, although this may not be of any practical importance. The use of a combination of two halves of normal distributions has been suggested by others, [Wolfram, Reference (70)], but the statistical theory behind this combination has hitherto not been developed. The following sections will describe this particular development work, but first some consideration is given to the choice of parameters for describing the required probability distribution functions.

4.3.1.3 MODE OR MEAN AS A MEASURE OF CENTRAL TENDENCY?

The mean or expected value of a distribution of a variable is the sum of the possible values the variable can take weighted by the probability of this outcome. The mode or most likely value is simply the value of the variable with the greatest probability. The two parameters are often confused, and this can introduce significant errors in calculations.

In economic investment calculations the probability distribution of costs and cost escalations will almost always be positively skewed. This follows in simple terms as a result of an inflationary world economy where deflation is almost unknown. A positively skewed probability distribution has an expected value which is greater than the most likely value, and based upon the law of averages the use of the most likely value therefore results in an underestimate of the true costs and consequently in an overestimate of the profits if a number of investments are undertaken.

A second general explanation comes from the basic theory of competition which can be found in most economic textbooks. Consider a company introducing a new product. If the company was initially in a monopoly situation with a symmetrical profit distribution, then the effect of introducing free competition if the product was successful, would be to make the competitors introduce similar or better products. This would reduce the profit potential of the company which first introduced the new product. If, on the other hand, the new product was unsuccessful, then the competitors would contribute nothing to reducing the losses of the introducing company. The net result is therefore a negatively skewed distribution where profits are restricted upwards due to competition, but with no curtailment on losses. Consequently, the most likely value is greater than the expected value and will give an overestimate of the profitability.

The mean value should therefore always be used for estimating variables. If the use of the most likely value is desired then the statistical treatment of the data will have to be developed to take account of this. Only for symmeterical distributions will the mean and the mode coincide, and this problem can be ignored.

4.3.1.4 THE CHOICE OF ADDITIONAL PARAMETERS TO DESCRIBE THE P.D.F. OF THE VARIABLE

Having established the mean as the most appropriate descriptor of the central tendency of the variable, the next step is to decide upon the most appropriate parameters to describe the probability distribution of the variable. The variance or standard deviation is the most commonly used measure of spread about the mean, and used in combination with a coefficient of skewness the distribution can be defined. In practice the variance and the standard deviation can only be calculated from a data sample, and are difficult to quantify on the basis of subjective estimates. A more favourable set of parameters to use in connection with subjective estimates are the upper and lower limits of the probability distribution for a non-continuous distribution and upper and lower limits with associated probabilities of exceeding these limits for a continuous distribution. This set of parameters, together with the mean value will for most types of distributions give a complete description of its shape.

The choice of parameters to describe the p.d.f. reflects the difference between the risk situation and uncertainty , as explained at the beginning of this Chapter. In the case of risk analysis, the amount of prior information is normally sufficient to describe the p.d.f. in terms of a mean value, standard deviation and a measure of assymetry.

4.3.2 A NEW METHOD OF OBTAINING PROBABILITY DISTRIBUTION FUNCTIONS USING SCALED PARTS OF UNIFORM NORMAL DISTRIBUTIONS

Based upon the arguments presented in the previous sections, the objective is to find an approximate probability distribution function to describe the uncertainty in the individual variable on the basis of a given expected mean value and upper and lower limits of the variable, with associated probabilities of being greater or less than these respective limits. A distribution type consisting of a combination of 2 halves of normal distributions was the initial choice primarily on the grounds of flexibility.

The normal distribution is defined by the equation:

$$f(x) = \frac{1}{\sqrt{2\pi}\,\sigma} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

where σ = standard deviation

and μ = mean or expected value

Each of the 2 truncated distributions will be one half of an ordinary normal distribution defined by the above general equation. The two truncated distributions will be joined at the modal point where f(x) takes

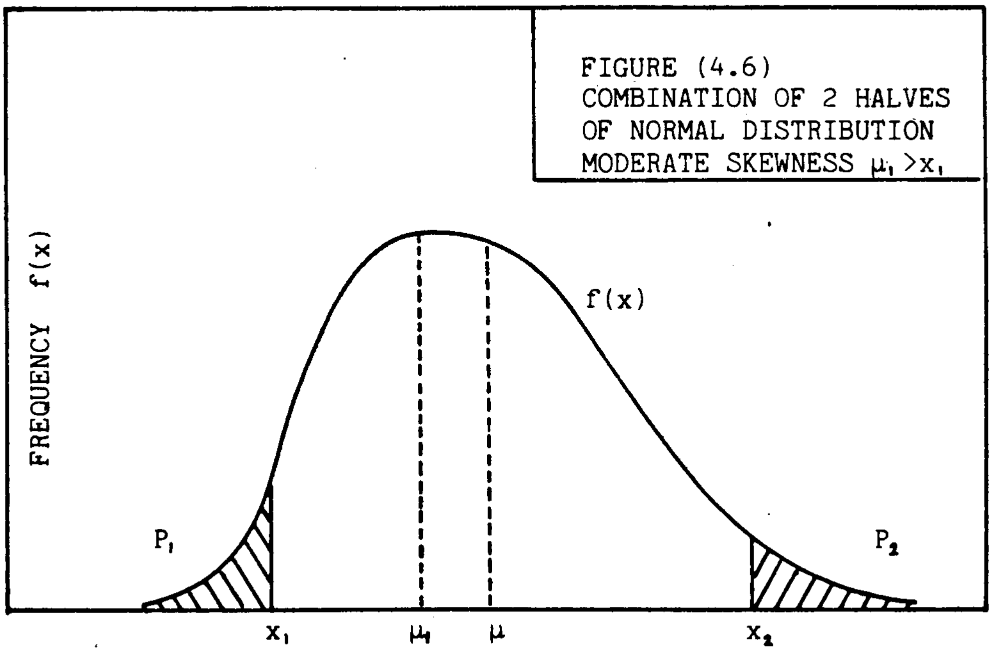


FIGURE (4.6)
COMBINATION OF 2 HALVES OF NORMAL DISTRIBUTION
MODERATE SKEWNESS $\mu_1 > x_1$

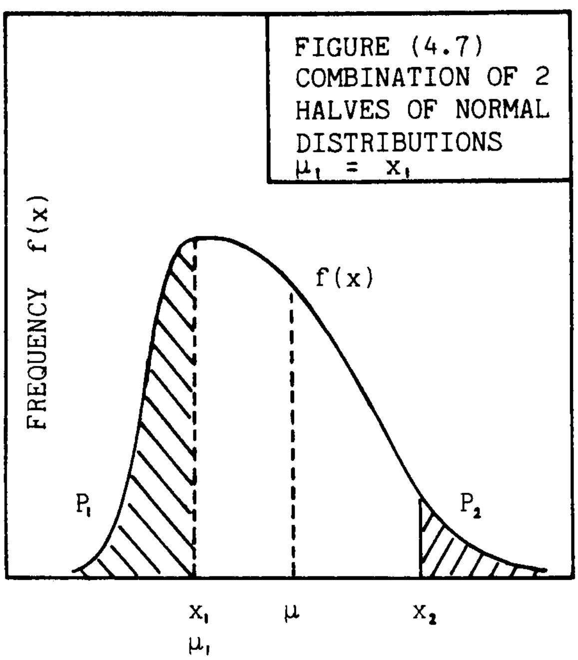


FIGURE (4.7)
COMBINATION OF 2 HALVES OF NORMAL DISTRIBUTIONS
$\mu_1 = x_1$

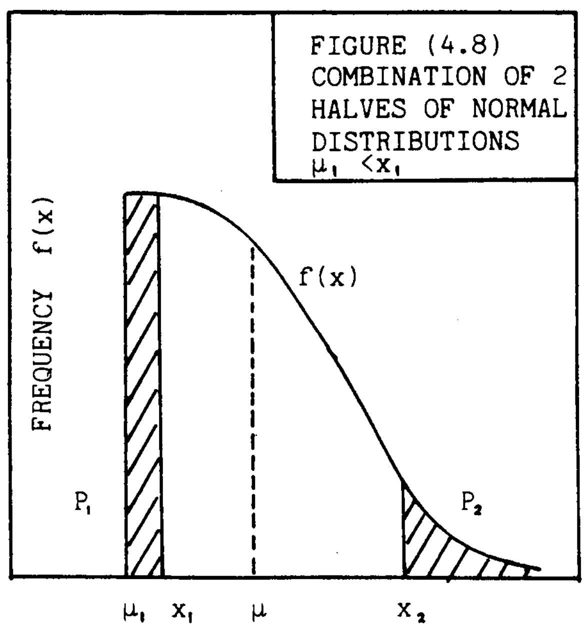


FIGURE (4.8)
COMBINATION OF 2 HALVES OF NORMAL DISTRIBUTIONS
$\mu_1 < x_1$

μ_1 = mean of each normal distribution
μ = mean of combined distribution
p_1 = lower probability tail
x_1 = ordinate corresponding to lower probability
p_2 = upper probability tail
x_2 = ordinate corresponding to upper probability

a maximum value and the first derivative, $f'(x)$, is zero. The scale of $f(x)$ depends on μ and σ so that the area under the p.d.f. always equals unity. To ensure continuity at the joining point each truncated distribution will therefore have to be multiplied by a scaling factor. The general situation is illustrated in Figure (4.6) where μ_1 is the joining point of the two distributions.

If the two truncated distributions are obtained from normal distributions with standard deviations σ_1 and σ_2, the probability distribution function of the combined distribution can be defined as:

$$f(x) = a \frac{1}{\sqrt{2\pi}\,\sigma_1} e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_1}\right)^2} \qquad \text{for } x \leqslant \mu_1 \qquad (1)$$

$$f(x) = b \frac{1}{\sqrt{2\pi}\,\sigma_2} e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_2}\right)^2} \qquad \text{for } x \geqslant u_1 \qquad (2)$$

Based on the known parameters x_1, p_1, x_2, p_2 and μ, the standard deviations σ_1 and σ_2 of the two normal distributions from which the truncated halves are derived will have to be evaluated together with the scaling factors a and b and the value of joining point or modal point μ_1.

We first require that the area under the p.d.f. equals unity:

$$\int_{-\infty}^{+\infty} f(x)\, dx = 1$$

hence: $a \times \frac{1}{2} + b \times \frac{1}{2} = 1$ or $a + b = 2$ (3)

Secondly we require continuity in the p.d.f. at $x = \mu_1$

hence: $$a \frac{1}{\sqrt{2\pi}\,\sigma_1} e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_1}\right)^2} = b \frac{1}{\sqrt{2\pi}\,\sigma_2} e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_2}\right)^2} \qquad \text{at } x = \mu_1$$

or $$a\,\sigma_2 = b\,\sigma_1 \tag{4}$$

Combining (3) and (4) gives $(2-b)\,\sigma_2 = b\,\sigma_1$

$$b = \frac{2\sigma_2}{\sigma_1 + \sigma_2} \tag{5}$$

and $$a = \frac{2\sigma_1}{\sigma_1 + \sigma_2} \tag{6}$$

hence we can rewrite (1) and (2)

$$f(x) = \frac{2}{\sqrt{2\pi}\,(\sigma_1+\sigma_2)}\, e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_1}\right)^2} \qquad \text{for } x \leqslant \mu_1$$

and $$f(x) = \frac{2}{\sqrt{2\pi}\,(\sigma_1+\sigma_2)}\, e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_2}\right)^2} \qquad \text{for } x \geqslant \mu_1$$

The expected value of a continuous distribution is defined as:

$$E(x) = \int_{-\infty}^{+\infty} x\, f(x)\, dx$$

and since this is the same as the mean value we have:

$$E(x) = \frac{2}{\sqrt{2\pi}\,(\sigma_1+\sigma_2)} \left[\int_{-\infty}^{\mu_1} x\, e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_1}\right)^2} dx + \int_{\mu_1}^{+\infty} x\, e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_2}\right)^2} dx \right]$$

Put $z_1 = \dfrac{x-\mu_1}{\sigma_1}$ and $z_2 = \dfrac{x-\mu_1}{\sigma_2}$

hence: $\dfrac{dz_1}{dx} = \dfrac{1}{\sigma_1}$ and $\dfrac{dz_2}{dx} = \dfrac{1}{\sigma_2}$

$$E(x) = \frac{2}{\sqrt{2\pi}\,(\sigma_1+\sigma_2)} \left[\int_{-\infty}^{0} (\sigma_1 z_1 + \mu_1)\sigma_1 e^{-\frac{1}{2}z_1^2}\, dz_1 + \int_{0}^{+\infty} (\sigma_2 z_2 + \mu_1)\sigma_2 e^{-\frac{1}{2}z_2^2}\, dz_2 \right]$$

and after evaluating the integrals :

$$\underline{E(x) = \mu = \mu_1 + \frac{2\,(\sigma_2 - \sigma_1)}{\sqrt{2\pi}}} \tag{7}$$

The probability of $x < x_1 = p_1 = \int_{-\infty}^{x_1} f(x)\, dx$

$$p_1 = \int_{-\infty}^{x_1} \frac{2}{\sqrt{2\pi}\,(\sigma_1+\sigma_2)}\, e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_1^{\,2}}\right)} dx$$

$$p_1 = \frac{2\sigma_1}{\sigma_1+\sigma_2}\int_{-\infty}^{x_1}\frac{1}{\sqrt{2\pi}\,\sigma_1}e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_1}\right)^2}dx$$

$$\underline{p_1 = \frac{2\sigma_1}{\sigma_1+\sigma_2}\;\Phi\left(\frac{x_1-\mu_1}{\sigma_1}\right)}$$

and similarly
$$p_2 = \int_{x_2}^{+\infty} f(x)\;dx$$

$$p_2 = \int_{x_2}^{+\infty}\frac{2}{\sqrt{2\pi}\,(\sigma_1+\sigma_2)}e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_2}\right)^2}dx$$

$$p_2 = \frac{2\sigma_2}{\sigma_1+\sigma_2}\int_{x_2}^{+\infty}\frac{1}{\sqrt{2\pi}\,\sigma_2}e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_2}\right)^2}dx$$

$$\underline{p_2 = \frac{2\sigma_2}{\sigma_1+\sigma_2}\left[1-\Phi\left(\frac{x_2-\mu_1}{\sigma_2}\right)\right]}$$

from (7) we have that :
$$\mu_1 = \mu + \frac{2(\sigma_2-\sigma_1)}{\sqrt{2\pi}}$$

hence:
$$\underline{p_1 = \frac{2\sigma_1}{\sigma_1+\sigma_2}\;\Phi\left[\frac{x_1-\mu+2(\sigma_2-\sigma_1)/\sqrt{2\pi}}{\sigma_1}\right]} \qquad (8)$$

and
$$\underline{p_2 = \frac{2\sigma_2}{\sigma_1+\sigma_2}\left[1-\Phi\left(\frac{x_2-\mu+2(\sigma_2-\sigma_1)/\sqrt{2\pi}}{\sigma_2}\right)\right]} \qquad (9)$$

Hence we have a set of three equations (7), (8) and (9) with three unknowns σ_1 , σ_2 and μ_1 which can only be solved numerically. The method desribed above is correct provided for a positively skewed distribution the ordinate x_1 of the lower probability limit p_1 is less than the joining point μ_1 ,and for a negatively skewed distribution the ordinate x_2 of the upper probability limit p_2 is greater than the joining point μ_1 of the two normal distributions. To find the criteria for which this is true we first consider the positively skewed distribution and evaluate the criterion for which $x_1 = \mu_1$ in terms of the given parameters x_1, x_2, p_1 , p_2 and μ , as shown in Figure (4.7).

From (7) if $x_1 = \mu_1$ we have: $x_1 = \mu - \frac{2(\sigma_2 - \sigma_1)}{\sqrt{2\pi}}$ (10)

Since σ_1 and σ_2 are unknown at this stage we want to find expressions for these in terms of x_1, x_2, p_1, p_2, and μ .

$$p_1 = \frac{2\sigma_1}{\sigma_1 + \sigma_2} \int_{-\infty}^{x_1} \frac{1}{\sqrt{2\pi}\,\sigma_1} e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_1}\right)^2} dx$$

$$p_1 = \frac{2\sigma_1}{\sigma_1 + \sigma_2} \times \frac{1}{2} = \frac{\sigma_1}{\sigma_1 + \sigma_2}$$

or $$\sigma_1 = \frac{\sigma_2 p_1}{1 - p_1} \qquad (11)$$

$$p_2 = \frac{2\sigma_2}{\sigma_1 + \sigma_2} \int_{x_2}^{+\infty} \frac{1}{\sqrt{2\pi}\,\sigma_2} e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_2}\right)^2} dx$$

from (3), (5) and (6) we have:

$$a + b = 2 \quad \text{with } a = \frac{2\sigma_1}{\sigma_1 + \sigma_2} \quad \text{and } b = \frac{2\sigma_2}{\sigma_1 + \sigma_2}$$

and since $p_1 = \frac{\sigma_1}{\sigma_1 + \sigma_2}$ we get

$$2p_1 + \frac{2\sigma_2}{\sigma_1 + \sigma_2} = 2$$

$$\frac{2\sigma_2}{\sigma_1 + \sigma_2} = 2 - 2p_1$$

and hence: $$p_2 = (2 - 2p_1)\int_{x_2}^{+\infty} \frac{1}{\sqrt{2\pi}\,\sigma_2} e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_2}\right)^2} dx$$

or: $$\int_{x_2}^{+\infty} \frac{1}{\sqrt{2\pi}\,\sigma_2} e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_2}\right)^2} dx = \frac{p_2}{2 - 2p_1}$$

The integral of the normal distribution function on the l.h.s. can be evaluated by making the transformation:

$$z_2 = \frac{x - \mu_1}{\sigma_2}$$

or since $\mu_1 = x_1$ $$z_2 = \frac{x - x_1}{\sigma_2}$$

and the integral now becomes the integral of the standard normal distribution with mean zero and standard deviation 1.

Entering the tabulated values of the integral of the standard normal distribution at the point $\frac{p_2}{2 - 2p_1}$ will therefore yield a numerical value for z_2 and we can hence obtain a value for σ_2 :

$$\sigma_2 = \frac{x_2 - x_1}{z_2} \tag{12}$$

From (10) $\sigma_2 - \sigma_1 = \frac{\sqrt{2\pi}}{2}(\mu - x_1)$

and from (11) $\sigma_2 - \frac{\sigma_2 p_1}{1-p_1} = \frac{\sqrt{2\pi}}{2}(\mu - x_1)$

$$\sigma_2\left(\frac{1-2p_1}{1-p_1}\right) = \frac{\sqrt{2\pi}}{2}(\mu - x_1)$$

and from (12) $\frac{x_2 - x_1}{z_2}\left(\frac{1-2p_1}{1-p_1}\right) = \frac{\sqrt{2\pi}}{2}(\mu - x_1)$

hence we get
$$\frac{x_2 - \mu}{\mu - x_1} = \frac{\sqrt{2\pi}\, z_2 (1-p_1)}{2(1-2p_1)} - 1 \tag{13}$$

Equation (13) gives a relationship between x_1, x_2 and μ for which $x_1 = \mu_1$.

Provided the ratio $\frac{x_2 - \mu}{\mu - x_1}$ is less than or equal to the expression on the r.h.s. of equation (13), the ordinate x_1 of the lower probability limit p_1 will be less than the joining point μ_1 and the earlier described method can be used. If the ratio $\frac{x_2 - \mu}{\mu - x_1}$ is greater than the expression on the r.h.s. of equation (13), the lower probability p_1 must be expressed as two integrals.

Hence:
$$p_1 = \int_{-\infty}^{\mu} \frac{2}{\sqrt{2\pi}(\sigma_1+\sigma_2)} e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_1}\right)^2} dx + \int_{\mu}^{+\infty} \frac{2}{\sqrt{2\pi}(\sigma_1+\sigma_2)} e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_2}\right)^2} dx$$

$$= \frac{\sigma_1}{\sigma_1+\sigma_2} + \frac{\sigma_2}{\sigma_1+\sigma_2} - \int_{x_1}^{+\infty} \frac{2}{\sqrt{2\pi}(\sigma_1+\sigma_2)} e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_2}\right)^2} dx$$

$$p_1 = 1 - \int_{x_1}^{+\infty} \frac{2}{\sqrt{2\pi}(\sigma_1+\sigma_2)} e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_2}\right)^2} dx \tag{14}$$

or
$$p_1 = 1 - \left\{ \frac{2\sigma_2}{\sigma_1+\sigma_2} \left[1 - \Phi\left(\frac{x_1-\mu_1}{\sigma_2}\right) \right] \right\} \tag{15}$$

A similar evaluation for a negatively skewed distribution gives the following relationship between x_1, x_2, and μ for which $x_2 = \mu_1$:

$$\frac{x_2 - \mu}{\mu - x_1} = \left[\frac{\sqrt{2\pi} * z_1 (1 - p_2)}{2 * (2p_2 - 1)} - 1 \right]^{-1} \tag{16}$$

Provided the ratio $\frac{x_2 - \mu}{\mu - x_1}$ is equal to or greater than the expression on the r.h.s. of equation (16) the basic method given by equations (7), (8) and (9) can be used.

If the ratio $\frac{x_2 - \mu}{\mu - x_1}$ is less than the expression on the r.h.s. of equation (16), the upper probability p_2 will have to be expressed as:

$$p_2 = 1 - \int_{-\infty}^{x_2} \frac{2}{\sqrt{2\pi}(\sigma_1 + \sigma_2)} e^{-\frac{1}{2}\left(\frac{x - \mu_1}{\sigma_1}\right)^2} dx \tag{17}$$

$$p_2 = 1 - \frac{2\sigma_1}{\sigma_1 + \sigma_2} \Phi\left(\frac{x_1 - \mu_1}{\sigma_1}\right) \tag{18}$$

Clearly as the combined distribution becomes increasingly skewed in either direction the standard deviation of the normal distribution from which one of the two halves is taken decreases and eventually approaches zero. This is the limiting condition for the skewness which the combined distribution can accommodate. At this point the distribution effectively becomes a scaled truncated half of a normal distribution, and the ratio $\frac{x_2 - \mu}{\mu - x_1}$ becomes fixed for any given set of lower and upper probabilities p_1 and p_2, [Figure (4.8)]. The limiting condition can be evaluated as follows for a positively skewed distribution. Taking expected values we get:

$$E[x] = \mu = \int_{-\infty}^{+\infty} x \, f(x)dx \approx \int_{\mu}^{+\infty} x \, f(x)dx$$

Transforming the co-ordinates to the standard normal distribution with mean = 0 and standard deviation = 1 gives:

$$z_1 = \frac{x_1 - \mu_1}{\sigma_2} \quad \text{or} \quad \sigma_2 z_1 = x_1 - \mu_1 \tag{19}$$

and

$$z_2 = \frac{x_2 - \mu_1}{\sigma_2} \quad \text{or} \quad \sigma_2 z_2 = x_2 - \mu_1 \tag{20}$$

Since $\sigma_1 \approx 0$, we have from (7) $\mu_1 = \mu - \frac{2}{\sqrt{2\pi}}\sigma_2$ (21)

Substituting (21) into (19) and (20) gives:

$$\sigma_2 z_1 = x_1 - \mu + \frac{2}{\sqrt{2\pi}}\sigma_2$$

and

$$\sigma_2 z_2 = x_2 - \mu + \frac{2}{\sqrt{2\pi}}\sigma_2$$

and therefore:

$$\frac{x_2 - \mu}{\mu - x_1} = \frac{z_2 - \frac{2}{\sqrt{2\pi}}}{\frac{2}{\sqrt{2\pi}} - z_1} \tag{22}$$

where z_1 and z_2 can be found in standard tables of the normal distribution when p_1 and p_2 are given. The ratio $\frac{\mu - \mu_1}{x_2 - x_1}$ also becomes fixed at this point and can be evaluated from the equation :

$$\frac{\mu - \mu_1}{x_2 - x_1} = \frac{\frac{2}{\sqrt{2\pi}}}{z_2 - z_1} \tag{23}$$

Similarly for a negatively skewed distribution we obtain the following set of conditions:

$$\frac{x_2 - \mu}{\mu - x_1} = \frac{z_2 + \frac{2}{\sqrt{2\pi}}}{-z_1 - \frac{2}{\sqrt{2\pi}}} \tag{24}$$

and

$$\frac{\mu - \mu_1}{x_2 - x_1} = \frac{-\frac{2}{\sqrt{2\pi}}}{z_2 - z_1} \tag{25}$$

Equations (7), (8), (9), (13), (14), (15), (16), (17), (18), (22), (23), (24) and (25) now completely define all the possible combinations of two truncated normal distributions with the limiting conditions for skewness given by equations (16) and (22) for positively and negatively skewed distributions respectively.

It was mentioned earlier that the joining point μ_1 and standard deviations σ_1 and σ_2 of the distributions from which the two truncated halves are taken can only be evaluated numerically. A computer program was written for this purpose. A computer program can effectively select the appropriate set of equations, evaluate the limiting conditions and search through a series of alternative values for σ_1 and σ_2 to find the correct combination.

One of the advantages of dealing with the normal distribution is that the distribution can be standardised by the simple transformation $Z = \frac{x-\mu}{\sigma}$ and tables of the standard normal distribution can therefore serve any normal distribution.

Having developed the theory behind the combination of truncated normal distributions it was quickly realised that a standardisation was possible. By producing a set of standard curves the parameters σ_1, σ_2 and μ_1 could be evaluated on the basis of the input variables μ, x_1, x_2, p_1 and p_2. The use of the computer program for evaluating the distribution of each individual variable could therefore be eliminated after having constructed the standard set of curves. This standardisation was achieved by expressing the variables in terms of non-dimensional ratios:

i) $\frac{x_2-\mu}{\mu-x_1}$ ii) $\frac{\mu-\mu_1}{x_2-x_1}$ iii) σ_2/σ_1

all of which are effectively shape descriptors.

Because of symmetry it was decided that it would be more convenient to express the ratios $\frac{x_2-\mu}{\mu-x_1}$ and σ_2/σ_1 as logarithms. For a series of combinations of lower and upper tail probabilities p_1 and p_2, diagrams were produced of:

$$1)\qquad \ln\left(\frac{x_2-\mu}{\mu-x_1}\right) \qquad \text{vs} \qquad \frac{\mu-\mu_1}{x_2-x_1}$$

and

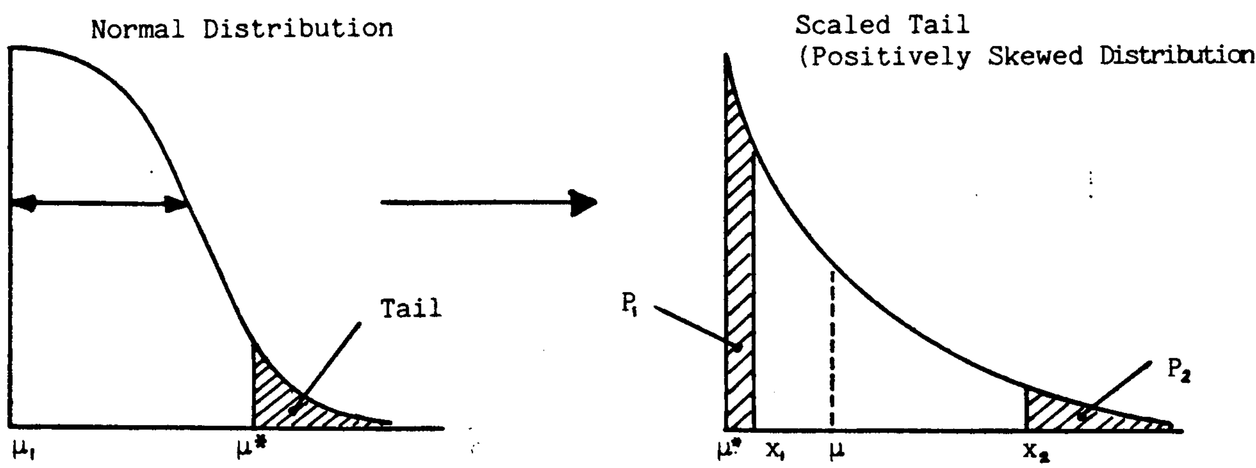
2) $\ln\left(\frac{x_2 - \mu}{\mu - x_1}\right)$ vs $\ln\left(\sigma_2/\sigma_1\right)$

The process of obtaining σ_1 , σ_2 and μ now simply consists of calculating $\frac{x_2 - \mu}{\mu - x_1}$ and taking off the corresponding values of $\frac{\mu - \mu_1}{x_2 - x_1}$ and σ_2/σ_1 from the diagrams. Using equation (7) this gives 3 equations with 3 unknowns which can be solved for σ_1 , σ_2 and μ_1 respectively.

Figures (4.10) to (4.13) present the diagrams which have been drawn separately for positive and negative skewness. The smallest probability tail given is at the 5% level. The reason for this is that subjective estimates of small probability tails are associated with high inaccuracy. Estimates of probability tails to the nearest 10% level can normally be achieved with a reasonably high degree of confidence, while at the lower end the choice between for example a 1% or a 3% tail can be a fairly arbitrary decision. A factor of 3 can therefore easily be introduced into the calculation, and will markedly influence the shape of the probability distribution.

In certain cases a greater degree of skewness than can be provided by the single half of the normal distribution may be required. The beta or gamma distribution is well suited for the purpose of representing variables of extreme skewness, but it was realised that an equally suitable representation could be achieved by again using parts of the normal distribution with an appropriate scaling factor to ensure that the area under the probability distribution function is equal to unity. Increasing skewness is thus accommodated by using a gradually decreasing tail of the normal distribution with a corresponding increasing scaling factor. In cases of extreme skewness the distributions obtained using

FIGURE (4.9)
METHOD FOR OBTAINING HIGHLY
SKEWED DISTRIBUTIONS



μ_1 = mean of each normal distribution

σ = standard deviation of normal distribution

μ^* = limiting value of ordinate at non-continuous end of distribution

p_1 = lower probability tail

x_1 = ordinate corresponding to lower probability

p_2 = upper probability tail

x_2 = ordinate corresponding to upper probability

μ = mean value of combined distribution

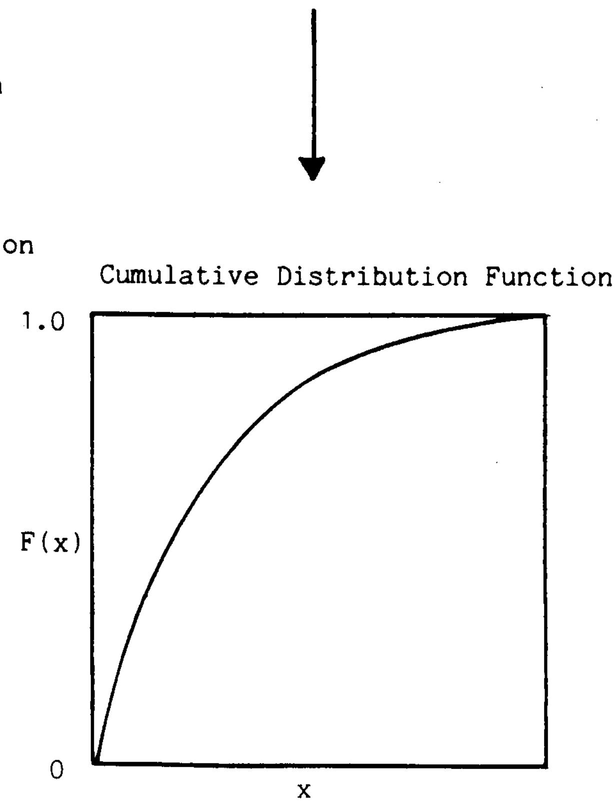


FIGURE (4.10) $\ln\left[\frac{x_2 - \mu}{\mu - x_1}\right]$ vs $\left[\frac{\mu - \mu_1}{x_2 - x_1}\right]$

COMBINATION OF TWO HALVES OF NORMAL DISTRIBUTION, POSITIVE SKEWNESS

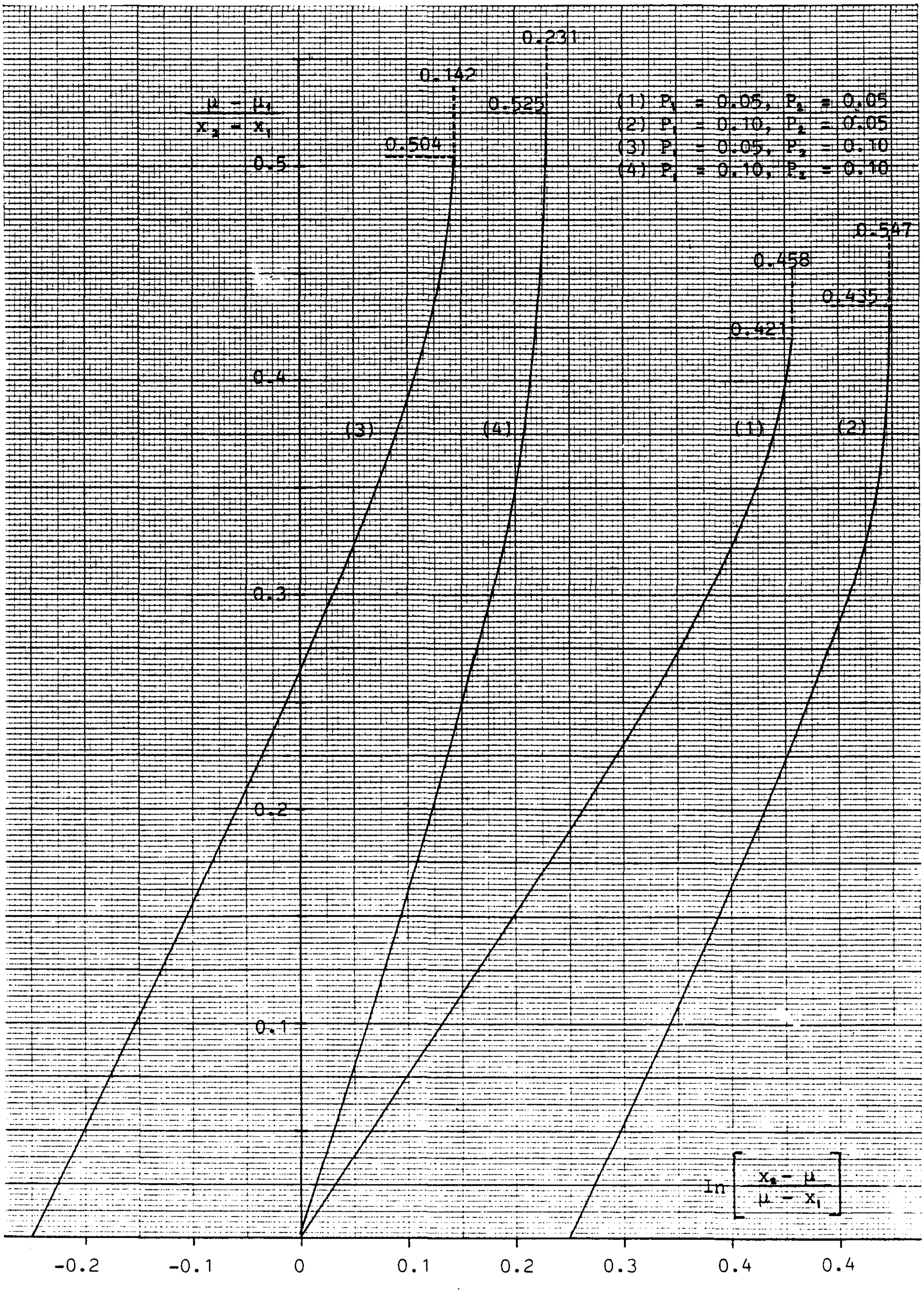


FIGURE (4.11) $\ln\left[\frac{x_2 - \mu}{\mu - x_1}\right]$ vs $\left[\frac{\mu - \mu_1}{x_2 - x_1}\right]$

COMBINATION OF TWO HALVES OF NORMAL DISTRIBUTIONS, NEGATIVE SKEWNESS

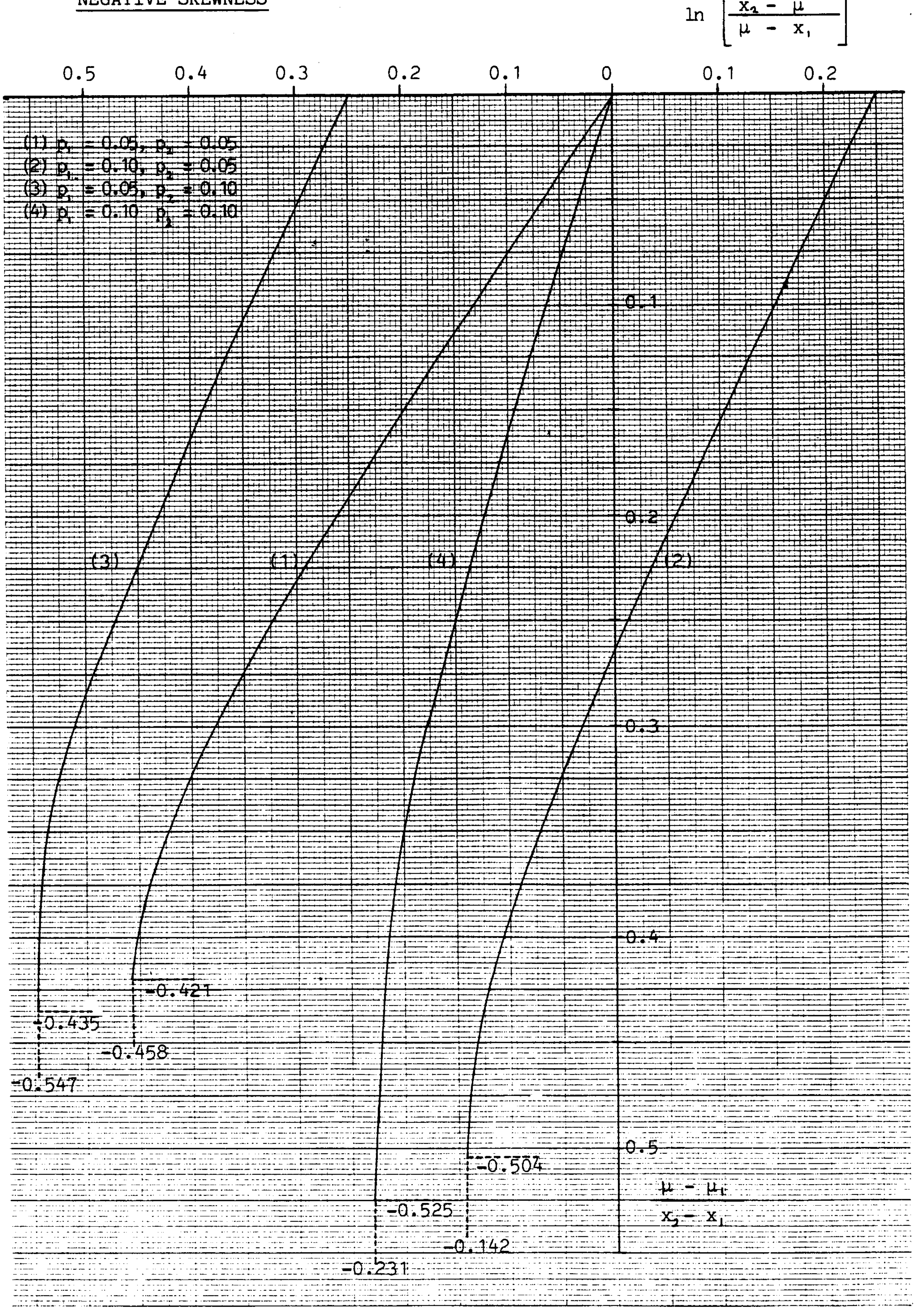


FIGURE (4.12) $\ln\left[\frac{x_2 - \mu}{\mu - x_1}\right]$ vs $\ln\left[\sigma_2/\sigma_1\right]$

COMBINATION OF TWO HALVES OF NORMAL DISTRIBUTION, POSITIVE SKEWNESS

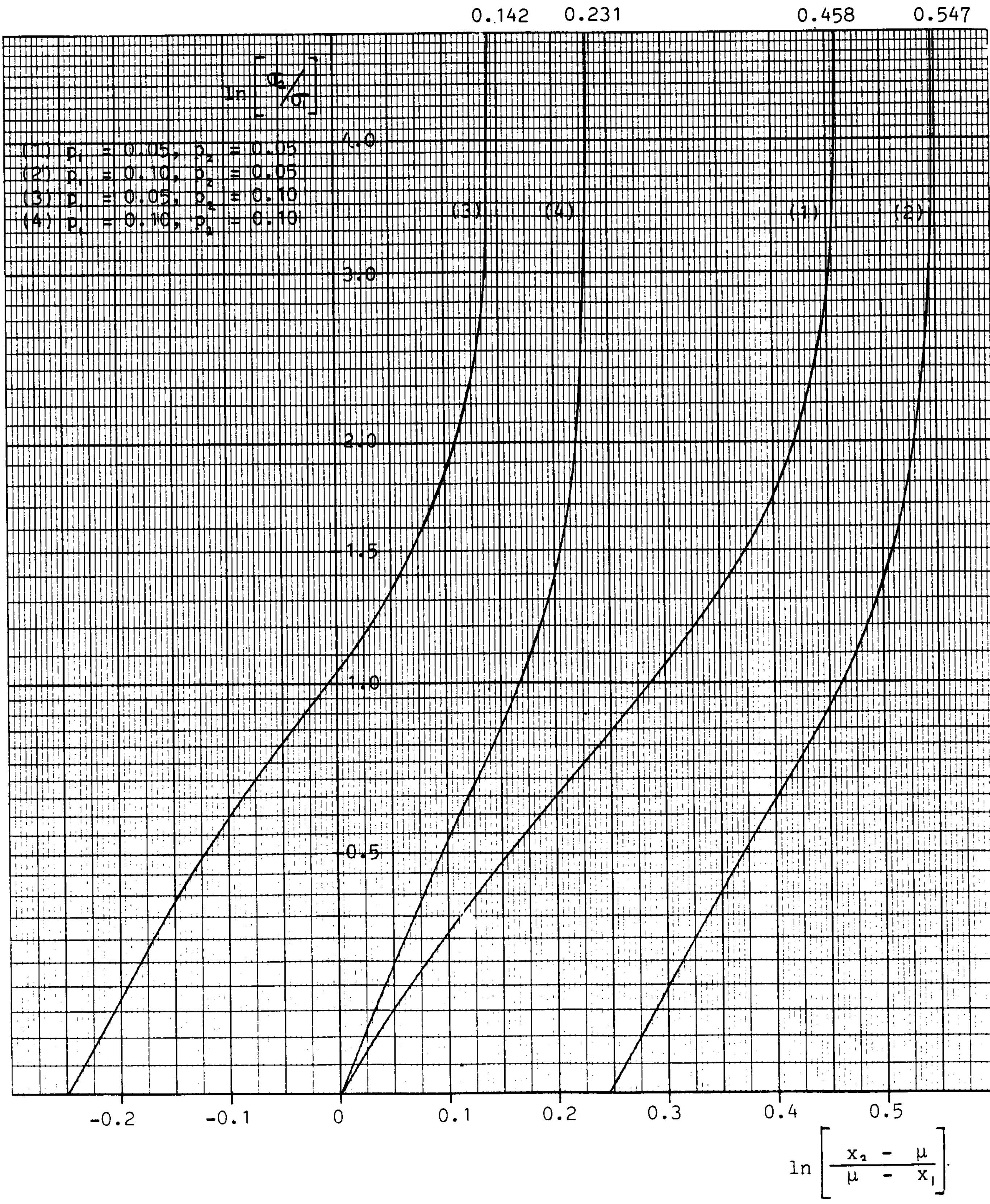


FIGURE (4.13) $\ln\left[\frac{x_2 - \mu}{\mu - x_1}\right]$ vs $\ln\left[\sigma_2/\sigma_1\right]$

COMBINATION OF TWO HALVES OF NORMAL DISTRIBUTION, NEGATIVE SKEWNESS

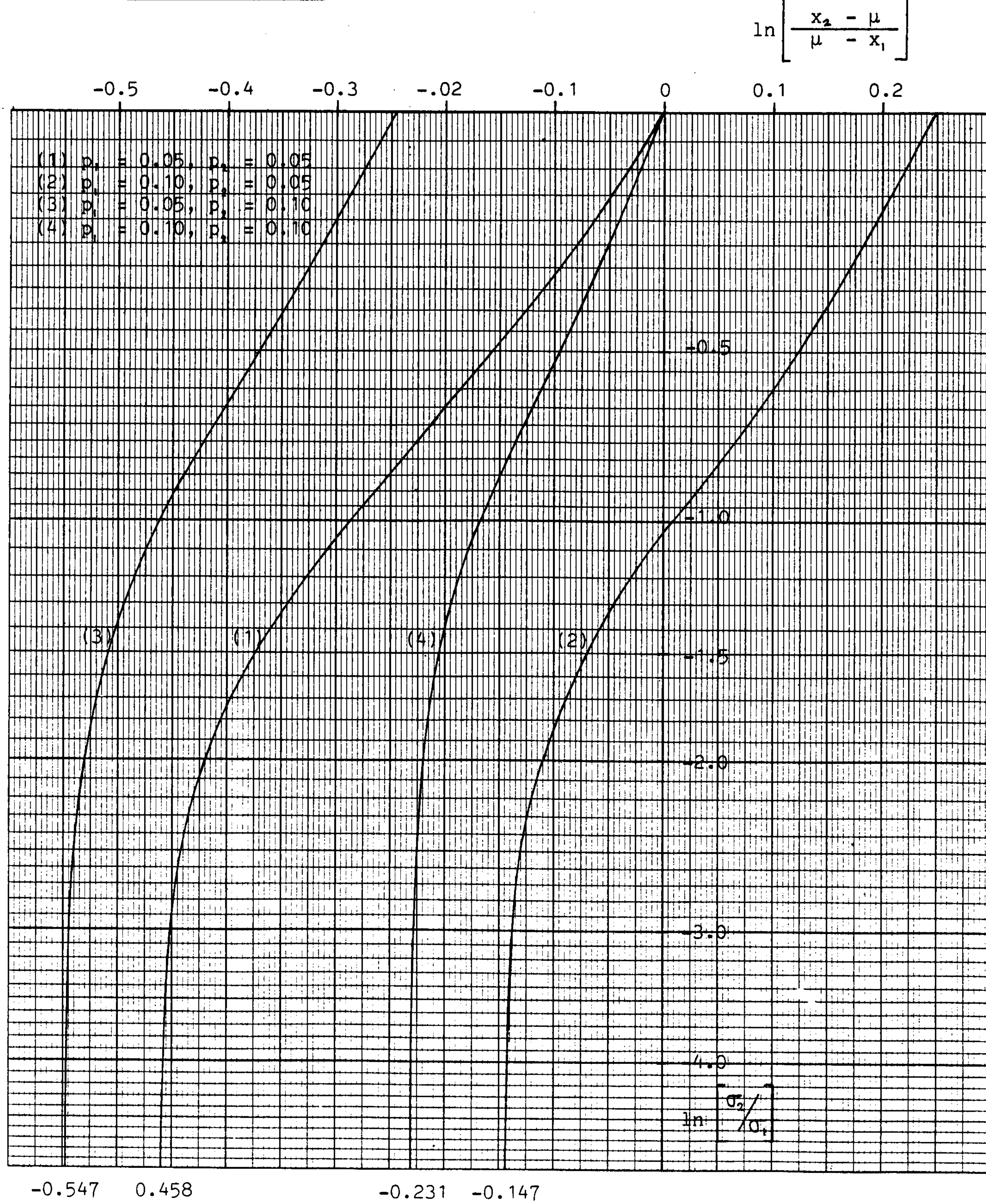


FIGURE (4.14) $\ln\left[\frac{x_2 - \mu}{\mu - x_1}\right]$ vs $\left[\frac{\mu - \mu_1}{x_2 - x_1}\right]$

SCALED PART OF SINGLE NORMAL DISTRIBUTION, HIGH POSITIVE SKEWNESS

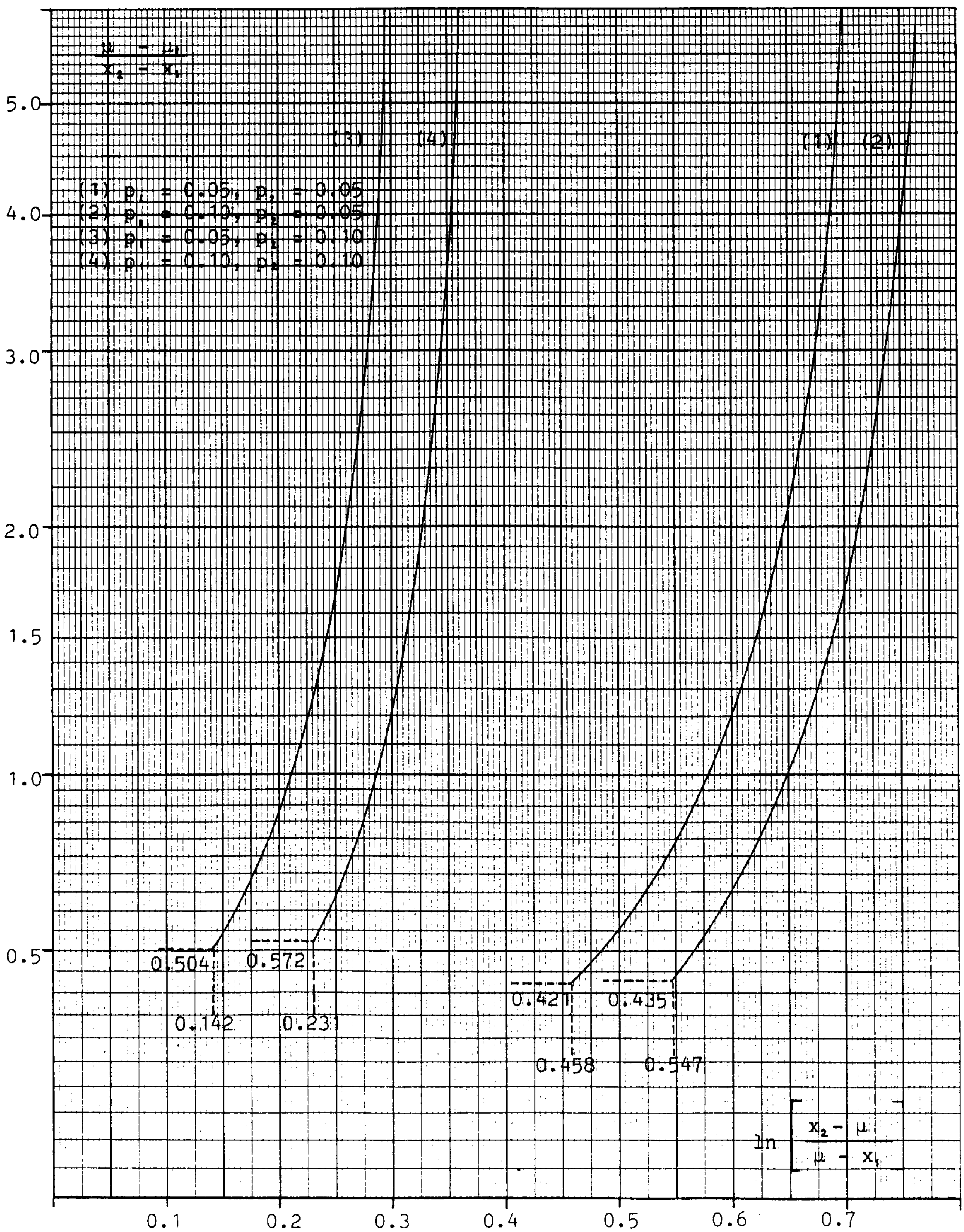


FIGURE (4.15) $\ln\left[\frac{x_2 - \mu}{\mu - x_1}\right]$ vs $\ln\left[\frac{\mu - \mu_1}{\sigma_2}\right]$

SCALED PART OF SINGLE NORMAL DISTRIBUTION, HIGH POSITIVE SKEWNESS

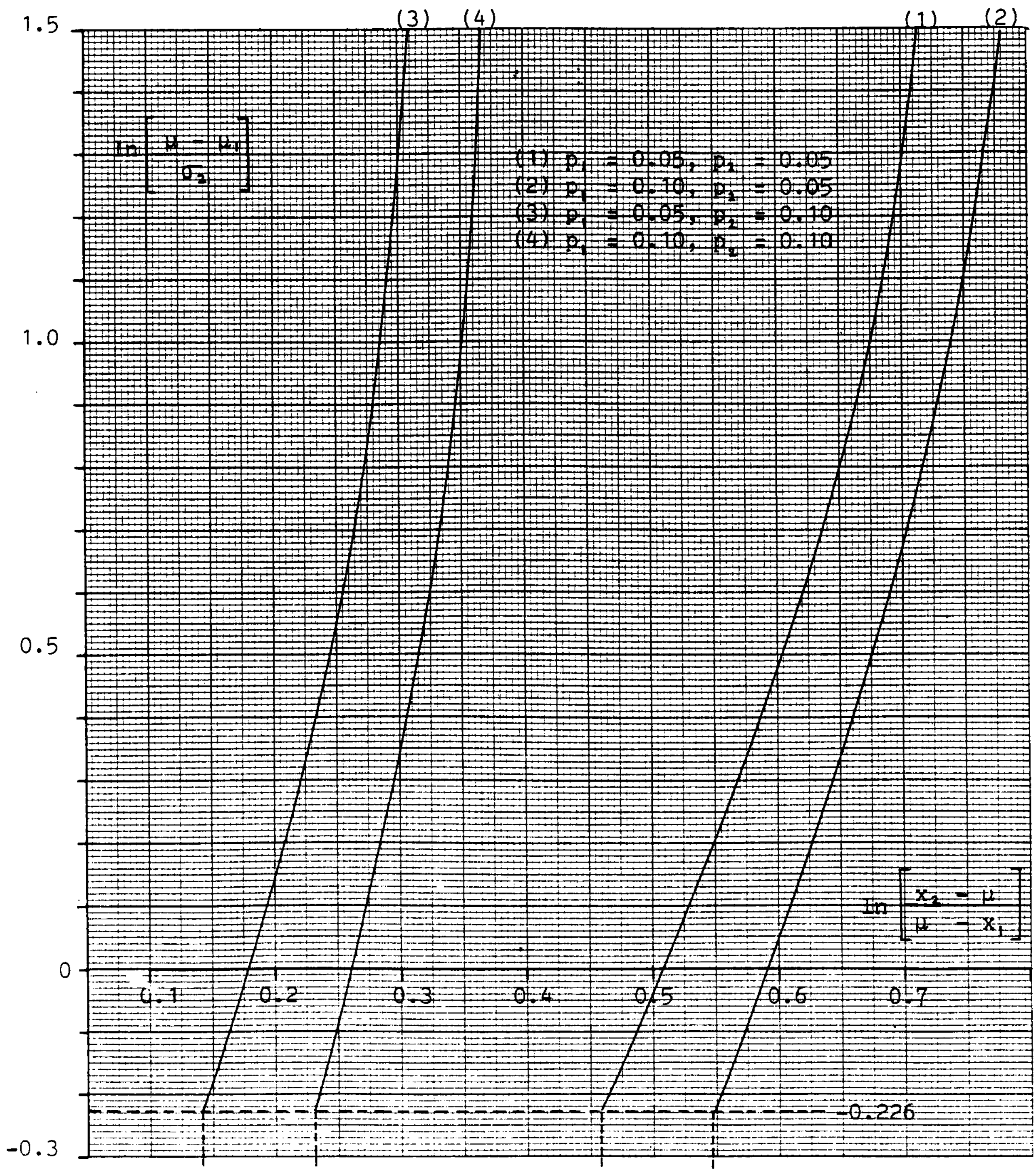
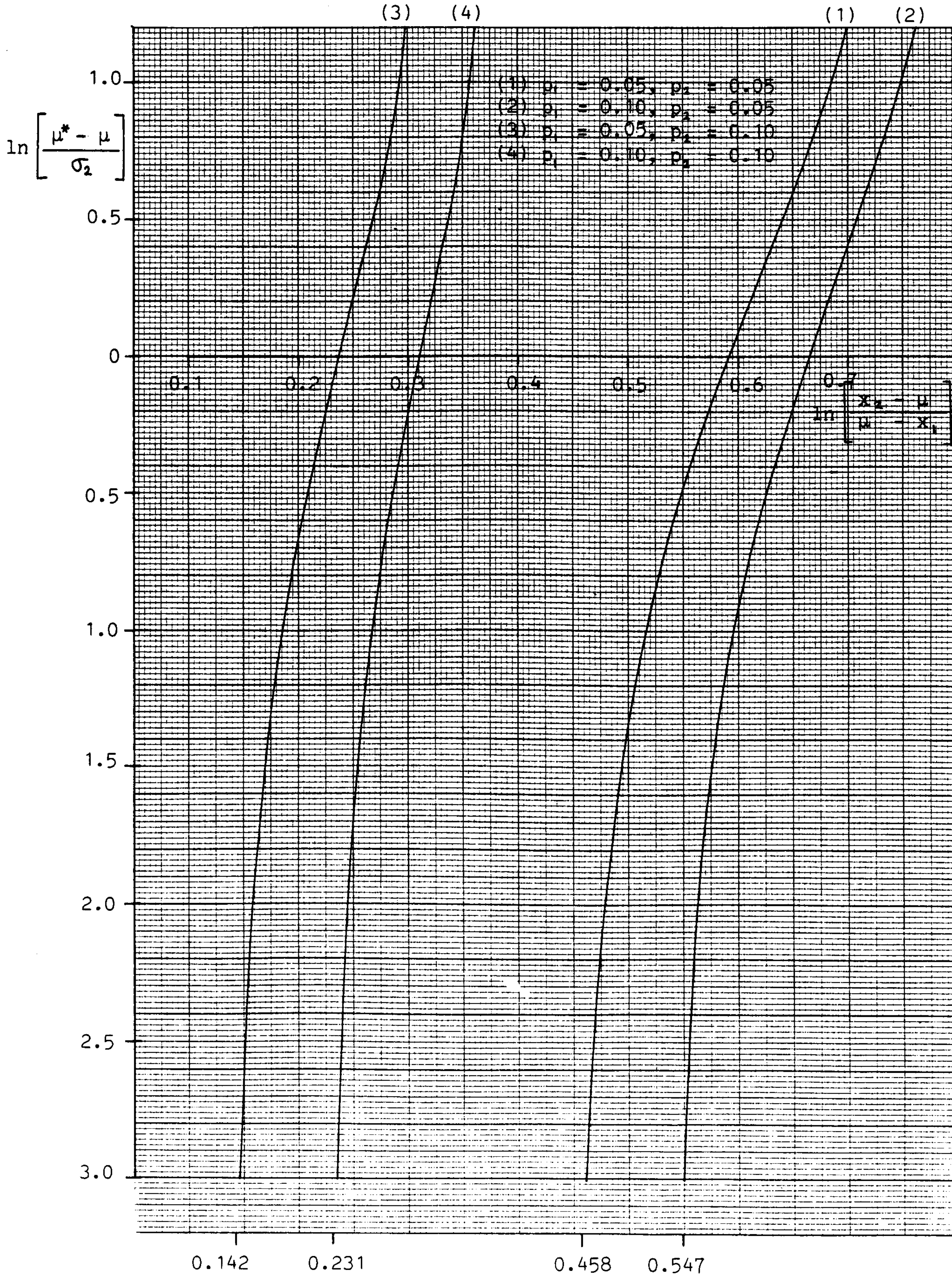


FIGURE (4.16) $\ln\left[\frac{x_2 - \mu}{\mu - x_1}\right]$ vs $\ln\left[\frac{\mu^* - \mu}{\sigma_2}\right]$

SCALED PART OF SINGLE NORMAL DISTRIBUTION, HIGH POSITIVE SKEWNESS



this method will be similar in appearance to the equivalent distributions obtained using the beta or gamma function. The process is illustrated in Figure (4.9) (Only the relevant half of the normal distribution is shown).

A further similarity with the gamma function is that the distribution is continuous at one end and non-continuous at the other. This violates the earlier concept of continuity at both ends, but is a necessary requirement in order to achieve the desired skewness and will, in practice, make no difference to the resulting calculations.

For the proposed family of distributions with extreme skewness the same basic description parameters μ , p_1 , p_2 , x_1 and x_2 were maintained and a new method developed for obtaining the required descriptive parameters. These are the mean value μ_1 and standard deviation σ of the normal distribution from which the required tail is taken, and the limiting vaue of the ordinate at the non-continuous end of the distribution μ^* . The scaling factor is calculated as the inverse of the integral of the required tail of the normal distribution.

For a given set of description parameters μ , p_1 , p_2 , x_1 and x_2, the required parameters μ_1 , σ and μ^* can only be obtained numerically using an iterative process. A computer program was written for this part of the analysis and a series of calculations performed for a range of values of μ , x_1 and x_2, based upon the same combinations of p_1 and p_2 as used in the earlier calculations for the combination of two truncated halves of normal distribution. Again it was found that a simple standardisation was possible by expressing the parameters in terms of the four non-dimensional ratios:

(i) $\frac{x_2 - \mu}{\mu - x_1}$ ii) $\frac{\mu - \mu_1}{x_2 - x_1}$ iii) $\frac{\mu - \mu_1}{\sigma}$ iv) $\frac{\mu^* - \mu_1}{\sigma}$

For a series of combinations of upper and lower probabilities p_1 and p_2 diagrams were produced of:

$$(1) \quad \ln\left(\frac{x_2 - \mu}{\mu - x_1}\right) \quad \text{vs} \quad \frac{\mu - \mu_1}{x_2 - x_1}$$

$$(2) \quad \ln\left(\frac{x_2 - \mu}{\mu - x_1}\right) \quad \text{vs} \quad \ln\left(\frac{\mu - \mu_1}{\sigma}\right)$$

and $$(3) \quad \ln\left(\frac{x_2 - \mu}{\mu - x_1}\right) \quad \text{vs} \quad \ln\left(\frac{\mu^* - \mu_1}{\sigma}\right)$$

This set of 3 diagrams presents a rational method of obtaining the probability distribution function of a skewed variable for which the former model based upon two truncated halves of normal distributions is no longer valid. The diagrams are presented in Figures (4.14) to (4.16). Most economic variables will, if they are not symmetrical, tend towards positive skewness, and this is the situation provided for in the diagrams. If a negatively skewed distribution should be required, the correct ratios can be obtained by altering the sign of the x-axis and changing $(\mu - \mu_1)$ to $(\mu_1 - \mu)$ and $(\mu^* - \mu_1)$ to $(\mu_1 - \mu^*)$ on the y-axis.

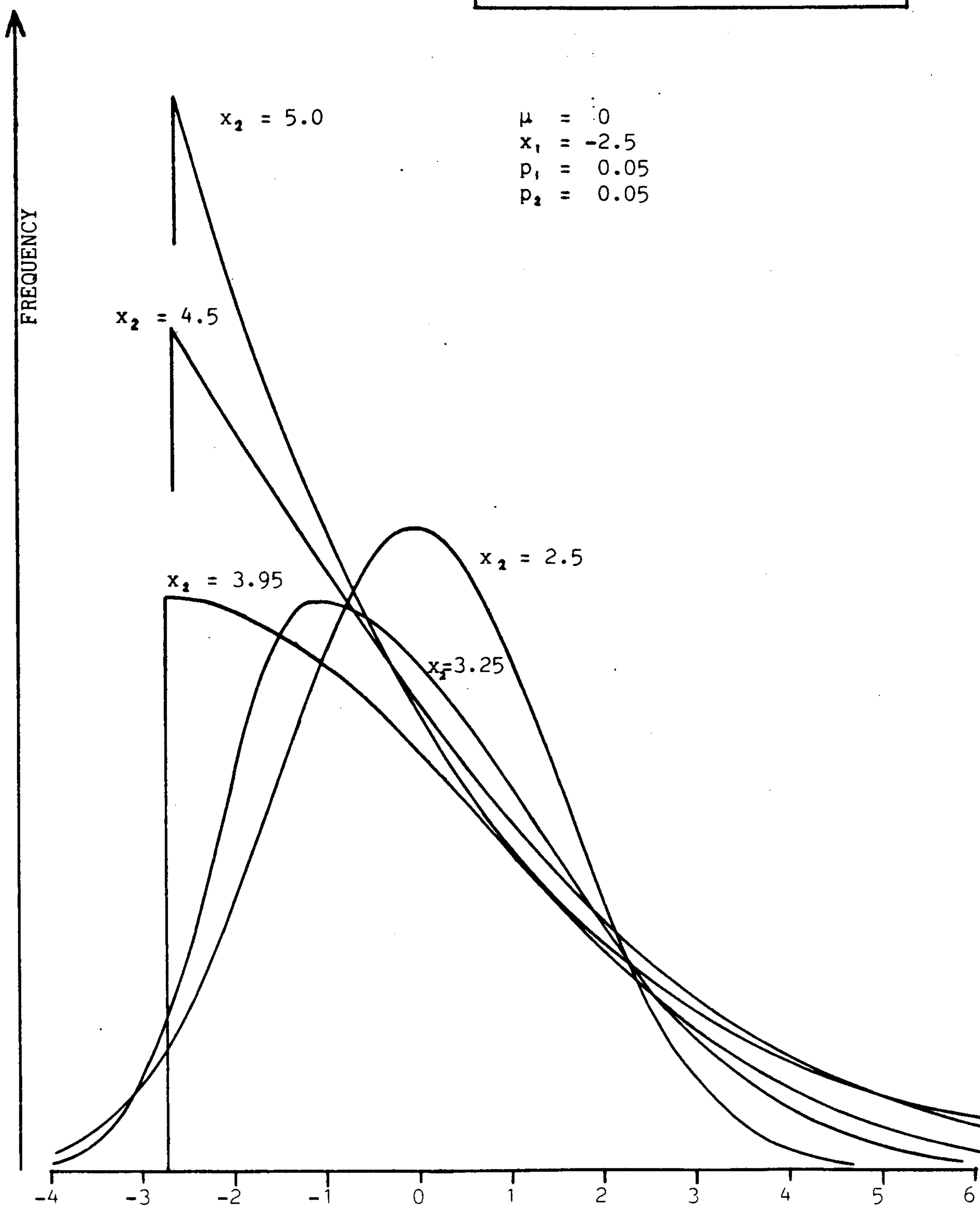
The initial model based upon the combination of two truncated halves of normal distributions, and the later extension to accommodating higher degrees of skewness by using a scaled-up tail of a single normal distribution, now constitutes a method which can be used to obtain a representative distribution function for any reasonable combination of the basic description variables μ, x_1 and x_2 within the combinations of p_1 and p_2 provided.

Only 5% and 10% combinations of the upper and lower tail probabilities p_1 and p_2 have been provided. This presents a limited choice only, but is justified on the grounds that extending the number of available combinations would simply serve to confuse the analyst in the process of estimating subjective probabilities, and could result in less accurate estimates.

The method can, of course, also be used if more accurate information than subjective estimates is available. In this case the known parameters are used to calculate the required remaining parameters from the diagrams. If a frequency distribution is available in the form of a histogram, this should always be compared with the suggested probability distribution function to ensure that the model does in fact fit the actual variable.

Figure (4.17) demonstrates the flexibility of the proposed distribution model. A variable is estimated to have an expected value of 0 with a 0.05 probability of being less than -2.5 and initially a 0.05 probability of exceeding +2.5. In this first case the resultant distribution is a symmetrical normal distribution. Gradually increasing the upper tail ordinate for the 0.05 probability limit, while other parameters remain constant, results in an increasingly skewed distribution. At a value of +3.95 the distribution is effectively a scaled single half of a normal distribution, and for an upper tail ordinate of +5.0 an extreme degree of skewness is obtained. This high degree of skewness would not be expected to be found often in practice, but is useful in testing the behaviour of a probabilistic cash flow simulation model under different sets of conditions.

FIGURE (4.17)
COMBINATION OF PARTS OF
NORMAL DISTRIBUTIONS -
EXAMPLE TO DEMONSTRATE
VARIOUS DEGREES OF SKEWNESS



4.4 THE DEVELOPMENT OF A PROBABILISTIC CASH FLOW SIMULATION MODEL BASED UPON THE PROPOSED NEW METHOD OF DESCRIBING UNCERTAINTY IN THE INDIVIDUAL VARIABLES

4.4.1 INTRODUCTION

In the previous section a general probabilistic model for the representation of variables associated with uncetainty has been proposed. The introduction to Chapter 2 presented the principal concepts of model-building, with particular reference to a deterministic model, where variables take single values only and relationships between variables are fixed.

Having realised that a number of the variables in the deterministic model are associated with various degrees of uncertainty, it became clear that satisfactory answers to the problems of hull maintenance could not be provided unless a method of taking this uncertainty into account was included. The introduction to the present Chapter argued that due to the complex relationship between the variables in the deterministic model this could only be achieved using a method of stochastic simulation, usually referred to as a Monte Carlo simulation. The objective of this section is to provide this required stochastic extension to the basic deterministic model.

In a stochastic model at least one variable is of random nature, and for the purpose of stochastic simulation this randomness is expressed in terms of a probability distribution function. Individual values of the variable are thus obtained by a process of sampling from this distribution. Having already developed the deterministic model and a general method for obtaining probability distributions, this sampling procedure is the remaining element required to link the two. To complete the stochastic model, consideration will also have to be given to the point in time at which different variables should be sampled and to the possible correlation between variables. Finally, a method of analysing and interpreting the results is required.

4.4.2 THE DEVELOPMENT OF A SAMPLING METHOD

The process of stochastic sampling can be divided into two separate parts:

1) The generation of a uniform random number

and

2) Random variate generation

The generation of one or more uniform random numbers is always required irrespective of the method used for random variate generation. True random numbers can only be generated from a random phenomenon, and this can be difficult to create in a computer. Most efficient computer based generators are therefore instead based upon deterministic recurrence procedures in which the required random number is calculated from the immediately preceding value using a mathematical formula. This implies that the sequence of random numbers generated is dependent on the starting value, and the sequence will also repeat itself once the initial value re-occurs. Strictly speaking, the sequence of numbers generated is therefore only pseudo-random in nature, but provided they are uniformly distributed and statistically independent, this will be of no practical importance.

The most commonly used method of generating pseudo random numbers is normally referred to as the mixed congruential generator. It can be expressed in terms of the congruence relationship:

$$x_{i+1} = (ax_i + c)(\text{mod } m) \text{ for } i = 1,2, \ldots\ldots n,$$

where a, c and m are non-negative integers.
A uniformly distributed number between 0 and 1 is subsequently calculated from:

$$u_i = \frac{x_i}{m}$$

If c = 0, the congruence relationship reduces to:

$$x_{i+1} = ax_i(\text{mod } m)$$

This is the multiplicative congruence generator, and is the method of random number generation used in the present study. The multiplicative generator will have a shorter periodic sequence than the mixed generator for the same value of m, but is more efficient to compute. Provided m is chosen sufficiently large, the starting value x_i is relatively prime to m, and a meets certain congruence conditions, the period will be large enough for most calculations and certainly adequate for the present study. For maximum efficiency and as a matter of convenience, it was decided to use an available NAG Library Routine, [Reference (77)], for this particular part of the calculation. The congruence relationship in the NAG Routine takes the form:

$$x_{i+1} = 13^{13} \times x_i \pmod{2^{59}}$$

and $$u_i = x_i / 2^{59}$$

The next step is to decide on a method of random variate generation. The two most common methods in use are the inverse transform method and the acceptance-rejection method. Figure (4.2) in an earlier part of this Chapter has already provided an illustration of the inverse transform method in conjunction with a general description of the Monte Carlo method. This method is described mathematically as follows:

If x is a random variable with cumulative proability distribution function F(x), then since F(x) is a non-decreasing function the inverse function $F^{-1}(y)$ can be defined for any value between 0 and 1 as the smallest x satisfying F (x)>y. The proof for the hypothesis that if u is a uniformly distributed number between 0 and 1, then $x = F^{-1}(u)$ can be found in most textbooks on the subject of stochastic sampling and the Monte Carlo method and can be summarised in a single line as:

$$\text{Probability } p[x \leq X] = p[F^{-1}(u) \leq X] = p[u \leq F(X)] = F(X)$$

A basic requirement for this method to work is that the inverse function $F^{-1}(y)$ can be found analytically. If this is not possible, then a different method like the the acceptance-rejection method will be a more accurate and efficient choice. This method completely avoids the use of the cumulative distribution function, and consists instead of choosing an appropriate secondary distribution from which random variates can easily be generated. Sampling then takes place from this alternative distribution, and every random variate generated is subjected to a test to determine whether it is acceptable for use as a sample from the original distribution. The efficiency of this method is greatest when the shape of the secondary distribution is similar to the original distribution from which samples are required.

The present problem is to provide a sampling method for a distribution consisting of 2 truncated halves of normal distributions, as well as for a distribution generated from a scaled tail of a normal distribution, and which is continuous at one end and non-continuous at the other. For the first type, a suitable sampling procedure was obtained by using a standard NAG routine for the generation of random variates from the standard normal distribution, combined with a selection routine to ensure a correct sampling sequence between the two truncated halves. The NAG routine is based upon a special form of the acceptance-rejection method introduced by Brent in Reference (78). Selection of sampling sequence has been based upon the fundamental criterion that the percentage number of samples drawn from one truncated half must equal the percentage contribution which the area under this truncated half contributes to the area under the total probability distribution function. The total area under the probability distribution function equals unity with a contribution $\frac{\sigma_1}{\sigma_1 + \sigma_2}$ from the lower truncated half and $\frac{\sigma_2}{\sigma_1 + \sigma_2}$ from the upper truncated half. Where σ_1 is the standard deviation of the normal distribution from which the lower truncated half is taken, and σ_2 is the standard deviation of the normal distribution from which the upper truncated half is taken. For every individual sampling a uniform random number $u(0,1)$ is generated using the above described routine. If this number is less than or equal to $\frac{\sigma_1}{\sigma_1 + \sigma_2}$ then sampling takes place from the lower truncated half, otherwise from the upper truncated half. The steps of the routine are illustrated in the flow diagram to the procedure "SAMPLE" in Figure (4.18). Unfortunately, the same process of sampling could not be successfully employed for the family of extreme skewed distributions, principally because only samples within the tail would be valid, and a substantial number of the samples generated from the NAG routine would have to be rejected making the overall efficiency low. Instead a new sampling method was developed on the basis of the inverse transformation principle using a numerical approximation to the inverse function presented by Hastings in Reference (79). If the cumulative distribution function takes the form:

$$F\ (x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} e^{-\frac{1}{2}z^2} dz$$

then the inverse function defined for any value between 0 and 1 can be expressed as:

$$x = F^{-1}(y) \doteq v - \sum_{i=0}^{2} a_i (v)^i / [\sum_{i=1}^{3} b_i (v)^i + 1]$$

where $v = \sqrt{\ln(1/y\ )}$ with $0 < p \leqslant 0.5$

$a_0 = 2.515517$ $b_1 = 1.432788$

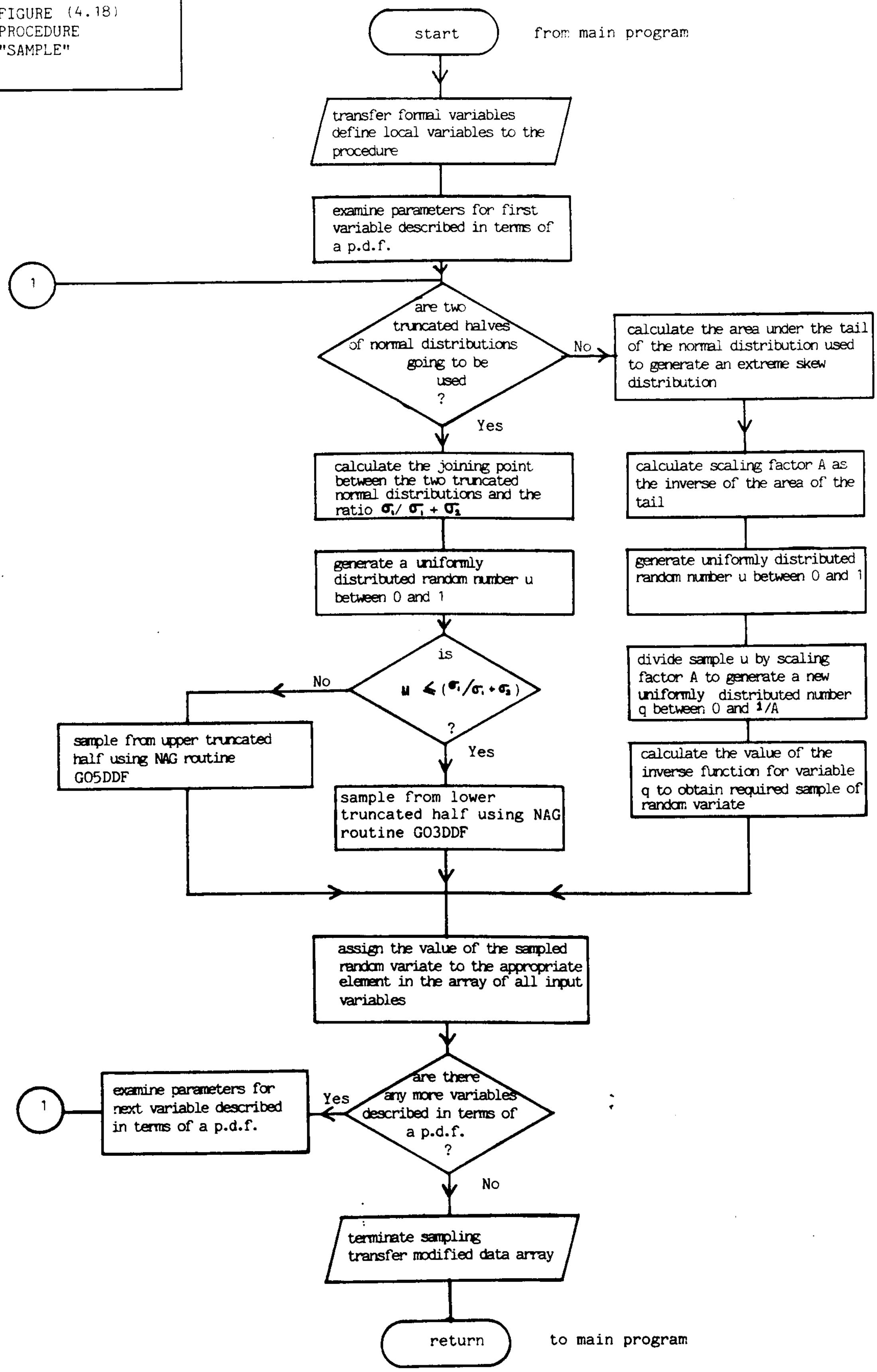
$a_1 = 0.802853$ $b_2 = 0.189269$

$a_2 = 0.010328$ $b_3 = 0.001308$

and with maximum error = 0.00045

Sampling takes place by first generating a uniformly distributed random number between 0 and 1. Instead of introducing a scaling factor to the inverse function and re-defining the interval over which this function is defined, each uniformly distributed random variate is divided by the

FIGURE (4.18)
PROCEDURE
"SAMPLE"



scaling factor A, so that effectively sampling of uniformly distributed random numbers takes place over the interval between 0 and 1/A. The required random variate is thus calculated directly using the above numerical approximation to the inverse function. Transformation to the appropriate set of scales is carried out using the standard transformation $x=\mu+z\sigma$ for a positively skewed distrbution and $x=\mu-z\sigma$ for a negatively skewed distribution, where μ and σ are the mean and standard deviation of the normal distribution from which the required tail has been obtained. The steps in the routine are illustrated in the flow diagram to the standard sampling procedure "SAMPLE" in Figure (4.18).

4.4.3 REQUIRED MODIFICATIONS TO PROCEDURES FROM THE DETERMINISTIC MODEL FOR THE PURPOSE OF ACCOMMODATING STOCHASTIC VARIABLES

Stochastic simulation can in simple terms be described as a statistical sampling experiment with the model and therefore involves all the problems normally encountered in the design of statistical experiments. In particular, it is important to ensure that sampling takes place at the correct point in time, and that correlation between variables is properly accounted for. A detailed analysis was made of each individual variable in the model with a view to identification of possible sources of correlation. This analysis immediately pointed out inflation as a principal and complex source of correlation with respect to a number of other economic variables. If the rate of inflation is low, say 1 to 3% per annum, then the effects of correlation will not be significant and can for most purposes be ignored. With higher rates of inflation, say 5 to 6% or above, a correct method for the treatment of inflation becomes of major importance, and guidelines should be established. When future items of income and expenditure are expressed in money terms, the uncertainty of inflation is introduced into the calculation of each item of cash flow. The degree of correlation may, however, vary from one variable to another with complete correlation if the uncertainties are due entirely to inflation, and only partial correlation if uncertainties are introduced from other sources as well. Zero correlation will not occur since all economic variables are, in one way or another, affected by inflation. This results in the almost impossible task of estimating the degree of correlation between uncertainties in the various cash flows. A cross correlation matrix could be introduced, but the problems associated with estimating the degree of correlation for each individual item still remains. The only practical way of getting around this problem is to perform all calculations in real terms, thereby effectively eliminat ing the inflation element from the analysis. This method works very well, provided there are no substantial fixed cash flow items at future points in time, which would have to be inflated to present value terms prior to inclusion in the analysis. The provision also has to be made that interest rates and tax rates can be estimated relative to the rate of inflation. The present model is well suited to these requirements, and all subsequent probabilistic cash flow simulations will be performed in real terms.

Having taken the inflation element out of the calculations, all the remaining economic variables are assumed to be independent with zero cross correlation. Fundamental technical and operational variables are assumed constant for each vessel type, or case study, and the problem of estimating correlations is not relevant. The remaining sources of correlations to be examined are hull roughness and maintenance variables. In Chapter 1 a partial correlation has already been established between the average hull roughness at indocking and the change in AHR during drydocking resulting from touch-up and re-application of antifouling paint. The relationship was expressed as:

Change in AHR = −0.094 x (indocking AHR) + 37 + E (Units=μm)

Sampling of the random variate will in this case take place from the distribution of the error term E, and the change in AHR can subsequently be calculated from the above formula. The point in time at which sampling takes place for this variate is of some importance. In the analysis of roughness data in Chapter 1, the rate of roughness increase in service was estimated from an approximately random sample of hull roughness measurements on vessels of various ages. The average rate of increase in AHR in service therefore represents an average value over a number of years, and sampling from the probability distribution function of this variable should take place once only for every simulation. The rate of change of roughness in drydock has been obtained from samples taken at individual drydockings, and for the statistical sampling to be correct a new random variate should be generated at every drydocking during the simulation. Some degree of correlation will also exist between the average hull roughness before and after a complete reblast as demonstrated by Byrne in Reference (13), but in the absence of reliable data to quantify this correlation it has been ignored, and the two variables are assumed to be completely independent. Further sources of correlation are discussed in the later case studies on uncertainty.

The generation of random variates prior to every simulation has required no modifications to existing calculation procedures from the deterministic techno-economic model. Sampling and compilation of a data-file takes place outside the procedures, and every simulation is simply another deterministic calculation with a modified data-file. Only the variables relating to the change in AHR during drydocking have necessitated some major changes to existing procedures as a result of the requirement for random variates to be generated at the point in time of every drydocking. The modifications have taken the form of introducing an internal sampling procedure to the 4 procedures "PO1INCR", "PO2INCR", "SP1LOSS" and "SP2LOSS", as well as extending the formal parameter list to allow the distribution parameters of the random variable to be transferred to each of these procedures. Based on the assumption that the random variate to be sampled in connection with the calculation of the change in AHR during drydocking is symmetrical or moderately skewed, a special sampling routine, "RSAMP", was developed. This procedure is similar to the part of the general sampling procedure "SAMPLE", handling the probability distribution functions generated from two truncated halves of normal distributions. Modifications also had to be made to the parameter lists of the procedures, "PENALTYCHOICE", "OPERMODE" and "FUELOPT" to enable "RSAMP" to be called within "PO1INCR", "PO2INCR", "SP1LOSS" and "SP2LOSS". The following table presents the names of modified procedures for use in the probabilistic calculations, with the names of corresponding procedures from the deterministic calculations, to which reference should be made for complete flow diagrams and descriptions of programming logic.

Name of Modified Procedure for use in Monte Carlo Analysis	Name of corresponding Procedure from the Deterministic Model
P01MONTE	P01INCR
P02MONTE	P02INCR
SP1MONTE	SP1LOSS
SP2MONTE	SP2LOSS
FOPTMONTE	FUELOPT
PCHOMONTE	PENALTYCHOICE
OPMOMONTE	OPERMODE

4.4.4 THE DEVELOPMENT OF A MAIN PROGRAMME WITH SUPPORT ROUTINES FOR STOCHASTIC SIMULATION AND DATA ANALYSIS

The process of stochastic simulation, which has been explained as a statistical sampling experiment with the model, is effectively a repeated series of deterministic calculations, with new values of input variables obtained for every calculation using a method of statistical sampling. Results from each individual calculation are stored for subsequent statistical analysis upon completion of the required number of simulations.

A new procedure, "MAINCALC", was designed to handle the repeated series of deterministic calculations. The various steps in this procedure are illustrated in the form of a new flow diagram in Figure (4.19). Essentially, "MAINCALC" is a simplified version of the main program for the deterministic techno-economic analysis, "ECOMAIN", where the majority of options have been removed, and the procedure has been tailormade for the particular task of comparing two specified maintenance strategies as efficiently as possible.

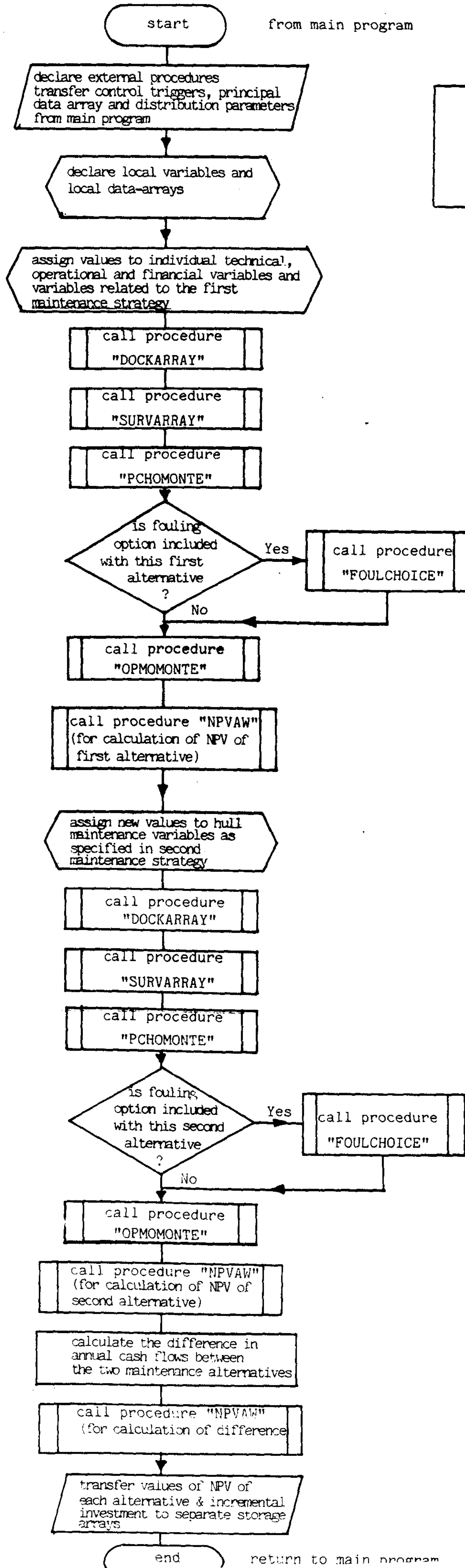


FIGURE (4.19)
PROCEDURE
"MAINCALC"

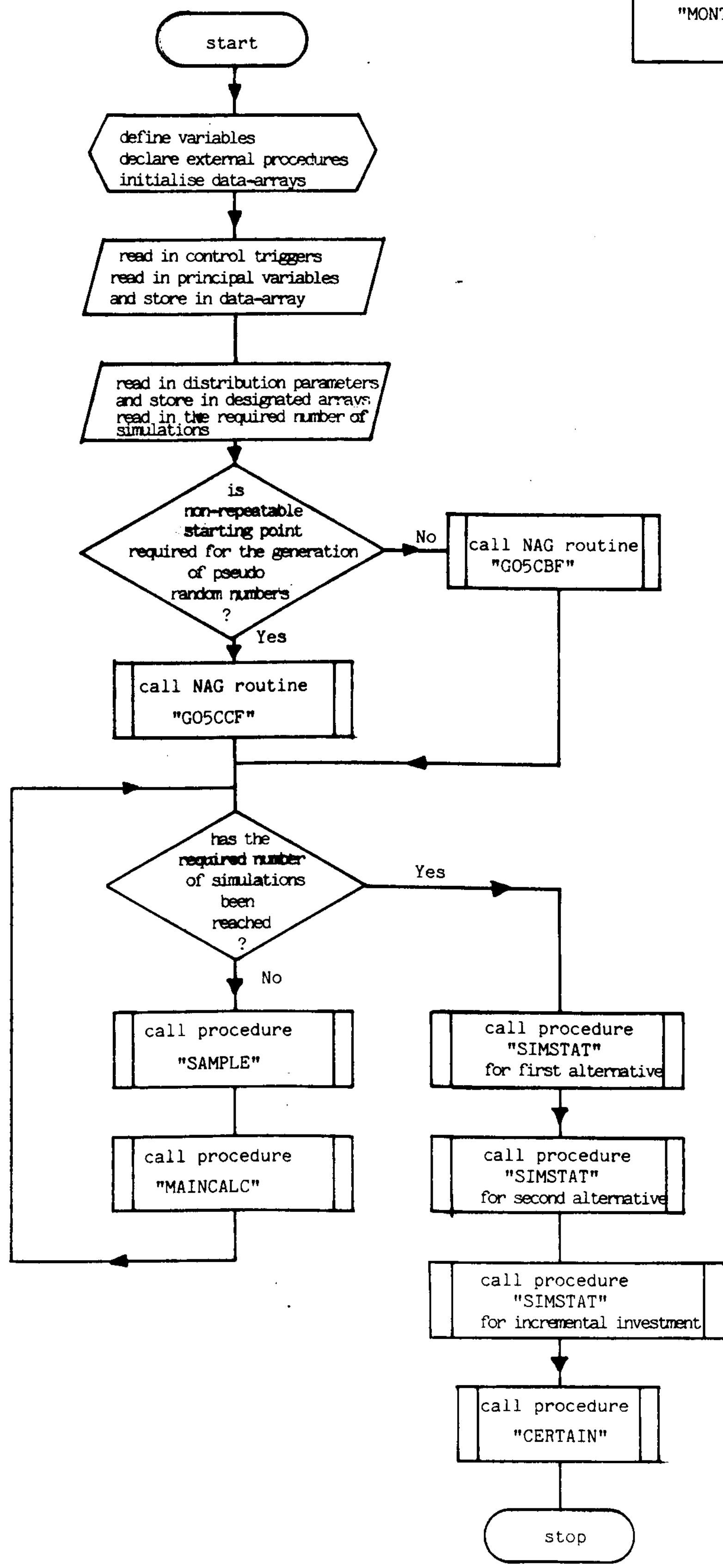
Two further procedures have been added for data analysis, "SIMSTAT" and "CERTAIN". "SIMSTAT" simply sorts the results into groups for presentation as a discrete frequency distribution and calculates the basic parameters mean value, standard deviation, skewness and kurtosis, using standard methods. "CERTAIN" is an optional routine for calculating a single number representation of the results using a logarithmic utility function of the form:

$$\underline{U(x) = A + B \ln (x + C)}$$

The principles behind the use of a general logarithmic approximation to the utility function have already been introduced earlier in this Chapter and require no further explanations here. This function is defined for $x > -C$ where C is defined as the "negative of the minimum acceptable return on the investment". In the event of one or more values of x being less than $-C$, the procedure is simply terminated, and an error message produced stating that the Certainty Equivalent can not be calculated.

The final part to be considered is the main program itself. Essentially, this consists of commands for reading in the required data, followed by calls of the various routines already described. A flow diagram is provided in Figure (4.20). Data values for all principal variables are read directly into a single one dimensional array, and each variable is identified by the element number it occupies in this array. The model has been built around the initial criterion that any of the principal variables can be described as stochastic variables in terms of a probabilistic distribution function. For the purpose of the present study this is an unnecessary requirement, since only a limited number of

FIGURE (4.20)
MAIN PROGRAM
"MONTE"



stochastic variables will be considered. In the wider sense, this facility greatly extends the usefulness of the model as a general operational model which can be used to study other related stochastic problems in ship operation. Distribution parameters for each stochastic variable are held in a separate array, and are identified by the element number the variable occupies in the data array. The sampling routine, "SAMPLE", is called prior to every simulation for the generation of the required random variates and assigning values to the appropriate elements in the data array. Only after a completely new data array has been generated are the actual individual variables assigned values. The required number of simulations is specified as a parameter in the data file. The value given to this parameter depends upon the required accuracy of the calculations. A standard procedure for estimating the number of simulations required to achieve a specified degree of accuracy in the final results can be derived as follows:

Assume that the expected net present value of the investment under consideration is an unknown quantity μ. Consider X as a random variable with the same expected value $E(x) = \mu$ and corresponding standard deviation σ and $X_1, X_2, \ldots X_N$ are N independent variables with distributions identical to X then, according to the Central Limit Theorem, the distribution of the sum $S_N = X_1 + X_2 + \ldots X_N$ will be approximately normal with mean value $N{*}\mu$ and standard deviation $\sqrt{N}\sigma$ provided N is sufficiently large. From tables of the standard normal distribution we can express the probability:

$$P\left\{ N\mu - 1.96\sigma\sqrt{N} < S_N < N\mu + 1.96\sigma\sqrt{N} \right\} \approx 0.95$$

or

$$P\left\{ \left| \frac{1}{N} \sum_{i=1}^{N} (X_j - \mu) \right| < \frac{1.96}{\sqrt{N}} \right\} \approx 0.95$$

This relationship holds equally well if instead N samples are taken from the distribution of the single variable X since $X_1, X_2, \ldots . X_N$ and X have identical distributions. Based on the assumption that the distribution of the final result is approximately normal, a more general relationship between the expected error and the number of simulations can therefore be formulated. If the mean value is required to be within the error bounds $\pm e$ of the true value with probability (1 - p), then the required number of simulations is $N = \left(\frac{z\sigma}{e}\right)$ where z is the value of the ordinate on the standard normal distribution, giving an upper tail probability of p/2. Expressing the error e in terms of the standard deviation σ gives:

1) Number of simulations required for the mean value to be within $\sigma/10$ of the true value with probability 0.95 is 384.

2) Number of simulations required for the mean value to be within $\sigma/20$ of the true value with probability 0.95 is 1537

Upon completion of the required or specified number of simulations the procedures "SIMSTAT" and "CERTAIN" are called for the calculation of output statistics. Results from every simulation in net present value terms for each alternative and the incremental investment are also output separately to files for further statistical analysis, if required.

4.5 A SURVEY OF DECISION MAKERS' ATTITUDES TOWARDS UNCERTAINTY IN INVESTMENT DECISIONS

The use of a generalised logarithmic utility function to represent a decision maker's attitude towards uncertainty in investment decisions has been discussed in the present chapter. Some practical support for the use of this model may be found in Reference (72). Since no information is available for the shipping industry at the particular investment levels associated with improved hull maintenance, it was decided to conduct a special survey using a standard questionnaire. A specimen of this questionnaire is provided at the end of the present section.

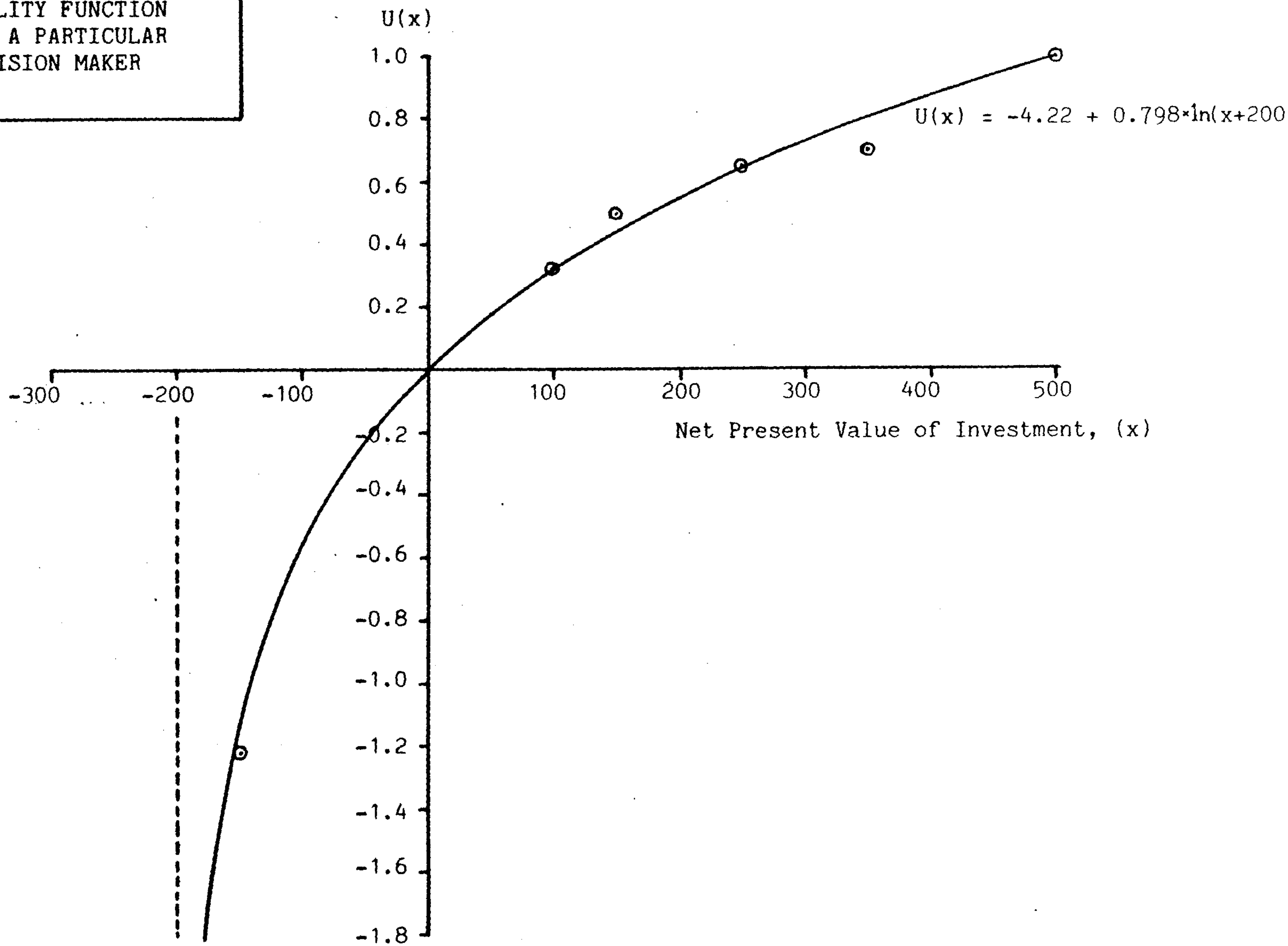
The questionnaire was distributed to six different persons familiar with investment decisions at higher levels of management in shipowning companies. Unfortunately, only one completed form was received within the required time limit. This reply was from an experienced decision maker familiar with taking between one and two investment decisions annually at the \$10 million level, and between ten and fifteen decisions at the \$250,000 level. The results have been plotted in Figure (4.21) and a best line fitted in accordance with the general utility model.

$$\underline{U(x) = A + B\ \ln(x + C)}$$

Although the attitudes displayed by the individual points are slightly contradictory, the total result tends to give support to the logarithmic utility model. The characteristics of one particular decision maker is clearly an insufficient basis on which to draw general conclusions, and the results shown in Figure (4.21) are therefore only presented as support for the proposed generalised form of the utility function.

The principal reasons for the limited response to the survey are belived to be the lack of available time at top management level for activities unrelated to the running of the company. Secondly it is believed that the majority of decision makers in higher levels of management are unfamiliar with the concepts of utility theory, and

FIGURE (4.21)
UTILITY FUNCTION
FOR A PARTICULAR
DECISION MAKER



QUESTIONNAIRE FOR ESTABLISHING A DECISION - MAKER'S ATTITUDE TOWARDS RISK TAKING IN CAPITAL INVESTMENTS

The objective of the following set of questions is to establish a utility function for small to medium size investments in the marine industry. (For example investments in materials or equipment which will improve the fuel efficiency of ships in service).

As a decision maker you are given an investment problem with 2 possible alternative outcomes:

Alternative A is a probabilistic outcome.

Alternative B is a certain outcome.

Investment Description:

Capital investment in year 0 = $250,000 which is repaid uniformly over a 5 year investment life to give Net Present Values (NPV) as indicated (before tax).

Discount Factor = 15% in money terms (5% in real terms assuming inflation at 10%). The Internal Rate of Return is provided as additional information for the decision-maker.

Table I:

Faced with the gamble presented in Alternative A you are asked to specify the certain outcome under Alternative B which you would be willing to accept instead of gamble A.

Table II:

In this case the monetary values of the outcomes A and B are both given and you are asked to specify the probabilities under Alternative A which would make you indifferent between outcomes A and B.

	INDIFFERENCE TABLE I			
Question Number	ALTERNATIVE A			ALTERNATIVE B
	Probability	NPV	Internal Rate of Return	Certain NPV
1	0.5 (50%) 0.5 (50%)	$ 500,000 $ 0	86% 15%	
2	0.7 (70%) 0.3 (30%)	$ 500,000 $ 0	86% 15%	
3	0.5 (50%) 0.5 (50%)	$ 250,000 $ 0	56% 15%	
4	0.8 (80%) 0.2 (20%)	$ 500,000 $-150,000	86% Negative	

	INDIFFERENCE TABLE II			
Question Number	ALTERNATIVE A			ALTERNATIVE B
	Probability	NPV	Internal Rate of Return	Certain NPV
5		$ 500,000 $ 0	86% 15%	$ 250,000
6		$ 500,000 $-150,000	86% Negative	$ 0

Please also indicate the monetary level at which you are used to taking:

1 - 2 investment decisions per annum $

10-15 investment decisions per annum $

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MAY 1982

therefore also reluctant to answer this type of questions. In retrospect, a more satisfactory result could probably have been obtained by the use of personal interviews, preferably an initial interview followed by a second interview to eliminate contradictory replies. However, the problems associated with obtaining a sufficient amount of top management time for the purpose of conducting the interviews still remain the major difficulty.

4.6 AN INVESTIGATION INTO THE FUNDAMENTAL BEHAVIOUR OF THE PROPOSED ECONOMIC MODEL UNDER CONDITIONS OF UNCERTAINTY

Having developed a techno-economic model, with particular reference to conditions under uncertainty, the next step is to examine some principal characteristics of the model using different assumptions about the statistical properties of individual variables. The sensitivity analysis performed in Chapter 3 has provided valuable information about the relative importance of individual variables upon the final results using net present value as the economic criterion. From this analysis the principal variables affecting the difference in net present value terms between alternative hull maintenance strategies have also been identified.

(i) The principal variables are:

(1) Fuel price escalation or freight rate escalation

(2) Rate of roughness increase in service

(3) Roughness increase in drydock resulting from maintenance procedures

(4) Average hull roughness at outdocking after reblast and renewal of coating system

(5) Additional days required in drydock for reblast and renewal of coating system

(6) Hydrodynamic importance of hull roughness (i.e. the relationship between roughness and drag)

(ii) Additional variables having a minor effect upon the results:

(7) Paint system costs

(8) Charges for the hire of drydock

(9) Cost of reblast or alternative method for the removal of old coating systems

(iii) Additional variables of importance, but assumed constant for the purpose of the present case studies:

(10) Interval between drydockings

(11) Propulsion efficiency

(12) Specific fuel consumption

(13) Voyage distance (i.e. proportion of time spent at sea)

The fundamental difference between constant speed and constant power operation has already been discussed in Chapters 2 and 3. Combined with the results of the sensitivity analysis in Chapter 3 it may be concluded that fuel price escalation is important for vessels operated at constant speed. For vessels operated at constant power the prediction of future freight rates becomes the predominant variable, and the relative development in fuel price can effectively be ignored. This has the important consequence that for container and other liner type of vessels operated essentially at constant speed, and for which the amount of published data relating to freight rates is limited, this information is in fact unimportant for the purpose of evaluating alternative hull maintenance strategies. For oil tankers and carriers of dry bulk cargoes details of voyage and time charter rates are frequently published, and it is possible to estimate historical trends on the basis of which future predictions can be made.

As discussed earlier in the present Chapter, probabilistic cash flow simulations are best carried out in real terms to avoid problems of correlation between individual cost escalations and the discount rate used. This procedure has been followed throughout the present series of calculations and a discount rate of 7.5% in real terms has been used to give a close correspondence with the value of 17.5% in money terms used in the principal deterministic case studies of Chapter 3.

Since the purpose of the present section is to illustrate the fundamental behaviour of the probabilistic cash flow simulation model under conditions of uncertainty, only one vessel with a typical set of alternative maintenance strategies has been examined in detail.

The vessel chosen is Ship A with the following two hull maintenance alternatives:

<u>Alternative 1</u>: Same as Alternative 1 of Case Study 3.1 in Chapter 3, with roughness Scenario 3, but outdocking AHR after reblast and recoat is 150 μm instead of 125 μm.

<u>Alternative 2</u>: Same as alternative 2 of Case Study 2.1 in Chapter 3.

The behaviour of the model is first examined using uniform normal distributions to reflect the uncertainty in the principal variables listed above. The properties of the individual distributions have been based on the following assumptions about each variable:

(1) Fuel price escalation:

Mean value = 0 , with 0.05 probability of being greater than + 2.5% and 0.05 probability of being less than - 2.5%

(2) Rate of roughness increase in service: Conventional high performance system based upon the distributions of Figure 1.2 in Chapter 1, with mean value of 1.85 and standard deviation 1.71. For the self polishing type of system under roughness Scenario 3 of Case Study 3.1, the mean value for the roughness increase is half that of the average value for the well maintained conventional system. The standard deviation of the probability distribution is also halved from 1.71 to 0.855 in order to reflect the likelihood of less extreme values of roughness development for this type of paint system.

(3) Roughness increase in drydock due to maintenance procedures: For all paint systems the correlated relationship between average hull roughness at indocking and the change in roughness during drydocking from Chapter 1 and illustrated in Figure (1.3) is used.

(4) Average hull roughness at outdocking after reblast and renewal of coating system:

Mean value = 150 μm , with 0.05 probability of being greater than 200 μm and 0.05 probability of being less than 100 μm

(5) Additional days required in drydock for reblast and renewal of coating system:

Mean value = 5 days , with 0.05 probability of being greater than 7 days and 0.05 probability of being less than 3 days

(6) Hydrodynamic importance of hull roughness:

Mean value = 60% of prediction by ITTC correlation formula for hull roughness,
with 0.05 probability of being greater than 75%
and 0.05 probability of being less than 45%

Prior to the start of the simulations the chosen case study was evaluated deterministically using the mean values for the individual variables. For a 6 year calculation period the difference in net present value terms between Alternatives 1 and 2 was found to be $1,620,000.

The effects of uncertainty upon the distribution of the net present value was first examined separately for items (1), (4), (5) and (6) and in a combined form for items (2) and (3) with zero correlation between the rate of roughness increase for the two alternative strategies. The results are presented as discrete frequency distributions in Figures (4.22) to (4.26). All calculations are based upon 400 simulations to give a mean value within $\sigma/10$ of the true value, with probability 0.95, where σ is the standard deviation of the distribution of the final result, and the prior assumption is made that the distribution of the net present value is approximately uniformly normal. From the final distributions in Figures (4.21) to (4.26), the conclusion may be drawn that when the effects of uncertainty in single variables are examined, the final distribution of net present value is approximately normal if the distributions of the individual variables are also uniformly normal. The standard deviations of the distributions of the final results also verify the relative importance of individual variables as first established in the sensitivity analysis performed in Chapter 3.

Clearly, the uncertainty associated with the development of hull roughness with time is the most important single factor. The assumption has been made that zero correlation exists between the rates of roughness increase with time for the two alternative paint systems. This assumption may not be entirely true since the development of hull roughness with time

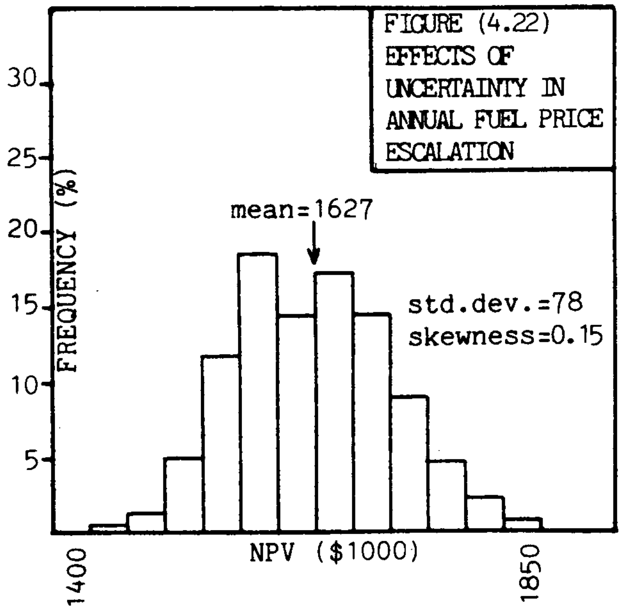


FIGURE (4.22) EFFECTS OF UNCERTAINTY IN ANNUAL FUEL PRICE ESCALATION

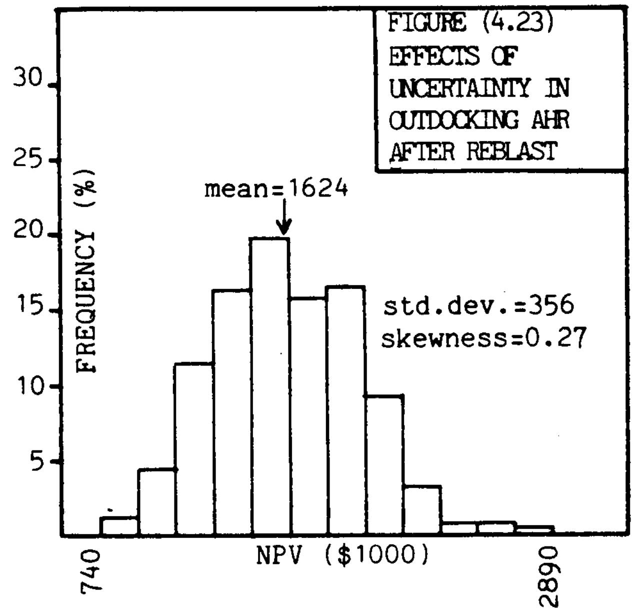


FIGURE (4.23) EFFECTS OF UNCERTAINTY IN OUTDOCKING AHR AFTER REBLAST

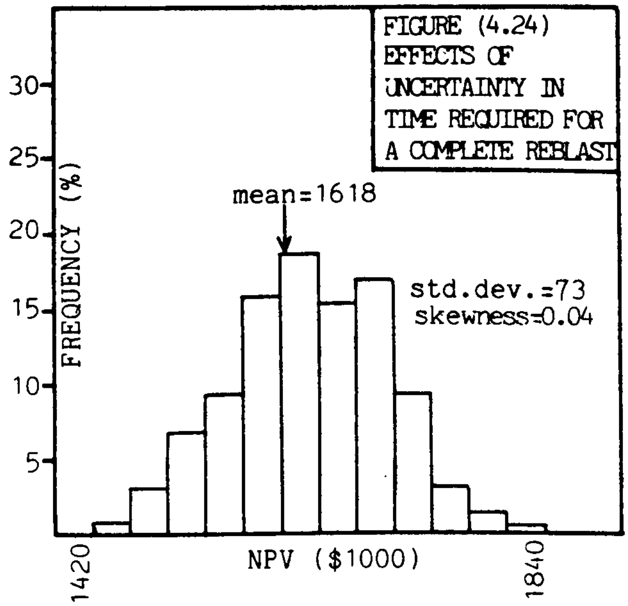


FIGURE (4.24) EFFECTS OF UNCERTAINTY IN TIME REQUIRED FOR A COMPLETE REBLAST

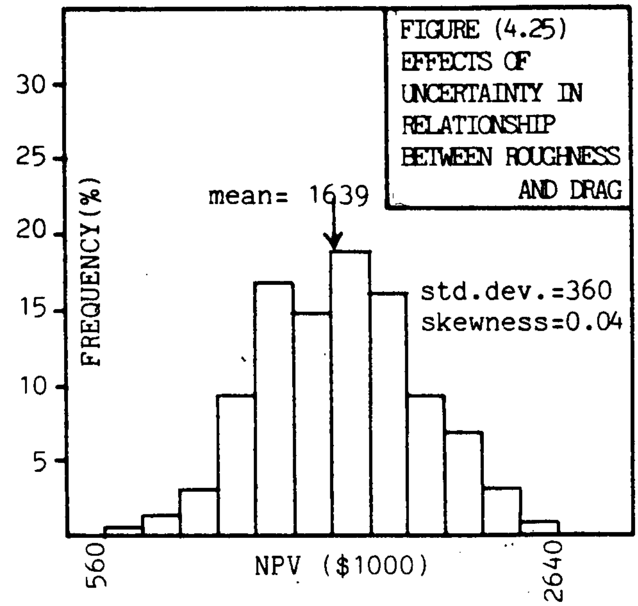


FIGURE (4.25) EFFECTS OF UNCERTAINTY IN RELATIONSHIP BETWEEN ROUGHNESS AND DRAG

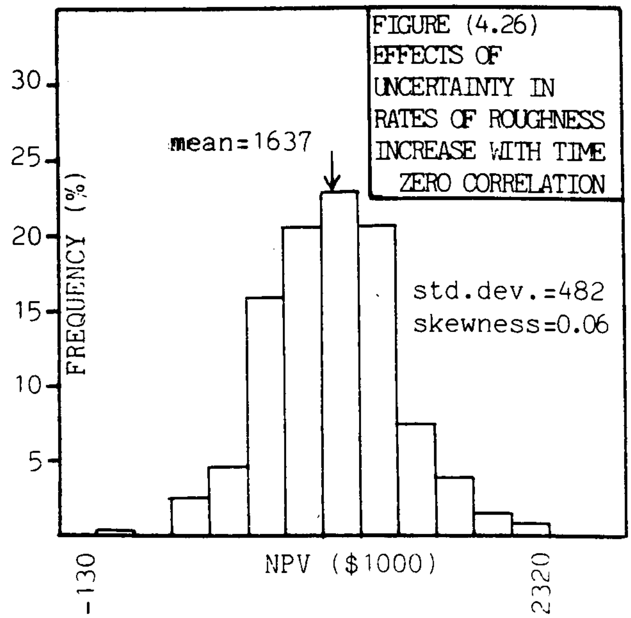


FIGURE (4.26) EFFECTS OF UNCERTAINTY IN RATES OF ROUGHNESS INCREASE WITH TIME ZERO CORRELATION

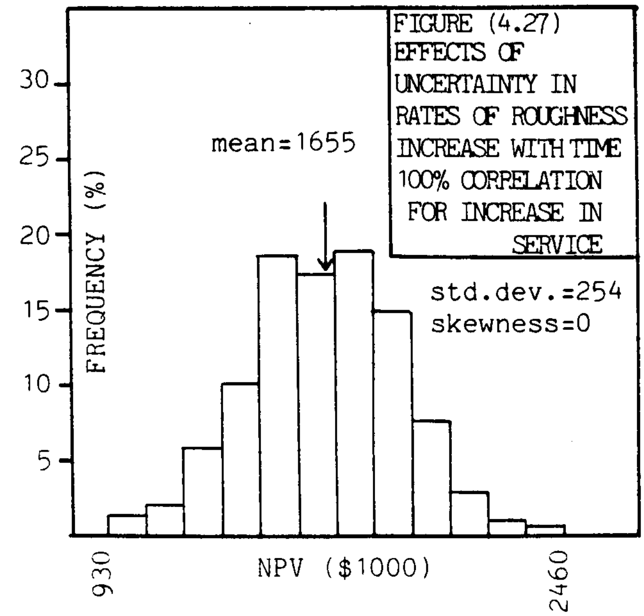
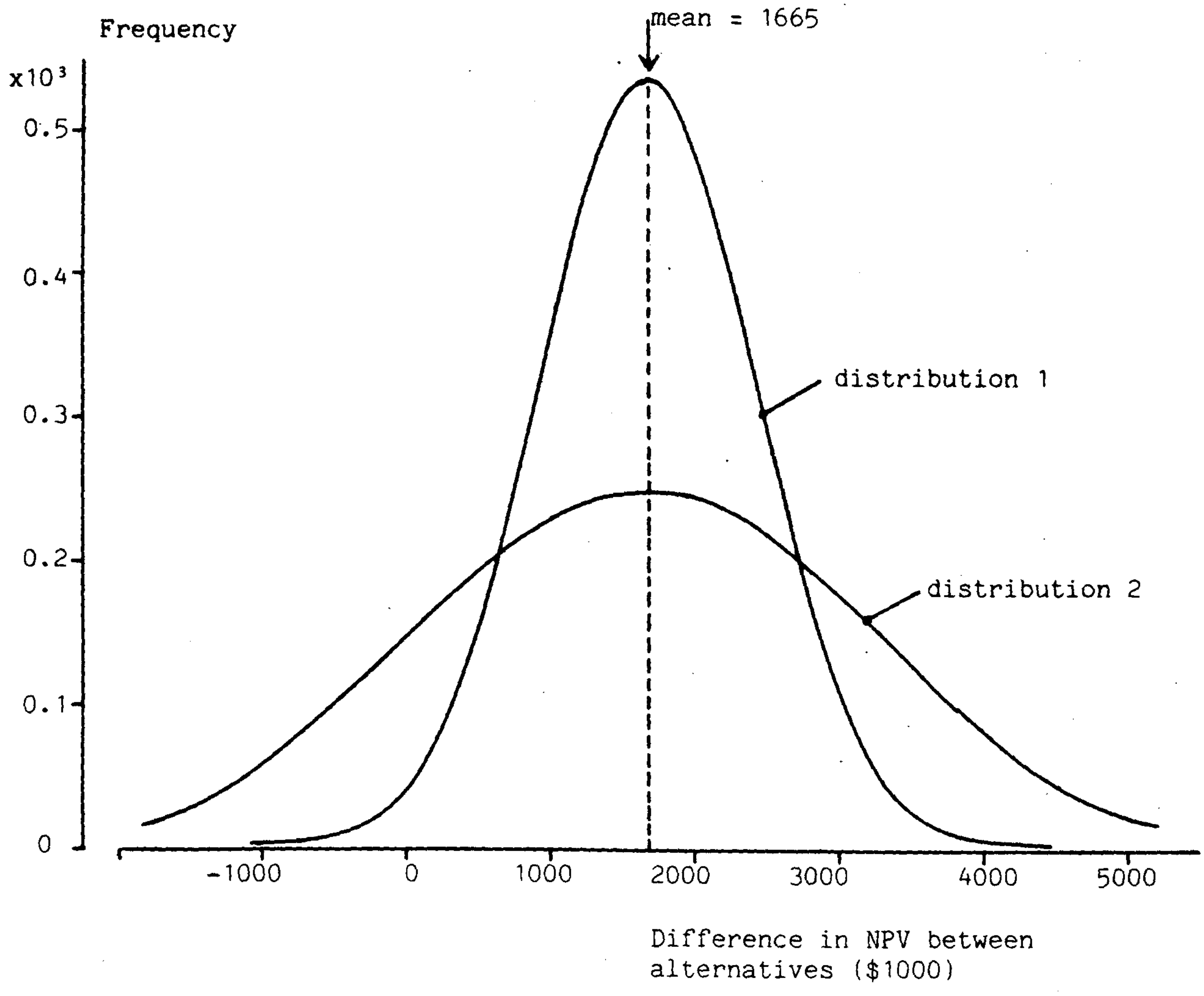


FIGURE (4.27) EFFECTS OF UNCERTAINTY IN RATES OF ROUGHNESS INCREASE WITH TIME 100% CORRELATION FOR INCREASE IN SERVICE in service is due to a number of reasons, some of which are independent of the paint system in use. The hypothesis of 100 % correlation between the rates of roughness increase in service for the two alternative systems was tested, and the resultant distribution is presented in Figure (4.27). As shown, this assumption has effectively halved the standard deviation of the final result. If also the random terms in the partially correlated expression for calculating the change in roughness during drydocking are partially correlated, this results in a further reduction in the standard deviation of the final distribution. In practice, some correlation would be expected, but this is probably closer to zero than 100 % . A 100 % correlation between corresponding roughness variables for both alternatives would, of course, result in the previously calculated deterministic result. In all subsequent calculations, the assumption of zero correlation between roughness variables in the two alternative maintenance systems is used, and the results therefore display the maximum range and standard deviation which can be expected.

A combined evaluation including uniform normal probability distributions for all principal variables listed as item (1) to (6) above resulted in the frequency distribution shown in Figure (4.29). The resultant distribution has a small positive skewness, but for most practical purposes can be assumed to be uniformly normal. It should be noted that the range and standard deviation is only slightly higher than the values obtained in Figure (4.26) when the effects of uncertainty in the development of roughness with time were examined separately. At this point it is also of interest to compare the results obtained in Figure (4.29) with the results of a deterministic analysis using 'high' and 'low' estimates. This is one of the most common methods used to include the effects of uncertainty in economic calculations. The ordinate corresponding to the start of the 5% lower tail of the frequency distribution in Figure (4.29) is $+440,000. In other words, there is a 95% chance that the return on the investment is greater than this figure. For the purpose of calculating the 'low' estimate using the deterministic analysis, the corresponding ordinates for the 5% 'low' tail of distributions for individual variables was used. The resultant 'low' estimate of the difference in net present value terms between hull maintenance alternatives 1 and 2 was found to be $-940,000. Consequently, the use of high and low estimates would result in an estimated distribution of the net present value represented by Distribution 2 in Figure (4.28), while the true distribution obtained using the method of probabilistic cash flow simulation is identical to Distribution 1 of the same figure. This case study has demonstrated one of the principal advantages of the simulation method compared with simpler methods of accounting for uncertainty in the principal variables. The reduction in the estimated standard deviation of the final result is significant and increases with the number of variables associated with uncertainty.

For completeness the combined evaluations, including probability distributions for all principal variables, and with zero correlation between roughness variables for the two maintenance alternatives, have been repeated for Ships B, C and D. These three vessels are assumed to be operated at constant power, and the annual escalation in fuel price is maintained fixed while the annual escalation in freight rate is represented in terms of a probability distribution function. This distribution was evaluated from an estimated mean value of zero, with a 0.05 probability of being greater than +5% and a 0.05 probability of being

FIGURE (4.28)
COMPARISON BETWEEN ESTIMATED DISTRIBUTION FROM "HIGH" AND "LOW" ESTIMATES AND DISTRIBUTION FROM COMPLETE SIMULATION



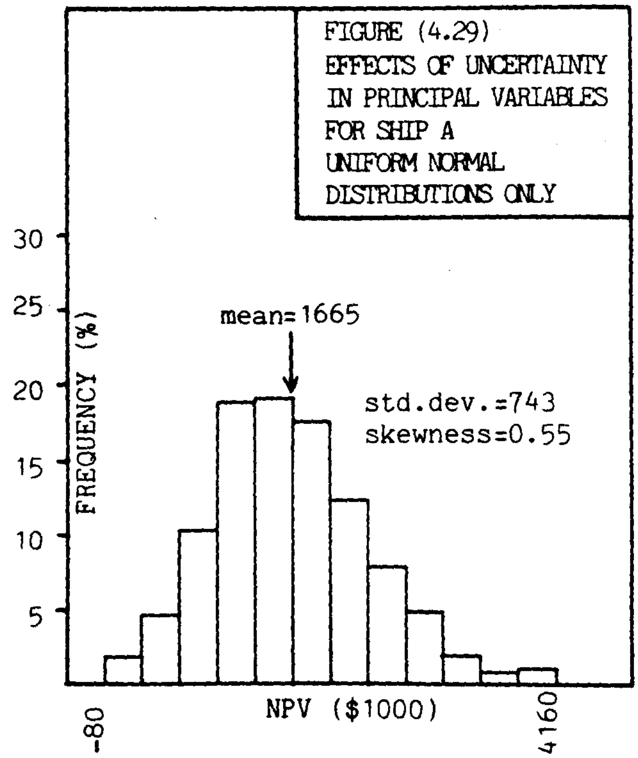


FIGURE (4.29)
EFFECTS OF UNCERTAINTY IN PRINCIPAL VARIABLES FOR SHIP A
UNIFORM NORMAL DISTRIBUTIONS ONLY

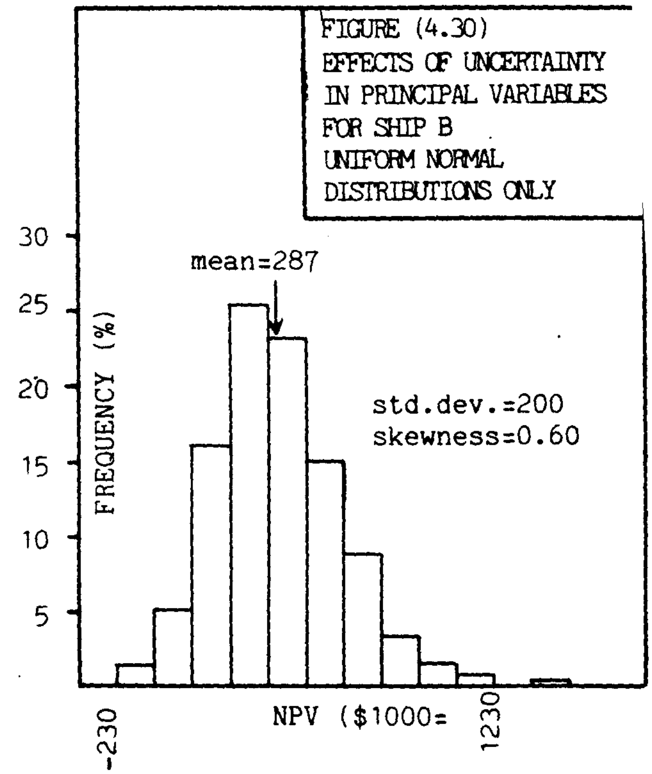


FIGURE (4.30)
EFFECTS OF UNCERTAINTY IN PRINCIPAL VARIABLES FOR SHIP B
UNIFORM NORMAL DISTRIBUTIONS ONLY

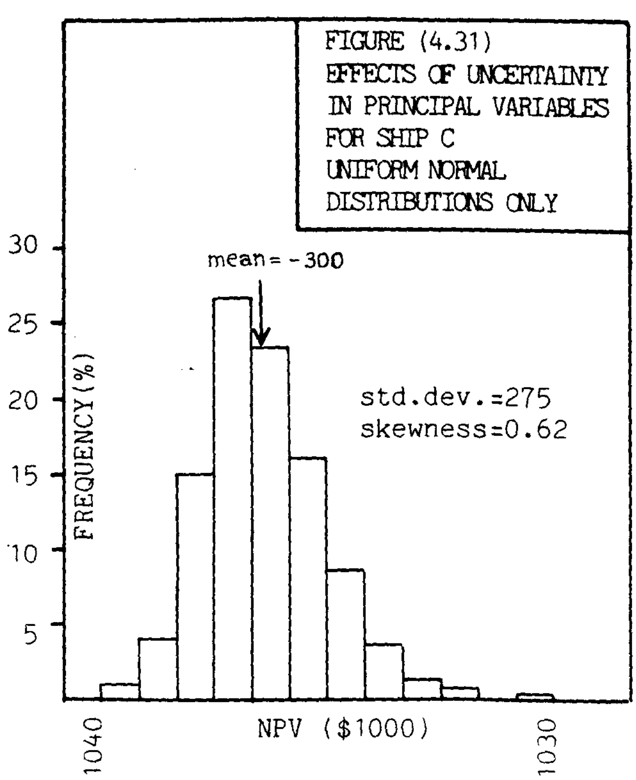


FIGURE (4.31)
EFFECTS OF UNCERTAINTY IN PRINCIPAL VARIABLES FOR SHIP C
UNIFORM NORMAL DISTRIBUTIONS ONLY

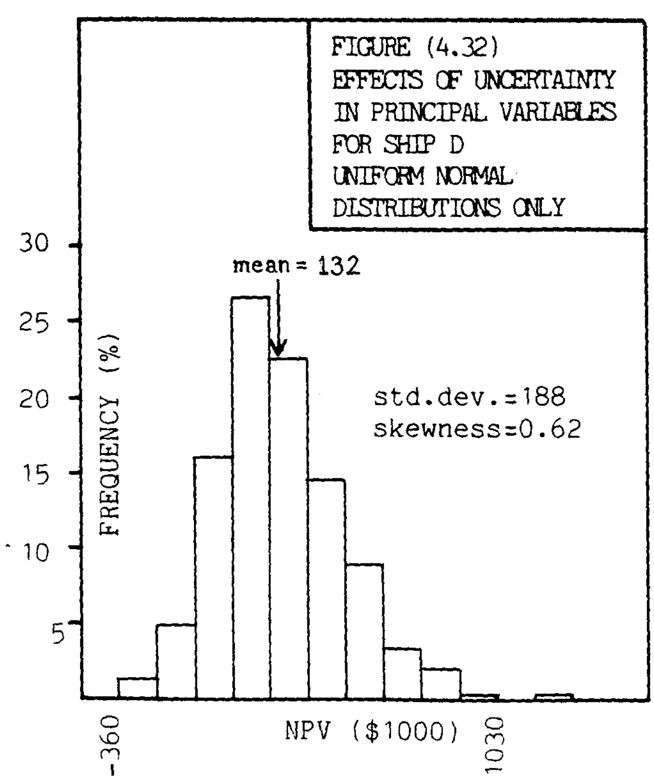


FIGURE (4.32)
EFFECTS OF UNCERTAINTY IN PRINCIPAL VARIABLES FOR SHIP D
UNIFORM NORMAL DISTRIBUTIONS ONLY

less than -5% . The same distribution is used for Ships B, C and D. The increased standard deviation in the distribution of freight rate compared with fuel price has been used to reflect the greater chance of fluctuations in freight rate normally experienced in practice. Frequency distributions of the difference in net present value between the two maintenance alternatives are presented in Figures (4.30), (4.31) and (4.32) for Ships B, C and D, respectively. Again, a small positive skewness is observed in all three resultant distributions. The origin of this positive skewness was found to be the one third power law between the average hull roughness and the increment to the frictional coefficient of resistance.

The second part of the present investigation has taken the form of examining the behaviour of the model under conditions where skewed distributions are used to represent some of the principal variables. Only three of the principal variables under consideration are expected to be associated with some degree of skewness. These are:

(1) Fuel price or freight rate escalation

(4) Average hull roughness at outdocking after reblast and renewal of coating system

(5) Additional days required in drydock for reblast and renewal of the coating system

Based upon medium term forecasts, fuel prices are more likely to increase than decrease. The same argument applies to freight rates in the presently depressed freight market, where freight rates are already at record low levels. The average hull roughness after reblast and renewal of the coating system is more likey to be higher than the expected value, and this same direction of skewness would also be expected for the additional days required in drydock for this additional hull maintenance.

Since the objective of the present section is to investigate the behaviour of the model, highly skewed distributions have been used based upon the following probability estimates:

<u>Annual Fuel Price Escalation:</u>

Mean value = 0 , with 0.05 probability of being greater than +5% and 0.05 probability of being less than -2.5%

<u>Annual Freight Rate Escalation:</u>

Mean value = 0 , with 0.05 probability of being greater than +10% and 0.05 probability of being less than -5%

<u>Outdocking AHR after Reblast and Recoat:</u>

Mean value = 150μm , with 0.05 probability of being greater than 250μm and 0.05 probability of being less than 100μm

<u>Additional Days in Drydock:</u>

Mean value = 5 days, with 0.05 probability of being greater than 9 days and 0.05 probability of being less than 3 days

The standard method developed earlier in the present Chapter has been used to evaluate the individual probability distributions corresponding to the above estimates, and the resulting distributions are shown in Figures (4.33) to (4.36). In practice, more moderately skewed distributions would be expected.

The same exercise performed earlier on the set of uniform normal distributions has been repeated for the highly skewed distributions using Ship A as an example. First the effects of uncertainty upon the distribution of the net present value was examined separately for the three distributions in Figures (4.33), (4.35) and (4.36). The results are presented in Figures (4.37) to (4.39), which all clearly demonstrate the expected result that the skewness in the initial distribution is transferred directly to the final distribution of the net present value.

Secondly, a combined evaluation was performed with highly skewed distributions for variables (1), (4) and (5), and uniform normal distributions for the remaining principal variables (2), (3) and (6). The resultant distribution for Ship A is shown in Figure (4.40). Despite the fact that three of the variables are represented by highly skewed distributions, the final distribution of the net present value is approximately uniformly normal. This follows principally as a result of one highly skewed distribution tending to neutralise the combined effect of the remaining two highly skewed distributions. The total number of variables represented in terms of probability distribution functions included in this example is too small to draw any clear conclusions, but the results tend to confirm the expected results on the basis of several theoretically formulated extensions to the Central Limit Theorem, most notably the Lindeberg Theorem, [References (80) and (81)], in which a set of relaxed conditions for the statistical properties of individual variables are presented.

Again, for completeness, the combined evaluations including probability distributions for all principal variables have been repeated for Ships B, C and D. The final frequency distributions of net present values are presented in Figures (4.41), (4.42) and (4.43). Some degree of skewness may be observed, especially for Ship C. This is because one particular highly skewed distribution is predominant, and the number of distributions

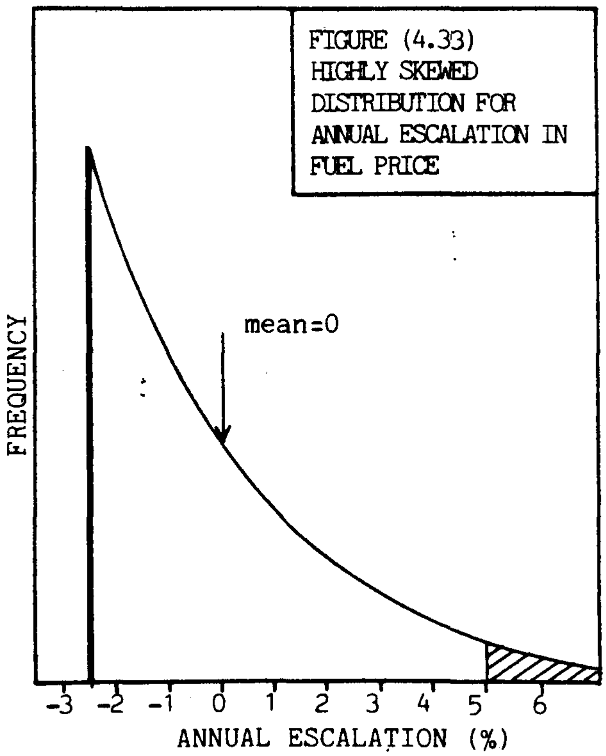


FIGURE (4.33) HIGHLY SKEWED DISTRIBUTION FOR ANNUAL ESCALATION IN FUEL PRICE

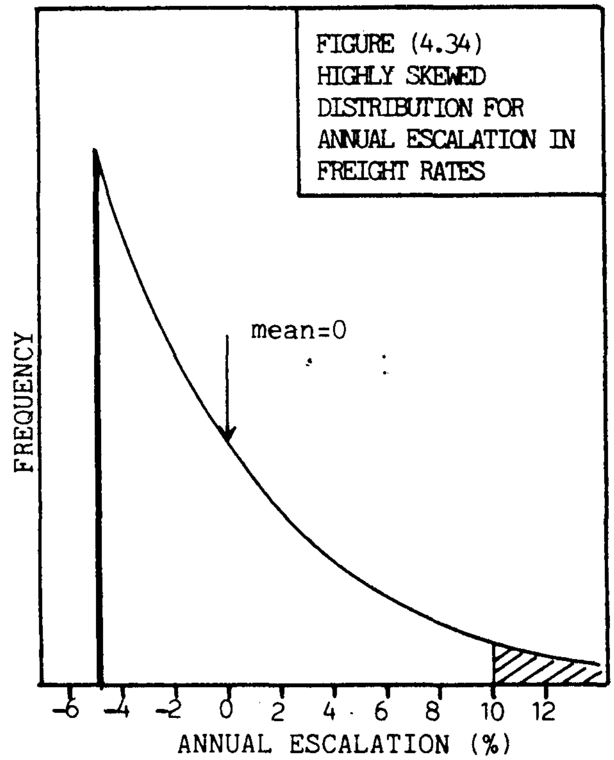


FIGURE (4.34) HIGHLY SKEWED DISTRIBUTION FOR ANNUAL ESCALATION IN FREIGHT RATES

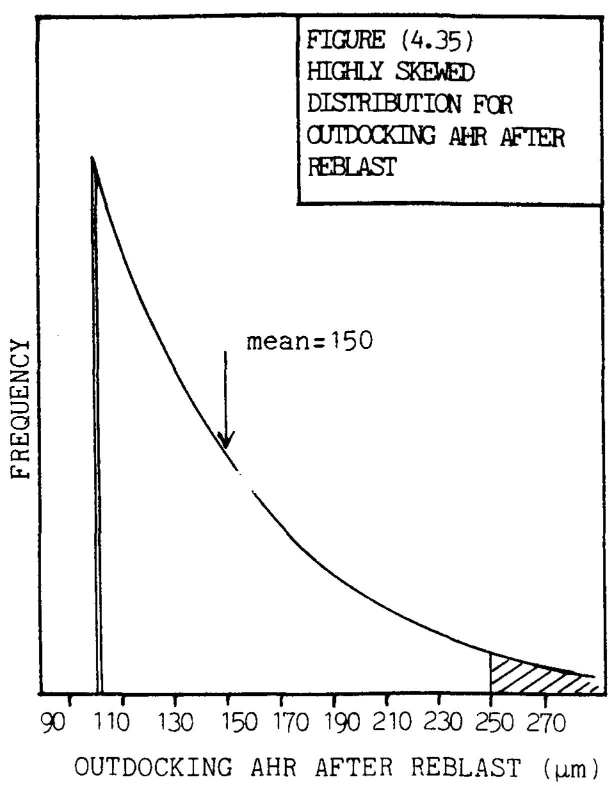


FIGURE (4.35) HIGHLY SKEWED DISTRIBUTION FOR OUTDOCKING AHR AFTER REBLAST

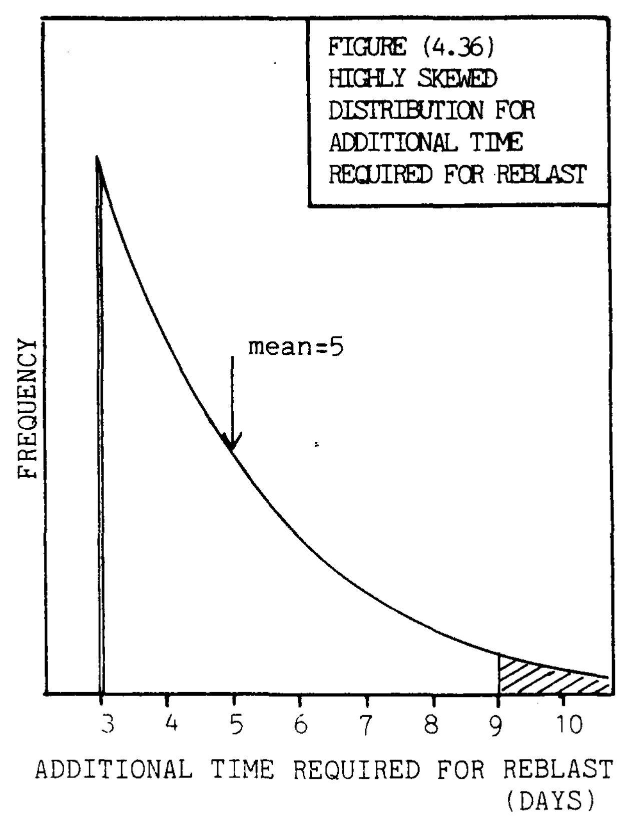


FIGURE (4.36) HIGHLY SKEWED DISTRIBUTION FOR ADDITIONAL TIME REQUIRED FOR REBLAST

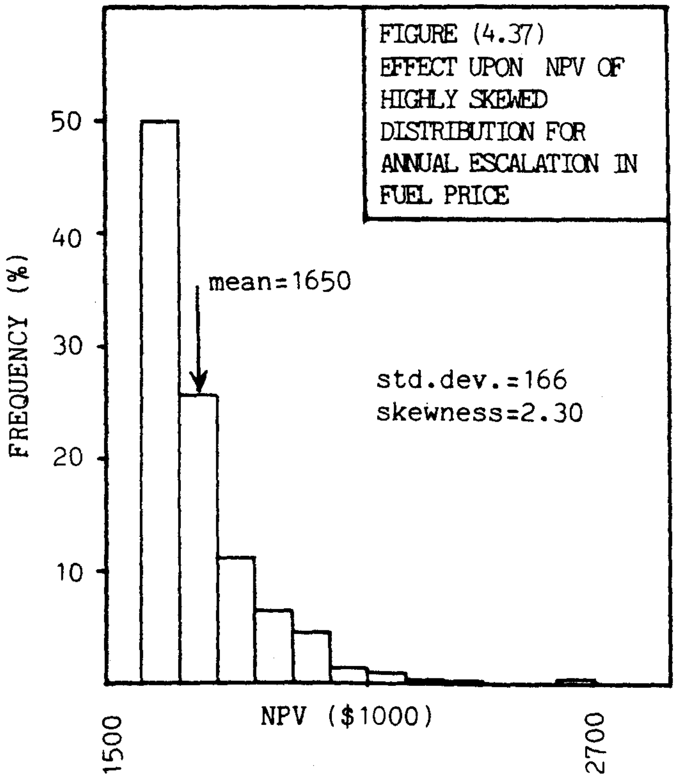


FIGURE (4.37)
EFFECT UPON NPV OF
HIGHLY SKEWED
DISTRIBUTION FOR
ANNUAL ESCALATION IN
FUEL PRICE
50
40
30
20
10
FREQUENCY (%)
mean=1650
std.dev.=166
skewness=2.30
1500
NPV ($1000)
2700

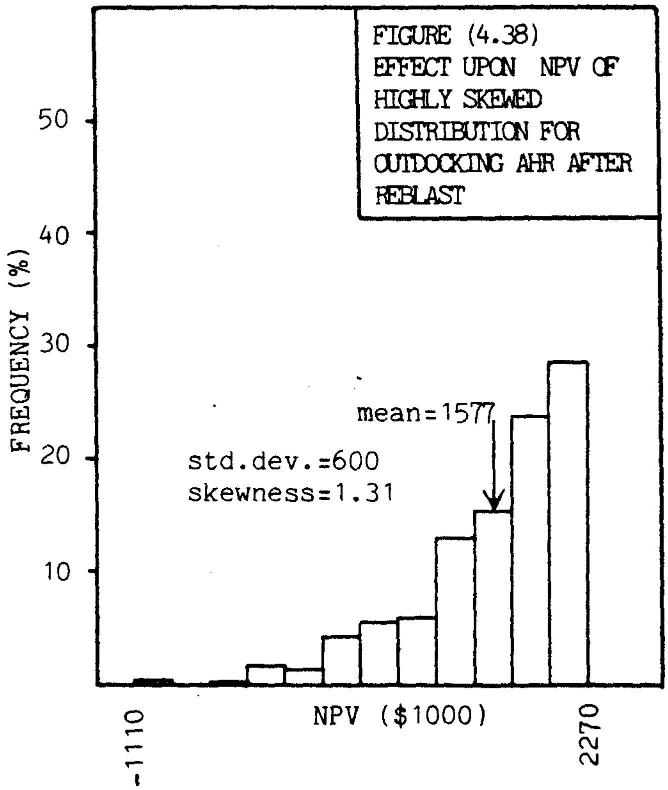


FIGURE (4.38)
EFFECT UPON NPV OF
HIGHLY SKEWED
DISTRIBUTION FOR
OUTDOCKING AHR AFTER
REBLAST
50
40
30
20
10
FREQUENCY (%)
mean=1577
std.dev.=600
skewness=1.31
-1110
NPV ($1000)
2270

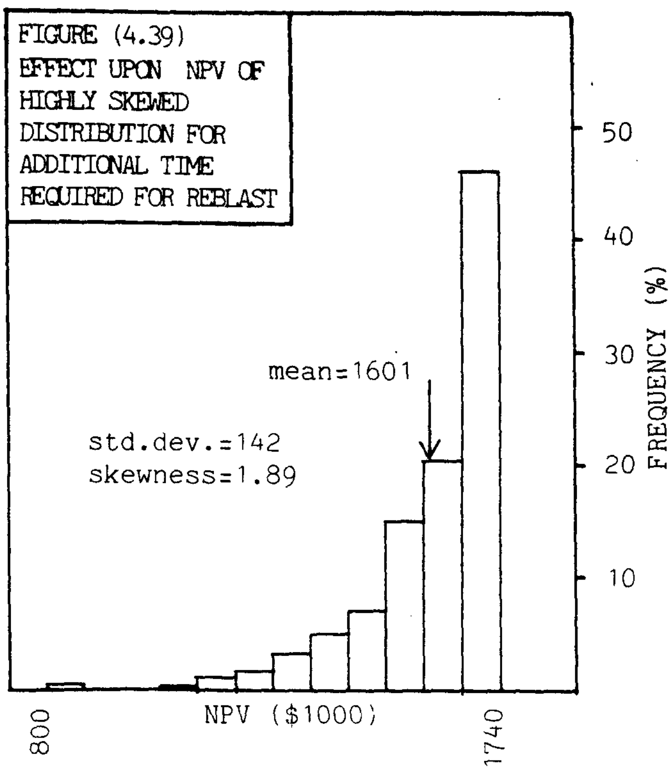


FIGURE (4.39)
EFFECT UPON NPV OF
HIGHLY SKEWED
DISTRIBUTION FOR
ADDITIONAL TIME
REQUIRED FOR REBLAST
50
40
30
20
10
FREQUENCY (%)
mean=1601
std.dev.=142
skewness=1.89
800
NPV ($1000)
1740

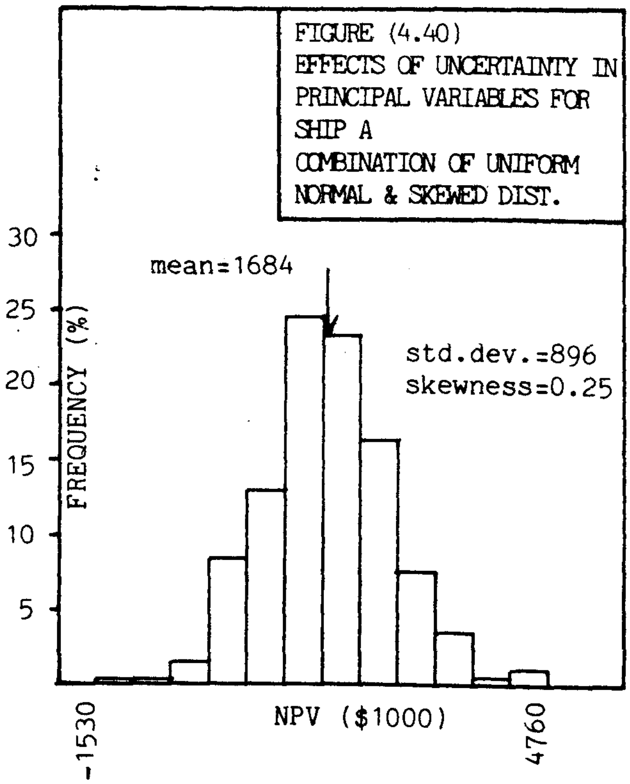


FIGURE (4.40)
EFFECTS OF UNCERTAINTY IN PRINCIPAL VARIABLES FOR SHIP A
COMBINATION OF UNIFORM NORMAL & SKEWED DIST.

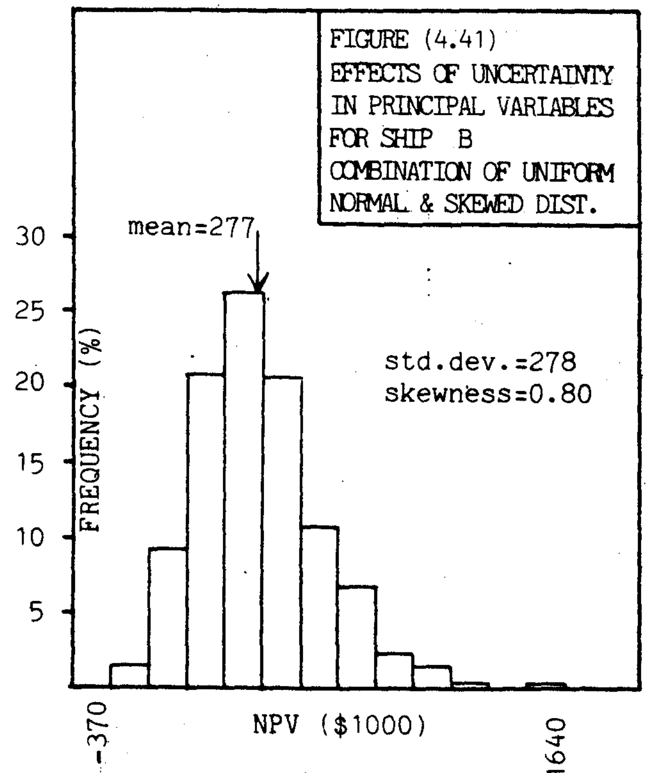


FIGURE (4.41)
EFFECTS OF UNCERTAINTY IN PRINCIPAL VARIABLES FOR SHIP B
COMBINATION OF UNIFORM NORMAL & SKEWED DIST.

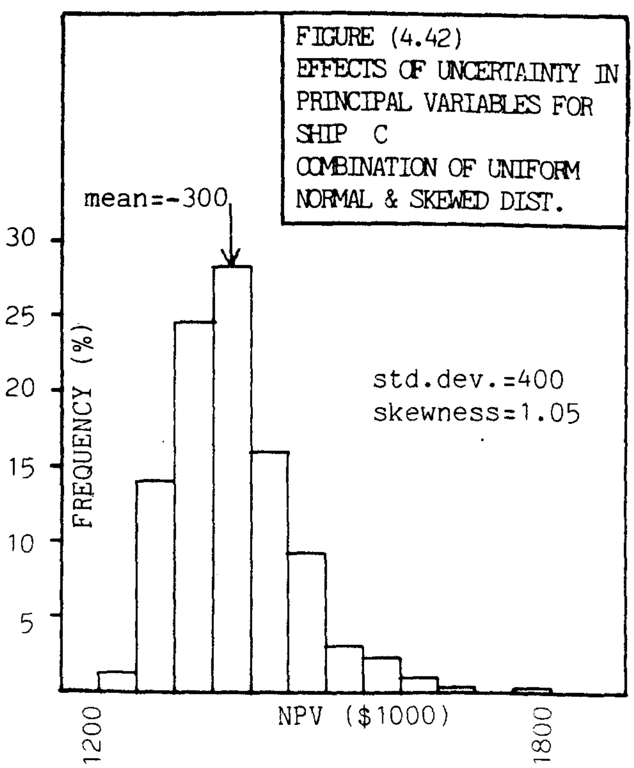


FIGURE (4.42)
EFFECTS OF UNCERTAINTY IN PRINCIPAL VARIABLES FOR SHIP C
COMBINATION OF UNIFORM NORMAL & SKEWED DIST.

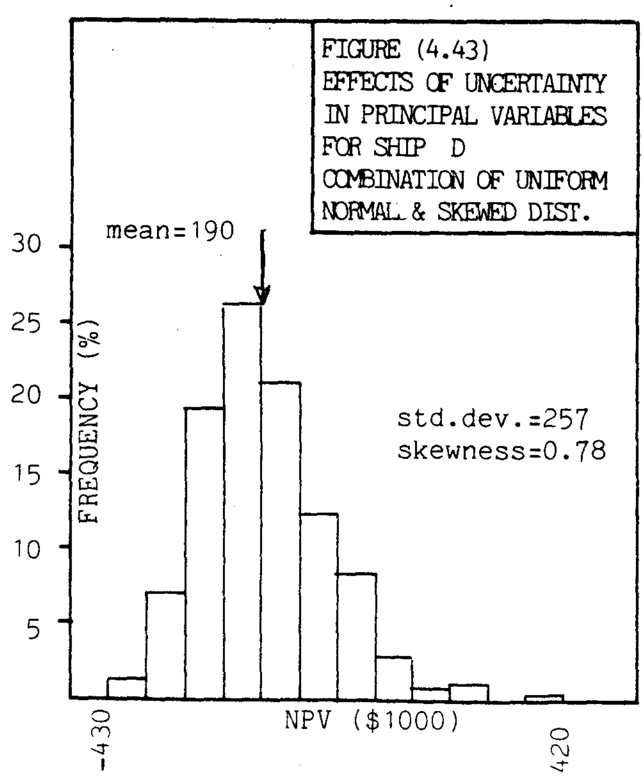


FIGURE (4.43)
EFFECTS OF UNCERTAINTY IN PRINCIPAL VARIABLES FOR SHIP D
COMBINATION OF UNIFORM NORMAL & SKEWED DIST.

of various degrees of skewness included is insufficient to make the extended version of the Central Limit Theorem apply.

4.7 ALTERNATIVE HULL MAINTENANCE STRATEGIES EXAMINED IN THE LIGHT OF UNCERTAINTY

The purpose of this section is to examine some of the deterministic case studies from Chapter 3 under conditions of uncertainty. Only a few selected cases are examined, and it should be emphasised that the results are only intended to serve as estimates of the possible effects of uncertainty in principal variables. Chapter 3 has already demonstrated that each case should be evaluated entirely upon its own merits and this same recommendation also applies to the problem of quantifying uncertainty in the final result.

The maintenance strategies of principal interest in the face of uncertainty are Case Studies 2.1, 2.2, 3.1 and 5 from Chapter 3, where 2.2 is in fact an extension to 2.1, and the two Case Studies may be evaluated in a combined form. The options presented in Case Studies 2.3 and 3.2 are essentially policy decisions for management. Both Case Studies may therefore be regarded as deterministic for the purpose of the present calculations, resulting only in a constant displacement of the mean value and corresponding distribution for the remaining case studies under consideration.

In the previous section the principal variables affecting the difference in net present value terms between alternative hull maintenance strategies have been identified, and special assumptions about the statistical properties of selected variables have been used to examine the behaviour of the proposed model, with particular reference to the statistical properties of the distribution of net present value. The purpose of the present investigation is to perform a similar evaluation for the selected case studies using best estimates for the statistical properties of individual variables.

The statistically objective results of the analysis in Chapter 1 have been used to estimate individual distributions for variables (2) and (3) relating to the development of hull roughness for the conventional high performance system. For the alternative self polishing system the standard deviation of the distribution of roughness increase with time in service is subjectively estimated to be half the value calculated for the conventional system. The hydrodynamic importance of hull roughness, identified as variable (6), has been estimated in Chapter 1 on the basis of experimental work to take a mean value equal to approximately 60% of the corresponding value predicted by the ITTC correlation formula for hull roughness. No further information is available to give probability estimates on either side of this mean value, and the subjective estimate from the previous section based upon a uniform normal distribution is therefore used.

For the purpose of calculating the expected annual escalations of fuel prices and freight rates with corresponding statistical properties, a survey of historical trends was performed. The results of this investigation are presented in Figures (B-1) and (B-2) of Appendix B. Although historical trends are not a satisfactory basis on which to make future predictions, they provide some degree of objectivity to estimates which otherwise may appear to be entirely subjective. As shown in Figures (B-1) and (B-2) short term fluctuations are high, especially for freight rates, but the important conclusion may be drawn that the freight rates for crude oil and dry bulk cargoes follow similar trends. The same estimated distribution for annual escalation in freight rates may therefore be used for Ships C and D. In the present case studies this assumption has also been extended to Ship B. Figures (B-1) and (B-2) indicate that over the last medium term period of 6 years there has been little change in the real value of freight rates and fuel prices. It is believed that recent falls in real terms of fuel prices as well as freight rates may result in a greater chance of future increases than further decreases in real terms. Public statements by major oil companies have presented medium term predictions of annual escalations for the next 5 to 8 years principally in the range between -2.5 percent and +2.5 percent in real terms. The greater fluctuations experienced in the freight market should be reflected in the respective distributions of annual escalations. On the basis of the limited amount of information available, the following subjective estimates have been made for the annual escalations in fuel prices and freight rates for a medium term period of between 5 and 8 years:

Annual Fuel Price Escalation:

Mean value = 0 , with 0.05 probability of being greater than +3.75%
and 0.05 probability of being less than -2.5%

Annual Freight Rate Escalation:

Mean value = 0 , with 0.05 probability of being greater than +7.5%
and 0.05 probability of being less than -5%

Both the remaining two principal variables are related to the maintenance procedures in drydock. The average hull roughness at outdocking after reblast and recoat depends on the quality of workmanship as well as the condition of the shell plating. The expected value is therefore likely to be higher than the average value observed for new ships. In addition the distribution is likely to be skewed with a greater probability tail towards higher roughness values.

The additional time required in drydock for reblast and renewal of the coating system is more dependent on the number of coats of paint required and the drying time between them, than the actual size of the vessel. A reasonable assumption is therefore to use the same number of additional days for all four ships types under consideration. In order to allow for the possibilities of delays the distribution should be skewed with a greater probability tail towards higher numbers of additional days. The following subjective estimates have therefore been used:

Outdocking AHR after Reblast:

Mean value = 150μm, with 0.05 probability of being greater than 225μm
and 0.05 probability of being less than 100μm

Additional Days in Drydock:

Mean value = 5days, with 0.05 probability of being greater than 8 days
and 0.05 probability of being less than 3 days

Individual probability distributions corresponding to the above estimates have been evaluated using the standard method developed earlier in the present Chapter.

The first set of hull maintenance alternatives to be examined have been Case Studies 2.1 and 2.2 from Chapter 3. Specifications for both alternative strategies are as described in Case Study 2.1 but with average hull roughness after reblast and recoat at 150 μm, instead of 125 μm. Zero correlation is assumed between corresponding roughness variables for the two alternative maintenance strategies. All calculations have been based upon 400 repeat simulations, although greater errors in the estimated mean value compared with earlier predictions in Section 4.4.4 may be expected, due to the skewness in some of the variables. Results for Ship A are presented in Figures (4.44) to (4.47) for two different values of average hull roughness immediately prior to drydocking and three different periods of calculation. The results clearly demonstrate a high degree of uncertainty, which is primarily due to uncertainty in the parameters relating to the development of roughness with time. Despite the substantial uncertainty observed in the results, three important conclusions may be drawn from this study.

(1) The resultant distribution is approximately uniformly normal

(2) The standard deviation of the resultant distribution is independent of the average hull roughness immediately prior to the start of the calculations

(3) The standard deviation of the resultant distribution is proportional to the time period of calculation

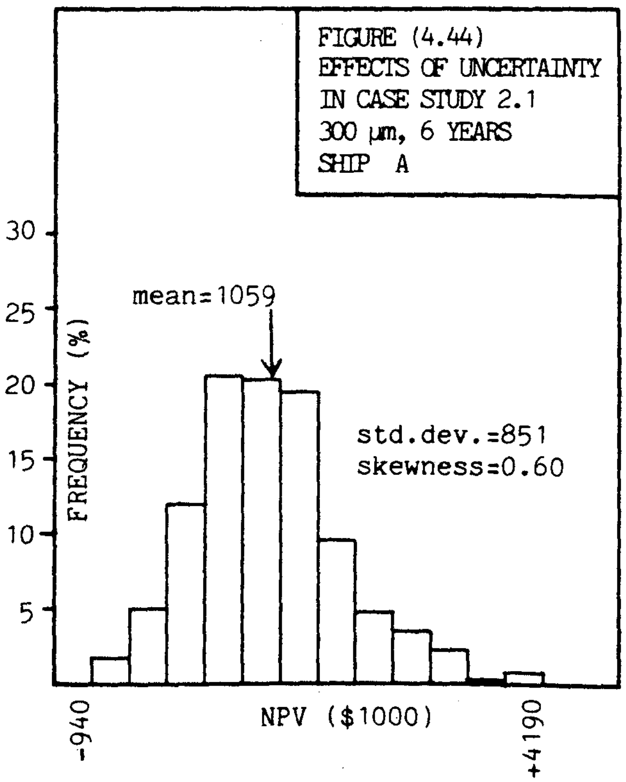


FIGURE (4.44)
EFFECTS OF UNCERTAINTY
IN CASE STUDY 2.1
300 μm, 6 YEARS
SHIP A
mean=1059
std.dev.=851
skewness=0.60
FREQUENCY (%)
NPV ($1000)
-940
+4190

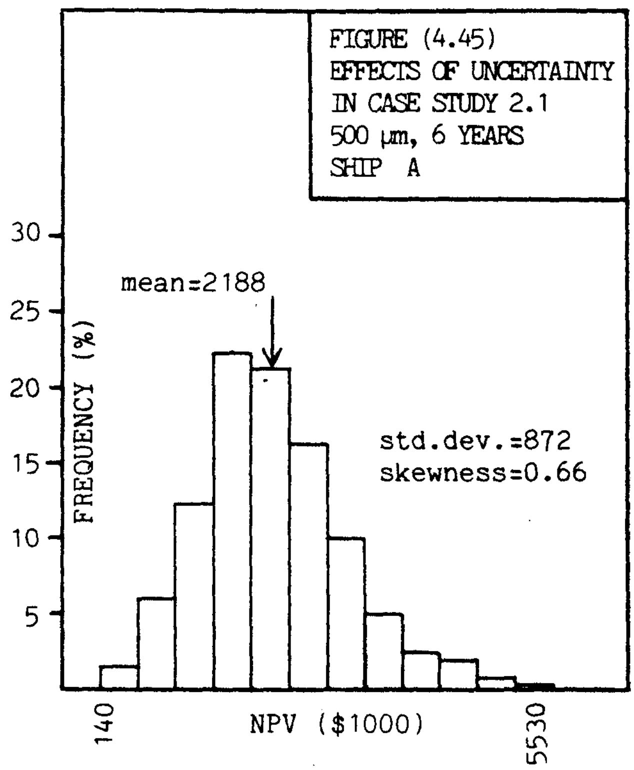


FIGURE (4.45)
EFFECTS OF UNCERTAINTY
IN CASE STUDY 2.1
500 μm, 6 YEARS
SHIP A
mean=2188
std.dev.=872
skewness=0.66
FREQUENCY (%)
NPV ($1000)
140
5530

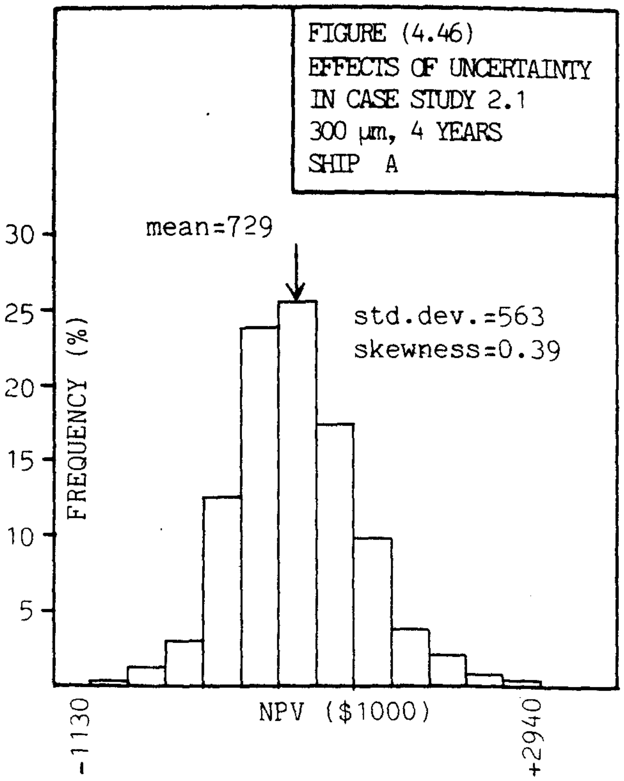


FIGURE (4.46)
EFFECTS OF UNCERTAINTY
IN CASE STUDY 2.1
300 μm, 4 YEARS
SHIP A
mean=729
std.dev.=563
skewness=0.39
FREQUENCY (%)
NPV ($1000)
-1130
+2940

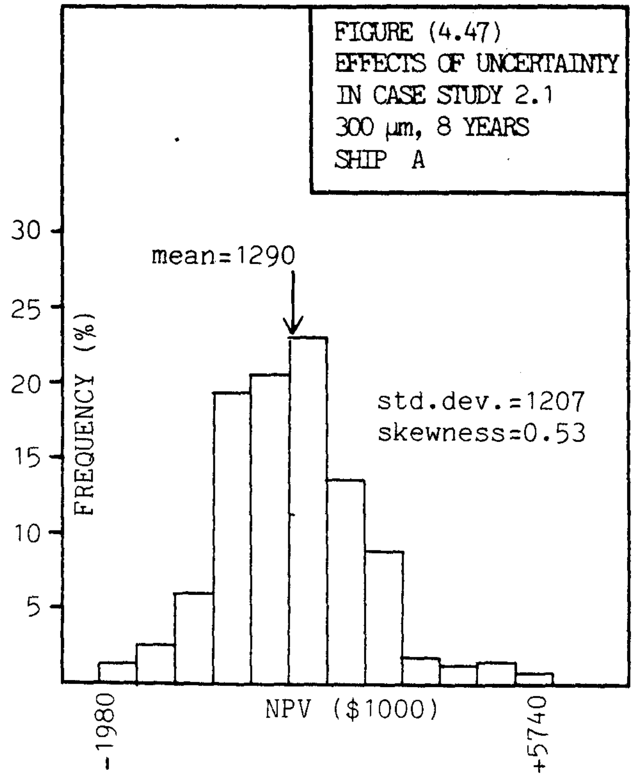


FIGURE (4.47)
EFFECTS OF UNCERTAINTY
IN CASE STUDY 2.1
300 μm, 8 YEARS
SHIP A
mean=1290
std.dev.=1207
skewness=0.53
FREQUENCY (%)
NPV ($1000)
-1980
+5740

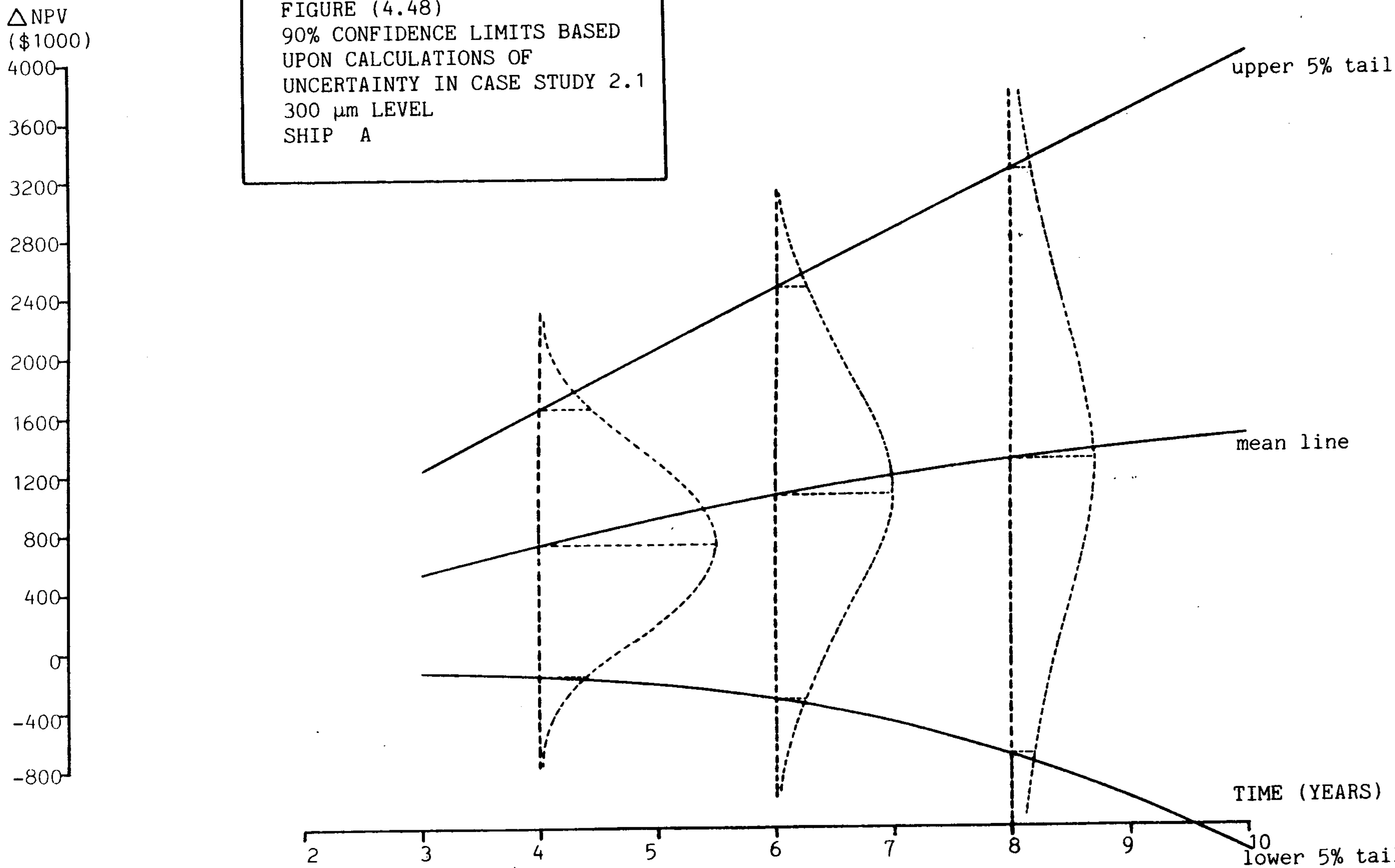


FIGURE (4.48)
90% CONFIDENCE LIMITS BASED
UPON CALCULATIONS OF
UNCERTAINTY IN CASE STUDY 2.1
300 μm LEVEL
SHIP A

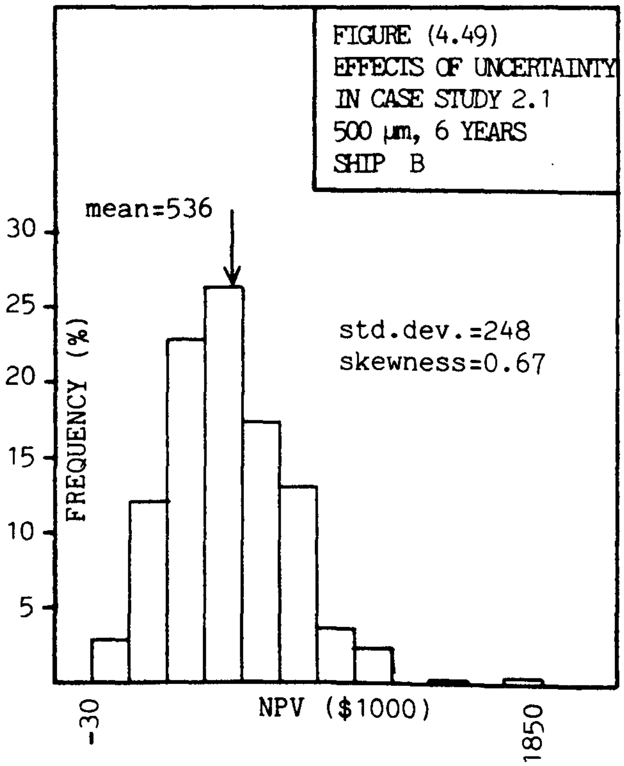


FIGURE (4.49)
EFFECTS OF UNCERTAINTY
IN CASE STUDY 2.1
500 μm, 6 YEARS
SHIP B
mean=536
std.dev.=248
skewness=0.67
FREQUENCY (%)
30
25
20
15
10
5
-30
NPV ($1000)
1850

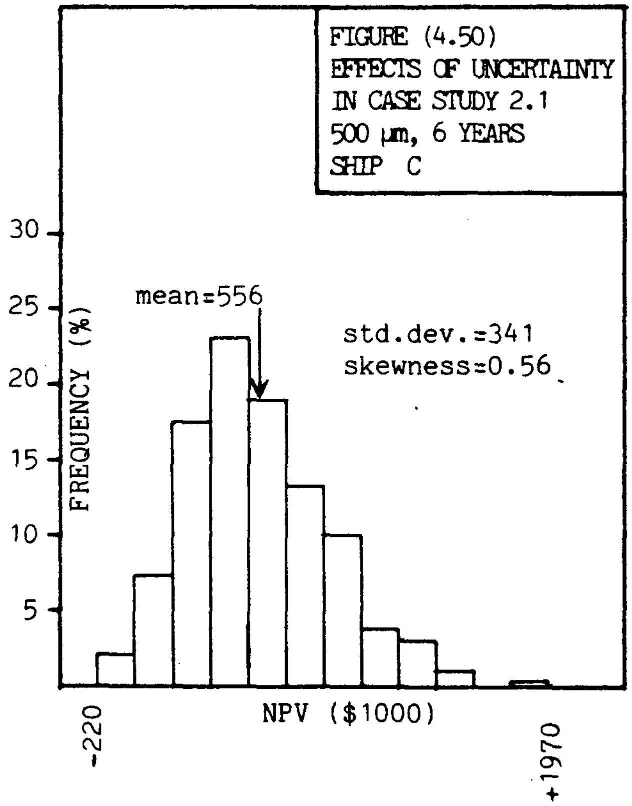


FIGURE (4.50)
EFFECTS OF UNCERTAINTY
IN CASE STUDY 2.1
500 μm, 6 YEARS
SHIP C
mean=556
std.dev.=341
skewness=0.56
FREQUENCY (%)
30
25
20
15
10
5
-220
NPV ($1000)
+1970

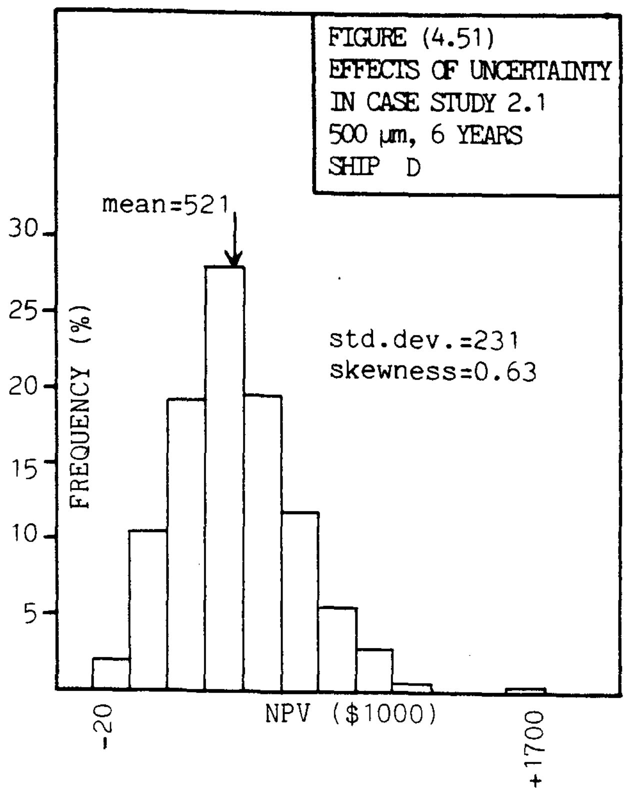


FIGURE (4.51)
EFFECTS OF UNCERTAINTY
IN CASE STUDY 2.1
500 μm, 6 YEARS
SHIP D
mean=521
std.dev.=231
skewness=0.63
FREQUENCY (%)
30
25
20
15
10
5
-20
NPV ($1000)
+1700

This set of conclusions has the important consequence that for the same ship, only one calculation of uncertainty is required for the combined evaluation of case studies 2.1 and 2.2. From this single distribution the uncertainty in the result for any combination of indocking roughness and period of calculation may be found. The results of the earlier deterministic case study may subsequently be presented with confidence limits as shown in Figure (4.48).

For completeness the calculations have also been repeated for Ships B, C and D, using an average hull roughness of 500 μm at indocking and a 6 year calculation period. The results are presented in Figures (4.49) to (4.51). A small degree of skewness may be observed in the results, but this it not significant, and for most practical purposes the distributions can be assumed uniformly normal.

The evaluation of uncertainty in Case Study 3.1 from Chapter 3 has taken a similar form to the calculations already performed for Case Study 2.1, although some simplifications have been possible. Both alternative strategies in Case Study 3.1 involve the complete removal of the old coating system and the build-up of a new system starting with a clean steel surface. As a result, the evaluations are based upon a comparison between two alternative hull coating systems, and the calculation of corresponding differences in the deterioration of hull surface condition with time required to justify a more expensive system. No information is available to suggest that the actual paint system employed has any significant influence upon the quality of surface finish achieved in connection with a complete reblast and renewal of the coating system. The two alternative coating systems may therefore be assumed to have the same outdocking hull roughness upon completion of the work, provided the same method of paint application is used. The same argument applies to the additional time required in drydock for this reblast and renewal of the coating system, where deviations from the expected time are not expected to be related to the paint system in use. Consequently, for the purpose of the present case study, a 100% correlation between the two alternative maintenance strategies may be assumed for the two principal variables (4) and (5), and both may effectively be assumed fixed with a value equal to the mean value. No further correlation is expected to exist between corresponding variables for the two alternative maintenance strategies.

Results for Ship A based upon 400 simulations are presented in Figures (4.52) to (4.54) for roughness Scenarios 2 and 3 as specified in Chapter 3, and two different periods of calculation. From Figures (4.52) and (4.54) it can be seen that the standard deviation of the resultant distribution is again strongly correlated to the period of calculation. In addition, the standard deviation is dependent on the roughness scenario assumed for the self polishing coating alternative. This correlation is less than the correlation with time and may be neglected for the purpose of simplified studies. The results also indicate that the standard deviation of the final result is less than half the value observed in the previous Case Study for the same period of calculation. In the case of Ship A the resultant distribution is slightly skewed but for most practical purposes can be assumed uniformly normal. Additional calculations have demonstrated that the standard deviation of the resultant distribution is almost independent of the average hull roughness after reblast and recoat, provided the value is the same for both alternative strategies. Figure (4.55) presents the results of the same

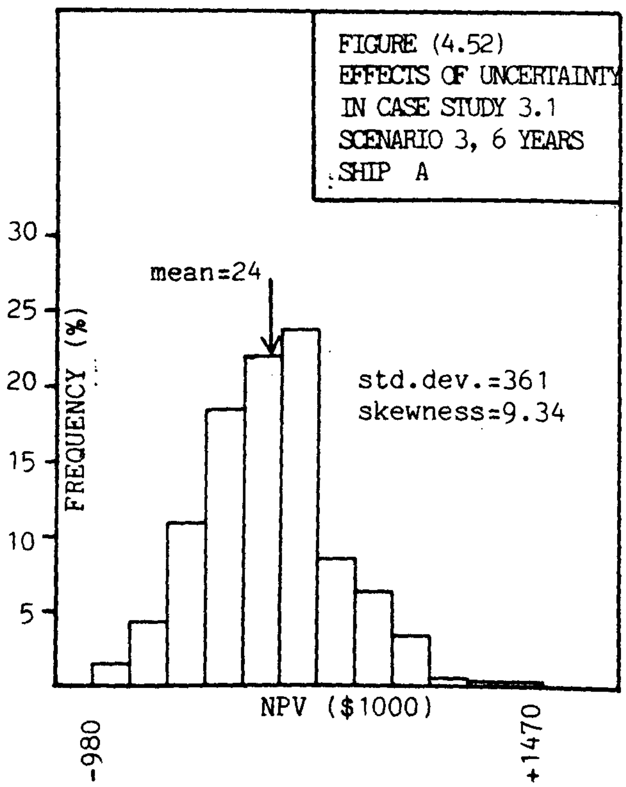


FIGURE (4.52)
EFFECTS OF UNCERTAINTY
IN CASE STUDY 3.1
SCENARIO 3, 6 YEARS
SHIP A

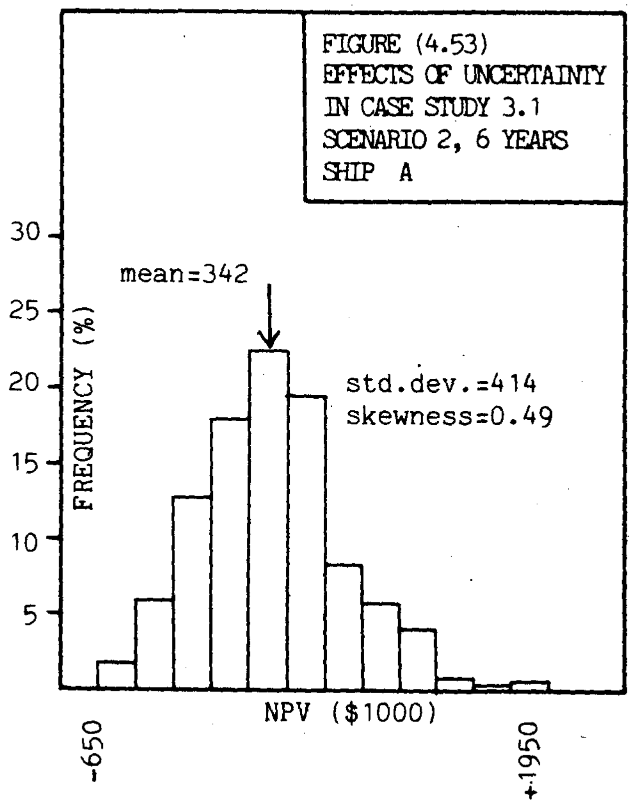


FIGURE (4.53)
EFFECTS OF UNCERTAINTY
IN CASE STUDY 3.1
SCENARIO 2, 6 YEARS
SHIP A

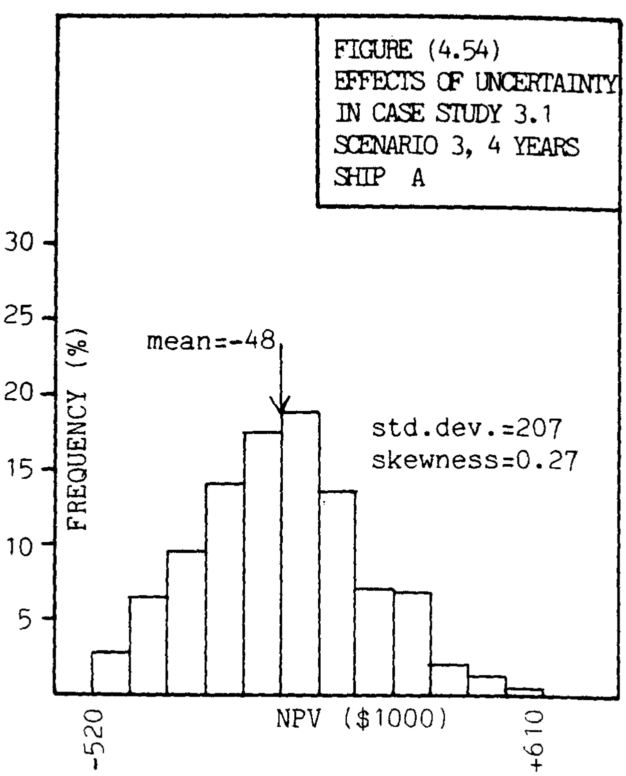


FIGURE (4.54)
EFFECTS OF UNCERTAINTY
IN CASE STUDY 3.1
SCENARIO 3, 4 YEARS
SHIP A

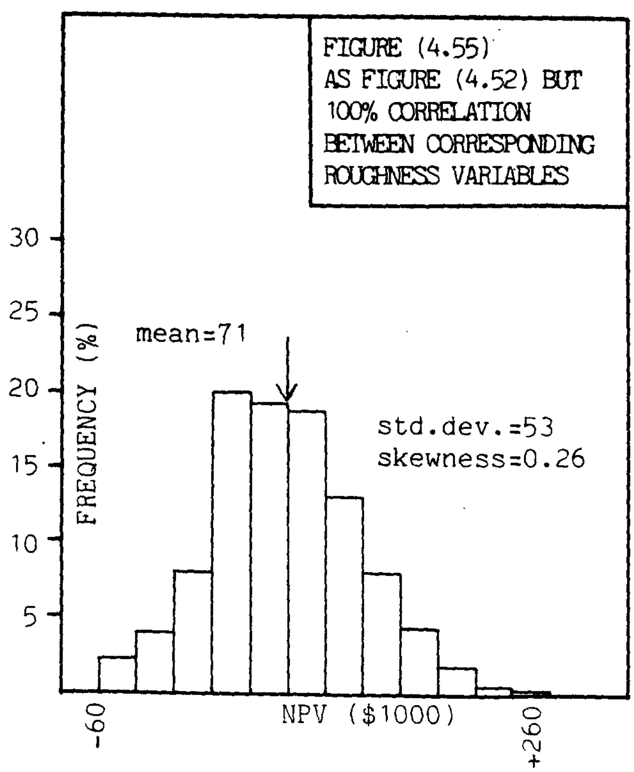


FIGURE (4.55)
AS FIGURE (4.52) BUT
100% CORRELATION
BETWEEN CORRESPONDING
ROUGHNESS VARIABLES

Case Study for roughness Scenario 3 and a 6 year calculation period, using fixed values equal to the mean value for all variables related to the development of hull roughness with time. In practice, this is the same as assuming 100% correlation between corresponding roughness variables for the two alternative maintenance strategies. As shown in Figure (4.55), the standard deviation of the resultant distribution has been reduced considerably, indicating that in the present Case Study it is the uncertainty associated with change in hull surface condition over time which is predominant. The uncertainties in fuel price escalations and the hydrodynamic importance of hull roughness are less important if the probability estimates used in the present case studies are correct.

For completeness the calculations have also been repeated for Ships B, C and D, using roughness scenario 3 and a 6 year calculation period with zero correlation between corresponding roughness variables for the two alternative maintenance strategies. The results are presented in Figures (4.56) to (4.58).

The principal benefit in economic terms of an advanced self polishing paint system is expected to be the efficient elimination of the problems associated with hull fouling. This superiority of the self polishing systems has already been demonstrated in the survey of hull fouling presented in Chapter 1, but as explained in the same Chapter, the successful settlement and growth of fouling organisms is associated with a high degree of uncertainty, even when a sufficient set of favourable conditions exist. The same high degree of uncertainty is also present in the estimated speed and power penalties associated with hull fouling. In an attempt to quantify the penalties associated with fouling and the

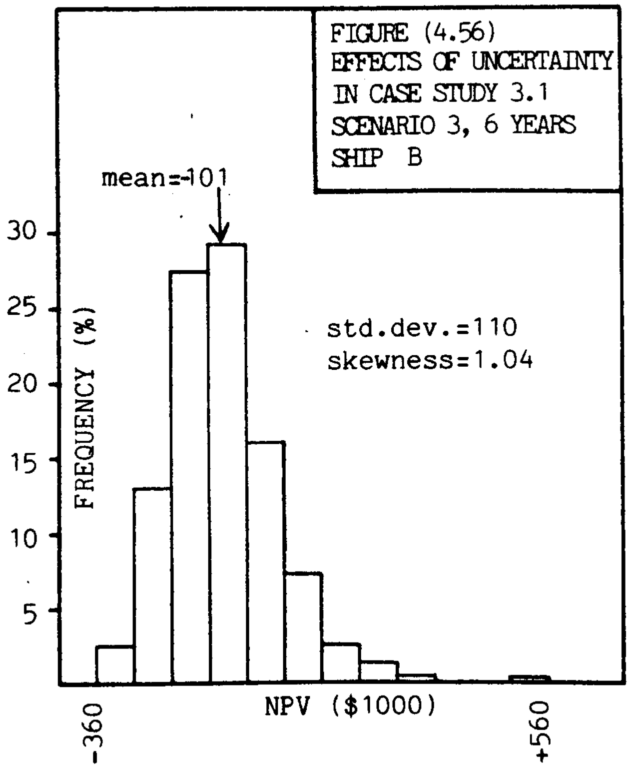


FIGURE (4.56)
EFFECTS OF UNCERTAINTY
IN CASE STUDY 3.1
SCENARIO 3, 6 YEARS
SHIP B
mean=-101
std.dev.=110
skewness=1.04
FREQUENCY (%)
30
25
20
15
10
5
-360
NPV ($1000)
+560

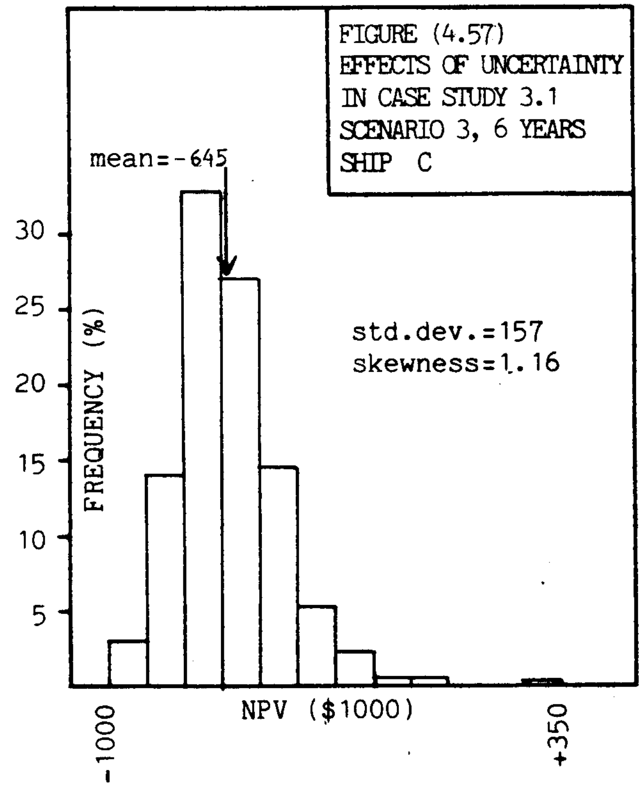


FIGURE (4.57)
EFFECTS OF UNCERTAINTY
IN CASE STUDY 3.1
SCENARIO 3, 6 YEARS
SHIP C
mean=-645
std.dev.=157
skewness=1.16
FREQUENCY (%)
30
25
20
15
10
5
-1000
NPV ($1000)
+350

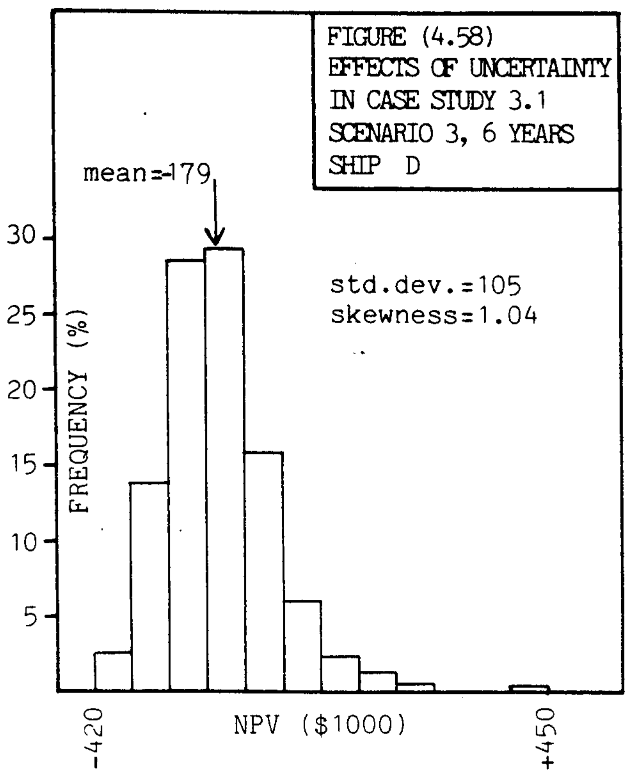


FIGURE (4.58)
EFFECTS OF UNCERTAINTY
IN CASE STUDY 3.1
SCENARIO 3, 6 YEARS
SHIP D
mean=-179
std.dev.=105
skewness=1.04
FREQUENCY (%)
30
25
20
15
10
5
-420
NPV ($1000)
+450

effect this uncertainty has upon the economic comparison between a conventional antifouling system and a self polishing system, a combined evaluation has been made of Case Studies 3.1 and 5 from Chapter 3.

Specifications for the two alternative maintenance strategies are the same as for Case Study 3.1 except that the high performance conventional paint system is associated with a certain possibility of successful fouling settlement within the 24 month drydocking period. Table(1.4) in Chapter 1 indicated that approximately 60% of all conventionally coated vessels enter drydock in a fouled condition after a period of 24 months in service. Combined with the additional subjective estimate that the probability of no fouling settlement within a period of 36 months is small, say 0.02 , this result may be used in conjunction with the method developed earlier in the present Chapter to evaluate an approximate probability distribution for subsequent use in the analysis. The average speed loss in a fouled condition is estimated to be 10% with a 0.05 probability of being less that 5% and a 0.05 probability of being greater than 15% . Finally, the time period from initial settlement of fouling to a fully saturated state is estimated to have a mean value of 3 months, with ordinates corresponding to the same 0.05 upper and lower probabilities at 1 month and 5 months, respectively.

Results for Ship A from this combined study, including the possible effects of fouling, are presented in Figure (4.59). As shown, the resultant distribution is highly positively skewed with a significant tail towards higher investment returns. The mean value has increased in accordance with the results already presented in Chapter 3. Compared with the earlier results presented in Figure (4.52), this inclusion of probability of fouling has reduced the probability of a negative investment outcome from 0.53 to 0.25. The increment to the mean value and standard deviation of the resultant distribution due to the probability of fouling is constant, irrespective of the roughness scenarios assumed.

Results of the same combined study for Ships B, C and D are presented in Figures (4.60) to (4.62). All distributions indicate the same degree of skewness.

Some final comments are required about the general logarithmic utility function and the calculation of the certainty equivalent as a single number representation of the resultant distribution. The results of the case studies in the present section almost all have the common feature of a high standard deviation in the final distribution. If the utility function presented in Section (4.5) is representative of the average decision-maker, this results in a number of cases with probabilities of losses greater than the maximum tolerable loss, as defined by the utility function. The certainty equivalent therefore becomes unobtainable using the present method. In the remaining cases, where the method has provided valid results, the effects of the large standard deviations obtained in the final distributions have been that the principal part of this distribution is located in the corresponding upper region of the utility function, where almost risk neutrality may be observed. As a result the certainty equivalent and the mean value of the distribution have nearly the same numerical value, and the certainty equivalent is found to provide little or no additional information to aid the decision maker.

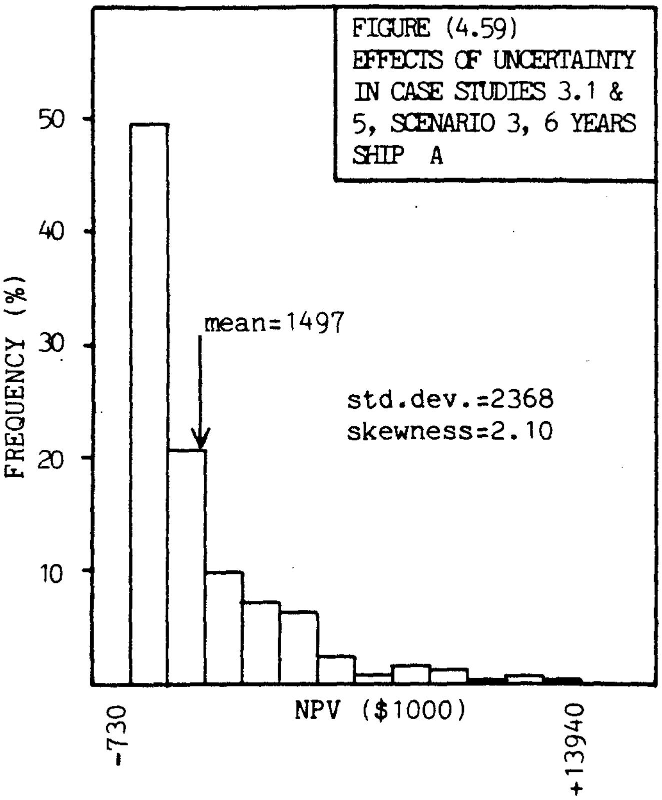


FIGURE (4.59)
EFFECTS OF UNCERTAINTY IN CASE STUDIES 3.1 & 5, SCENARIO 3, 6 YEARS SHIP A

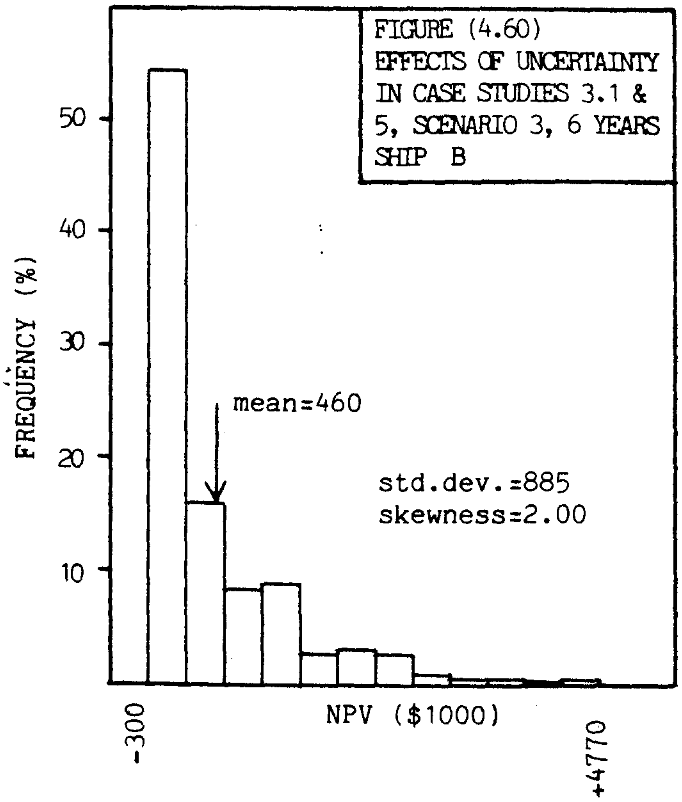


FIGURE (4.60)
EFFECTS OF UNCERTAINTY IN CASE STUDIES 3.1 & 5, SCENARIO 3, 6 YEARS SHIP B

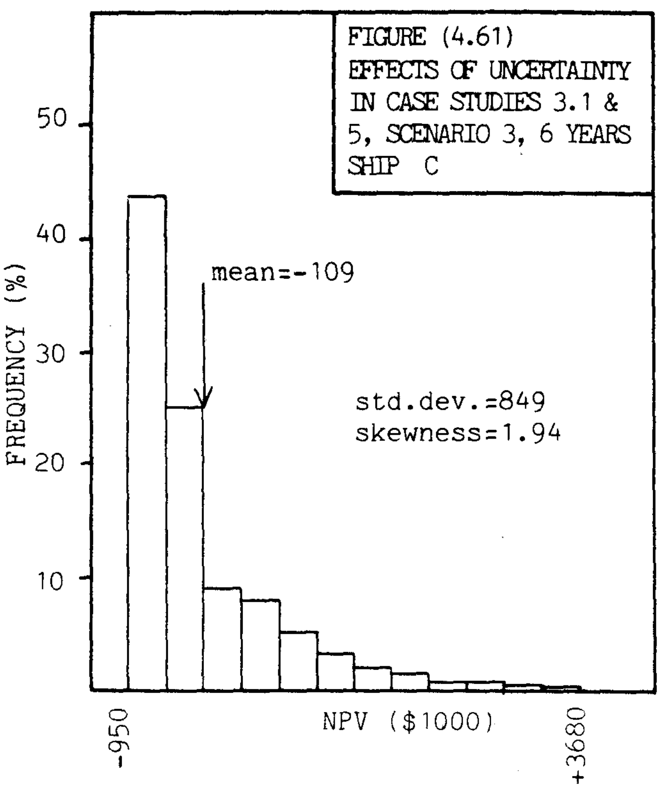


FIGURE (4.61)
EFFECTS OF UNCERTAINTY IN CASE STUDIES 3.1 & 5, SCENARIO 3, 6 YEARS SHIP C

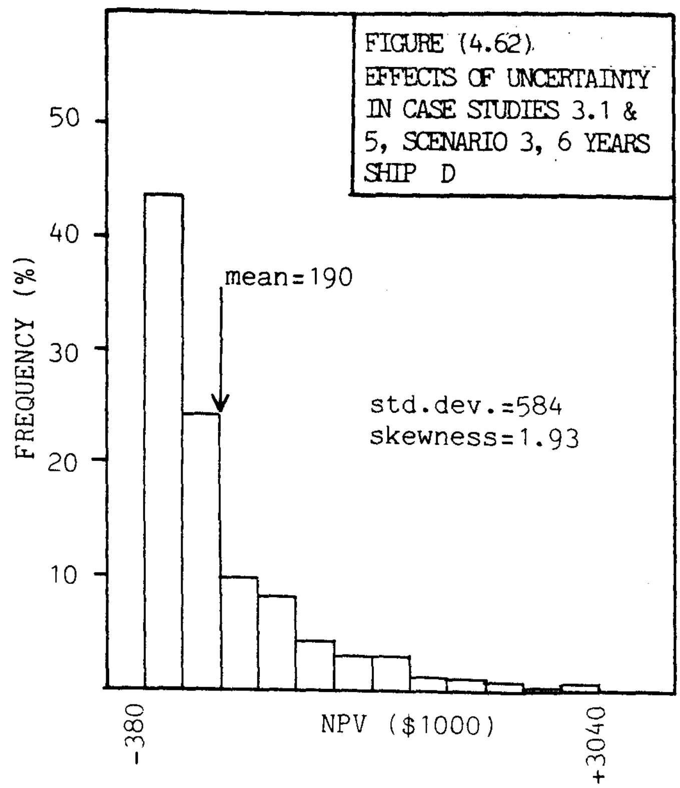


FIGURE (4.62)
EFFECTS OF UNCERTAINTY IN CASE STUDIES 3.1 & 5, SCENARIO 3, 6 YEARS SHIP D

CONCLUSIONS

1. Alternative economic methods and measures of merit have been discussed and Net Present Value and Discounted Profit to Investment Ratio have been identified as the most suitable economic criteria in the evaluation of alternative hull maintenance strategies.

   Tax considerations and methods of finance may in special cases influence the relative ranking between investment alternatives, but can be ignored for most calculations involving incremental investments in hull or propeller maintenance. If required, after tax net present values may be obtained by simply reducing the before tax net present value by the appropriate tax liability.

2. Measurements of hull roughness found on ships in service have been collected from various sources, and the expected average increase in hull roughness with time in service has been calculated for conventional antifouling paint systems with corresponding probability distributions. The changes in hull roughness due to the maintenance procedures in drydock are correlated to the average hull roughness at indocking, and a separate distribution describing this correlation has been evaluated. Insufficient data exist to perform a similar analysis for the self polishing types of antifouling paints, but indications are that significant reductions in the

average rate of increase in hull roughness with time in service may be experienced, compared with conventional paints, especially if mechanical damage to the paint surface can be avoided.

3. The relationship between hull roughness and ship resistance is fundamental to the economic comparison between alternative hull maintenance strategies. Conclusions from a performance monitoring experiment on two sister-ships are that the ITTC correlation formula for hull roughness over-estimates this relationship, and that approximately 60% of the value calculated by the ITTC formula is a reasonable predictor for use in economic calculations. Results obtained using integral prediction methods for the calculation of turbulent skin friction give support to the general conclusions drawn from the monitoring experiment, but tend to suggest that the true relationship between roughness and frictional resistance is less than 50% of the value predicted by the ITTC formula.

4. The extent of hull fouling has been investigated for two principal antifouling systems. The results indicate that approximately 60% of all large ocean going vessels coated with conventional high performance antifouling paints enter drydock in a fouled condition after a period of 24 months in service, with the majority being in a heavily fouled condition. For vessels coated with self polishing paints, the corresponding figure is in the region of 10% with none in a heavily fouled condition.

5. The effects of hull roughness upon propulsion efficiency have been examined, based upon the assumption that the open water efficiency and the hull efficiency are affected by the presence of hull roughness, and the

relative rotative efficiency remains constant. Sufficient evidence also exists to suggest that the thrust deduction fraction remains unaffected, and that the changes in hull efficiency experienced are entirely due to changes in the wake fraction. The results of the analysis have demonstrated that added resistance due to hull roughness results in a significant decrease in the open water efficiency due to the increased loading on the propeller. At the same time the hull efficiency experiences an increase due to the increase in the effective wake, and the resultant change in the total efficiency is therefore minimal.

6. A deterministic techno-economic model of ship operation, with special reference to hull and propeller maintenance, has been developed. Although specifically developed for the purpose of evaluating alternative hull and propeller maintenance strategies, the model is sufficiently flexible to allow comparisons with other energy saving investments to be made.

   The case studies performed in Chapter 3 for a set of four principal ship types have demonstrated the need for the evaluation of alternative hull maintenance strategies in the full commercial context of ship operation, where technical,as well as operational and commercial factors are taken into consideration. In particular, this applies to the difference between constant speed and constant power operation. Most ocean going vessels are operated at constant power, and consequently freight rates are more important for the investment outcome than fuel prices.

7. Specific conclusions drawn from the case studies are that the amount of capital expenditure on improved hull maintenance, which can be justified

in economic terms, is critically dependent on ship type. For high speed container vessels the amount of capital available for each square metre of wetted surface area may be eight or nine times higher than the corresponding figure for a VLCC, which is slow steaming in a depressed freight market, with insufficient revenues to ensure profitable operation.

The prevention of high values of hull roughness carries a high financial premium. For all four vessels considered in the present case studies it is justifiable, in economic terms, to reblast and renew the hull coating system on ships with an average hull roughness of 300 μm or more, provided an outdocking roughness comparable with the average new ship standard can be achieved. The economic penalty resulting from poor quality of workmanship in drydock is high. Following the initial decision to reblast and renew the entire coating system, the following decision between a conventional and a self polishing antifouling paint system depends principally on factors such as the expected reduction in the rate of increase in hull roughness in service with a self polishing system, the ability of a self polishing system to eliminate an earlier fouling problem experienced with conventional antifouling paints, and possible changes in management policy towards longer intervals between drydockings when self polishing paints are employed.

For the fast container vessel each one of these factors is alone sufficient to justify the self polishing system, while for the VLCC the combined advantage of all three factors is a necessary requirement.

8. The case study evaluations in Chapter 3 have resulted in the introduction of two simplified methods of calculation; one based upon the generalised

results presented for four ship types, and a second method using a simplified tabular calculation procedure where results from a constant speed basis are transformed to a constant power basis, using a proposed simplified formula. The results obtained from both simplified methods are in good agreement with results obtained from the complete economic model.

9. Copper-Nickel cladding of the underwater hull has been proposed as an alternative to conventional hull painting procedures for new ships. This alternative has been examined in a separate case study for a large high-speed containership, and the conclusion has been drawn that this alternative is only marginally attractive in economic terms under the most favourable set of assumptions.

10. The hydrodynamic and economic penalties of propeller roughness have been examined for a 4-bladed fixed pitch propeller. In absolute terms propeller roughness is less important than hull roughness, but due to the small surface areas involved the capital expenditure available to ensure a smooth surface condition is of a magnitude 10 to 20 times greater than the costs involved. The results permit a high degree of error in the calculation procedure without altering the general conclusions, and further consideration of propeller maintenance has therefore, from the economic point of view, been considered unnecessary.

11. The presence of a large number of alternative hull maintenance strategies has resulted in the development of a rational search method for the calculation of optimum strategies based upon the principles of dynamic programming. This model is best suited for application at a preliminary stage in the analysis, with the specific task of selecting provisional

optimum maintenance strategies, prior to a more detailed set of calculations using the principal deterministic model.

12. Principal variables in the techno-economic evaluation of alternative hull maintenance strategies have been identified in a comprehensive sensitivity analysis. In addition to fuel price, freight rate and the hydrodynamic importance of hull roughness, the variables related to roughness increase with time in service and in drydock, the additional time required in drydock for hull maintenance and the quality of workmanship in connection with a complete renewal of the coating system have been found to be of significant importance. The cost of the antifouling paint system is, surprisingly, less important for the investment results.

13. All the variables considered to be of principal importance in the comparative evaluation between alternative hull maintenance strategies are associated with various degrees of uncertainty. Analytical methods for the analysis of uncertainty in economic calculations are based upon the requirement that the economic measure of merit can be expressed in the form of a mathematical function. This method has been found unsuitable for the present problem where a complex non-functional relationship exists between some of the principal variables. Instead the technique of probablistic cash flow simulation has been found to be the only satisfactory method capable of providing a quantitative assessment of uncertainty in the present problem.

14. A new technique based upon the use of scaled combinations or single parts of uniform normal distributions has been developed, following the general conclusion that existing standard probability distributions are incapable

of providing the required degree of flexibility in connection with subjective probability estimates. This new method allows complete distributions to be obtained on the basis of estimated mean values and upper and lower tail probabilities only. The technique is flexible and capable of accommodating almost any degree of skewness. In addition, the new technique has allowed simple sampling methods to be employed, based upon the principles of random number generation.

15. A complete probabilistic cash flow simulation model has been developed on the basis of the existing deterministic model and the proposed new technique for transforming subjective probability estimates into complete probability distribution functions. The model is capable of handling any one of the input variables in a probabilistic form, although for most cases only a few variables are expected to be associated with uncertainty.

General conclusions drawn from a selected set of case studies are that the uncertainties associated with investments in improved hull maintenance procedures are high. When all principal variables are represented in terms of probability distributions, the resultant distribution of net present value is approximately uniformly normal under most conditions, except for when the probability of hull fouling with conventional antifouling paints is included. In this case a highly skewed resultant distribution is obtained with a significant tail towards high investment returns. The most significant contribution to high uncertainty in the final distribution of net present value is due to uncertainty in the development of hull roughness with time in service. This uncertainty is critically dependent on the correlation between corresponding roughness variables of alternative coating systems, but the lack of available information has made the construction of a cross-correlation matrix impossible.

16. Suggestions for future work are principally directed towards obtaining more information about the behaviour of various coating systems with time in service, especially for the new type of self polishing antifouling paints, to allow the construction of a complete cross correlation matrix for the development of hull roughness with time between alternative coating systems.

A more satisfactory relationship between hull roughness and added resistance as basis for the present techno-economic model would also be desirable, although the present relationship is believed to be sufficiently accurate for most economic evaluations of hull maintenance. As the present work has demonstrated, other variables are at the moment more significant.

In addition, it would be desirable to be able to extend the existing dynamic programming model to a condition where different drydocking intervals may be used for different coating systems in the same set of calculations.

The combined evaluation of hull and propeller surface condition deterioration may also be of some interest, but this will first require a more detailed investigation into the problem of changes in flow characteristics around the aft end of the hull due to the presence of hull roughness.

Finally, it would be of interest to pursue the investigation into the attitude of decision makers towards uncertainty in investment calculations to a more satisfactory level, although this may on its own be the topic of a complete dissertation.

Apart from the proposed extension to the present dynamic programming model, answers from any of the suggested areas of further research may be accommodated in the present set of models without significant modifications.