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Preliminary power prediction during early design stages of a ship

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PRELIMINARY POWER PREDICTION DURING EARLY DESIGN STAGES OF A SHIP

BY

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Cape Town, South Africa

November 1996

DECLARATION

The contents of this dissertation represent my own work and the opinions contained herein are my own and not necessary those of the Cape Technikon.

Signature: ...[signature]...   Date: 21 Jan 97

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SYNOPSIS

A need exists whereby the preliminary power requirement of a ship can be rapidly estimated. Because the majority of methods available for this purpose are manual and consist of a number of independent components, they are tedious and time consuming to use. With the advent of the personal computer and its widespread acceptance, it was logical to examine the various components involved to determine their suitability for computerisation and general accuracy. In total eleven hull resistance prediction methods were examined, eight of which were computerised. Model test data of four vessels were used to evaluate these eight programs. The method providing the best results was selected to form the core of an integrated Power Prediction program.

Factors such as appendage resistance, fouling and hull roughness were examined and appropriate methods selected for inclusion into the integrated program.

Various propeller series were examined and evaluated against a variety of examples and model data. Two propeller optimisation programs were written and a general method for determining the optimum characteristics from K_T-K_Q polynomials is described.

Methods for determining propulsion coefficients were examined and their results compared with those obtained from model tests. The method providing the best overall results was incorporated into the Power Prediction program

Added resistance due to sea state was broken down into two components, namely wind and wave resistance. Only the head sea and wind conditions were considered. Various methods for estimating wind resistance were examined and a program developed capable of providing resistance estimates regardless of wind direction. The problem of added resistance due to waves was examined and two programs written around the methods examined. To facilitate prediction estimates, sea state was chosen as the prime function. Wave height is estimated for the appropriate sea state and wind speed in turn from the wave height

Actual sea trial data of a twin screw channel ship is used to determine the overall accuracy of the Power Prediction Program.

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NOMENCLATURE

SYMBOL	TITLE	UNIT
a_i	Regression coefficient	
A_{BT}	Transverse area of bulbous bow	m^2
A_c	Admiralty coefficient	
Ae	Expanded area of propeller blades	
A_L	Lateral projected area of ship above waterline	m^2
Ao	Area of propeller disk	m^2
A_{SS}	Longitudinal projected area of superstructure	m^2
A_T	Transom area	m^2
A_T	Transverse projected area of ship above waterline	m^2
Ax	Maximum section area	m^2
b_i	Regression coefficient	
B	Moulded breadth	m
BAR	Blade area ratio	
Bx	Breadth at station of maximum section area	m
c_i	Regression coefficient	
C	Distance of centroid of lateral projected area from bow	m
Ca	Ship-model correlation factor	
Caa	Wind resistance coefficient	
Cd_{app}	Appendage drag coefficient	
C_B	Block coefficient on basis of waterline length	
C_M	Midship section coefficient	
C_N	Wind yawing moment coefficient	
C_P	Prismatic coefficient	
C_F	Frictional resistance coefficient	
C_R	Residuary resistance coefficient	
C_{stern}	MARIN afterbody form coefficient	
C_T	Total resistance coefficient	
C_{Tm}	Total resistance coefficient of Model	

SYMBOL	TITLE	UNIT
C_{Ts}	Total resistance coefficient of Ship	
C_V	Viscous resistance coefficient $\{(1+k_1)C_F + C_a\}$	
C_{VP}	Vertical prismatic coefficient	
C_W	Waterplane coefficient	
C_{XW}	Fore and aft wind force coefficient	
Cx	Maximum section area coefficient	
C_{YW}	Lateral wind force coefficient	
d	Propeller boss diameter	m
D	Propeller diameter	m
D_{opt}	Optimum propeller diameter	m
f	Froude coefficient	
Fn	Froude Number $\left(V/\sqrt{gL}\right)$	
F_∇	Volumetric Froude Number $\left(V/\sqrt{g\nabla^{1/3}}\right)$	
g	gravitational acceleration	m/s^2
Hs	Significant wave height	m
K_T	Thrust coefficient $(T/\rho n^2 D^4)$	
K_Q	Torque coefficient $(Q/\rho n^2 D^5)$	
k_c	Wind direction coefficient	
k_{yy}	Longitudinal radius of gyration	m
J	Advance coefficient V_A/nD	
L or LWL	Length on waterline	m
L_{ft}	Length on waterline in feet	ft
LCB	Longitudinal centre of buoyancy(Positive value forward of amidships, Negative value aft of amidships)	m
LCG	Longitudinal centre of gravity	m
L_{OA}	Length overall	m
L_{pp}	Length between perpendiculars	m
M	Number of distinct groups of masts or kingposts seen in lateral projection.	
N	Revolutions per minute	rpm
n	Revolutions per second	rps
P	Pitch of propeller	m
Pe	Effective power	kW

SYMBOL	TITLE	UNIT
P/D	Propeller pitch-diameter ratio	
Q	Propeller Torque	Nm
r^2	Coefficient of determination	
R_A	Added resistance	N
R_{AA}	Wind resistance	N
R_{APP}	Appendage resistance	N
R_B	Pressure resistance of bulbous bow	N
Rn	Reynolds Number	
R_{AW}	Frequency dependant wave resistance response	
$\overline{R}_{AW}$	Average added wave resistance	
R_F	Equivalent flat plate frictional resistance	N
R_R	Residuary resistance	N
R_T	Total resistance	N
R_{TR}	Pressure resistance of immersed transom	N
R_W	Wavemaking and wavebreaking resistance	N
R_{WAVE}	Added resistance due to waves (sea state)	N
S	Wetted surface area	m^2
$Sapp$	Wetted surface area of appendages	m^2
S_L	Length of perimeter of lateral projection of model excluding waterline and slender bodies such as masts and ventilators.	m^2
$S_{(\omega)}$	Wave spectrum	
t	Propeller blade thickness	m
t	Thrust deduction factor	
T	Draught	m
T	Propeller thrust	N
v	Velocity	m/s
Va	Speed of advance	m/s
Vs	Ship speed	m/s
V_k	Ship speed	knots
V_R	Relative wind velocity	knots
w	Taylor wake fraction	

SYMBOL	TITLE	UNIT
wt	Taylor wake fraction based on thrust identity	
z	Number of propeller blades	
Δ	Mass displacement (sea water)	tonne
∇	Volume of displacement	m^3
σ_{AW}	Non-dimensional added resistant coefficient	
ρ	Density	kg/m^3
ν	Kinematic viscosity	m^2/s
ω	Wave frequency	
ω_e	Frequency of encounter	
λ	Average hull roughness	
ψ	Propeller blade rake angle	
η_B	Propeller behind ship efficiency	
η_o	Propeller open water efficiency	
η_r	Relative Rotational Efficiency	
S_ζ	Wave amplitude	
$S_\zeta(\omega_e)$	Energy spectrum of the sea	$m^2/Rad/sec$
$(1+k1)$	Hull form coefficient	
$(1+k2)$	Appendage form coefficient	
$DL\ ratio$	Displacement-length ratio $\{\Delta_{ton}/(L_{ft}/100)^3\}$	Long Ton/ft^3
$L/\nabla^{1/3}$	Length-displacement ratio	
∇/L^3	Volumetric coefficient (Taylor speed length ratio)	
$\copyright$	Froude's resistance coefficient $\left(\dfrac{579,7Pe}{\Delta^{2/3}v_k^{\ 3}} \right)$	

STANDARD VALUES

Density of seawater (ρ_{sw})	1025 kg/m^3
Density of freshwater (ρ_{fw})	1000 kg/m^3
Density of air (ρ_{air})	1.28 kg/m^3
Kinematic viscosity of seawater @15°C (ν_{sw})	1.18831E-6

CONVERSION FACTORS

1 knot	=	0.51477 m/s
1 long ton	=	1,01605 tonne
$\Delta_{ton}/(L_{ft}/100)^3$	=	28571 ∇/L^3
$V_k/\sqrt{L_{ft}}$	=	3,36134 Fn
1hp	=	0.7457 kW
$\dfrac{L}{\nabla^{1/3}}$	=	$\left(\dfrac{28570}{DL\ ratio}\right)^{1/3}$

1 INTRODUCTION TO THE GENERAL THEORY OF POWER PREDICTION

1.1 INTRODUCTION

There are a limited number of computer programs on the market for predicting the required propulsion power of a ship and those available generally deal only with hull resistance and propeller efficiency. Environmental effects such as hull fouling, sea state, wind etc. are totally ignored. Theories abound for all aspects of the powering problem, however, the accuracy and reliability of these are open to debate. The object of this study is to develop an integrated computer program capable of providing an acceptably accurate estimation of the operational propulsion power requirement during the early design stages. The problem is a fairly complex one, and to fully appreciate it requires an understanding of the surrounding issues.

Hypothetically the design of an optimum ship for a given mission profile is possible, practically however, this is not true. Ship design by nature is an iterative process complicated by various trade-offs e.g. cost, strength, speed, manoeuvrability, seakeeping, payload, etc. The problem is further exacerbated, since it is no longer economically viable to tailor propulsion machinery for a specific ship.

The acquisition process for any ship (merchant ship, warship, research ship, etc.) starts with an exploratory phase to determine whether the ship is needed and if so, the envisaged functional requirements and mission profile. With this information at hand the design process begins. This process is best illustrated by the well-known design spiral (Figure 1.1).

1. Assessment
2. Model experiment
3. Empirical formulae
4. Calculation
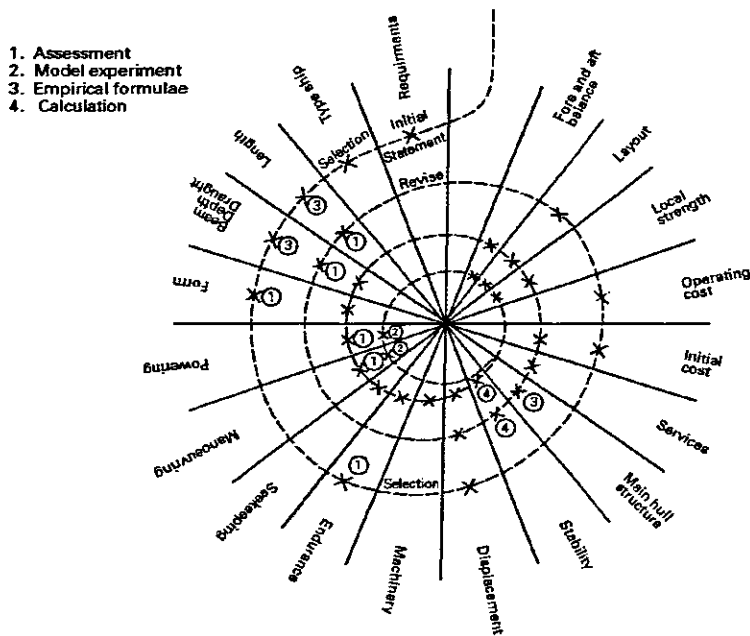
Figure 1.1 - Design Spiral (Rawson & Tupper, 1982:581)

The initial parameter values of a new ship design are derived from an analysis of the requirements, generally using either empirical formulae or a geometric scaling of a proven design. Each parameter has an impact on one or more of the others. Typically, once a hull is broadly defined, an estimate is made of the brake power required to drive it through the water at the required speed. The brake power required dictates the physical size of the propulsion plant and this influences the size of the engine room. The engine room size in turn has an impact on the size of the ship. Generally an increase in ship size necessitates an increase in brake power to maintain the originally specified speed.[1] Any increase in power would again influence the size of the propulsion plant and the cycle starts all over again. This iteration is repeated until a point is reached where the speed, required power and ship size is matched. This example is simplified as the effect of other parameters such as stability, strength, seakeeping, engine types and costs, etc., have been ignored.

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[1] This is not always the case, a ship whose length speed ratio is such that it lies on or near the top of the main hump of the wave resistance curve will benefit from an increase in length in the form of lower wave making resistance.

The importance of estimating the propulsion requirements with reasonable accuracy at an early stage of the design process can thus be appreciated. This is true for both warships and merchant ships. Warships are generally cost constrained and space is at a premium, whilst excess machinery space in a merchant ship does not earn revenue but adds to both initial acquisition and lifetime running costs. In the preliminary design stage, the hull form is only vaguely defined by the various form coefficients (e.g. block coefficient, prismatic coefficient, etc.) and principal dimensions (e.g. length, draught, beam, etc.). These parameter values are not yet rigidly fixed and at best only a rough lines plan may have been produced.

The powering estimation is further complicated in that the propulsive device (propeller) must be optimised within the constraints of the design and the propeller open water efficiencies for the various speeds under consideration must be determined. Another factor that must be considered is the manner in which the propulsive device interacts with the hull.

To facilitate the development of an acceptable method for predicting the preliminary propulsion power requirement, the problem is broken down into the following components which either directly attribute to, or influence its value;

- hull resistance

- appendage resistance

- effect of hull roughness

- effect of hull fouling

- propulsion factors

- transmission of power (propeller)

- wind resistance

- influence of sea state (wave height)

This is not the most scientifically accurate breakdown available, however, it is a generally acceptable one used in everyday practice.

To realistically achieve the objective of this study and facilitate evaluation of the various methods associated with each component requires the development and evaluation of numerous independent software modules. The modules providing the most acceptable results being integrated in the final stages to provide the required end product.

1.2   HULL RESISTANCE

Hull resistance can be predicted with various degrees of accuracy using either theoretical, statistical, experimental or empirical methods or a combination of these. Existing theoretical methods do not allow one to predict hull resistance with any confidence (Newman, 1990). They require a detailed knowledge of the hull geometry which is not available during early design stages and are therefore beyond the scope of this work.

1.2.1   Experimental Prediction

Both model testing and methodical series can be considered experimental prediction methods. They differ in that with model testing the full scale results are scaled from the results of tests carried out on a model that is geometrically similar to the proposed ship. In a methodical series the full scale results are predicted from data extrapolated from a series of tests carried out on a range of models having systematically varied design parameters.

Model testing is an expensive procedure (costing from approximately a quarter to one million plus UK pounds sterling) and is therefore generally only carried out in the latter design stages. It is briefly touched upon as it is fundamental to the development of all methodical series

1.2.1.1 Model Testing.

The basis of experimental prediction lies in model testing. This requires that both model and ship are dynamically as well as geometrically similar. Using dimensional analysis, it can be shown that for dynamic similarity, the Reynolds number (Rn) and Froude number (Fn) must be the same for both ship and model.

This results in an impracticable solution, as the only way to achieve this is to make the model the same size as the ship.

Naval architectural text books credit Froude with the generally accepted approach used to resolve this problem. He postulated that resistance of a ship (R_T) comprised two components, residuary resistance (R_R) and an equivalent flat plate frictional resistance (R_F).

$$R_T = R_R + R_F$$

When size changed (i.e. from ship to model) these components scaled independently according to their own laws. Residuary resistance was assumed to be a function of Froude Number and obtained from tank towing tests. Frictional resistance was determined from the equation $R_F = fSV_k^{1.825}$ which was developed from the results of experiments which he carried out on flat planks

Dimensional analysis indicates that frictional resistance is a function of Reynolds Number and wavemaking resistance a function of Froude Number. A flaw therefore exists in Froude's method as residuary resistance comprises not only of wavemaking resistance but also eddy resistance, viscous pressure drag and frictional resistance due to the curved shape of the ship. These latter three components are influenced by both Froude and Reynolds Number. Nevertheless, Froude's method still provides satisfactory results

Total resistance and the two components which comprise it are often portrayed as non-dimensional coefficients. This is achieved by dividing each by $0{,}5\rho Sv^2$, i.e.

$$\frac{R_T}{0{,}5\rho Sv^2} = \frac{R_R}{0{,}5\rho Sv^2} + \frac{R_F}{0{,}5\rho Sv^2}$$

$$C_T = C_R + C_F$$

The flat plate frictional resistance or non-dimensional friction resistance coefficient (C_F) is generally determined from a skin friction or correlation line. The most widely used line at present is what is generally referred to as the 1957 ITTC correlation line.

$$C_F = 0{,}075 / (Log_{10}Rn - 2)^2$$

This was the line agreed to at the 1957 International Tank Towing Conference (ITTC, 1957). Prior to this, Froude's friction constants obtained from his flat plank experiments were widely used in Europe whilst the Schoenherr friction line, i.e.

$$0{,}242 / \sqrt{C_F} = Log_{10}(Rn \times C_F)$$

was favoured in the USA

1.2.1.2 Methodical Series.

The methodical series or a standard series is derived from a series of models tested in a towing tank. During these tests the design parameters of one or more parent hulls are systematically varied, usually one at a time. The results obtained are cross faired and presented in a graphical or tabular format.

William Froude must be credited with the development of the first methodical series (Froude, 1877) however the popularity of the methodical series is generally attributed to Admiral D.W. Taylor who in 1910 (Taylor, 1911) introduced the well-known Taylor Series. This series is regarded as the forerunner of the methodical series type prediction method. Various other methodical series exist. The British BSRA Series and the American Series 60 are probably the best known of these and the most comprehensive.

In their original published formats, methodical series are cumbersome and time consuming to use, however, if used within their range of application they provide acceptable results.

1.2.2 Statistical Methods

This method implies the creation of a mathematical model by applying regression techniques to resistance data. The source of data generally used is methodical series results, results from a wide range of tank towing experiments and actual ship data. The latter two types are commonly referred to as random data. More recent statistical methods include data from all three sources.

Doust (Doust & O'Brien, 1959) is generally credited with the introduction of statistical analysis into the field of resistance prediction. Since then the idea of replacing tank tests with this type of prediction method has been mooted. Todd (1967) forecast that it could replace many of the routine model tank tests while more recently Schneiders (1990) indicated that the level of accuracy of statistical prediction was comparable with that achieved in tank tests.

1.2.3 Empirical Methods

Empirical methods generally comprise one or more relatively simple equations that indicate overall power required rather than hull resistance. In many instances these equations are a combination of theory and 'rule of thumb'. They were extremely popular in the heyday of slide rules and log tables.

1.3 APPENDAGE RESISTANCE

An appendage can be simply defined as any item protruding from the hull of the ship (e.g. shafts, rudders, etc.) or causing a deviation in the natural flow of the hull lines (e.g. sonar dome, bowthruster, etc.). Appendages are usually sited well below the water surface and are therefore not prone to wavemaking. Their effect on resistance is mainly attributed to friction, i.e. a function of Reynolds number. Further, appendages lie largely within the boundary layer where the flow on the full scale ship is non-uniform. This does pose problems in model testing which is carried out at corresponding ship speeds (same Froude Number for model and ship) but not same Reynolds Number.

1.4 RESISTANCE DUE TO FOULING

In carrying out economic studies regarding viability of a proposed new vessel, it is desirous to have an indication of resistance at various stages of her operational service. This knowledge is also essential if an optimum service profile is to be developed, e.g. trade off between revenue earned and cost of additional fuel if vessel is allowed to remain in service in her fouled (dirty) state.

1.4.1 The Effects of Fouling

The frictional resistance of a ship is at its lowest immediately after its underwater surface has been cleaned and freshly painted. From this point on there is a gradual increase in the frictional resistance brought on by the fouling of the bottom with seaweed, barnacles, etc. This process continues until the ship's bottom is again cleaned and painted. The rate at which fouling takes place is dependent on the operational area of the ship (the warmer the water, the higher the fouling rate), the operational profile (the longer the periods in harbour, the higher the fouling rate) and the antifouling properties of the paint used.

1.4.2 Problems in Estimating Resistance Due to Fouling

Estimating a value for the increase in frictional resistance due to fouling is complicated by the following factors:-

- actual operating profile of every ship is different.

- quality of the antifouling paint may not differ noticeably from batch to batch, however the quality of application may differ vastly. This could be due to poor preparation of the surface, bad workmanship, adverse weather conditions during application, etc.

- the antifouling paint may suffer mechanical damage, e.g. the action of the rubbing of the anchor cable against the hull, the striking of a piece of driftwood, etc.

- the rate of growth on the underwater hull surface is not uniform.

- effectiveness of type of antifouling applied (organotin compounds more efficient than copper based compounds)

To obtain an indication of the added resistance due to fouling, some knowledge of the envisaged operational area of the ship and the type of antifouling applied is necessary.

1.5 RESISTANCE DUE TO HULL ROUGHNESS

The hull of a ship is constructed from numerous steel plates welded together.

The surface qualities of these plates when delivered to a shipyard differ from country to country and dependent on storage methods from shipyard to shipyard. Oxidisation (rust) plays an important role during construction and the quality of the surface deteriorates rapidly if no heed is paid to minimising its effects. Once constructed the harsh environment in which a ship must operates further encourages surface deterioration. This can be minimised by regular painting, cathodic protection, etc. nevertheless a certain degree of deterioration still occurs. Regular dry-docking and painting reduces the rate of deterioration, but the damage is permanent and the surface can never be brought back to its original condition.

The surface quality of the hull has a direct influence on resistance, the poorer the quality the greater the influence. It is therefore necessary to determine an average value for hull roughness and a method to account for resistance due to it plus a method to determine additional resistance when hull roughness exceeds the average.

1.6   THE PROPELLER

Effective power can be considered the power necessary to tow a ship through the water. In practice, it is not a viable proposition to power a ship by towing, therefore one or other propulsive device must be used to transform the power produced by the ship's main engines into thrust. Devices available range from a water paddle to a water jet, none however are 100% efficient. For the purpose of this study only the normal screw type propeller will be considered i.e. no consideration given to highly skewed, surface piercing and super cavitating versions.

1.6.1   Propeller Efficiency

The efficiency of a propeller is influenced by various aspects of hull form geometry, therefore it must be optimised for the ship on which it is to be used. The number of blades, pitch, blade area, diameter, rotational speed, etc. must be determined in order to ensure that the required thrust is delivered and that

cavitation is kept to an acceptable limit. The aim of selecting a propeller is to ensure maximum efficiency in the transmitting of the shaft power into thrust force.

The various parameters are dependent on one another, typically increasing the diameter of a propeller together with a reduction on speed will increase efficiency. This however induces other constraints, i.e. slow turning shafts imply large and expensive gearboxes (which in turn could increase the size of the ship) also very large propellers make it difficult to dock the ship. Additionally a very large propeller would probably require a greater shaft angle from the horizontal plus modifications to the stern to avoid vibration induced by pressure pulses. Both of these factors result in part or whole as a loss of efficiency gained from the larger slow turning propeller.

Propeller efficiency during the preliminary design stage is generally estimated from the open water tests on a methodical propeller series. Results from the open water tests are generally plotted as graphs of Thrust Constant (K_T) and Torque Constant (K_Q) against Advance Coefficient (J). These are all non-dimensional quantities that are obtained as follows:-

$$K_T = \frac{T}{\rho D^4 n^2} \qquad\qquad K_Q = \frac{Q}{\rho D^5 n^2}$$

$$J = \frac{Va}{nD}$$

Open water efficiency (η_O) represented in terms of these non-dimensional quantities is:-

$$\eta_o = \frac{K_T}{K_Q} \times \frac{J}{2\pi}$$

To facilitate estimation of propeller results, diagrams such as the $Bp\text{-}\delta$, $Bu\text{-}\delta$ and $\mu\text{-}\sigma$ have been derived from the $K_T\text{-}K_Q\text{-}J$ series diagrams. Whilst easier to use, they are dimensional and make use of imperial units.

1.6.2 Cavitation

The water flow through the propeller is subject to variations in pressure. If the pressure decreases to the vapour pressure of the liquid at the prevailing temperature, the fluid changes to a vapour. This is known as cavitation and it leads to a loss in efficiency due to the disturbing effect it has on the flow along the propeller surface. An additional harmful effect is that when these vapour cavities collapse, they implode causing mechanical damage to the propeller.

Propellers must therefore be designed to avoid or at least minimise the effects of cavitation.

1.7 PROPULSION COEFFICIENTS

An interaction between the hull and propeller occurs because the hull carries with it a certain layer of water (boundary layer theory). This phenomena is accounted for by utilising the following factors

- Taylor wake factor (or Froude wake factor)
- Relative Rotational Efficiency

Additionally a Thrust Deduction Factor is used to account for the pressure reactions on the hull caused by the propeller.

The problem faced is that these factors have to be estimated for a hull form which is not yet totally defined in the early stages of resistance prediction.

1.7.1 Wake Fraction (w)

Due to the form of the ship, the velocity of the water around the hull varies. Velocity is less than average at the ends and greater than average at amidships. The viscosity of the water also contributes to this effect as the hull drags water along with it thus imparting a forward velocity to the water at the stern. A third contributory effect to the velocity of the water at the stern is wave making. In ships where there is heavy wave making at the stern, the particles of water on the hull which are moving in circles, move either forward or aft relative to the hull.

It follows that the water in the neighbourhood of the propeller has some forward velocity, and in consequence the speed of advance (V_a) of the propeller through the water in this region is less than the ship speed (V_s). This difference in velocity is accounted for by means of a wake fraction (w), i.e.

$$Va = Vs(1 - w)$$

1.7.2   Relative Rotational Efficiency (η_r)

Flow conditions vary between the open water condition and when the propeller is operating behind a ship. This is due, typically, to the influence of the hull form geometry which creates turbulence and inequality of the flow field, and the presence of the rudder. Relative Rotational Efficiency (η_r) accounts for this variation in the flow conditions and is defined as the ratio of the propeller efficiency behind the ship (η_B) to the open water efficiency (η_o), i.e.

$$\eta_r = \frac{\eta_B}{\eta_o}$$

1.7.3   Thrust Deduction Factor (t).

The thrust deduction factor accounts for the increase in resistance due to the propeller suction. It is defined as the difference in thrust (T) and ship resistance (R_T) and is generally expressed as a fraction of the thrust, i.e.

$$T = \frac{R_T}{(1 - t)}$$

The quantity ($1-t$) describes the resistance augmentation where the propeller pressure field changes hull flow patterns.

1.8   INFLUENCE OF WEATHER.

Both wind strength and sea state (i.e. wave height) can have a negative impact on the resistance of a ship. Therefore, to estimate the size of the propulsion plant for a new ship, some indication of the weather patterns experienced in the envisaged area of operation is needed. Information of this type is freely available, however,

the manner in which it is applied to the problem varies from fairly simple empirical/regression equations to extremely complex mathematical solutions.

1.8.1 Wind Resistance

The effect of wind on the projected area of the hull and superstructure gives rise to an added resistance component. The velocity and angle of the wind relative to the vessel plays an important role in determining the value of this component. Wind resistance by comparison to underwater hull resistance is minimal, probably accounting for less than 5% of the total resistance during ship trials (Dove, 1973). Nonetheless it must be accounted for if a realistic power prediction method is to be achieved.

1.8.2 Resistance Due To Sea State

When a ship encounters waves there is an increase in resistance. In head waves this resistance can be attributed to

- diffraction effect of a moving hull on the encountered waves

- the indirect effect of pitching and heaving motions caused by the waves.

In a beam and quartering sea, heavy rolling accompanied by yawing adds to this resistance.

The traditional method for estimating resistance due to sea state was to increase the ship's propulsion power by between 15% and 30% (Strom-Tejsen et al, 1973). An increase in power to maintain a stipulated speed is accompanied by an increase in fuel consumption. When considering a warship with predetermined mission profiles, the amount of fuel on board must be sufficient to complete the mission at a maximum defined sea state. Should the sizing of the fuel tanks be on the conservative side (accommodate a 30% power margin), the size of the vessel is bound to grow and may become unobtainable due to cost implications. Should the tanks be undersized, the ship may find itself in the embarrassing or disastrous situation of not being able to complete its mission.

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Another associated problem is the determination of the maximum speed at which the ship can be safely driven in a particular sea state. There is no point in supplying additional power to overcome forces of the environment if it means the ship will be structurally damaged at those speeds.

1.9 CONCLUSION.

The main objective of this study is to produce a computer program capable of predicting the propulsion power requirements for a wide range of vessels during the early design stage. Ideally the program should be fully integrated, capable of handling all the individual components of the problem and possess the following criteria;

- be capable of providing reasonably accurate estimates
- accommodate any combination of generic data
- be easy to use
- be easy to tailor/customise
- minimise tedious, time-consuming calculations

To achieve this objective requires an investigation of each component involved and an evaluation of the various methods available for dealing with it. This is followed by the integration of the selected methods into a fully integrated Power Prediction Program, and culminates in an evaluation of the integrated solution

2 POWER PREDICTION THEORIES AND METHODS

2.1 INTRODUCTION

Prior to the development of any application software, it is essential to determine what theories and methods are available. A fairly extensive literature study covering all the components of the power prediction problem was therefore necessary. The primary objective of this study was to examine the suitability of the available methods with regard to accuracy, range of application, shortfalls and suitability for programming.

The study was carried out by component, however, certain of the methods investigated dealt with one or more related components. No one method encompassed all the components required to estimate power.

2.2 HULL RESISTANCE PREDICTION METHODS

This section of the study revolves around displacement hull forms, however, semi-displacement hull forms are included, as this type of hull acts in a manner similar to the displacement hull at lower speeds. It is therefore necessary to review the origin, range of application, presentation of results and method of application of available methods.

2.2.1 The Taylor Gertler Standard Series (Gertler, 1954)

The Taylor Gertler series is essentially a reanalyses of the original Taylor Standard Series test data obtained from tank tests at the U.S. Experimental Model Basin over the period 1906-1914.

While it may be argued that the hull form of this series is somewhat dated, the series still appears valid for modern ship forms. At the David Taylor Model Basin in the United States, it is used as a yardstick to gauge resistance characteristics of

new models (Yeh, 1965) whilst the United States Navy uses Gertler's reanalyses for predicting smooth water hull resistance prior to model testing (DDS-051-1, 1984). More recently it has been used for hull form design studies (Brett Wilson, 1992).

2.2.1.1   Description of the Taylor Standard Series

The series was derived from a single parent model which evolved from several parents based on the British Drake class armoured cruiser, HMS Leviathan. The Leviathan was a twin-screw vessel with a cruiser type stern and a bulbous ram bow extended on a raised forefoot. These features were retained in the original parent of the series, however in the actual parent of the series, the forefoot was dropped to the baseline, a three percent bulb was adopted and the maximum section moved to mid-length. The midship section in this final parent was, apart from a small deadrise and relatively large bilge radius, roughly rectangular. With the exception of the bulb, the forward sections were generally U-shaped with the aft sections being somewhat V-shaped. For the major part of the length, the keel was flat, rising at the extreme stern to form a centreline skeg designed to accommodate a single hinge-type rudder.

Two series of experiments made up the original Taylor Series, namely the Series 21 with beam-draught ratio 3,75 and the Series 22 with a beam-draught ratio of 2,25. The prismatic coefficients covered by both series ranged from 0,48 to 0,86.

The resistance data obtained from the tank tests was reduced to residual resistance using the US. Experimental Model Basin 20 foot plank data and the resultant data presented as a series of contours of residual resistance per ton plotted against longitudinal prismatic coefficient and displacement length ratio. In predicting full scale effective horsepower, Tideman friction constants are used to determine the frictional component of resistance.

The original series had numerous shortcomings, namely;

- no allowance was made for blockage correction
- changes in water temperature were not considered

- the models were not provided with turbulence simulators

- the results were dimensional

- Taylor assumed that residual resistance varied linearly with beam-draught ratio

2.2.1.2 Reanalyses by Gertler

Over the period 1941 to 1951 Gertler reanalysed the work of Taylor. This reanalyses, commonly known as the Taylor Gertler series, covered Taylor's original Series 21 ($B/T = 3,75$) and Series 22 ($B/T = 2,25$) results plus a new beam-draught ratio of 3,00. The results for this latter case were achieved by interpolation using the reworked data of the unpublished Series 20 which had a beam-draught ratio of 2,92.

Gertler's reanalyses of Taylor's data encompassed corrections for temperature, transitional flow and blockage. The final data is presented in a non-dimensional format, consisting of curves of residual resistance coefficient versus speed-length ratio (and Froude Number) for various even numbers of volumetric coefficient. Separate families of curves exist for each longitudinal prismatic coefficient at each beam-draught ratio. By introducing the third beam-draught ratio all the shortfalls in the original Taylor Standard Series were eliminated.

The range of application of the series is as shown in Table 2.1

Table 2.1   Taylor Gertler Series - Range of Application

B/T	2,25	-	3,75
C_P	0,48	-	0,86
V/L^3	0,001	-	0,007
Fn	0,15	-	0,60

In the reanalyses, the residuary resistance coefficient was reduced from the model total resistance coefficient using the Schoenherr skin friction line.

2.2.1.3 Application of Taylor Gertler Series

A total resistance coefficient (C_T) is determined from the sum of the residuary resistance coefficient (C_R) and a frictional resistance coefficient (C_F) plus an allowance for hull roughness (C_a), i.e.

$$C_T = C_R + C_F + C_a$$

The residuary resistance coefficient is obtained from the Taylor Gertler graphs of volumetric coefficient plotted against speed-length ratio and residual resistance coefficient. Residual resistance at intermediate volumetric coefficients and B/T ratios is obtained by linear interpolation.

Frictional resistance is estimated using the Schoenherr skin friction line. To account for hull roughness, Gertler proposed that a value of 0,0004 be added to the friction coefficient. This value, added to the Schoenherr friction coefficients provides good agreement with the Froude coefficients for average medium speed cargo vessels of that time.

2.2.1.4 Approximation by Fisher (Fisher, 1972)

Fisher, in his procedure for the economic optimisation of ships designed for the Australian ore trade, derived a series of equations for estimating residuary resistance coefficients (C_R) from the work of Taylor and Gertler.

A metricated version of the equations, as extracted from the FORTRAN subroutine, are as follows:

Beam Draught ratio ≥ 3

$$C_R = \left\{ CRB + 0{,}12(B/T - 3) + 50\left(\nabla/L^3 - 0.007\right) \right\} / 1000$$

Beam Draught ratio < 3

$$C_R = \left\{ CRB - 0{,}2533(3 - B/T) + 50\left(\nabla/L^3 - 0.007\right) \right\} / 1000$$

Where

$$CRB = -1{,}83 + 14{,}02\,SLX - 27SLX^2 + 18{,}32SLX^3$$

$$SLX = (3{,}3613Fn) + Cp - 0{,}7$$

The equations underestimate residuary resistance coefficient in the higher speed ranges, however Fisher considered this of little consequence as his optimum designs fell in the lower speed range where accuracy was greatest.

The range of application of the equations is given in Table 2.2

Table 2.2   Fisher's Equations – Range of Application

B/T	2,25	-	3,75
C_P	0,70	-	0,80
V/L^3	0,005	-	0,007
F_n	0,15	-	0,28

The frictional resistance coefficient is calculated using the 1957 ITTC correlation line with an additional allowance of 0,0004 to account for hull roughness. The wetted surface area is estimated from Saunder's graphs at a block coefficient of 0,993.

2.2.1.5 University College, London, Approximation (Brown, 1994)

For warship design exercises, the University College, London (UCL) derived resistance coefficients from the Taylor series. These were modified slightly to provide a better fit to modern hull forms while at the same time incorporating the 1957 ITTC correlation line data.

Resistance coefficients for a frigate hull form with the following form coefficients are given over a range of Froude number.

- Volumetric coefficient (V/L^3) 0,002

- Beam-Draught ratio   3,75

- Prismatic coefficient   0,60

Corrections are then applied to these resistance coefficients for changes in displacement-length ratio, beam-draught ratio, prismatic coefficient and transom area. The range of application for the UCL approximation is given in Table 2.3.

Brown indicates that this method of estimation generally provides results which

are within 8% of those obtained from model tests.

Table 2.3   UCL Approximation - Range of Application -

B/T	3,0	-	4,0
C_p	0,55	-	0,65
$\nabla/L3$	0,0015	-	0,0025
Fn	0,15	-	0,60

2.2.2   DTMB Series 64 (Yeh, 1965)

The DTMB Series 64 series originated in America at the David Taylor Model Basin, Washington. The series arose from a need to gain information on ships with speed length ratio of two and above. The objective of the series, which comprised 27 models, was to carry out exploitative studies on high speed, low-wave drag hull forms.

The range of applicability of this series is limited, nevertheless it is considered of interest as its results have been included in two independent random data regression analyses, namely by Holtrop (1984) and Fung (1991).

2.2.2.1   Description of Series

This series was developed from a single parent having a round after body chine line. The principal characteristics of the parent hull are shown in Table 2.4.

Table 2.4   Principal Characteristics of Series 64 Parent Hull

Length on waterline	3,048	m
Beam	0,305	m
Draught	1,219	m
Mass displacement (Fresh water)	42,638	kg
Block coefficient	0,450	
Prismatic coefficient	0,630	
Maximum section area coefficient	0,714	
Half angle of entrance (ie)	7°	
Length displacement ratio $(L/\nabla^{1/3})$	6,590	

In general, the Series 64 models had a fine angle of entrance (half angle between

3,7° and 7,8°), downward sloped stems (25° -30°) with cut away forefoot and maximum beam at Station 14. The maximum section area occurred at station 12, with section shapes varying from extreme V to extreme U and no sharp bilge radius. The stems were wide and flat below the design waterline. Transoms were immersed with sharp cut-off at the end. All had the following constant values

- Length on waterline   3,048 m

- Prismatic coefficient   0,630

- longitudinal centre of buoyancy aft of middle length   6,56%

Three block coefficients were examined (0,35; 0,45 and 0,55) at three breadth-draught ratios (2, 3 and 4), with overlapping of the displacement length ratio occurring with variation in block coefficient. The range of the parameters varied as shown in Table 2.5, this can be considered the range of application of the series.

Table 2.5   Series 64 - Range of Application

CB	B/T	∇/L^3
0,35	2 - 4	15 - 35
0,45	2 - 4	20 - 45
0,55	2 - 4	25 - 55

Based on past experience at the David Taylor Model Basin with models of this type, no turbulence stimulators were used.

2.2.2.2 Presentation of Results.

The Series 64 results are presented as contours of speed-length ratio plotted against residuary resistance in pounds per ton of displacement (R_R/Δ) and displacement-length ratio. The residuary resistance in pounds per ton of displacement was reduced from the test results using the Schoenherr skin friction line. The results are also presented in a tabular format.

2.2.2.3 Method of Application

Total resistance of the bare hull is calculated from

$$R_T = R_F + R_R$$
$$= 1/2\rho S v^2 (C_F + C_a) + (R_R/\Delta)\Delta_{ship}$$

Residuary resistance per ton of displacement is determined from the graphs provided. This involves three way interpolation,

- between displacement-length ratio at each block coefficient within each beam-draught ratio

- at constant displacement-length ratio across beam-draught ratio

- at each displacement-length ratio and beam-draught ratio across the block coefficient.

Frictional resistance is calculated using the Schoenherr skin friction line. For estimating wetted surface area, Yeh provided wetted surface area contours and the following empirical formula;

$$S/\sqrt{\Delta L} = 38,76375 - 7,248125(B/T) + 1,2780625(B/T)^2$$
$$- 91,13C_B + 26,425(B/T)C_B - 4.105(B/T)^2 C_B$$
$$- 91,1C_B^2 - 26,775(B/T)C_B^2 + 3,874(B/T)^2 C_B^2$$

where S =   wetted surface area in ft^2

            L =   waterline length in ft

            Δ =   Mass displacement in imperial ton.

To account for a hull roughness, a correlation allowance (C_a) of 0,0004 to 0,0008 is recommended depending on the type of paint used.

2.2.3   NPL High Speed Round Bilge Series (Bailey, 1976)

The NPL High Speed Round Bilge Series originated in the United Kingdom from the then Ship Division of the National Physical Laboratory. The series initially comprised 22 models but in a quest to investigate the effects of longitudinal center of buoyancy the series was extended by another 10 models. Apart from resistance experiments, the series also covered the effect of spray rails, the

influence of transom wedges and propulsion, manoeuvring and seakeeping experiments.

The range of application of this series is very limited, however it is considered relevant as Fung (1991) included its results in his regression data base.

2.2.3.1 Description of Series

The series was based on a single parent having a round bilge hull and designed for operation at Froude Numbers ranging from 0,3 to 1,2. The hull form was characterised by straight entrance waterlines, rounded after body sections and straight buttock lines terminating sharply at the transom. From previous knowledge of advantageous resistance considerations, the hull was designed so that longitudinal centre of buoyancy lay in the after body. All the models in the series were 2,54m long with a block coefficient of 0,397. The longitudinal centre of buoyancy for the initial 22 models tested was 6,4% aft of amidships whilst for the remaining 10 models was varied from 2,0 to 3,8% aft of amidships. The principal characteristics of the parent hull, designated 100A, are shown in Table 2.6.

Table 2.6   Principal Characteristics of NPL Series Parent Hull (100A)

Length on waterline	2,540	m
Beam	0,406	m
Draught	0,140	m
Mass displacement	57,330	kg
Block coefficient	0,397	
Prismatic coefficient	0,693	
Maximum section area coefficient	0,573	
Half angle of entrance (ie)	11°	
Length displacement ratio $(L/\nabla^{1/3})$	6,590	

The variation of hull form parameters for the initial 22 models of the series is shown in Table 2.7. These can be considered the range of application of the series.

Table 2.7   NPL Series - Variation of Parameters

$L/\nabla^{1/3}$	L/B			B/T		
8,3	7,50	-	6,25	4,02	-	5,80
7,1	7,50	-	4,54	2,51	-	6,87
6,59	7,50	-	3,33	2,01	-	10,21
5,76	6,25	-	3,33	1,93	-	6,80
5,23	5,41	-	3,33	1,94	-	5,10
4,86	4,54	-	3,33	2,19	-	4,08
4,47	4,54	-	3,33	1,72	-	3,19

Variation of parameters for the 10 models used to investigate effect of longitudinal centre of buoyancy is shown in Table 2.8.

Table 2.8   NPL Series - Variation of Parameters for LCB Investigation

$L/\nabla^{1/3}$	L/B			B/T			$LCB \% L_{pp}$		
7,1	7,50	-		2,51			−2,0	-	−5,2
5,76	5,41	-	4,54	2,59	-	3,67	−2,0	-	−3,8
5,23	5,41	-	4,54	1,94	-	2,75	−2,0	-	−3,8

2.2.3.2 Presentation of Resistance Results

The resistance data is presented as a series of graphs of volumetric Froude number (F_∇) plotted against length-displacement ratio ($L/\nabla^{1/3}$) and residuary resistance-displacement ratio (R_R/Δ). Residuary resistance was extracted from the total model resistance using the 1957 ITTC correlation line.

Various other graphs are given, e.g. specific resistance coefficient, running trim, rise and fall of hull at its LCG, effect of LCB on resistance, etc.

2.2.3.3 Method of Application

Total resistance (R_T) is determined from the sum of residuary resistance and frictional resistance plus an allowance for hull roughness, i.e.

$$R_T = (R_R / \Delta)\Delta + \left[(C_F + C_a) \times 0{,}5\rho S V^2 \right]$$

Residuary resistance is obtained from the graphs of F_∇ plotted against

$L/\nabla^{1/3}$ and R_R/∇. Linear interpolation is necessary between the F_∇ values and also between the graphs in order to obtain the correct L/B ratio. If the LCB of the hull is different to that of the series, then a correction must be made using the graphs of the 'Effect of position of LCB on resistance'.

Frictional resistance is calculated from the 1957 ITTC line, and wetted surface area can be estimated from the graph supplied. To account for hull roughness, Bailey proposed that a value of 0,0002 be added to the friction coefficient, i.e. a correlation coefficient (C_a).

2.2.4   VTT Mathematical Model (Lahtiharju, 1991)

In an attempt to extend existing series to higher block coefficients and beam draught ratios, the VTT Ship Laboratory Technology Research Center of Finland carried out tests on a series of four round bilge and two hard chine models based on the NPL parent form. The results of these tests together with the NPL series data, the SSPA tests on small fast displacement vessels and the results of existing VTT tests on suitable models, were statistically analysed. In developing the regression equations, a total of 65 round bilge and 13 hard chine models were used. Separate equations were developed for the round bilge and for the hard chine vessels, however, only the round bilge method is applicable to this study.

2.2.4.1 The VTT Series

The hull of the NPL parent (model 100A) formed the basis of the VTT series models with the longitudinal centre of buoyancy and the transom beam to maximum beam ratio being kept the same as the NPL parent. Block coefficient formed a new parameter in the series. All the VTT series models with the exception of one of the hard chine models, had a smaller design draught and larger block coefficient than the NPL parent.

The models were all made of wood and provided with turbulence stimulating studs fitted at stations ½, 1½ and 2½ (of 10). No appendages were fitted. Resistance was measured at 24 values of volumetric Froude number ranging from

0,6 to 3,8.

2.2.4.2 The Mathematical Model

The VTT mathematical model for round bilge vessels is presented as an equation of total resistance-displacement ratio (R_T/∇) of a 45,36 tonne vessel and is strictly only applicable for $F_\nabla = 1.8$ to $F_\nabla = 3,2$

$$R_T / \Delta_{(45,36)} = a_0 + \sum_{i=1}^{6} a_i P_i + \left(\sum_{i=7}^{10} a_i P_i\right) F_\nabla + \left(\sum_{i=11}^{13} a_i P_i\right) F_\nabla^2 + \left(\sum_{i=14}^{16} a_i P_i\right) F_\nabla^3 + \left(\sum_{i=17}^{24} a_i P_i\right) F_\nabla^4$$

where

P_{0-24} hull form parameters or their cross-products

No interpolation is required as the equation is a continuous function of volumetric Froude number.

Total resistance per tonne displacement is obtained from the regression equation together with the following correction for frictional resistance;

$$\left(\frac{R_T}{\Delta}\right)_{corr} = \left(\frac{R_T}{\Delta}\right)_{45,36} + \left\{(C_F + C_a) - C_{F45,36}\right\} 0.5 \frac{S}{\nabla^{2/3}} F_\nabla^2$$

where $C_{F45,36}$ is the frictional resistance coefficient of the 45,36 tonne vessel.

This is simply another way of expressing the generally accepted method used in scaling up the results of model resistance tests i.e. the total resistance of the 45,36 tonne standard vessel (the model) is reduced to a residuary resistance coefficient to which the frictional coefficient of the actual vessel and a correlation allowance is then added. Correlation allowance for the model is assumed to be zero.

The 1957 ITTC correlation line formula is used to determine the frictional resistance coefficient for both actual and the standard 45,36 tonne vessel. No method of estimating wetted surface area is given

Based on literature available, Lahtiharju et al indicated that the value of the correlation allowance may lie between 0,0002 and 0,0008 depending on ship size, with a value of 0,00025 generally accepted as average for a semi-displacement

hull.

Resistance in kilonewton is obtained by multiplying the corrected resistance per tonne value with the actual vessel displacement mass (tonnes) and gravity

The method when tested against ten models not forming part of the regression data base yielded a 3% difference between measured and calculated resistance with a standard deviation of about 5% model over the range of volumetric Froude number 1,8 to 3,2.

2.2.4.3 Range of Application

The range of application of the method (round bilge) as determined by the main dimensions of the vessels used in the analysis is given in Table 2.9.

Table 2.9   VTT Series - Range of Application

Length-displacement ratio ($L/\nabla^{1/3}$)	4,47 -	8,30
Beam-displacement ratio (B^3/∇)	2,25 -	3,35
Length-breadth ratio (L/B)	3,33 -	8,21
Beam-draught ration (B/T)	1,72 -	10,21
Transom to max. section area ratio (A_T/A_X)	0,16 -	0,82
Maximum section area coefficient (C_X)	0,567 -	0,888

For Volumetric Froude numbers less than 1,5 the VTT prediction uses the Mercier-Savitsky method (Mercier, 1973). A weighted average value is applied over the range 1,5 to 1,8.

2.2.5   The YP Series (Compton, 1986)

The YP Series was developed by the staff of the U.S. Naval Academy Hydromechanical Laboratory as a contribution to the Naval Sea Systems Command - Norfolk Detachment design of a new yard patrol craft for the Academy. The series covers soft and hard chine semi-planing transom stern hulls.

The range of applicability of this series is very limited, however it has been included for completeness as it complements the DTMB Series 64 and the NPL

High Speed Round Bilge Series. Only the soft chine results are considered of interest.

2.2.5.1 Description of Series

The series comprised tests on three soft chine and three hard chine models. The models all measured 1,524m (5ft) between perpendiculars and were constructed of wood. The models were tested at Froude numbers ranging from 0,05 to 0,625 and at each of the following three LCG positions

- Forward   2,44 % L_{pp} aft of amidships
- Middle   7,78 % L_{pp} aft of amidships
- Aft   13,12% L_{pp} aft of amidships

The models were all of wooden construction and finished with multiple coats of clear spar varnish. Turbulence stimulation was provided in the form of three vertical rows of brass studs fitted at stations 1½, 2½ and 3½ of 10.

Table 2.10 indicates the hull form characteristics of the soft chine models. The starting point of the series being Model YP 81-1.

Table 2.10   U.S.N. Academy Series – Soft Chine Hull Form Characteristics

	YP 81-1	YP 81-2	YP 81-3
Length-breadth ratio	4,590	3,97	5,17
Beam-draught ratio	3,840	5,05	3,06
Length-displacement ratio	5,695	5,689	5,741
Block coefficient	0,437	0,432	0,432
Prismatic coefficient	0,720	0,724	0,716
Half angle of entrance	17,5°	20,9°	16,5°

2.2.5.2 The Mathematical Model.

Compton provides graphs of residual resistance coefficient as a function of speed and displacement for each of the LCG conditions tested. However the series is primarily considered to be a mathematical model as the digitised results were treated as dependent variable values in a multiple linear regression analysis. The

hull shape and loading parameters were treated as independent variables with separate regression analyses being carried out for each fixed speed. With the exception of the displacement-length term, the equation is non-dimensional. By converting the displacement-length term to an equivalent volumetric coefficient, the following non-dimensional equation is achieved

$$C_R \times 10^3 = a_0 + a_1(L/B) + a_2\{28571\nabla / L^3\} + a_3(LCG/L \times 10^2)$$

Where $a_{0\text{-}3}$ are regression coefficients given as functions of Froude number.

The residuary resistance coefficient is obtained by solving the given regression equation. Frictional resistance coefficient is determined from the 1957 ITTC correlation line formula. A standard value of 0,0004 is used as a correlation allowance for hull roughness. No method of estimating wetted surface area is provided

2.2.5.3 Range of Application.

The range of application of the series as indicated by Compton is given in Table 2.11. with the imperial displacement-length ratios rewritten as non-dimensional length-displacement ratios.

Table 2.11 U.S.N Academy Series - Range of Application

Length-displacement ratio ($L/\nabla^{1/3}$)	5,75	-	6,48
Length-breadth ratio (L/B)	4,00	-	5,20
Beam-draught ration (B/T)	1,72	-	10,21
$LCG - L_{pp}$ ratio	−0,13	-	−0,02
Volumetric Froude number	0,30	-	1,50

2.2.6   The I.O. Series (Zborowski, 1973)

The I.O. Series was developed in Poland at the Gdansk Technical University and comprised of thirteen twin screw, open stern transom models. The results of the original tank tests were never published, however Zborowski (1973) utilised these results to develop an algorithm for estimating resistance and power. The application of the series was directed at preliminary design of high speed cargo

ships, typically the container or semi-container ship.

2.2.6.1 Description of Series

The models which formed the series all had the following constant values

- length $(L = L_{pp})$ 1,9m
- midship section (C_m) 0,977

No particular hull is defined as a parent, however the parameters systematically varied are shown in Table 2.12.

Table 2.12   I.O. Series – Variation of Hull Parameters

C_B	$L/\nabla^{1/3}$	B/T			C_P		LCB % L_{pp}
0,518	6,0	2,25	-	3,35	0,530		-2,250
0,518	6,5	2,25	-	3,35	0,530		-2,250
0,518	7,0	2,25	-	3,35	0,530		-2,250
0,564 - 0,645	6,5	3,35			0,577 -	0,657	-2,335 - -2,40
0,600	6,5	2,80			0,628		-2,400

The models were tested over Froude numbers ranging from 0,25 to 0,35. Turbulence stimulation was provided by means of a 1,5mm diameter trip wire.

2.2.6.2 Presentation of Results

Zborowski presented his data in both graphical and tabular format. The graphical presentation comprises a series of graphs encompassing Froude Numbers 0,25 to 0,35 in increments of 0,01 of:

- total resistance coefficient of model plotted against length displacement ratio and beam draught ratio, and

- total resistance coefficient of model plotted against length displacement ratio and block coefficient

2.2.6.3 Method of Application

The application of the series is similar to the extrapolation method used at towing

tanks. The main difference is that the total model resistance coefficients (C_{Tm}) are obtained from the graphs (or tables) provided instead of from the model test data. The format of the calculation however remains the same i.e.

$$C_{Ts} = C_{Tm} - k(C_{Fm} - C_{Fs}) + C_a$$

where k is a form factor.

Landweber's approximation of the Schoenherr frictional line is used to determine the frictional coefficient (C_F) for model and ship.

$$C_F = 1/(3,5 Log\,Rn - 5,96)^2$$

The choice of the Schoenherr line is somewhat surprising as by 1973 the 1957 ITTC line had to all intents and purposes succeeded it. These two lines are fairly similar at Rn values above 10^7. Below this point the ITTC line has a steeper slope (higher C_F value). Generally the ITTC line can be used in any extrapolation process, as long as it goes back to the model results. This is undoubtedly true for large models (length > 3m) with Reynolds Numbers > 10^7, however it is not considered prudent to do so in this case as Rn for the I.O. models will always tend to be lower than this due to the shortness of the models (1,9m).

2.2.6.4 Range of Application.

Based on the given variations in the various hull form parameters, it can be concluded that the range of application of the series, is as indicated in Table 2.13

Table 2.13   I.O. Series - Range of Application

Length-displacement ratio	6,000	-	7,000
Beam-draught ratio	2,250	-	3,350
Block coefficient	0,518	-	0,645
Prismatic coefficient	0,530	-	0,657

2.2.7   D.T.M.B. Series 60 (Todd, 1963)

In 1948, the Society of Naval Architects and Marine Engineers jointly with the American Towing Tank Conference sponsored the preparation five parent lines

for a series of single screw merchant ships. The lines were developed by the David Taylor Model Basin and the models subsequently tested there under the Bureau of Ships Fundamental Hydromechanics Research Program.

2.2.7.1 Description of Series

Development of the Series 60 was based on systematic variations of length-breath ratio, beam-draught ratio, displacement length ratio and longitudinal centre of buoyancy position of five parent forms having block coefficients of 0,60; 0,65; 0,70; 0,75 and 0,80. The models were all twenty foot long with vertical stem and a stern with an aperture for a single screw. In total, the series comprises tests on sixty two models, all fitted with turbulence stimulators. The parameters systematically varied, are shown in Table 2.14.

Table 2.14 Series 60 – Variation of Hull Parameters

C_B	C_M	C_P	L/B			B/T			LCB % L_{pp}		
0,60	0,978	0.614	6,50	-	8,50	2,5	-	3,5	−2,48	-	+0,52
0,65	0,982	0,661	6,25	-	8,25	2,5	-	3,5	−2,46	-	+1,37
0,70	0,986	0,710	6,00	-	8,00	2,5	-	3,5	−2,05	-	+2,55
0,75	0,990	0,758	5,75	-	7,75	2,5	-	3,5	+0,48	-	+3,46
0,80	0,994	0,805	5,50	-	7,50	2,5	-	3,5	+0,76	-	+3,51

The sections of the Series 60 have a U-shaped character throughout with no rise of floor and a progressively reducing bilge radius with increasing fullness.

2.2.7.2 Presentation of Results

The Series 60 results are presented graphically by the DTMB in;-

- the Taylor style, i.e. for given values of B/T and $V / \sqrt{Lwl}$, charts of contours of R_R in pounds per ton of displacement against C_B and L/B.

- terms of R.E. Froude's circular notation, i.e. for given values of B/T and circular K, charts of contours of $\copyright_{400}$ against C_B and L/B. The estimation uses the Schoenherr frictional coefficient plus a model-ship correlation allowance of 0,0004.

In order to facilitate the comparison of the Series 60 results with British data, Lackenby & Milton (1964) presented the results as curves of $\textcircled{C}_{400}$ plotted against C_B using:-

- R.E. Froude's skin friction corrections

- the 1957 ITTC model-ship correlation line.

- Schoenherr skin friction coefficient plus 0,0004 correlation allowance

Correction factors for variations in LCB, B/T and L/B are obtained from separate sets of contours.

2.2.7.3 Mathematical Model (Shaher Sabit, 1972)

Shaher Sabit applied both curve fitting and regression analysis to the Series 60 data in an attempt to developed a suitable mathematical model. Using curve fitting, he obtained excellent agreement however the equations consisted of between 33 and 66 terms. In the regression analysis he examined both power and polynomial functions and determined that the polynomial function provided the best results.

In the equation, cross-coupling terms to take into account the effect of the interaction of the various hull form parameters on resistance. The general form of the equation is

$$
\begin{aligned}
C_{R400_{(v/\sqrt{L})}} = a_1 &+ a_2(L/B) + a_3(B/T) \\
&+ a_4 C_B + a_5 LCB + a_6(L/B)^2 \\
&+ a_7(B/T)^2 + a_8 C_B{}^2 + a_9(LCB)^2 \\
&+ a_{10}(L/B)(B/T) + a_{11}(L/B)C_B \\
&+ a_{12}(L/B)LCB + a_{13}C_B(B/T)C_B \\
&+ a_{14}(B/T)LCB + a_{15}C_B LCB + a_{16}C_B{}^2 LCB
\end{aligned}
$$

Where

a_{0-15} regression coefficients given as functions of Taylor speed-length ratio.

and $C_{R400_{(v/\sqrt{L})}} = 2.4938 \times \textcircled{C}_{400} \times LBP/\nabla^{1/3}$

The range of application of the mathematical model is given in Table 2.15

Table 2.15 Series 60 – Range of Application

L/B	5,5	-	8,5
B/T	2,5	-	3,5
C_B	0,60	-	0,80
LCB	-2,48	-	3,51
CR_{400}	9,013	-	25,688

No numerical value for the accuracy of the regression equations is provided.

2.2.8   The SSPA Cargo Liner Series (Williams, 1969)

The SSPA Cargo Liner Series originated in Sweden at the Swedish State Shipbuilding Experimental Tank (SSPA), Gothenburg. The series, which covers fast single screw cargo ships, was developed from the results of four series of experiments together with their later extensions.

2.2.8.1 Description of Series

Development of the SSPA Cargo Liner Series was based on:-

- systematic variations of length-displacement ratio, beam-draught ratio and longitudinal centre of buoyancy of two independent series having block coefficients of 0,525 and 0,675

- a 'cross-over' series covering block coefficients 0,6 to 0,75

- tests covering variations of length-breadth ratio at block coefficients 0,625 to 0,725.

- variations in length-displacement ratio for a 0,575 block coefficient parent form

The series has moderate U section shapes and covers a variation of hull form parameters as shown in table 2.16. This can also be considered the valid range of application of the series.

Table 2.16   SSPA Cargo Liner Series - Variation of Hull Parameters -

C_B	$L / \nabla^{1/3}$		L/B		$LCB \ \% L_{pp}$
0,525	5,63	- 6,89	6,18	- 8,35	-2,00
0,575	5,47	- 6,68	6,18	- 8,35	-1,85
0,600	5,99		7,24		-1,70
0,625	5,32	- 6,50	6,18	- 8,35	-1,50
0.650	5,83		7,24		-1,25
0,675	5,18	- 6,33	6,18	- 8,35	-0,75
0.700	5,69		7,24		-0,10
0,725	5,06	- 6,18	6,18	- 8,35	+0,45
0,750	5,56	-	7,24		+0,85

The models were all constructed of paraffin wax and varied in length from 5,5m to 6,6m. Turbulence stimulation was provided by means of a 1mm diameter trip wire sited at station 19.

2.2.8.2   Presentation of Results

In the graphical overall analysis, the results are presented as a family of contours of length-displacement ratio plotted against Froude number and residuary resistance coefficient for each block coefficient. The residuary resistance coefficient was reduced from the test results using the 1957 ITTC line. A standard beam-draught ratio of 2,4 is used with corrections for variation from the standard supplied as a function of block coefficient. It is assumed to be independent of Froude number. The corrections are based on the equation

$$10^3 \Delta Cr = 0,60 \left(C_B - 0,25 \right) \left(B / T - 2,40 \right)$$

The position of longitudinal centre of buoyancy is considered a function of block coefficient and no corrections are supplied for any deviations.

Extrapolation of the presented resistance data to full scale is performed using the 1957 ITTC line. As standard practice, the SSPA tank adds a correlation allowance (C_a) of 0,0004 to account for hull roughness of the ship.

2.2.8.3 Mathematical Model. (Shaher Sabit, 1976).

Using the results obtained from the model tests, Shaher Sabit developed an analytical expression for residuary resistance coefficient which encompassed corrections for variations from the standard for beam-draught ratio and longitudinal centre of buoyancy. He used cross-coupling terms to take into account the effect of the interaction of the various hull form parameters on resistance. The general form of the equation is :-

$$10^3 C_R = a_0 + a_1 C_B + a_2 C_B^{\,2} + a_3 C_B^{\,3}$$
$$+ a_4\left(L / \nabla^{1/3}\right) + a_5\left(L / \nabla^{1/3}\right)^2 + a_6\left(L / \nabla^{1/3}\right)^3$$
$$+ a_7 C_B\left(L / \nabla^{1/3}\right) + a_8 C_B^{\,2}\left(L / \nabla^{1/3}\right) + a_9 C_B\left(L / \nabla^{1/3}\right)^2$$
$$+ a_{10}(B / T - 2,4) + a_{11} C_B(B / T - 2,4)$$
$$+ a_{12}\left(LCB - LCB_S\right) + a_{13} C_B\left(LCB - LCB_S\right)$$
$$+ a_{14}\left(LCB^2 - LCB_S^{\,2}\right) + a_{15} C_B\left(LCB^2 - LCB_S^{\,2}\right)$$

Where

$a_{0\text{-}15}$ regression coefficients given as functions of Froude number.

for $0{,}625 > C_B > 0{,}525$

$$LCB_S = 8{,}499945 - 40.999807 C_B + 39{,}999832 C_B^{\,2}$$

for $0{,}725 > C_B > 0{,}625$

$$LCB_S = 27{,}093853 - 102.000307 C_B + 90{,}000227 C_B^{\,2}$$

2.2.9 BSRA Methodical Series (Pattullo & Parker, 1959; Lackenby & Milton, 1964)

The British Ship Research Association (BSRA) Methodical Series was developed in Britain from resistance data obtained from models tested in the No 1 Tank of the Ship Division, National Physical Laboratory, Teddington. The series covers single screw cargo ships and is derived from four independent parent forms covering first a range of block coefficient and longitudinal centre of buoyancy variations and second variations of length-breadth and length displacement ratio.

2.2.9.1 Description of Series

The series was based on four parent hulls all having the same stern profile and the same midship section. The relationship between block coefficient and longitudinal centre of buoyancy in the load condition is given by

$$LCB \text{ \% of } L_{pp} \text{ from amidships} = 20 \ (C_B - 0,675)$$

The basic characteristics of the parent hulls are shown in Table 2.17.

Table 2.17 Principal Characteristics of BSRA Series Parent Hulls

Model Number	C_B	$LCB \text{ \% } L_{pp}$
NPL 3747	0,65	-0,5
St A. XY	0,70	+0,5
NPL 3155	0,75	+1,5
NPL 3861	0,80	+2,5

The models were made from BP wax and were all fitted with either trip wires or studs to stimulate turbulence.

The first set of resistance data published covered variations of block coefficient and longitudinal centre of buoyancy (Pattullo & Parker, 1959; Moor et al, 1961). The models each measured 5,541 m between perpendiculars with a constant midship section coefficient of 0,98 at a draught of 0,36 m. The midship section having an 83 mm bilge radius, 6.9 mm rise of floor and a 6,9 mm half siding.

The variations in longitudinal centre of buoyancy position with change in block coefficient were obtained by swinging the sectional area curves. Five different longitudinal centre of buoyancy positions for each block coefficient variation were examined. The selections of these were based on the practical range for that fullness of form and are shown in Table 2.18.

Table 2.18   BSRA Series - Variation of *LCB* with C_B

C_B	$LCB \% L_{pp}$
0,65	−2 - +1
0,70	−1 - +2
0,75	+0 - +3
0,80	+0,5 - +3,5

The second set of resistance data published covered variations of length-displacement and breadth-draught ratio (Lackenby, 1964). Two groups of models were tested for each block coefficient, in the first group the length-displacement ratio was varied from the parent form while keeping the breadth-draught ratio constant and in the second group, the breadth-draught ratio was varied with constant length-displacement ratio.

Generally for the first group of models (*B/T* constant, varying $L/\nabla^{1/3}$), the displacement was kept the same as the parent hull resulting in the models having different lengths between perpendiculars. In the second group ($L/\nabla^{1/3}$ constant, varying *B/T*), the length between perpendiculars was generally kept the same as the parent (5,541 m). The exceptions in both groups were the 0,7 block coefficient models which had a constant length between perpendiculars of 5,081m.

The approximate range of application of the BSRA series is shown in Table 2.19.

Table 2.19   BSRA Series - Range of Application

C_B	B/T	$L/\nabla^{1/3}$	$LCB \% L_{pp}$
0,65	2,12 - 3,93	4,28 - 6,40	-2 to +1
0,70	2,12 - 3,93	4,22 - 6,26	-1 to +2
0,75	2,12 - 3,93	4,33 - 6,11	+0 to +3
0,80	2,12 - 3,93	4,60 - 5,97	+0,5 to +3,5

2.2.9.2   Presentation of Results

The resistance data for both sets is presented in the form of Froude's resistance

coefficients (©) corrected to the standard 121,92 (400 ft) BSRA ship using Froude's frictional coefficients. A conversion chart is provided for the 1957 ITTC ship-model correlation line.

The first set of resistance data comprises a set of contours of speed in knots plotted against © and block coefficient for each of the following draughts, 26 ft, 21 ft and 16 ft level trim and 16 ft trimmed 8/400 by the stern. Contours of corrections to the standard © for any deviation in longitudinal centre of buoyancy are also provided.

The second set of data comprises a similar set of contours of speed in knots plotted against © and block coefficient for each of the following draughts, 26 ft, 21 ft and 16 ft level trim and 16 ft trimmed 8/400 by the stern. In addition, for each of these draughts, the following contours of correction factors to be applied

- breadth-draught ratio other than the standard parent value of 2,12

- length-displacement ratios other than those corresponding to the standard parent form dimensions for a particular block coefficient

2.2.9.3 Mathematical Model (Shaher Sabit, 1971)

Shaher Sabit stated that in carrying out the overall analyses, the researchers at BSRA had made use of two widely used assumptions, namely:-

- *The rate of change of the resistance coefficient (©$_{400}$) with respect to the length-displacement ratio is dependant only on the block coefficient for the speed-length ratios under consideration and is independent of the breadth-draft ratio.*

- The rate of change of the resistance coefficient (©$_{400}$) with respect to the position of the longitudinal centre of buoyancy is dependant only on the block coefficient for the speed-length ratios under consideration and is independent of the breadth-draft ratio and length-displacement ratio.

These assumptions were necessitated due to the series not being continuous in all

the directions of the varied parameters. Shaher Sabit indicated that his own research invalidated these assumptions and that the second assumption has led to the wide range of different optimum *LCB* positions suggested by various researchers.

His solution to this problem was to develop a regression equation at each speed-length ratio connecting the dependant resistance coefficient with the independently varied hull parameters. This resulted in the following analytical expression for the resistance coefficient of a standard 121,92 m (400 ft) BSRA ship

$$
\begin{aligned}
C_{R400_{(v/\sqrt{L})}} = {} & a_0 + a_1\left(L/\nabla^{1/3}\right) + a_2\left(B/D\right) + a_3 C_B \\
& + a_4\left(LCB\right) + a_5\left(L/\nabla^{1/3}\right)^2 + a_6\left(B/D\right)^2 \\
& + a_7 C_B{}^2 + a_8\left(LCB\right)^2 + a_9\left(L/\nabla^{1/3}\right)\left(B/D\right) \\
& + a_{10}\left(L/\nabla^{1/3}\right)C_B + a_{11}\left(L/\nabla^{1/3}\right)\left(LCB\right) \\
& + a_{12}\left(B/D\right)C_B + a_{13}\left(B/D\right)\left(LCB\right) \\
& + a_{14}\left(LCB\right)C_B + a_{15}C_B\left(LCB\right)C_B{}^2
\end{aligned}
$$

Where

a_{0-15} regression coefficients given as functions of Froude number.

The *a* coefficients were determined by the theory of minimal variance with a standard error in the order of three percent (Shaher Sabit, 1966). Three equations were developed, i.e. one for each of the original level trim draughts. The results of these equations together with the results of the BSRA method are graphically compared with the resistance curves of three of the original BSRA models and it is shown that the regression equations provides better general agreement with the extrapolated model data than the BSRA methodical series data..

2.2.10 MARIN Mathematical Model (Holtrop & Mennen Method)

The MARIN mathematical model originated at the Maritime Research Institute Wageningen in the Netherlands and is generally attributed to Holtrop and Mennen

2.2.10.1 Development of the Model.

The mathematical model first made its appearance in 1977 (Holtrop & Mennen, 1977). This was followed a year later by an improved model which amongst other things, made allowance for bulbous bows and an improvement in estimating resistance of large waterplane area coefficient ships (Holtrop & Mennen, 1978). The model was then extended in order to improve the power prediction of ships with a high block coefficient and a low length breadth ratio and slender naval ships (Holtrop & Mennen, 1982). Despite this, predictions for high speed craft (Fn > 0,5) were often incorrect and in an attempt to rectify this, the data sample was extended to include the Series 64 hull forms and then reanalysed (Holtrop, 1984). The 1982 mathematical model was developed from 191 random model experiments and full scale data which increased to 334 for the 1984 model.

Table 2.20 taken from van Manen and van Oossanen (1988) shows the range of application for the 1984 model.

Table 2.20   MARIN Mathematical Model - Range of Application -

Ship Type	Fn	C_P		L/B		B/T	
	max.	min	max.	min	max.	min	max.
Tankers, bulk carriers (ocean)	0,24	0,73	0,85	5,1	7,1	2,4	3,2
Trawlers, coasters, tugs	0,38	0,55	0,65	3,9	6,3	2,1	3,0
Container ships, destroyer types	0,45	0,55	0,67	6,0	9,5	3,0	4,0
Cargo liners	0,30	0,56	0,75	5,3	8,0	2,4	4,0
Ro-Ro's, car ferries	0,35	0,55	0,67	5,3	8,0	3,2	4,0

2.2.10.2 The Mathematical Model.

In the model, the total resistance of the hull is divided into the following components:-

- equivalent flat plate resistance (R_F)

- form resistance of hull $(1+k_1)$

- appendage resistance (R_{APP})

- pressure resistance of bulbous bow near surface of water (R_B)

- wave-making and wave breaking resistance (R_W)

- pressure resistance of immersed transom stern (R_{TR})

- model ship correlation resistance (R_A)

$$R_{total} = R_F\left(1+k_1\right) + R_{APP} + R_W + R_B + R_{TR} + R_A$$

Equations were developed for each of these components with the exception of frictional resistance which is calculated from the 1957 ITTC correlation line.

Wavemaking and wavebreaking is calculated from the following equation

$$R_W / \nabla \rho g = C_1 C_2 C_3 \; \exp\left\{mFn^d + m_1 \cos(\lambda Fn^{-2})\right\}$$

which is a simplified adaptation of Havelock's wavemaking equation (van Manen & van Oossanen, 1988)

$$R_W / \nabla \rho g = C_1 \exp^{-mFn^{-2/g}} + \exp^{-mFn^{-2}}\left\{C_2 + C_3 \cos(\lambda Fn^{-2})\right\}$$

where C_n, m and λ are hull dependent coefficients.

By applying different relationships to the hull dependant coefficients, the equation is further divided into two speed regimes, i.e. Fn < 0,4 and Fn > 0,55. Linear interpolation is used to determine values between the two speed regimes.

A standard deviation of 6,9% on model resistance is claimed (UCL, 1988)

2.2.11 Fung's Mathematical Model

To support NAVSEA ship synthesis design programs during early stages of ship design, Fung (1991) developed a mathematical model to predict resistance and power of transom stern hull forms

2.2.11.1 Development of the Model

In developing his mathematical model, Fung carried out regression analysis on three overlapping sets of data which consisted of:-

- an initial set containing 426 test conditions

- an additional 337 conditions added to extend coverage of length displacement ratio and the inclusion of cruiser sterns

- final data reduced to 529 test conditions by the exclusion of cruiser sterns.

The first data set comprised data obtained from various high speed displacement hull form methodical series (e.g. Bailey Series, Series 64, etc.) plus a certain amount of random model test data. Fung postulated that by mixing the methodical with the random test data the data distribution and analytical capability of the model would be enhanced, as the following disadvantages of each data type would be minimised by the other:-

- Random model test data obtained over long periods - possible changes could have occurred with regard to the testing facilities and data acquisition techniques.

- Methodical series do not posses good random rectangular distributions but provide trends.

The range of application of the mathematical model as indicated by the tables of the residuary resistance components and various scatter diagrams is shown in Table 2.21

Table 2.21 Fung's Mathematical Model - Range of Application

$L/\nabla^{1/3}$	4,567	-	10,598
B/T	2,200	-	5,200
L/B	3	-	18
C_W	0,670	-	0,840
C_P	0,520	-	0,700
C_X	0,620	-	1,000
ie	3°	-	20°

2.2.11.2 The Mathematical Model.

The mathematical model for residuary resistance coefficient was developed using multiple step-wise regression analysis for 18 different speed length ratios. The equation ignores the effect of the interaction of the hull form parameters and therefore contains no cross-coupling terms (Fung found the effect of these to be inconclusive). The equation comprises reciprocal, quadratic and linear terms as follows:-

$$Cr_1 = C_1 + a_1 \times \left(\frac{\Delta}{L^3} \times 28571 \right) + a_2 \Big/ \left(\frac{\Delta}{L^3} \times 28571 \right) \Bigg]$$

$$Cr_2 = C_2 + a_3 \times \left(\frac{B_x}{T_x} \right) + a_4 \Big/ \left(\frac{B_x}{T_x} \right)$$

$$Cr_3 = C_3 + a_5 \times C_P + \frac{a_6}{C_P} \qquad\qquad\qquad \Bigg\} \ \text{Reciprocal}$$

$$Cr_4 = C_4 + a_7 \times C_X + \frac{a_8}{C_X}$$

$$Cr_5 = C_5 + a_9 \times ie + \frac{a_{10}}{ie}$$

$$Cr_6 = C_6 + a_{11} \times \left(\frac{A_{20}}{A_x} \right) + a_{12} \times \left(\frac{A_{20}}{A_x} \right)^2 \Bigg\}$$

$$\qquad\qquad\qquad\qquad\qquad\qquad\qquad \text{Quadratic}$$

$$Cr_7 = C_7 + a_{13} \times \left(\frac{B_{20}}{B_x} \right) + a_{14} \times \left(\frac{B_{20}}{B_x} \right)^2 \Bigg\}$$

$$Cr_8 = C_8 + a_{15} \times \left(\frac{T_{20}}{T_x} \right)$$

$$Cr_9 = C_9 + a_{16} \times \left(\frac{A_0}{A_x} \right) \qquad\qquad\qquad \Bigg\} \ \text{Linear}$$

$$Cr_{10} = C_{10} + a_{17} \times \frac{S}{(L \times D)^{0.5}}$$

Where a_{1-17} are regression coefficients and C_{1-10} constants which when summed equal zero.

Residuary resistance coefficient is obtained by summing the terms i.e.

$$C_R = Cr_1 + Cr_2 + Cr_3 + Cr_4 + Cr_5 + Cr_6 + Cr_7 + Cr_8 + Cr_9 + Cr_{10}$$

Frictional resistance is then calculated using the 1957 ITTC Line. To account for

hull roughness, a standard value of 0,0004 is added to the friction coefficient.

Values for the regression coefficients and constants were not published, instead Fung provided tables of the residuary resistance components for each function of hull form over Froude number 0,18 to 0,68

Equations for estimating transom depth ratio (T_{20}/T_X), wetted surface area and half angle of entrance at the early stages of the design are given. The latter two however, require a knowledge of the position of the longitudinal centre of buoyancy, a term not used in the regression equation.

2.2.11.3 Fung's Mathematical Model for Cruiser Sterns

In the discussion to the paper 'The Performance of a Systematic Series of Ice Capable Hull Forms in Open Water' (Zahn et al, 1992), Fung provided the following regression equation together with its coefficients for estimating the resistance of cruiser stern ships.

$$
\begin{aligned}
C_{TL} = & \, a_1 \times \left(\frac{\Delta}{L^3} \times 28571 \right) + a_2 \Big/ \left(\frac{\Delta}{L^3} \times 28571 \right) + a_3 \times \left(\frac{B_x}{T_x} \right) + a_4 \Big/ \left(\frac{B_x}{T_x} \right) \\
& + a_5 \times C_P + \frac{a_6}{C_P} + a_7 \times C_X + \frac{a_8}{C_X} + a_9 \times ie + \frac{a_{10}}{ie} + a_{11} \times \left(\frac{LCB}{LWL} \right) \\
& + a_{12} \times \left(\frac{LCB}{LWL} \right)^2 + a_{13} \times \left(\frac{A_0}{A_x} \right) + a_{14} \times \left(\frac{A_0}{A_x} \right)^2 + a_{15} \times \left(\frac{A_{20}}{A_x} \right) \\
& + a_{16} \times \left(\frac{A_{20}}{A_x} \right)^2 + a_{17} \times \left(\frac{B_{20}}{B_x} \right) + a_{18} \times \left(\frac{B_{20}}{B_x} \right)^2
\end{aligned}
$$

The equation provides an estimate of the dimensional Telfer Resistance Coefficient (C_{TL}) and is similar in format to that used for transom stern ships, i.e. it contains reciprocal, linear and quadratic terms but no cross-coupling terms.

The range of application for the equation is not indicated, necessitating a degree of caution when applying it. Notwithstanding, it complements the equation for transom stern ships and thus contributes to increasing the area of application of Fung's method.

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2.2.12   Empirical Equations

Empirical methods arose from the need to obtain rapid estimations of power during the preliminary design stages and for contract purposes at a time when slide rules were the order of the day. The introduction of high speed computers into the design environment has made this method virtually but not quite redundant. They are still predominant in Naval Architecture and Marine Engineering course syllabi and are mentioned in most modern textbooks relating to this field.

Empirical equations are generally dedicated to a specific ship type, primarily due to their accuracy being directly influenced by hull form and operating conditions. Probably the oldest and best known empirical formula is the Admiralty Coefficient.

$$Power = \left(\Delta^{2/3} \, V_k^{\,3} \right) / A_C \qquad kWatt$$

The value of the Admiralty Coefficient (A_C) varies between 350 and 600 dependent on the type of ship. Munroe-Smith (1975:38) provided the following formula for estimating this value.

$$A_C = 26 \left(\sqrt{L} + 150 / V_k \right)$$

Brown (1994) gives some interesting insight to the origin of the Admiralty Coefficient. It was developed circa 1840 and was used to compare the nominal horsepower power per ton displacement of ships. The nominal horse power being based upon internal volume of the engine.

2.3   PREDICTION OF APPENDAGE RESISTANCE

Difficulties exist in scaling appendage resistance from models as each appendage has its own typical length which is much smaller than the model or ship length and accordingly therefore, running at its own Reynolds number. Researchers such as Hoerner and Peck have postulated empirical equations for estimating appendage drag (van Manen & van Oossanen, 1988), however they require that the appendage be reasonably well defined. Typically, for a rudder, the maximum

thickness, average chord length, frontal area of section of maximum thickness, etc. must be known. This information is generally not available at the early design stages and even if it were, the usefulness of the equations is questionable as the degree of definition required misleads one into expecting overly accurate results. This is not the case. Researchers in the field have found that these equations can over predict appendage resistance by up to 40% at a Froude number 0,5 or less and under predict by up to 100% at Froude number greater than 0,5 (van Manen & van Oossanen, 1988). The differences possibly attributable to the physical location of the appendages examined, for example, the shadowing effect of any appendages in tandem, interaction due to appendages abreast of one another and differences in wake velocities.

2.3.1   Treatment of Appendage Resistance.

To estimate appendage resistance in the early design stage requires a method that can be applied generally and which at the same time delivers results with an acceptable degree of accuracy. Only three methods appear to fulfil these criteria, namely;

- expressing appendage resistance as a percentage of total resistance/ power based on similar type ships.

- use of the 1957 ITTC line combined with a form coefficient $(1+k_2)$

- statistical analysis based on parameters such as waterline length, propeller type, diameter, etc.

2.3.1.1   Percentage based on similar type ship.

This appears to be the most common method available and is proposed by, amongst others, Saunders (1957) and Brown (1994). The methods proposed by them differ in that Brown utilises a constant percentage increase over the speed range, whilst Saunders provides for a varying percentage increase with a difference of up to 30% over the speed range.

2.3.1.2   ITTC line combined with Form Coefficient.

The basis of this method is to treat the appendage as a 2-D flat plate of similar

surface area to which a form coefficient $(1+k_2)$ is applied to correct for 3-D effects. Holtrop and Mennen (1978, 1982) advocates the use of this method and provides $1+k_2$ values for a variety of streamlined, flow orientated appendages. Appendage resistance is estimated from

$$R_{app} = 0,5 \rho V^2 S_{app} \left(1 + k_2\right)_{eq} C_F$$

where

$$\left(1 + k_2\right)_{eq} = \frac{\sum \left(1 + k_2\right) S_{app}}{\sum S_{app}}$$

2.3.1.3   Statistical Analysis.

With the exception of Fung (1991), this method does not appear to be widely utilised. For twin screw open stern ships, Fung categorised the problem as a function of propeller diameter and type, i.e. fixed or controllable pitch. He quantified the resistance characteristics of the appendages by the equation

$$Cd_{app} = \left(\frac{12,458 Pe_{app} \times 1E3}{L \times V_k^3}\right) \Big/ D$$

and estimated the drag coefficient for a ship with fixed pitch propeller from

$$Cd_{app} = 3,312 - \left(2,727 L/304,8\right) + 1,488 \times \left(L/304,8\right)^2$$

and for a controllable pitch propeller from

$$Cd_{app} = 5,1341 - 0,0276 L + 9,0927 E - 6 \times \left(3,2808 L\right)^2 - 3,8721 E - 9 \times \left(3,2808 L\right)^3$$

2.4   IMPACT OF FOULING ON RESISTANCE.

Various studies have been carried out with regard to the effect of fouling on frictional resistance and resultant energy performance. Trials carried out in the early fifties on the 'Lucy Ashton' painted with a smooth, bituminous aluminium paint having no antifouling properties showed an average increase in frictional resistance of 0.8 percent per day (Smith, 1955). The absence of antifouling

properties from the paint used on the Lucy Ashton however diminishes the usefulness of the results in estimating added resistance.

Added resistance due to fouling plays an important role in through life costing analysis. Consider for example the additional operating costs incurred from fouling on the American Pacific Fleet aircraft carriers. Hering (1980) estimated that if fouling were allowed to continue unchecked on these vessels, the fuel penalty would increase by three-quarter percent per month for the first 24 months and half percent per month thereafter. This equates roughly to an increase in fuel costs of 288% over a period of 30 months. The period considered is not excessive. It is not uncommon for operators such as Exxon to operate vessels in tropical waters for extended periods of 30 months between dry-docking (Ellingsen et al, 1977).

2.4.1 Fouling Control

In order to minimise the effects of marine growth on the underwater hull, recourse is made to painting it with a paint containing a biocide. Paints of this type comprise two basic groups, the conventional antifouling and the self polishing copolymer (SPC).

Conventional antifouling paints generally contain copper which is slowly leached out to form a toxic interface with the sea water. The life of such a paint system varies from about fifteen months to about three years.

The early 1970's saw the introduction of the SPC's. They have an organo-tin base (usually tributyltin) which is chemically bound to a suitable polymer. The release of the toxin is triggered by surface hydrolysis in sea water. This depletion method is not fully understood, however it is believed that it is mainly dependent on mechanical or biological removal of the hydrolysed layer and is only slightly dependent on solubility in sea water (Preiser, 1977). The life of today's SPC system is about five years.

The capability of the SPC in retarding marine growth on a hull is exceptional when compared to conventional antifoulings, however, environmentally it is less

friendly. This has resulted in legislation being passed in many countries banning the application of antifoulings containing tributyltin (e.g. Japan, New Zealand, Austria, etc.) whilst others have posed limits on the release rates (e.g. Australia - less than 5 μg TBT/cm^2/day, USA and Canada - less than 4 μg TBT/cm^2/day). Notwithstanding this, antifoulings containing tributyltin have over the last number of years captured the largest share of the market and indications are that it will continue to do so (MER, 1994). In 1984 the British Agriculture Ministry Scientists condemned the use of tributyltin in certain applications, two years prior it had been tested and banned in France (Smith, 1984). This combined with the more recent legislation of many countries indicates that stricter legislation is inevitable and consequently must impact negatively on the future use of antifouling paints containing tributyltin

2.4.2   Estimation of Added Resistance due to Fouling

When estimating added resistance due to fouling, it is important to make a distinction between the two groups of antifouling paint. If an SPC is applied then the resulting added resistance due to fouling can be regarded as negligible. Published approaches to this problem by both the Royal Navy and the United States Navy assume the use of a conventional antifouling paint.

2.4.2.1   The Royal Navy Approach

The Navy Department of the Ministry of Defence (MOD) originally allowed for fouling by increasing the skin frictional resistance by a standard value per day out of dry dock, i.e. 0.25% in temperate waters and 0,5% in tropical waters (Rawson & Tupper, 1982:399) A 'deep and dirty' state being utilised in determining the frictional resistance, defined as the deep displacement condition of the ship six months out of dock.

Trials carried out over a two year period on four frigates (two in temperate and two in tropical water) and two destroyers (both in temperate water) led the MOD to revise these values to increases of 56% six months out of dock in tropical water and 28% six months out of dock in temperate water. Pro-rata rates being

applied for longer or shorter periods (UCL, 1988). This equates to an increase in frictional resistance of 0,3068% per day in tropical water and 0,1534% per day in temperate water. The percentage increase in added resistance of two of the vessels involved in the trials closely followed the 0,25% line, falling off after about nine months. The trend that can be deduced from these graphs indicate that added resistance generally tends to fall off after about 9-15 months.

2.4.2.2 The United States Navy Approach.

After a two year period out of dry dock, the United States Navy makes allowance for the added resistance due to fouling by adding a fixed value of 0.0007 to the Correlation Coefficient (DDS-051-1, 1984). No mention is made of values applied for intermediate periods so it is assumed that a linear pro-rata value is used.

2.5   RESISTANCE DUE TO HULL ROUGHNESS

2.5.1   Hull Roughness

Circa 1980 the mean value of hull roughness of new ships beginning service was 129 µm with a mean initial rate of increase of between 20 - 30 µm per year dependent on the coating system used, cathodic protection, the number of drydockings and the quality of work carried out at the drydockings. The practical limit using the technology available was 70 µm, whilst values in excess of 200 µm were not unknown on new ships (Townsin, 1980)

Hull roughness over the period 1980 - 1986 showed a further decrease. Pre-trial roughness surveys carried out by BMT Ltd on 11 new vessels yielded a mean value of 113 µm, whilst in Japan the mean hull roughness of six new buildings during this period was 107 µm (Townsin et al, 1986).

2.5.2   Hull Roughness Above 150 µm

To account for the power increase due to hull roughness above the 150 µm value, Holtrop and Mennen (1982) postulate the formula adopted by the 1978 ITTC

from work reported by Bowden and Davidson (Townsin, 1985).

$$\Delta C_F 10^3 = 105 \left(\frac{\gamma}{L}\right)^{1/3} - 0,64$$

where ΔC_F =   Roughness allowance

             γ =   Average of hull roughness (m)

The basis of this formula was obtained from 15 trial measurements of ten ships equipped with thrustmeters. It is surprising to note that Reynolds number was not included even though the problem is essentially one of frictional resistance.

The 1984 ITTC realised that this formula itself included correlation error. Roughness drag was then reduced to

$$\Delta C_F 10^3 = 44 \left[\left(\frac{\gamma}{L}\right)^{1/3} - 10 R n^{-1/3} \right] + 0,125$$

Grigson (1987) argues that neither of the formula proposed by the ITTC have a valid scientific basis, and concludes that the quality of the surface topography is as important as the height of roughness in governing viscous drag.

2.6 PROPELLER SERIES

2.6.1 Wageningen B-Screw Propeller Series. (van Lammeren et al, 1969).

The Wageningen B-screw series evolved from the A4-40 screw series tests carried out at the NSMB in 1936. The aerofoil blade sections of this series had a number of disadvantages, namely; the narrow blade tips and aerofoil sections over the complete blade made them unsuitable for use under cavitation conditions and they had unfavourable backing characteristics.

This led to the development of the B-screw series, starting with the B4-40 which had wider blade tips and aerofoil sections only near the hub. Over the years the range of this series was gradually increased to 21 screws. Circa 1968 fairing of the series by means of regression analysis was began together with corrections for Reynolds number using the Lerbs equivalent profile method (van Lammeren et al,

1969).

Briefly in the Lerbs equivalent profile method, the blade section at 0.75R is assumed to be equivalent for the whole blade. The theoretical minimum drag coefficient of the equivalent blade section is calculated using the Hoerner method whilst the lift and drag coefficients and the corresponding angle of attack are deduced from the K_T K_Q values obtained from the open water tests.

2.6.1.1 Details the B-Screw Series

The propellers making up the B-screw series have from 2 to 7 blades with blade-area ratios ranging between 0,30 and 1,05. The blades have circular back sections near the blade tips and aerofoil sections near the hub

A summary of the range and characteristics of the B-screw series is given in Table 2.22 (compiled from van Lammeren et al, 1969 and Wright, 1965)

Table 2.22 Summary of B-Screw Characteristics

	Number of blades					
	2	3	4	5	6	7
Expanded area ratio (A_E/A_O)	0,30 0,38	0,35 0,50 0,65 0,80	0,40 0,55 0,70 0,85 1,00	0,45 0,60 0,75 1,05	0,50 0,65 0,80	0,55 0,70 0,85
Pitch ratio (P/D)	0,5 - 1,4	0,5 - 1,4	0,5 - 1,4	0,5 - 1,4'	0,6 - 1,4	0,6 - 1,4
Blade thickness ratio (t/D)	0,055	0,050	0,045	0,040	0,035	0,035
Boss diameter ratio (d/D)	0,180	0,180	0,167	0,167	0,167	0,180
Pitch reduction at blade root	0	0	20%	0	0	0
Blade rake angle (φ)	15°	15°	15°	15°	15°	5°

The results of the B-screw series have been presented both graphically and mathematically in a wide variety of formats. Graphical formats include the well known non-dimensional KT-J and KQ-J diagrams and the dimensional B_p-δ, B_u-δ and μ-σ diagrams. More recently a new form of optimisation diagram was

proposed by Loukakis and Gelegenis (1989) where families of curves with constant values for Va, $SHP.n^2$ and $T.n^2$ (for D_{opt}) and Va, SHP/D^2 and T/D^2 (for n_{opt}) are plotted on P/D versus $n.D$ axes.

2.6.1.2 Mathematical Model

Various mathematical models have been presented for the B-screw series. The initial model presented as polynomials by van Lammeren et al (1969), covered only the four and five bladed screws and did not take into account the effects of Reynolds number. Based on these polynomials Shaher Sabit (1976) developed regression equations for optimum efficiency of the series covering both the optimum diameter and the optimum rate of rotation approach.

A mathematical model from the Wageningen Ship Model Basin covering the full range of the series with corrections for Reynolds number effects was presented by Oosterveld and van Oossanen (1975). The model took the following form

$$K_T, K_Q = \sum_{s,t,u,v} \left[C_{stuv}.(J)^s.(P/D)^t.(A_E/A_O)^u.(z)^v \right]$$

where C_{stuv} are regression coefficients.

Polynomials were also provided to correct for the effects of Reynolds number above 2×10^6. It is interesting to note that Loukakis and Gelegenis (1989) advise against applying the correction for Reynolds number. This is based on their investigations which tend to indicate that the polynomials at Reynolds number 2×10^6 tend to take into account in an approximate manner the full size propeller roughness effect.

Based on this mathematical model, Yosifov et al (1986) developed optimum characteristic equations for diameter (D_{opt}) and speed of rotation (n_{opt}) for both the K_T-J and the K_Q-J diagrams. These equations took the following form

$$n_{opt}: J, P/D, n_o = \sum_{i=0}^{6} \sum_{j=0}^{6} \sum_{k=0}^{6} \left[A_{ijk}.(K_d)^i.(\log Rn)^j.(A_E/A_O)^k \right]$$

$$D_{opt}: J, P/D, n_o = \sum_{i=0}^{6} \sum_{j=0}^{6} \sum_{k=0}^{6} \left[A_{ijk}.(K_n)^i.(\log Rn)^j.(A_E/A_O)^k \right]$$

Where A_{ijk} are regression coefficients and

$$K_d = D.Va\sqrt{\frac{\rho}{T}} = \frac{J}{\sqrt{K_T}}$$

$$K_n = \frac{Va}{\sqrt{n}}\sqrt{\frac{\rho}{T}} = \frac{J}{\sqrt[4]{K_T}}$$

The equations are valid in the Reynolds number range 2×10^6 to 1×10^7 and over the range of blade area ratios given in Table 2.23

Table 2.23 Range of BAR Validity for B-Screw Optimum Equations

No of blades	A_E/A
2	0,30 - 0,38
3	0,35 - 0,80
4	0,40 - 1,00
5	0,45 - 1,05
6	0,50 - 0,80
7	0,55 - 0,85

2.6.1.3 Cavitation Considerations

The area of the propeller blade must be large enough to avoid cavitation conditions, whilst at the same time it must be kept as small as possible to avoid a loss in efficiency. To determine an acceptable blade area ratio Oosterveld and van Oossanen (1975) proposes the Keller formula, i.e:

$$\frac{A_E}{A_O} = \frac{(1,3+0,3Z)}{(P_o - P_V).D^2} + K$$

Where K = 0 for fast twin-screw ships

= 0,10 for other twin-screw ships

= 0,20 for single-screw ships.

However, amongst others, Wright (1965) and Loukakis and Gelegenis (1989) propose the use of the Burrill cavitation diagram for determining an acceptable blade area ratio.

An often used alternative to the preceding methods is to apply a loading coefficient i.e.

$$Loading\ Coefficient = \frac{Thrust}{\pi \times \frac{D^2}{4} \times BAR}$$

In this method the average pressure loading on the suction face of the propeller is limited to a value generally between 50 to 70 kPa.

2.6.2 Newton Rader Propeller Series (Newton, 1961)

The Newton Rader series resulted from a British Admiralty contract placed with Vosper Limited, Portsmouth for a limited methodical series of tests of ten inch (254 mm) model propellers suitable for high speed craft. The series, comprising twelve methodically varied, geometrically similar propellers were tested in the Vosper Cavitation Tunnel at nine cavitation numbers over a wide range of slip.

2.6.2.1 Details of the Newton-Rader Series.

The propellers making up the series were all three bladed with cambered-face segmental sections and constant radial pitch distribution. The parent of the series had a blade area ratio of 0,71 and at 0,7 radius a pitch ratio of 1,25. A summary of the propellers tested is shown in Table 2.24

Table 2.24 Summary of Newton Rader Series Propeller Models

Blade area ratio	Pitch ratio (P/D)			
0,48	1,05	1,26	1,67	2,08
0,71	1,05	1,25	1,66	2,06
0,95	1,04	1,24	1,65	2,04

Each propeller was tested at the following cavitation numbers; 0,25; 0,30; 0,40; 0,50; 0,60; 0,75; 1,00; 2,5 and ±5,5 (corresponding to atmospheric pressure).

The results were presented in tabular format and comprised J, K_T, K_Q and η values for each pitch ratio, blade area ratio and cavitation number.

2.6.2.2 Mathematical Model (Kozhukharof & Zlatev, 1983)

Using multiple linear regression analysis, Kozhukharof and Zlatev developed

polynomials for describing the performance of the Newton-Rader series. These equations took the following form

$$K_T = \sum_{i=1}^{101} \left[A_i \cdot \left(\frac{J-0.55}{1.65} \right)^{a_i} \cdot (G)^{b_i} \cdot \left(\frac{P}{D} - 1 \right)^{c_i} \cdot \left(\frac{A_E}{A_O} \right)^{d_i} \right]$$

$$10K_Q = \sum_{j=1}^{101} \left[A_j \cdot \left(\frac{J-0.55}{1.65} \right)^{a_j} \cdot (G)^{b_j} \cdot \left(\frac{P}{D} - 1 \right)^{c_j} \cdot \left(\frac{A_E}{A_O} \right)^{d_j} \right]$$

Where

$$G = \exp \left[-0.3 \left| \ln \left(\frac{\sigma}{2.5} \right)^3 \right| \right]$$

The model was developed from the published results of the series with the exclusion of the data for atmospheric conditions. The accuracy of the model is not stated, however graphs of K_T, K_Q-J provided for both the original data and the mathematical model indicate a reasonably high level of correlation.

2.6.2.3 Cavitation Considerations

The Newton-Rader series was designed to operate under cavitation conditions and therefore no considerations are made for this effect.

2.6.3 Gawn Propeller Series (Gawn, 1953)

This series originated at the Admiralty Experimental Works (AEW), Haslar and comprised of a series of tests in the No. 2 Ship Tank with 20 inch (508 mm) diameter three bladed propellers in which the pitch and blade width were systematically varied.

2.6.3.1 Details of the Gawn Series

The propellers making up the series were all of the same basic type, i.e. three bladed with an elliptical blade outline, flat-face segmental sections and constant face pitch distribution. The series covered the range of blade area ratio from 0,2 to 1,1 in increments of 0,15 and uniform face pitch ratio from 0,4 to 2,0 in increments of 0,2. A total of 37 models were tested with no particular model

defined as the parent. The results were presented graphically for each propeller as curves of K_T, K_Q and η_o plotted to a base of J. Table 2.25 shows the range of models tested and also indicates the range application of the series. The wider range of applicability is due to extrapolation of the experimental results.

Table 2.25 Gawn Propeller Series - Range of Application

BAR	Range of P/D tested		Applicable range of P/D	
0,20	0,4	-	1,0	0,4	-	2,0
0,35	0,4	-	1,2	0,4		2,0
0,50	0,4	-	2,0	0,4	-	2,0
0,65	0,4	-	2,0	0,4	-	2,0
0,80	0,8	-	1,6	0,6	-	2,0
0,95	1,0	-	1,6	0,6	-	2,0
1,10	0,8	-	1,4	0,6	-	2,0

2.6.3.2   Mathematical Model (Shen & Marchal, 1995)

Using regression analysis, Shen and Marchal developed polynomials for describing the performance of the Gawn series. These equations took the following form

$$K_T,10K_Q = \sum_{i,j,k}\left[C_{ijk}\cdot\left(A_E / A_O\right)^i.\left(P/D\right)^j.\left(J\right)^k\right]$$

where C_{ijk} are regression coefficients.

No indication is given regarding the accuracy of the equations.

2.6.3.3   Cavitation Considerations

No particular method of determining cavitation criteria is advocated, however, the approaches recommended for the B-screw series can be utilised.

2.6.4   Gawn-Burrill Propeller Series (Gawn & Burrill, 1958)

The testing of the models for this series was carried out at King's College, Newcastle as a result of an Admiralty research contract. The series was tested in the cavitation tunnel of the Department of Naval Architecture and comprised of tests at different cavitation numbers with 16 inch (406,4 mm) diameter three

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bladed propellers in which the pitch and blade width were systematically varied.

2.6.4.1   Details of the Gawn-Burrill Series

The propellers making up the series were all of the same basic type, three bladed with an elliptical blade outline and flat-face segmental sections with constant face pitch distribution. The series covered a range of uniform face pitch ratio from 0,6 to 2,0 and blade area ratio from 0,5 to 1,1. Each propeller was tested at the following cavitation numbers; 0,50; 0,75; 1,00; 1,50; 2,00; and 6,3 (corresponding to atmospheric pressure). The parent of the series (model KCA 110) had a blade area ratio of 0,8 and at 0,7 radius a pitch ratio of 1,0.   A summary of the propellers tested is shown in Table 2.26

Table 2.26 Summary of Gawn-Burrill Screw Series

Pitch ratio (P/D)	0,6	0,8	1,0	1,2	1,4	1,6	2,0
Blade area ratio (BAR)	0,50	0,50	0,50	0,50	0,65	0,65	0,50
	0,65	0,65	0,65	0,65	0,80	0,80	0,65
	0,80	0,80	0,80	0,80	0,95	0,95	0,80
		0,95	0,95	0,95	1,10	1,10	0,95
		1,10	1,10	1,10			

The results were presented graphically for each propeller as curves of K_T, K_Q and η_o plotted to a base of J at each cavitation number

2.6.4.2   Cavitation Considerations

Use of the Burrill cavitation diagram is advocated for determining an acceptable blade area.   However all the approaches recommended for the B-screw series can also be utilised for the Gawn-Burrill series.

2.7   PROPULSION COEFFICIENTS

Propulsion coefficients are generally estimated using equations which are empirical in nature or have been developed using statistical techniques.   The majority of methodical series provide either curves or equations for estimating these coefficients, however, they are limited to use with the series in question.

2.7.1 General Empirical Methods

A wide variety of empirical equations exist for estimating the wake and thrust deduction factors. These range from fairly simplistic equations taking only the form or fullness of the ship into account to more detailed equations encompassing factors such as shaft angle.

2.7.1.1 Simplistic Equations

The more common of these simplistic equations include:-

a. D.W. Taylor's equation for wake fraction based on results obtained by Luke (Muckle, 1975:292)

$$w_t = -0,05 + 0,50C_B \qquad \text{for single-screw ships}$$

$$w_t = -0,20 + 0,55C_B \qquad \text{for twin-screw ships}$$

b. The Hecksher equations for wake and thrust deduction of a single screw ship (Poradnik Okretowca, 1960).

$$w_t = 0,7C_P - 0,18$$

$$t = 0,5C_P - 0,12$$

c. The Schiffbaukalender equations for wake and thrust deduction of a single screw ship (Poradnik Okretowca, 1960).

$$w_t = -0,24 + 0,75C_B$$

$$t = \frac{2}{3}w_t + 0.01$$

2.7.1.2 Complex Equations

Some of the more complex methods include:

a. Telfer's expression for wake fraction of single screw ships. This was based on data presented by Bragg (Muckle, 1975:292).

$$w_t = \frac{3}{1 - \dfrac{C_P}{C_W}} \times \frac{B.h}{L.T}\left(1 - \frac{3D + 2R}{2B}\right)$$

where R = propeller tip rake plus skew

h = height of shaft centre above keel.

b. Schoenherr's equations for wake fraction and thrust deduction (van Manen & van Oossanen, 1988:159

Single-screw ships

$$w_t = 0,10 + 4,5\left[\frac{C_{VP}.C_P.B/L}{(7 - 6C_{VP})(2,8 - 1,8C_P)}\right] + 0,5\left(\frac{h}{T} - \frac{D}{B} - k'K\right)$$

$$t = k.w_t$$

Where k' = 0,3 for normal stern

= 0,5 - 0,6 for stern with cutaway deadwood

k = 0,50 - 0,70 for vessels equipped with streamlined or contra rudders

= 0,70 - 0,90 for vessels equipped with double plate rudders attached to square shoulder posts

= 0,90-1,05 for vessels equipped with old style single plate rudders.

K is rake angle of propeller in radians.

Twin-screw ships with bossings and outboard turning propellers

$$w_t = 2C_B{}^5(1 - C_B) + 0,2\cos^2 \times \frac{3}{2}\varphi - 0,2$$

$$t = 0.25w_t + 0.14 \qquad \text{(applicable also to inboard turning propellers)}$$

Twin-screw ships with bossings and inboard turning propellers

$$w_t = 2C_B{}^5(1 - C_B) + 0.2\cos^2 \times \frac{3}{2}(90 - \varphi) + 0.2$$

Twin-screw ships with propellers supported by struts

$$w_t = 2C_B{}^5(1 - C_B) + 0.04$$

$$t = 0.70w_t + 0.06$$

Where φ = angle of bossing to horizontal.

The Taylor, Hecksher and Schiffbaukalender equations take into account only the fullness or the hull form, whilst on the other hand, Telfer's and Schoenherr's equations include a greater number of the variables which influence the wake fraction. The propulsion coefficients are influenced by speed, however, none of these formulae take this into account. Empirical equations for estimating relative rotational efficiency are extremely scarce.

2.7.2   Statistical Methods

Regression equations have been developed for use with both mathematical models and methodical series. In developing the MARIN mathematical model for resistance prediction, comprehensive equations were developed for wake factor, thrust deduction factor and relative rotational efficiency (Holtrop and Mennen, 1982 and Holtrop, 1984). Only the equations for wake fraction incorporate a speed related function. No indication is given of the standard error of the equations, however, they are reputed to be suitable for a wide range of ship types.

Parker (1966) developed equations for wake factor, thrust deduction factor and relative rotational efficiency based on the BSRA methodical series. The equations are only valid for this series. Speed-Length ratio was a function of all the equations. Standard error for the equations was 0,016 for wake fraction,

0,012 for thrust deduction factor and 0,015 for relative rotational efficiency. Parker noted that there was a tendency for errors in wake fraction to be compensated to some extent by errors in thrust deduction factor resulting in the overall error tending to be less than that predicted by statistical theory.

Finding that the available methods for estimating propulsion coefficients for the Series 60 inadequate, Shaher Sabit (1972) carried out regression analysis using the published results of their propulsion factors. The resulting equations where expressed as functions of length-breadth ratio, beam-draught ratio, block coefficient and *LCB* for a range of speed-length ratios. The standard error for these equations ranged from 0,019 to 0,022 for wake fraction, 0,014 to 0,025 for thrust deduction and 0,012 to 0,47 for relative rotational efficiency. The equations are only valid for the Series 60.

Shaher Sabit (1976) also carried out regression analysis of the propulsion coefficients of the SSPA Cargo Liner series, developing equations for wake fraction and thrust deduction. No standard error is indicated and speed did not form a function of any of the equations.

2.7.3 Miscellaneous Methods

In determining propulsion coefficients for use with the I.O. Series, Zborowski (1973) using the limited data at his disposal found a reasonable correlation with a parameter *m*, defined as

$$m = C_B\left(B/\Delta^{1/3}\sqrt{D/\Delta^{1/3}}\right)$$

where B and D are in feet and Δ in Tonnes sea water

He provided graphs of wake fraction, thrust deduction fraction, relative rotative efficiency and hull efficiency plotted against this factor *m*. No indication is provided regarding the accuracy of these graphs.

2.8   ESTIMATING THE EFFECTS OF WEATHER

In the context of this study, weather effects comprise the effects that wind speed and wave height (sea state) have on the powering problem.

2.8.1   Wind Resistance

Determining the flow of air over a ship is extremely difficult, mainly due to the wide variety of obstructions (e.g. superstructure, masts, funnels, etc.) that it encounters. These obstructions result in a non-uniform air flow with a variable boundary layer thickness. Nevertheless a variety of methods exist, which can provide a reasonable approximation of the effect of wind resistance. All ships when underway will encounter a resistance due to the still air. To estimate this resistance, the ITTC (1978) proposed the following formula:-

$$C_{AA} = 0,001 \frac{A_T}{S}$$

Todd (1967) provides the following formula to determine the influence of wind on of the ship during trial analysis:-

$$R_{AA} = k_c \times coefficient \times A_T \times V_R{}^2$$

where k_c is a wind direction coefficient (generally obtained from specific model experiments)

The main downfall of this formula is that in the preliminary design stage, wind direction coefficients are generally not available as no model tests would have been carried out.

The formula provided by Todd is broadly similar to the generic formula for determining resistance due to wind. i.e:-

$$R_{AA} = coefficient \times 0,5 \times \rho \times A_T \times V_R{}^2$$

with the value of the coefficient being dependant on hull shape and erections.

From experiments, D.W. Taylor derived a value of 1,28 for this coefficient. He further suggested that the air resistance for a normal ship could be assumed to be equivalent to that of a flat plate set normal to the direction of motion and having a breadth (B) equal to the beam of the ship and a height of $B/2$ (van Manen & van Oossanen, 1988). When these values are substituting into the above formula, the following equation is obtained:-

$$R_{AA} = 0,208 \times 0,5B^2 \times V_R{}^2$$

Ignoring the differences in the method of area representation, this equation compares favourably with that developed by Hughes in 1930, i.e.

$$R_{AA} = 0,196 \times A_T \times V_R{}^2 \qquad \text{(van Manen \& van Oossanen, 1988).}$$

These formulae consider the wind from dead ahead, however, van Manen & van Oossanen (1988) indicates that the effect of wind on resistance is generally greatest when the relative wind is about 30° off the bow. This probably due to a greater area of the vessel being exposed to the wind.

Isherwood (1972) using multiple linear regression on 49 sets of wind resistance data derived the following coefficients of wind resistance

a.   fore and aft force coefficient (C_{XW})

$$C_{XW} = a_0 + a_1 \frac{2A_L}{L_{OA}{}^2} + a_2 \frac{2A_T}{B^2} + a_3 \frac{2L_{OA}}{B} + a_4 \frac{S_L}{L_{OA}} + a_5 \frac{C}{L_{OA}} + a_6 M$$

(mean standard error = 0,103)

b.   lateral force coefficient (C_{YW})

$$C_{YW} = b_0 + b_1 \frac{2A_L}{L_{OA}{}^2} + b_2 \frac{2A_T}{B^2} + b_3 \frac{2L_{OA}}{B} + b_4 \frac{S_L}{L_{OA}} + b_5 \frac{C}{L_{OA}} + b_6 \frac{A_{SS}}{A_L}$$

(mean standard error = 0,044)

c.   yawing moment coefficient (C_N)

$$C_N = c_0 + c_1 \frac{2A_L}{L_{OA}^2} + c_2 \frac{2A_T}{B^2} + c_3 \frac{2L_{OA}}{B} + c_4 \frac{S_L}{L_{OA}} + c_5 \frac{C}{L_{OA}}$$

(mean standard error = 0,0127)

The equations yielded an acceptable level of correlation when compared with independent model data and published predictors. To facilitate the use of these equations when the independent variables are unknown, Isherwood supplied mean values for typical merchant types under various load conditions.

2.8.2 Added Resistance Due To Sea State.

Havelock (1945) is generally credited with the first real investigations into added resistance due to waves (sea state). Using first order equations of motion and potential flow theory he derived equations for added resistance due to wave reflection and added resistance due to heaving and pitching. The practical application of these equations is somewhat dubious due to assumptions made during their derivation. In developing the equation for added resistance due to wave refraction, Havelock considered the problem to be one of waves encountering at right angles a fixed vertical plane of infinite depth. With respect to the added resistance due to heaving and pitching, he considered the hull to be wall sided with elliptical water planes.

Over the years, the subject has been well researched and various theories propounded. Nevertheless, the usefulness of these theories during preliminary design is somewhat limited as they are derived either from a shape that is only broadly representative of a ship hull e.g. ellipse or they require a reasonably well defined hull. However, a common factor emerged from these theories, that is, in regular waves of any particular length, added resistance is proportional to the square of the wave height ($R_{AW} \propto H_{1/3}^2$) (Beck et al, 1989:119).

The general assumption made in analysing motions of a ship in an irregular sea is that of linear superposition. This leads to the relationship that the sum of the ship responses to a number of simple sine waves is equal to the ship response to the sum of the waves, i.e. the response in an irregular sea. Using regular waves,

if the added resistance (R_{AW}) is measured for enough different wave-encounter frequencies (ω_e), an accurate representation of the mean response curve for added resistance is obtained, $R(\omega_e)$.

$$R(\omega_e) = R_{AW} \Big/ \zeta_A^2$$

For a ship proceeding at a particular speed in an irregular sea, the average added resistance can be predicted from the mean response curve $R(\omega_e)$ and the energy spectrum of the sea $S_\zeta(\omega_e)$ using the method of superposition;

$$\overline{R}_{AW} = 2\int_0^\infty R(\omega_e) \; S_\zeta(\omega_e) \; d\omega_e$$

This forms the basis of the Moor and Murdey (1968, 1970) analysis and that of Jinkine and Ferdinande (1974) and Mackay and Schmitke (1978). The main difference being that Moor and Murdey used model tests to determine response curve values whilst the others used empirical methods to derive them.

2.8.2.1 Single Screw Ships in Head Seas

Moor and Murdey (1968) used multiple regression on the results of experiments carried out on 34 models in head waves at the Vickers Ship Model Experimental Tank, St. Albans. The results obtained were presented as an overall analysis covering pitch, heave and power increase. Nineteen of the models tested represented fast or medium speed dry cargo liners with block coefficients between 0,55 and 0,71. The remaining fifteen models represented tankers or bulk carriers with block coefficients between 0,74 and 0,88. The models were propelled in regular head waves at the self-propulsion point without any external tow force. The sea spectra used was the British Towing Tank Panel 1964 One Dimensional Sea Spectra. Calculations were made at wave heights 2,743; 4,237; 5,73 and 7,468 metres. It was noted that a bulbous bow had a significant effect on power increase, however no specific term was included in the equations to accommodate it.

Two years later Moor and Murdey (1970) presented a further analysis covering some of the models tested in the earlier analysis plus a number of additional ones.

In total forty-three models were analysed, sixteen representing fast or medium speed dry cargo liners with block coefficients between 0,55 and 0,71 and twenty-six representing tankers or bulk carriers with block coefficients between 0,74 and 0,88. Sea spectra and wave heights were as used in the earlier analysis. The analysis covered increases of propeller thrust, torque, rate of rotation, and power. In this analysis, terms accounting for the effect of a bulb were introduced into the equations.

The proposed equation for added power took the following format:-

$$\frac{5,74E5 \times \delta P}{L^{3,5}} = \left(\frac{2\pi\delta(nQ)}{\rho D^2 v^3}\right)\left(\frac{D}{L}\right)^2\left(\frac{V}{\sqrt{L}}\right)^3 \times 10^4$$

$$= a_0 + a_1(C_B - 0,5)^5 + a_2\frac{L}{B} + a_3\frac{L}{T} + a_4 Lcb + a_5\frac{k_{rr}}{L}$$

$$+ \beta\left(a_6 + a_7\frac{L}{T}\right) + a_8\frac{V}{\sqrt{L}}$$

Where a_{0-8} are regression coefficients and β the bulbous bow factor. β is given a value of zero if no bulb is fitted and one for hull forms with having a bulbous bow.

In Moor and Murdey's method, only the head sea condition is considered. This can be construed as a limitation, however it is not a serious one as added resistance is generally greatest in this condition. A more serious limitation is that the method is only applicable to single screw merchant ships having a block coefficient between 0,55 and 0,88. Use beyond these parameters is not advisable.

Analysing a number of Series 60 hull forms (0,80>C_B>0,65) and a destroyer hull form, Strom-Tejsen et al (1973) found that the results from the Moor and Murdey method when modified to equate them with the Pierson-Moskowitz sea spectrum, followed similar trends to those obtained by their analytical method. It is interesting to note that although the destroyer hull form lies outside the limits of the Moor and Murdey method (C_B=0,485) the correlation between the two methods was as good as that obtained for the Series 60 hulls lying within the limits of the method.

Babbedge, carrying out his statistical analysis of voyage data obtained from three fast cargo ships, compared added power requirements and speed loss with that predicted using the Moor and Murdey method (Babbedge, 1977). Reasonably high correlation was obtained for only one of the three ships, however Babbedge attributes the failure to predict the speed loss of the other two ships with reasonable accuracy to the fact that they were both twin screw ships operating at much greater speeds than can be obtained by a single screw ship of the same size i.e. Froude number of the ship was out of the range covered by Moor and Murdey

2.8.2.2 Fast Cargo Ships, Destroyer and Frigates in Head Seas

Jinkine and Ferdinande (1974) developed an empirical equation for predicting the added resistance of fast cargo ships in head seas. With respect to these ships, they found that experimental curves of the non-dimensional added resistant coefficient (σ_{AW}) plotted against wave frequency (ω) could be approximated by the following equation

$$\frac{\sigma_{AW}}{r_{max}} = \left(\frac{\omega}{\omega_{max}}\right)^b \exp\left\{\frac{b}{d}\left[1 - \left(\frac{\omega}{\omega_{max}}\right)^d\right]\right\}$$

where

$$b = \begin{cases} 11 & \omega \leq \omega_{max} \\ -8,5 & \omega > \omega_{max} \end{cases}$$

$$d = \begin{cases} 14 & \omega \leq \omega_{max} \\ -14 & \omega > \omega_{max} \end{cases}$$

$$\omega_{max}\sqrt{L/g} = 1,17 Fn^{-1/7}(k_{yy}/L)^{-1/3}$$

$$r_{max} = 3600(k_{yy}/L)^2 Fn^{1.5}\exp(-3,5Fn)$$

Mackay and Schmitke (1978) used these equations in their seakeeping prediction program, PHHS (Pitch and Heave in a Head Sea). However to account for the finer hull forms of destroyers and frigates, they derived additional curves for r_{max} and ω_{max}. The r_{max} curves derived are valid only for a ratio of longitudinal radius of gyration to length equal to 0,25. For any different ratio, it is necessary

to scale the curves in accordance with Jinkine and Ferdinande's original equation.

To facilitate the use of these curves within their program, they applied linear regression to the new curve for ω_{max} resulting in the following equation

$$\omega_{max}\sqrt{L/g} = 2,79 - 1,18Fn$$

The r_{max} curve for bulbous bow vessels was approximated by the linear equation

$$r_{max} = 48Fn$$

No equations were used to approximate r_{max} for V and U shaped hull sections, instead the values were represented as a series of data at intervals of 0,05 Froude Number.

The dimensional added resistance response (R_{AW}) is related to the non dimensional added resistance coefficient (σ_{AW}) by

$$R_{AW} = \sigma_{AW}\left(\rho g \zeta_A^2 B^2 / L\right)$$

The added resistance due to the waves is then obtained by evaluating the integral

$$\overline{R}_{AW} = 2\int_0^\infty R_{AW}/\zeta_A^2 \ S_\zeta(\omega_e) \ d\omega_e$$

2.8.2.3 Simple Empirical Formula.

a. *Aertssen's Empirical Formula* In a proposal to the 12th ITTC, Aertssen (1975) suggests that a first approximation for the percentage speed loss due to weather could be approximated by a formula of the form of the IMCO freeboard standard, i.e.

$$\frac{100 \times \nabla V}{V} = \frac{m}{L} + n$$

Where:

V	Ship speed
∇V	Loss of speed

| | *m* and *n* | Coefficients dependant on direction of waves, e.g. head, bow, beam or following. |

Values for the coefficients *m* and *n* are tabulated in Table 2.27. The equation accounts for the effects of both waves and wind.

Table 2.27 - Aertssen's *m* and *n* Coefficients

Beaufort Number	Head sea		Bow sea		Beam sea		Following sea	
	m	*n*	*m*	*n*	*m*	*n.*	*m*	*n.*
5	900	2	700	2	350	1	100	0
6	1300	6	1000	5	500	3	200	1
7	2100	11	1400	8	700	6	400	2
8	3600	18	2300	12	1000	7	700	3

Aertssen's equation is dependant only on ship length, therefore it cannot show the effects of any change in ship form.

b. *AEW, Haslar Empirical Formula*. Lloyd at the Admiralty Experimental Works, Haslar, developed the following formula to estimate the maximum speed possible in waves based on power limitations

$$\frac{V_w}{V_d} = 1 - 50\left(\frac{Hs}{L}\right)^2 \left\{ \frac{1}{Fn_d} - 3\left(\frac{Hs}{L}\right)^{0.25} \right\}$$

Where

| Fn_d | Froude Number at design speed V_d |
| V_w | Speed in waves corresponding to maximum power. |

If the speed corresponding to a particular power is substituted into the formula instead of design speed, an approximation can be obtained of the speed loss in the specified waves at that power.

No indication is provided regarding the basis for the development of this equation, however, by nature of its origin, it is assumed to apply mainly to slender ships.

2.8.3   Relationship Between Wind and Waves.

There is no fixed relationship between the spectra of a sea and the speed of the wind which generates it, however, the 11th ITTC agreed to a relationship which is applicable only to fully developed seas where duration and fetch are large (Rawson & Tupper, 1983:338). The ordinates of this curve are given in Table 2.28 and the relationship is considered satisfactory for use in preliminary design studies.

Table 2.28 –   Approximate Relationship between Wind Speed and Wave Height

Wind Speed (knots)	Significant Wave height (metre)
20	4,42
30	5,64
40	8,08
50	10,97
60	14,63

2.9   CONCLUSION.

The majority of resistance prediction methods provide one or other means of estimating wetted surface area of the hull, an essential component in determining frictional resistance. A limited number of methods included information on the propulsion coefficients, these generally being applicable only to the method with which they were supplied. A number of the methods provided an indication of one or other method for estimating appendage resistance and propeller efficiency. None of the resistance prediction methods took the problem to its final conclusion and not one of them included the added resistance due to wave height (sea state). The MARIN mathematical model is the most comprehensive method evaluated, however, even it covers only the smooth water condition.

Many of the component methods provided no indication of their level of accuracy. This was particularly noticeable for the MARIN mathematical model where the predicted level of accuracy was obtained from a third party source (UCL, 1988).

3 EVALUATION AND SELECTION OF METHODS

3.1 INTRODUCTION

To facilitate selection of the most suitable methods for incorporation into the final Power Prediction program, thirteen stand alone programs were developed. Eight covering hull resistance prediction (effective power), two covering propeller selection and optimisation, one covering resistance due to wind and two covering resistance due to sea-state. In addition, use was made of spreadsheet analysis. The programs were written in Pascal and designed to run on any IBM compatible computer fitted with a math co-processor and VGA/SVGA display.

Where available, the worked examples included with the theory were used for program validation. alternatively, recourse was made to either manual calculations or related published examples. The latter cases required careful examination to determine the cause of any deviations from expected results. From this process, the most appropriate methods have been identified for inclusion in the integrated Power Prediction Program.

3.2 RESISTANCE PREDICTION

The resistance prediction methods reviewed are expressed in one or more of the following formats

- tabular data

- graphical data

- mathematical model (regression equations).

The mathematical model lends itself to computerisation. The other two formats can be computerised, however, not directly. Typically, tabular data can be suitably transformed by;

- using statistical methods to derive one or more equations from the data and then utilising them in the computer source code.

- developing interpolating routines to directly manipulate the tabular data.

Graphical data can be treated in much the same way. The process is facilitated if recourse can be made to the original data. If this is unavailable, then key data points must be extracted from the graphs and tabulated.

Within the programs, data manipulation is achieved by using one or more of the following interpolation methods:-

- linear interpolation.

- Taylor's 2nd order interpolation (Aughey, 1968), however, any Lagrangian or other three point interpolation method could have been used with equal accuracy.

- Theilheimer cubic spline (Versluis, 1977).

At the higher and lower speed ranges, the resistance curves characteristically tend to flatten out. Therefore, when extrapolating beyond the bounds of the speed range of any method, linear extrapolation is assumed to best approximate this trend.

The Taylor 2nd order interpolation is used for general three point interpolation, whilst the Theilheimer spline is used when interpolation is required over a wide number of data points. A common Pascal routine, SPLINET.PAS, was developed for use in the programs requiring cubic spline interpolations.

In general, the computer programs have checks built in to determine any violation of the range of application of the method. When encountered, these violations generally do not cause the software to abort, but instead, place warnings in the output file.

Data used to evaluate the various resistance prediction methods comprise of tank test results for the following models:-

a.   <u>Corvette</u> (Model 5281). A $^1/_{22,818}$ scale polyurethane model of a twin screw corvette tested by the National Physical Laboratory (Project No 40.57, 1974).

b.   <u>Cargo Ship</u> (Model 3065-1011). A $^1/_{19}$ scale wooden model of a single screw medium speed cargo vessel tested by the Hamburg Ship Model Basin (Report WP 50/81, 1981).

c.   <u>Stern Trawler</u> (Model 4970). A $^1/_{13,69}$ scale model of a single screw diesel stern trawler tested by the National Physical Laboratory (Project No 51.3.15, 1969).

d.   <u>Patrol Boat</u> (Model 2133). A $^1/_{11,5}$ scale model of a quadruple screw patrol boat tested by the Hamburg Ship Model Basin. (HSVA Report, Type K.123, 1969). Only limited use was made of this model data.

Also used in the evaluation were published extracts from the tank tests of the USS Oliver Hazard Perry class frigate, Model 5279-1 (Woo et al, 1983)

The range of vessels selected for the evaluation is representative of ships which have been built or could be built in South Africa. Full scale ship particulars for all the models are given in Table 3.1

Table 3.1   Full Scale Ship Data

SHIP TYPE Model Number	Corvette 5281	Cargo Ship 3065-1011	Stern Trawler 4970	FFG7 - Frigate 5279-1	Patrol Boat 2133
Length on Waterline (m)	80,000	136,000	57,150	124,400	54,400
Length between Perpendiculars (m)	80,000	133,048	52,578	124,400	54,540
Beam, waterline (m)	10,300	19,50	11,735	13,700	7,060
Draught, mean (m)	3,150	6,000	4,471	4,400	2,675
Displacement, volume (m³)	1331,707	8776,000	1417,514	3369,756	387,200
Wetted Surface Area (m²)	884,734	2839,000	725,508	1689,500	468,700
Half angle of entrance (degrees)	12,500	-	19	8,800	-
Midship Section Coefficient	0,816	0,957	0,839	0,752	0,621
Prismatic Waterplane Coefficient	-	-	0,689	-	0,495
% LCB from amidships (m)	-3,000	-1,500	-3,334	-0,509	-2,990
Diameter of Thruster Tunnel (m)	-	2,000	-	-	-
Cross Section Area of Bulbous Bow	-	6,380	-	-	-
Height to centre of bulb (m)	-	2,000	-	-	-
No of Rudders	2	1	1	2	2
WSA Rudder -total (m²)	12,000	36,000	10,180	36,800	26.424
WSA of shafts (m²)	34,540	-	-	5,650	8,800
WSA of Shaft Brackets (m²)	0,000	-	-	6,000	1,468
WSA of Stabiliser Fins (m²)	13,000	-	-	-	-
WSA of Bilge Keels (m²)	39,600	-	-	90,500	-
WSA of Skeg (m²)	40,000	-	-	110,000	-
WSA of Strut Bossings (m²)	4,700	-	-	15,000	-
WSA of Hull Bossings (m²)	0,000	-	-	0,000	-
WSA of Sonar Dome (m²)	2,000	-	-	14,000	-
No of Propellers	2	1	1	1	4
Propeller Diameter (m)	2,900	4,750	2,700	5,029	1,334
No of Blades	3	4	4	5	3
Pitch Diameter Ratio	1,340	0,750	0,95	1,491	1,200
Expanded area ratio	0,667	0,630	0,45	0,607	0,850
Clearance between propeller and keel	0,650	1,200	0,615	1,100	0,800
Shafting efficiency (%)	97	100	100	100	100

3.2.1   The Taylor Gertler Standard Series

The format of this series does not lend itself ideally to computerisation and access
to the original experimental data is not available. Nevertheless, due to its
historical importance and its wide use, various methods based on it were
examined.

Table 3.2 Residual Resistance Comparison - Taylor Gertler and Fisher's equations

			$C_R \times 10^3$ at $V_k/\sqrt{L_\text{fl}}$															
B/T	C_P	∇/L^3		0,5			0,6			0,7			0,8			0,9	
		$\times 10^3$	Fisher	T/Gertler	% diff	Fisher	T/Gertler	% diff	Fisher	T/Gertler	% diff	Fisher	T/Gertler	% diff	Fisher	T/Gertler	% diff
2,25	0,70	5	0,43	0,41	4,88	0,53	0,49	8,16	0,75	0,68	10,29	1,20	1,08	11,11	1,98	1,94	2,06
		6	0,48	0,52	-7,69	0,58	0,56	3,57	0,80	0,75	6,67	1,25	1,17	6,84	2,03	2,10	-3,33
		7	0,53	0,59	-10,17	0,63	0,63	0,00	0,85	0,84	1,19	1,30	1,25	4,00	2,08	2,28	-8,77
	0,75	5	0,47	0,48	-2,08	0,62	0,58	6,90	0,94	0,99	-5,05	1,54	1,61	-4,35	2,54	2,56	-0,78
		6	0,52	0,55	-5,45	0,67	0,67	0,00	0,99	1,08	-8,33	1,59	1,73	-8,09	2,59	2,71	-4,43
		7	0,57	0,62	-8,06	0,72	0,72	0,00	1,04	1,15	-9,57	1,64	1,80	-8,89	2,64	-	
	0,80	5	0,53	0,51	3,92	0,75	0,75	0,00	1,20	1,50	-20,00	1,98	2,09	-5,26	3,22	-	
		6	0,58	0,58	0,00	0,80	0,81	-1,23	1,25	1,62	-22,84	2,03	-		3,27	-	
		7	0,63	0,64	-1,56	0,85	0,88	-3,41	1,30	1,73	-24,66	2,08	3,00	-30,67	3,32	-	
3,00	0,70	5	0,62	0,60	3,33	0,72	0,63	14,29	0,94	0,88	6,82	1,39	1,31	6,11	2,17	2,08	4,33
		6	0,67	0,67	0,00	0,77	0,72	6,94	0,99	0,97	2,06	1,44	1,38	4,35	2,22	2,23	-0,45
		7	0,72	0,73	-1,37	0,82	0,82	0,00	1,04	1,04	0,00	1,49	1,49	0,00	2,27	2,43	-6,58
	0,75	5	0,66	0,62	6,45	0,81	0,74	9,46	1,13	1,11	1,80	1,73	2,00	-13,50	2,73	3,10	-11,94
		6	0,71	0,69	2,90	0,86	0,82	4,88	1,18	1,20	-1,67	1,78	2,10	-15,24	2,78	3,20	-13,13
		7	0,76	0,73	4,11	0,91	0,92	-1,09	1,23	1,25	-1,60	1,83	2,20	-16,82	2,83	3,35	-15,52
	0,80	5	0,72	0,68	5,88	0,94	0,97	-3,09	1,39	1,48	-6,08	2,17	2,82	-23,05	3,41	-	
		6	0,77	0,73	5,48	0,99	1,02	-2,94	1,44	1,52	-5,26	2,22	2,94	-24,49	3,46	-	
		7	0,82	0,78	5,13	1,04	1,06	-1,89	1,49	1,57	-5,10	2,27	3,03	-25,08	3,51	-	
3,75	0,70	5	0,71			0,81			1,03			1,48			2,26		
		6	0,76			0,86			1,08			1,53			2,31		
		7	0,81			0,91			1,13			1,58			2,36		
	0,75	5	0,75	0,82	-8,54	0,90	0,85	5,88	1,22	1,12	8,93	1,82	1,85	-1,62	2,82	2,93	-3,75
		6	0,80	0,88	-9,09	0,95	0,89	6,74	1,27	1,22	4,10	1,87	1,95	-4,10	2,87	3,07	-6,51
		7	0,85	0,95	-10,53	1,00	0,97	3,09	1,32	1,30	1,54	1,92	2,05	-6,34	2,92	3,16	-7,59
	0,80	5	0,81	0,84	-3,57	1,03	0,97	6,19	1,48	1,50	-1,33	2,26	2,69	-15,99	3,50	-	
		6	0,86	0,90	-4,44	1,08	1,05	2,86	1,53	1,59	-3,77	2,31	2,82	-18,09	3,55	-	
		7	0,91	0,96	-5,21	1,13	1,12	0,89	1,58	1,67	-5,39	2,36	3,02	-21,85	3,60	-	

Fisher's method (Fisher, 1972) is easily incorporated into any program, however, the method when compared to the Taylor-Gertler data (Gertler, 1954), overestimates residual resistance coefficients by up to 30% in the higher speed ranges (see Table 3.2). The comparison provides a slightly biased outlook as the Taylor-Gertler method uses the Schoenherr skin friction line for estimating frictional resistance whilst Fisher advocates the use of the ITTC line. One would therefore expect Fisher's values to be slightly less at the lower end of the speed range to compensate for the higher friction resistance coefficient obtained from the ITTC formula. The level of accuracy of the Fisher method limits its suitability for general use in predicting resistance over a broad spectrum of displacement hull forms.

The UCL approximation (Brown, 1994) covers only a very small range of hull parameters. It uses the 1957 ITTC line for determining frictional resistance, therefore, similar residual resistance coefficient values were anticipated in the upper speed ranges with lower values expected at the bottom end of the speed range. Spreadsheet analysis of the method at $\nabla/L^3 = 0,002$; $B/T = 3,75$ and $C_P = 0,6$ revealed this trend, nevertheless, the values were far lower than expected (see Table 3.3). This could be attributable to the modifications made to the method by UCL in order to provide a better fit with modern hull forms. A maximum percentage difference of approximately 39% when compared to the Taylor-Gertler data creates some doubt about the usefulness of the method.

Table 3.3   **Residual Resistance Comparison - Taylor Gertler and UCL Approximation**

	$C_R \times 10^3$ at $V_k / \sqrt{L_A}$										
	0,6	0,7	0,8	0,9	1,0	1,1	1,2	1,3	1,4	1,5	1,6
UCL	0,49	0,50	0,56	0,78	1,10	1,34	1,80	2,60	3,70	4,40	4,73
T/Gertler	0,79	0,82	0,89	1,09	1,38	1,67	2,12	3,08	3,93	4,70	5,01
% diff.	-38,08	-39,01	-37,16	-28,47	-20,06	-19,88	-15,25	-15,48	-5,83	-6,43	-5,55

($\nabla/L^3 = 0,002$; $B/T = 3,75$; $C_P = 0,6$)

3.2.2   DTMB Series 64 (Yeh, 1965)

The tabular presentation of this series makes it reasonably attractive for converting into computer code. However, a low value was placed on the

usefulness of the method due to its limited range of application together with the fact that the published results had already been included in both the MARIN (Holtrop, 1984) and Fung's (1991) random data regression analyses.

3.2.3 NPL High Speed Round Bilge Series (Bailey, 1976)

The published results of this series were included in the random data regression analysis of Fung (1991). Apart from this, the range of application of this series is very limited and the results are only available graphically. It was therefore considered unsuitable for development into a computational code as the effort required could not be justified in terms of the usefulness of the program.

3.2.4 The VTT Prediction Method (Lahtiharju, 1991)

The VTT method covers a wider range of hull parameters than the NPL Series on which it is based. However, the actual speed range of the series is restricted to the higher Froude numbers. Nevertheless it was considered justifiable in developing a program based on it, primarily, because of the wider hull parameter range and secondly, because the method could be computerised with relative ease.

3.2.4.1 *Program development*

The program developed (VTTRP.PAS) is a direct application of the published regression equations. Both the hard chine and round bilge equations were used. Selection of the required hull form (hard or soft chine) is an input parameter. The regression coefficients are assigned to arrays within the program. Checks are programmed to ensure that the lowest speed required is within the applicable range of the method. If this is not the case, then it is automatically adjusted to the minimum allowable speed. A maximum of ten speeds are catered for. No interpolation was necessary as the equations are speed dependant.

3.2.4.2 Program Validation

The program was validated against the published total resistance curves of the Nova II model, a 45,36 tonne vessel. As expected, an exact match of the results was obtained when a zero correlation allowance was used. A check below the range of validity of the method (i.e. $F_V < 1,8$) produced results that were noticeably circumspect.

An additional check was made using the NPL series example at 30 knots (Bailey, 1976). In this case, the program over estimated the result by 2,3%.

The results obtained using the program do not display the characteristic humps and hollows of a speed-power curve. This can be attributed to the speed dependant equation, which tends to smooth the curve.

3.2.4.3 Program Evaluation.

With the exception of the Patrol Boat, none of the models truly fitted application range of the VTT method, nevertheless, they were examined to determine the program's suitability for general purpose resistance prediction.

Twin Screw Corvette. The vessel violates only the transom area ratio limit, having a ratio of less than the minimum required value of 0,16. The speed of the vessel is such that its top speed falls just below that recommended for the series, nevertheless, it is within the range covered by the regression equations. It was therefore possible to compare effective power at only two speeds. The results obtained are considered acceptable, effective power being overestimated by about 7% at the lower speed (see Table 3.4).

Table 3.4   Comparison of Effective Power -Twin Screw Corvette

Speed (knots)	Effective Power (kW)		% diff	Speed (knots)	Effective Power (kW)		% diff
	Program	Model 5281			Program	Model 5281	
30	11209	10474	7,02	32	12742	12085	5,43

Single Screw Medium Speed Cargo Ship. The transom-section area ratio of the vessel is <0,16 and the midship section coefficient is >0,888. Both these

parameter lie outside the range of application of the method, however, this is immaterial as no result could be obtained because the maximum speed of the vessel falls below the minimum speed range of the method ($F_V = 1,8$). The method is therefore unsuitable for predicting the effective power of the Cargo Ship.

Single Screw Stern Trawler. The transom area ratio of the vessel lies outside the range of the method (< 0,16), however, this is of no real significance because the maximum speed of the vessel falls below the minimum speed range of the method ($F_V = 1,8$). The method is therefore unsuitable for predicting the effective power of the Trawler.

American Frigate. The vessel dimensions violate three of the method's limits, namely, a length-displacement ratio > 8,3, a length-breadth ratio > 8,21 and a transom area ratio < 0,16. These factors play no role in the prediction as the volumetric Froude number of the vessel at its highest speed is below that covered by the method. The method is therefore unsuitable for predicting the effective power of the Frigate

Patrol Boat. This vessel falls within the range of application of the series, however, due to the limitations of the method, comparison is only possible at the higher speeds. This vessel is not considered to have a true displacement hull form, and better fits the definition of a semi-planing hull. When the theoretical power requirement of a semi-planing hull is compared with its displacement counterpart, they generally both display a similar power requirement at the lower end of the speed range. However, once the semi-planing hull starts to come onto a plane, there is a dramatic reduction in its power requirement in comparison to the displacement hull travelling at the same speed. The VTT method correctly displays this trend, however it errs on the low side, under predicting by about 11% at 40 knots. (see Table 3.5). Nevertheless, the results are considered acceptable for preliminary estimation purposes.

Table 3.5   Comparison of Effective Power -Patrol Boat

Speed	Effective Power (kW)		% diff	Speed	Effective Power (kW)		% diff
(knots)	Program	Model 2133		(knots)	Program	Model 2133	
25.00	2817.70	2999.82	6.46	35.00	5895.02	5341.99	-9.38
27.50	3506.12	3470.75	-1.01	37.50	6904.13	6187.56	-10.38
30.00	4232.06	4007.21	-5.31	40.00	8094.16	7195.60	-11.10
32.50	5010.95	4624.18	-7.72				

3.2.5   The YP Series (Compton, 1986)

The development of this series was aimed at relatively small vessels. It was selected for programming in an attempt to investigate how methods developed for small vessels coped when their use was extended to encompass larger vessels. The regression equations provided are ideally suited for use in a computer program.

3.2.5.1 Program development

The program developed (RSTH.PAS) is a direct application of the published regression equations. The regression coefficients are stored as arrays in the program. Although only the round bilge equations are of interest, both the hard chine and round bilge equations were programmed. Selection of the required hull form being indicated in the input file. The regression equations are solved at the given Froude numbers. A Theilheimer interpolating spline is then applied to this data to obtain values at the required intermediate speeds. A maximum of ten speeds are catered for. Beyond the bounds of the series, values are obtained by linear extrapolation using the slope of the total resistance coefficient curve between Fn 0,10 and 0,15 and Fn 0,55 and 0,60 respectively

3.2.5.2 Program Validation

No example was provided against which the program could be directly validated, however, effective power values were provided for hull YP81-7. It was therefore considered prudent to use these results for validation purposes as the hull in question had resulted from a study which utilised the YP Series in its investigation. The main particulars of the hull are shown in Table 3.6

Table 3.6 Main Characteristics of YP81-7

Length between perpendiculars	30,846 m	Wetted Surface Area	220,83 m²
Beam on waterline	6,523 m	LCG from amidships	-1,362 m
Mass Displacement	164,673 tonnes		

In general the program tended to under predict in the lower speed ranges and over predict in the higher speed ranges. For validation purposes, the percentage differences were considered unacceptably high, raising some doubt with regard to the accuracy of the programming. To resolve the issue, a spreadsheet was used to solve the regression equations using the YP81-7 data. The answers were identical to those produced by the program. The difference between the results obtained using the regression equations and those of YP81-7 can be partly attributed to the fact that YP81-7 differs from the series in that it has a more generous bilge radius, full length integral skeg-keel and a less deeply immersed transom. Even when allowance is made for these differences, the overly high discrepancy in the results casts some doubt on the reliability of the method. A comparison of the effective power together with percentage difference is given in Table 3.7.

Table 3.7 YP81-7 – Effective Power Comparison

Speed (Knots)	Effective Power (kW)		% diff	Speed (Knots)	Effective Power (kW)		% diff
	Program	YP81-7			Program	YP81-7	
4	3,727	2,9828	24,95	13	265,348	250,5552	5,90
5	7,206	7,457	-3,37	14	376,423	366,1387	2,81
6	12,643	14,1683	-10,77	15	553,158	523,4814	5,67
7	21,164	21,6253	-2,13	16	764,873	697,2295	9,70
8	34,274	32,8108	4,46	17	976,501	852,3351	14,57
9	52,658	53,6904	-1,92	18	1159,972	995,5095	16,52
10	80,601	83,5184	-3,49	19	1320,496	1131,973	16,65
11	129,41	119,312	8,46	20	1489,314	1269,927	17,28
12	194,578	169,2739	14,95				

3.2.5.3 Program Evaluation.

None of the models truly fitted into the range of application of the YP Series method, nevertheless, they were examined to determine the suitability of the program for general purpose resistance prediction.

Twin Screw Corvette. The vessel has a length-breadth ratio > 5,2 and a length-displacement ratio > 6,48. These parameters all lie outside the valid range of application of the method. The program indicates these irregularities and cautions against the use of the results. Results obtained vary from a 52% under prediction at the lower end of the speed range to a 44% over prediction at the top end of the speed range. These large discrepancies are attributed to the violation of the limits of the regression equations. The method is unsuitable for predicting the effective power of the Corvette.

Single Screw Medium Speed Cargo Ship. The vessel has a length-breadth ratio > 5,2 i.e. outside the valid range of application of the method. The method progressively overestimates effective power by about 13% at 11 knots to about 88% at 23 knots. This can be attributed to using the method beyond its valid limits. The method is unsuitable for predicting effective power of the Cargo Ship.

Single Screw Stern Trawler. The vessel has a length-displacement ratio <5,75; i.e. outside the valid range of application of the method. The method overestimates effective power across the entire speed range by about 200%. This is attributed the method being used outside its valid range. The method is unsuitable for predicting effective power of the Trawler

American Frigate. The vessel has a length-breadth ratio > 5,2 and a length-displacement ratio > 6,48. These parameters lie outside the range of application of the method. The program indicates these irregularities and cautions against the use of the results which vary from a 35% under prediction at the lower speed range to a 94% over prediction at the top of the speed range. The large discrepancies can be attributed to the violation of the limits of the regression equations. The method is not considered suitable for predicting the effective power of the Frigate

3.2.6   The I.O. Series (Zborowski, 1973)

This series was considered pertinent for programming as it is typical of the container type ship which abounds in active mercantile service. It was also

considered of interest to investigate the accuracy with which it could predict the resistance of a typical twin screw warship having a transom stern.

3.2.6.1 Program development

The tabular data provided by Zborowski was considered the most suitable option for computerisation. The initial approach adopted was to assign the data to arrays and then to simulate the manual method described. This was achieved by using an interpolating cubic spline to represent the curves between the bounds of the series (i.e. $0.35 > Fn > 0.25$) and thereafter by carrying out linear interpolation between;

- the curve of C_{Tm} plotted against length-displacement ratio and B/T to obtain the correct value at the required B/T

- the curve of C_{Tm} plotted against length-displacement ratio and C_B to obtain the correct value at the required C_B

- Froude Numbers for both sets of curves if the required Froude Number is not represented.

However, none of these three functions are linear, therefore by advocating the use of linear interpolation Zborowski introduces an unnecessary error into his algorithm. To minimise this error and improve the accuracy of the program (IORP.PAS), a three point interpolation routine was introduced to replace the linear routine.

Beyond the bounds of the series, results are obtained by linear extrapolation using the slope of the total resistance coefficient curve between Fn 0,24 and 0,25 and Fn 0,34 and 0,35 respectively

3.2.6.2 Program Validation.

To demonstrate his method, Zborowski provided a worked example for a ship having dimensions as given in Table 3.8

Table 3.8   IO Series-Particulars of Example Ship

Waterline length	121,920	m
Beam	16,940	m
Draught	6,016	m
Block coefficient	0,576	
Wetted surface area	2428,7	m²

The results obtained from the program correlate reasonably well with those provided by Zborowski (see Table 3.9).

Table 3.9   IO Series - Resistance Comparison

Fn	Resistance (kN)		% diff	Fn	Resistance (kN)		% diff
	Program	Example			Program	Example	
0,25	278,452	274,297	1,51	0,31	516,293	506,274	1,98
0,26	306,858	301,393	1,81	0,32	563,857	555,138	1,57
0,27	342,762	338,268	1,33	0,33	633,978	608,171	4,24
0,28	378,672	386,043	-1,91	0,34	712,572	689,290	3,38
0,29	421,127	425,891	-1,12	0,35	795,666	785,820	1,25
0,30	471,598	465,014	1,42				

The small discrepancies which occur between them can be directly attributed to:-

- early rounding off in the manual method

- accuracy with which the graphs can be read

- linear interpolation used in the manual method

As the program and method use a common data set, it can be inferred from the above factors that the answers obtained from the program are probably more accurate than those provided by Zborowski.

3.2.6.3   Program Evaluation.

None of the models truly fitted into the range of application of the IO Series method, nevertheless, they were examined to determine the suitability of the program for general purpose resistance prediction.

Twin Screw Corvette. The corvette is a twin screw open stern vessel, however, she has a block coefficient < 0,518 and a length-displacement ratio > 7. These

parameters lie outside the valid range of application of the method. Notwithstanding this fact, the results were disappointing, varying from a 44% under prediction at the lower end of the speed range to a 108% over prediction at the upper end. This was unexpected as the method is essentially an extrapolation of tabulated model data. The method is considered unsuitable for predicting the effective power of the Corvette.

Single Screw Medium Speed Cargo Ship. The method progressively overestimates effective power by about 9% at 11 knots rising to 23% at 23 knots. Below 18 knots, the data is obtained by linear extrapolation, the method effectively only covering the 18-23 knot range. Whilst the Cargo Ship has a transom stern, the method is not strictly applicable to her as she is only a single screw vessel and therefore has a different underwater afterbody shape. The program was expected to produce slightly higher resistance values than those obtained from the model tests, because, theoretically V-shaped underwater stern sections such as those found on the Cargo ship have a lower value of resistance in comparison to the U-shaped sections as found on the IO Series.

Table 3.10   Comparison of Effective Power - Single Screw Cargo Ship

Speed (knots)	Effective Power (kW)		% diff	Speed (knots)	Effective Power (kW)		% diff
	Program	Model 3065-1011			Program	Model 3065-1011	
11	718	660	8,85	18	3425	2970	15,32
12	945	870	8,64	19	4169	3540	17,78
13	1218	1110	9,69	20	5019	4190	19,79
14	1541	1390	10,83	21	6026	4930	22,23
15	1919	1710	12,24	22	7110	5820	22,17
16	2359	2060	14,51	23	8540	6920	23,41
17	2865	2480	15,52				

Single Screw Stern Trawler. The vessel has a length-displacement ratio < 6 and a block coefficient < 0,518; both of which lie outside the valid range of application of the method. The method underestimates effective power across the entire speed range by about 24% (see Table 3.11). The vessel has a single screw with V-shaped underwater stern sections. The results are therefore opposite to what was expected, however, the large underestimation is not

attributed to this difference in afterbody form, but rather to the use of the method beyond its valid limits. The method is unsuitable for predicting effective power of the Trawler

Table 3.11   Comparison of Effective Power - Stern Trawler

Speed (knots)	Effective Power (kW)		% diff	Speed (knots)	Effective Power (kW)		% diff
	Program	Model 4970			Program	Model 4970	
11,0	180	249	-27,76	13,5	424	591	-28,21
11,5	230	294	-21,96	14,0	497	692	-28,15
12,0	286	349	-18,07	14,5	589	807	-26,97
12,5	324	417	-22,31	15,0	742	946	-21,62
13,0	375	498	-24,75				

American Frigate. The vessel has a block coefficient < 0,518 and a length-displacement ratio > 7. These parameters lie beyond the range of application of the method. The program indicates these irregularities and cautions against the use of the results. Percentage differences in effective power were again unexpectedly high, varying from a 44% under prediction at the lower end of the speed range to a 108% over prediction at the upper end. The large discrepancies are attributed to the limits of the method being violated, therefore it is considered unsuitable for predicting the effective power of the Frigate

3.2.7   The DTMB Series 60 (Todd, 1963)

This series is one of the most common and is widely used in America. As discussed, it has been published in numerous formats, the most suitable from a programming point of view being the Shaher Sabit (1972) regression equations.

3.2.7.1   Program development

The computer program developed (SER60RP.PAS) uses Shaher Sabit's regression equations to determine circular C of a standard 400 ft ship at speed-length ratios 0,50 to 0.90 in steps of 0,05. The circular C value is then corrected for length using the Froude Circular O function, i.e.

$$\textcircled{C}_{400} - \textcircled{C}_{L} = (\textcircled{O}_{400} - \textcircled{O}_{L}) \; \textcircled{S} \; \textcircled{L}^{-0.175}$$

where

$$\textcircled{O} = (0.00871+0.053/(8.8+3.28 \; Lpp))*12.766/Lpp^{0.0875}$$

with *Lpp* in metres.

The circular notation is then converted to standard C_T, C_R and C_F values. A Theilheimer interpolating spline is applied to this data to obtain results at the required speeds.

Beyond the bounds of the series, results are obtained by linear extrapolation using the slope of the total resistance coefficient curve between *Fn* 0,149 and 0,164 and *Fn* 0,253 and 0,268 respectively. A maximum of ten speeds are catered for.

No propulsion coefficients are calculated.

3.2.7.2 Program Validation.

Shaher Sabit does not include an example whereby his method can be checked, however, use was made of an example included with Lackenby and Milton's (1964) presentation of the series. The main dimensions of the ship used in this example are given Table 3.12

Table 3.12   Particulars of Series 60 Example Ship

Length between perpendiculars.	94,488	m
Beam	15,240	m
Draught	5,944	m
Block coefficient	0,709	
LCB from amidships	2,78	m

The example included two sets of results, the first set based on the Froude skin friction correction and the second set on the ITTC model-ship correlation line. Neither set included a correlation allowance. The results obtained from the program in comparison with those of the Froude skin friction method, indicate that the program underestimates effective power by up to 6,5%. When compared with the ITTC method, the program overestimated by up to 15,5%. Nevertheless, the results are considered acceptable. An exact correlation

between the two methods was not expected due to the different approaches used, combined with the standard error of the regression analysis. The large difference between the program and the ITTC line results are possibly attributable to the fact that no correlation allowance was included. When a 0,0004 correlation allowance is included, the overestimation changes to one of underestimation, with the maximum difference in effective power being only about 3,9% (see Table 3.13).

Table 3.13 Series 60 – Resistance Comparison

	Program	Froude Skin Friction		ITTC Correlation Line		ITTC Correlation Line + Ca of 0,0004	
Fn	Pe (kW)	Pe (kW)	% diff	Pe (kW)	% diff	Pe (kW)	% diff
0.149	279.441	290.178	-3.700	242.412	15.275	280.522	-0.386
0.164	375.511	389.490	-3.589	328.019	14.478	378.738	-0.852
0.179	488.956	521.434	-6.229	440.948	10.887	506.789	-3.519
0.193	626.252	661.150	-5.278	567.575	10.338	651.278	-3.843
0.208	799.623	832.454	-3.944	715.561	11.748	820.097	-2.497
0.223	1059.305	1108.444	-4.433	967.369	9.504	1095.992	-3.347
0.238	1416.075	1469.062	-3.607	1301.122	8.835	1457.210	-2.823
0.253	1832.400	1897.290	-3.420	1705.605	7.434	1892.812	-3.192

3.2.7.3 Program Evaluation.

None of the models truly fitted into the range of application of the Series 60 method, nevertheless, they were examined to determine the suitability of the program for general purpose resistance prediction.

Twin Screw Corvette. The Corvette has a length-breadth ratio < 5,5 and percentage LCB position from amidships < -2,48. These parameters lie beyond the valid range of the regression equations, therefore, valid results were not expected. Examination of the predicted values show an under prediction of about 36% at 10 knots ranging to an over prediction of about 12% at 14 knots. Above 14 knots, values are obtained using linear extrapolation of the residuary resistance coefficient. Negative resistance values occurs from about 16 knots. This is due to a dip in value of the resistance coefficient at 15 knots. These negative values

highlight the unsuitability of the method for predicting the effective power of the Corvette.

Single Screw Medium Speed Cargo Ship. The vessel has a hull broadly similar to that of the Series 60 hull form, but with a block coefficient of less than 0,6. Results obtained were disappointing, particularly in the 16-20 knot range where there was up to a 32% over prediction in effective power. This is attributed to using the method beyond the valid limits of the regression equations. Beyond 19 knots the results are linearly extrapolated which accounts for the progressive reduction in percentage difference in power (see Table 3.14).

Table 3.14   Comparison of Effective Power - Single Screw Cargo Ship

Speed	Effective Power (kW)		% diff	Speed	Effective Power (kW)		% diff
(knots)	Program	Model 3065-1011		(knots)	Program	Model 3065-1011	
11	749	660	13,53	18	3920	2970	31,99
12	850	870	-2,31	19	4387	3540	23,92
13	1052	1110	-5,26	20	4862	4190	16,05
14	1357	1390	-2,41	21	5339	4930	8,30
15	1787	1710	4,51	22	5807	5820	-0,22
16	2316	2060	12,45	23	6257	6920	-9,58
17	3148	2480	26,92				

The method is not considered reliable enough for predicting the effective power of the Cargo Ship.

Single Screw Stern Trawler. Preliminary prediction of effective power was not possible as the vessel has a length-breadth ratio < 5,5; a block coefficient < 0,6 and percentage *LCB* position from amidships < -2,48. All of these parameters lie outside the range of application of the method. The program indicates these irregularities and cautions against the use of the results which can immediately be identified as incorrect (typically negative resistance values).

American Frigate. The Frigate has a length-breadth ratio > 8,5 and a block coefficient < 0,6. These parameters lie outside the valid range of the regression equations, therefore, valid results were not expected. Effective power values

obtained were erratic having extremely high and low values. The method is not suitable for predicting the effective power of the Frigate.

3.2.8   The SSPA Series (Williams, 1969)

This series is widely used in Sweden and is typical of the modern single screw fast cargo ship.   It has been published as a family of resistance curves and as regression equations, which, from a programming point of view, are ideal.

3.2.8.1   Program development

The program developed (SSPARP.PAS) uses the regression equations to calculate the total resistance coefficient for the ship at Froude numbers 0,18 to 0,30 in steps of 0,1. A Theilheimer interpolating spline is applied to this data to obtain results at the required speeds.

Beyond the bounds of the series, results are obtained by linear extrapolation using the slope of the total resistance coefficient curve between Fn 0,18 and 0,19 and Fn 0,29 and 0,30 respectively.   A maximum of ten speeds are catered for.

Checks are also programmed to determine violations of the range of application of the method. Violations of this nature do not cause the program to abort, but places warnings in the output file.

Propulsion coefficients are calculated using the equations supplied by Shaher Sabit.

3.2.8.2   Program Validation.

It became evident during validation of this program that certain of the regression coefficients were suspect, probably due to typographical errors in the publication. Typically a negative value of residuary resistance coefficient at a Froude number of 0,21 was obtained for a variety of ships. Using regression analysis and adopting an approach similar to that used by Shaher Sabit, new coefficients for Froude number 0,21 were generated. These new coefficients appear to provide reasonable correlation with the published resistance curves (r^2=0,97887). It is

difficult to determine what other errors exist as no example is provided against which the program could be checked against. The program was validated against the resistance curves of a SSPA Cargo Liner having dimensions as indicated in Table 3.16 (Williams, 1969).

Table 3.15 Revised Regression Coefficients for _Fn_=0,21

A_0	5,006	A_5	-0,201
A_1	0	A_6	0
A_2	-19,829	A_7	2,630
A_3	42,094	A_8	-7,918
A_4	-0,565	A_9	0,555

Table 3.16 SSPA Series- Test Ship Data

Waterline Length.	121,300	m
Beam	18,600	m
Draught	8,000	m
Block coefficient	0,685	
LCB from amidships	-0.438	%

Within the bounds of the theory, an acceptable level of correlation was obtained between the program results and the example with a maximum overestimation of 4,12% occurring at 0,22_Fn_. The resistance curves of the series do not extend beyond a Froude number of about 0,26 at which point the program starts underestimating resistance (see Table 3.17).

Table 3.17 SSPA Series - Resistance Comparison

Fn	Resistance (kN)		% diff	Fn	Resistance (kN)		% diff
	Program	Example			Program	Example	
0,18	188,58	183,725	2,64	0,23	334,228	326,165	2,47
0,19	212,155	208,144	1,93	0,24	369,782	368,301	0,40
0,20	237,662	232,917	2,04	0,25	436,529	431,749	1,11
0,21	268,993	260,991	3,07	0,26	517,999	553,177	-6,36
0,22	302,077	290,126	4,12	0,27	763,191	-	-

3.2.8.3 Program Evaluation.

None of the models truly fitted into the range of application of the SSPA method, nevertheless, they were examined to determine the suitability of the program for general purpose resistance prediction.

Twin Screw Corvette. The vessel has a beam-draught ratio > 3,0; a length-displacement ratio > 6,89 and block coefficient < 0,525. These parameters all lie outside the valid range of application of the method. The program indicates these irregularities and cautions against the use of the results. Examination of the results reveal an overestimation of about 2% at 18 knots rising rapidly to about 60% at 32 knots and decreasing to about 30% at 10 knots . The method is considered unsuitable for predicting the effective power of the Corvette.

Single Screw Medium Speed Cargo Ship. The vessel has a beam-draught of 3,25 which is slightly above the method's limit of 3,0. Initial examination of the results indicate the correct trend, however, closer examination reveals relatively high underprediction at the lower end of the speed range and an excessively high overprediction at the upper end of the speed range (see Table 3.18). This high degree of inaccuracy is attributed to using the method beyond its valid range. The method is considered unsuitable for predicting the effective power of the Cargo Ship.

Table 3.18   Comparison of Effective Power – Single Screw Cargo Ship

Speed (knots)	Effective Power (kW)		% diff	Speed (knots)	Effective Power (kW)		% diff
	Program	Model 3065-1011			Program	Model 3065-1011	
11	580	660	-12,16	18	3280	2970	10,44
12	779	870	-10,43	19	3678	3540	3,90
13	1030	1110	-7,18	20	4815	4190	14,93
14	1309	1390	-5,85	21	5730	4930	16,23
15	1679	1710	-1,82	22	8149	5820	40,01
16	2136	2060	3,67	23	10291	6920	48,71
17	2524	2480	1,78				

Single Screw Stern Trawler. The vessel has a length-displacement ratio < 5,06 and block coefficient < 0,525. Both these parameters lie outside the valid

range of application of the method. The program indicates these irregularities and cautions against the use of the results. Results obtained underestimate the effective power by an average of about 8,4% (see Table 3.19) The results obtained are considered reasonably good, however, a high degree of risk is involved should the method be used to predict the resistance of similar vessels having hull forms which violate the limits of the regression equations.

Table 3.19   Comparison of Effective Power - Stern Trawler

peed (knots)	Effective Power (kW)		% diff	Speed (knots)	Effective Power (kW)		% diff
	Program	Model 4970			Program	Model 4970	
11,0	238	249	-4,35	13,5	539	591	-8,81
11,5	279	294	-5,00	14,0	627	692	-9,43
12,0	329	349	-5,59	14,5	725	807	-10,10
12,5	386	417	-7,23	15,0	835	946	-11,75
13,0	432	498	-13,29				

American Frigate. The vessel has a beam-draught ratio > 3.0, a length-displacement ratio > 6.89 and block coefficient < 0,525. These parameters all lie outside the valid range of application of the method. The program indicates these irregularities and cautions against the use of the results. Results obtained underestimate the effective power by between 43-84%. The method is not considered suitable for predicting the effective power of the Frigate.

3.2.9   BSRA Standard Series (Pattullo & Parker, 1959; Lackenby & Parker, 1966)

This series is one of the most common and widely used in the United Kingdom. As previously discussed, the results have been published both graphically and as regression equations. The latter is ideal for programming and has therefore been used as the basis for the program.

3.2.9.1 Program development

The computer program developed (BSRARP.PAS) uses Shaher Sabit's (1971) regression equations to determine circular C of a standard 400 ft ship at speed-length ratios 0,50 to 0,80 in steps of 0,05. The circular C value is then corrected for length using the Froude Circular O function i.e.

$$\textcircled{C}_{400} - \textcircled{C}_L = (\textcircled{O}_{400} - \textcircled{O}_L)\ \textcircled{S}\ \textcircled{L}^{-0.175}$$

where

$$\textcircled{O} = (0.00871 + 0.053/(8.8 + 3.28\ Lpp)) * 12.766/Lpp^{0.0875}$$

with *Lpp* in metres.

The circular notation is then converted to standard C_T, C_R, and C_F values. No ship model correlation allowance is used. A Theilheimer interpolating spline is applied to this data to obtain results at the required speeds.

Beyond the bounds of the series, results are obtained by linear extrapolation using the slope of the total resistance coefficient curve between *Fn* 0,149 and 0,164 and *Fn* 0,253 and 0,268 respectively. A maximum of ten speeds are catered for.

Propulsion coefficients are calculated using the regression equations provided by Parker in the overall presentation of the BSRA Series (Parker, 1966).

3.2.9.2 Program Validation.

No worked example was provided by Shaher Sabit, however, Lackenby and Parker (1966) provide an example in their overall presentation of the series. The main dimensions of this example ship are shown in Table 3.20

Table 3.20   BSRA Series- Test Ship Data

Length between perpendiculars.	135,636	m
Beam	18,648	m
Draught	7,163	m
Block coefficient	0,711	
LCB from amidships	0.72	%

Results obtained compare favourably with those of the example, the program underestimating effective power by about 2,86% and overestimating by 0,43%. The small discrepancies are attributed to the standard error of the regression equations.

Table 3.21 BSRA Series – Comparison of Effective Power

Speed	Effective Power (kW)		% diff	Speed	Effective Power (kW)		% diff
(knots)	Program	Example		(knots)	Program	Example	
10,548	719,665	731,7837	-1,66	14,767	2183,382	2231,381	-2,15
11,602	966,928	990,3588	-2,37	15,821	2982,005	2969,269	0,43
12,657	1277,72	1313,196	-2,70	16,876	4094,774	4117,925	-0,56
13,712	1670,751	1719,399	-2,83				

3.2.9.3 Program Evaluation.

None of the models truly fitted into the range of application of the BSRA Series, nevertheless, they were examined to determine the suitability of the program for general purpose resistance prediction.

Twin Screw Corvette.   Preliminary prediction of effective power for this vessel was not possible as it has a length-displacement ratio > 6,79; a block coefficient < 0,6 and the percentage *LCB* position from amidships < -2,0.   All of these parameters lie outside the valid range of application of the method.   The program indicates these irregularities and cautions against the use of the results which are immediately identifiable as being incorrect (typically negative resistance values).

Single Screw Medium Speed Cargo Ship.   The vessel has a block coefficient < 0,6 which is the limit of the method.   At first glance the results appear reasonable, but closer examination reveals high under and overestimation of effective power, i.e. 53% at 14 knots and 39% at 23 knots respectfully (see Table 3.22).   The method is therefore not considered suitable for predicting the effective power of the Cargo Ship.

Table 3.22 Comparison of Effective Power – Single Screw Cargo Ship

Speed	Effective Power (kW)		% diff	Speed	Effective Power (kW)		% diff
(knots)	Program	Model 3065-1011		(knots)	Program	Model 3065-1011	
11	585	660	-11,44	18	3335	2970	12,28
12	661	870	-23,97	19	4219	3540	19,19
13	661	1110	-40,42	20	5269	4190	25,74
14	653	1390	-53,01	21	6503	4930	31,90
15	974	1710	-43,01	22	7941	5820	36,45
16	2090	2060	1,44	23	9606	6920	38,82
17	2597	2480	4,72				

American Frigate.   The vessel has a length-displacement ratio > 6,79 and a block coefficient < 0,6. Both these parameters lie outside the valid range of application of the method. The program indicates these irregularities and cautions against the use of the results. Results obtained range from an 800% overprediction to an underprediction of about 110%. The method is not considered suitable for predicting the effective power of the Frigate.

Single Screw Stern Trawler.   Preliminary effective power prediction for the vessel was not possible as it has a length-displacement ratio < 5,472; a block coefficient < 0,6 and percentage *LCB* position from amidships < -2,0. All these parameters lie outside the methods range of application. The program indicates these irregularities and cautions against the use of the results which are immediately identifiable as incorrect (typically negative resistance values).

3.2.10   MARIN Mathematical Model (Holtrop & Mennen, 1982; Holtrop, 1984)

The MARIN mathematical model has gained widespread acceptability. Its format is ideal for computerisation and equations are provided which enable a wide range of unknown parameters such as 'half angle of entrance' to be estimated.

3.2.10.1 Program development

The development of the program (HM.PAS) differs from the rest in that results which remain static over the required speed range (e.g. form coefficients, wetted surface area, etc.) are first calculated and then together with the input data,

written to the main output file. The remainder of the results are then calculated over the speed range and written to a temporary file (HM1.TMP). On completion, the results from the temporary file are read and appended in a suitable format to the main file. This strategy was adopted in order to verify the various coefficients calculated during the iterations whilst at the same time providing flexibility with the design of the output format.

The program includes estimates for appendages and propulsion coefficients based on the regression equations provided. It also contains options whereby values of parameters such as 'wetted surface area' can either form part of the input data or be calculated by the program.

3.2.10.2 Program Validation.

Holtrop (1984) provides input and output data for a hypothetical twin screw ship. The particulars of this ship are given in Table 3.23.

Table 3.23   MARIN Mathematical Model – Test Ship Data

Length on waterline.	50,00	m	Transverse bulb area	0	m²
Beam	12,00	m	Midship Section coefficient	0,78	
Draught forward	3,10	m	Waterplane area coefficient	0,80	
Draught aft	3,30	m	Wetted area of appendages	50	m²
Displacement volume	900	m³	Appendage resistance factor	3	
Half angle of entrance	25°		Stern shape coefficient	0	
LCB from amidships	-4,50	%	Transom area	10	m²

As expected, the results from the program correlated well with those provided in the example, with less than a half percent difference between them (see Table 3.24).

Table 3.24   MARIN Mathematical Model – Resistance Comparison

Speed (knots)	Resistance (kN)		% diff	Speed (knots)	Resistance (kN)		% diff
	Program	Example			Program	Example	
25	659,604	662	-0.36	31	803.897	807	-0.38
27	712,536	715	-0.34	33	860,138	864	-0.45
29	752,929	756	-0.41	35	920.803	925	-0.45

The small differences in the results are probably due to 'rounding off' within the program.

3.2.10.3 Program Evaluation.

The range of validity of the MARIN method encompassed the four vessels used for evaluation purposes plus the high speed patrol boat.

Twin Screw Corvette. The method underestimates the effective power of the Twin Screw Corvette by about 19% at 10 knots and overestimates it by about 17% at 32 knots (see Table 3.25). The underestimation in the lower speed ranges plays a minor role, however, the overestimation in the higher speed range could result in the vessel having a higher speed than called for by the design, i.e. about two knots greater (see Figure 3.1 a).

Table 3.25   Comparison of Effective Power -Twin Screw Corvette

Speed (knots)	Effective Power (kW)		% diff	Speed (knots)	Effective Power (kW)		% diff
	Program	Model 5281			Program	Model 5281	
10	182	224	-18,60	22	3365	3267	3,00
12	326	343	-4,84	24	5169	5036	2,65
14	557	537	3,75	26	7250	6863	5,64
16	897	843	6,41	28	9613	8728	10,14
18	1323	1343	-1,49	30	12235	10474	16,81
20	2052	2052	-0,02	32	14133	12085	16,95

Single Screw Medium Speed Cargo Ship. In the lower speed ranges, the method underestimates the effective power of the Cargo Ship by up to 17,5%, however, from about 18 knots up, there is a dramatic improvement in the results with slight over prediction starting to occur from about 20 knots (see Table 3.26). The under prediction in is not considered serious as it occurs in the lower speed range and its impact in all cases is less than one knot.

Table 3.26   Comparison of Effective Power - Single Screw Cargo Ship

Speed (knots)	Effective Power (kW)		% diff	Speed (knots)	Effective Power (kW)		% diff
	Program	Model 3065-1011			Program	Model 3065-1011	
11	551,279	660	-16,47	18	2847,819	2970	-4,11
12	717,136	870	-17,57	19	3514,991	3540	-0,71
13	919,843	1110	-17,13	20	4258,571	4190	1,64
14	1167,624	1390	-16,00	21	5063,674	4930	2,71
15	1470,203	1710	-14,02	22	5970,866	5820	2,59
16	1837,846	2060	-10,78	23	7064,242	6920	2,08
17	2288,853	2480	-7,71				

Single Screw Stern Trawler. The method yielded good results for the Stern Trawler, percentage differences varying from about minus four percent to about plus three percent (see Table 3.27). No problems are foreseen as the under prediction is minimal and occurs in the lower speed ranges

Table 3.27   Comparison of Effective Power - Stern Trawler

Speed (knots)	Effective Power (kW)		% diff	Speed (knots)	Effective Power (kW)		% diff
	Program	Model 4970			Program	Model 4970	
11,0	240	249	-3,83	13,5	607	591	2,75
11,5	290	294	-1,61	14,0	708	692	2,34
12,0	352	349	0,81	14,5	822	807	1,87
12,5	427	417	2,55	15,0	957	946	1,12
13,0	513	498	3,03				

American Frigate. The method under predicts effective power across the whole spectrum of speeds examined. In general, the percentage under prediction is fairly consistent, with a maximum difference of about 11,5% occurring at 14,8 knots (see Table 3.28).   The results obtained are regarded as barely satisfactory with the distinct possibly that if they were used for design purposes, the vessel would not achieve the desired top speed.

Table 3.28   Comparison of Effective Power - American Frigate

Speed (knots)	Effective Power (kW)		% diff	Speed (knots)	Effective Power (kW)		% diff
	Program	Model 5279-1			Program	Model 5279-1	
9,2	276,46	299	-7,54	20,8	3737,30	4056	-7,86
11,9	599,00	665	-9,93	24,0	6347,02	6487	-2,16
14,8	1198,52	1352	-11,35	27,0	10579,17	11169	-5,28
18,1	2373,20	2624	-9,56	30,3	16553,93	18062	-8,35

Patrol Boat.   As previously stated, this vessel is not considered to have a displacement hull form. Nevertheless, the MARIN method provided a reasonable estimate of effective power, particularly in the medium speed range. At the lower speeds, the under prediction is excessively high, however, this range plays a minimal role in the selection of the prime mover. As was expected, in the higher speed range, over prediction occurs, i.e. the vessel has started to plane, therefore less power is required.

Table 3.29   Comparison of Effective Power -Patrol Boat

Speed (knots)	Effective Power (kW)		% diff	Speed (knots)	Effective Power (kW)		% diff
	Program	Model 2133			Program	Model 2133	
6,00	42,88	21,27	-50,39	25,00	2817,70	2958,85	5,01
8,00	94,14	49,88	-47,02	27,50	3506,12	3745,65	6,83
10,00	177,99	101,21	-43,14	30,00	4232,06	4605,75	8,83
12,50	337,59	220,75	-34,61	32,50	5010,95	5581,92	11,39
15,00	578,10	408,51	-29,34	35,00	5895,02	6698,08	13,62
17,50	964,97	811,42	-15,91	37,50	6904,13	7967,78	15,41
20,00	1537,19	1406,83	-8,48	40,00	8094,16	9399,42	16,13
22,50	2172,66	2121,47	-2,36				
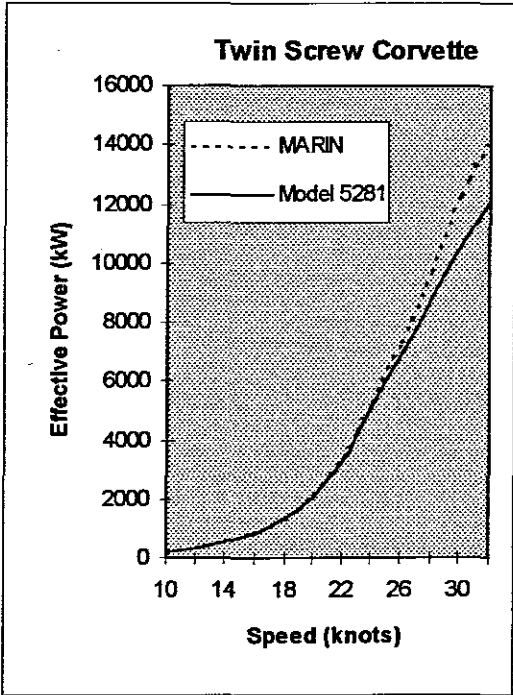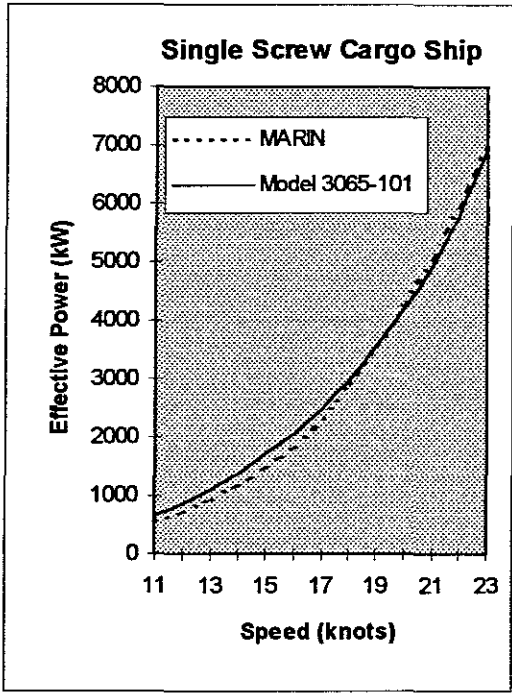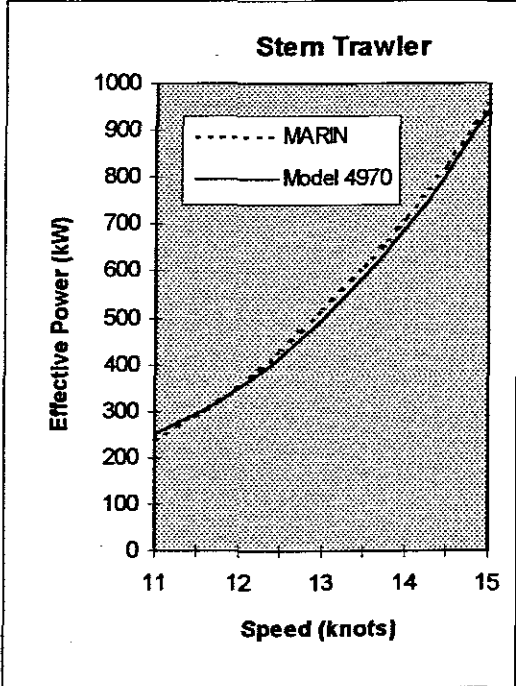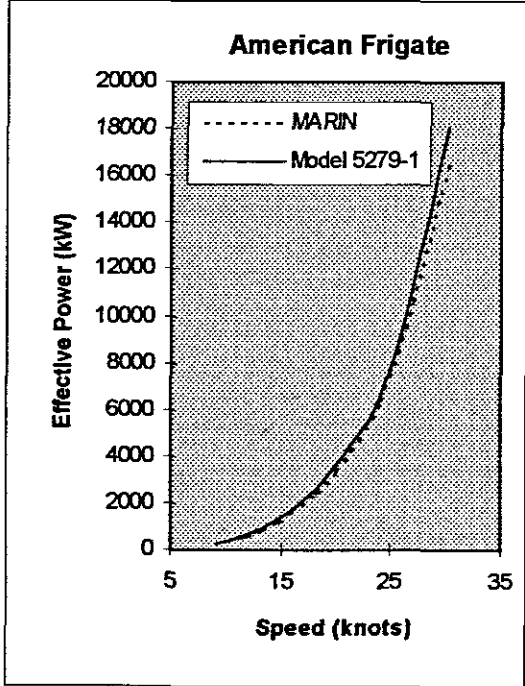
Figure 3.1   Comparison of Speed-Power Curves - MARIN Method

3.2.11 Fung's Mathematical Model (Fung, 1991).

3.2.11.1 Program development

By supplying values of residuary resistance coefficient for each hull form component instead of the regression coefficients for his transom stern equation, Fung ensures that, with respect to hull form parameters, the model cannot be used beyond its valid range of application. This leads to a more complex computer source code as numerous checks must be programmed to ensure that the resulting irregular cut-off limits within the tables are not exceeded.

The development of this program (FMRP.PAS) differs from the majority of the others in that the tabulated data is converted into ten free format files (CR1.BIN to CR10.BIN) instead of arrays. This decision was taken due to the large amount of tabulated data that had to be manipulated, whilst at the same time attempting to achieve a modicum of memory efficiency and speed. For each of the 18 speed-length ratios, three adjacent records, two of which straddle the required hull form component, are identified and read into an array. Taylor's second order interpolation formula is applied to these records, to obtain the interpolated residuary resistance coefficient for that component. The validity of the data over the 18 speed-length ratios is checked and if necessary, the range reduced accordingly.

To obtain the residuary resistance coefficient over the desired speed range, a Theilheimer interpolating spline is used within the bounds of the method (i.e. $0,35$ $>Fn >0,25$). Beyond the bounds of the method, results are obtained by linear extrapolation using the slope of the residuary resistance coefficient curve between Fn $0,24$ and $0,25$ and Fn $0,34$ and $0,35$ respectively.

With the exception of speed range, any violation of the range of application causes the program to halt with an appropriate error message.

3.2.11.2 Program Validation.

Fung provided input and output data for a twin screw ship having particulars as shown in Table 3.30. A correlation allowance of 0,0005 was used in line with that used in the example.

Table 3.30   Test Ship Data for Fung's Mathematical Model

Length on waterline.	145,085	m	Half angle of entrance	8,5°	
Beam	14,630	m	Section coefficient	0,8010	
Draught	4,279	m	Prismatic coefficient	0,6092	
Draught aft	3,30	m	Wetted surface area	2109.828	m²
Displacement volume	4546,824	m³			

The results obtained compare favourably with those given by Fung, the maximum percentage difference being less than one percent (see Table 3.31). The results obtained by Fung are achieved by direct solution of his regression equations whilst those from the program are from the manipulation of data sets generated by these equations. The small discrepancies in the results are attributed to 'rounding off' during generation of the data sets.

Table 3.31   Fung's Mathematical Model - Comparison of Effective Power

Speed (knots)	Effective Power (kW) Program	Effective Power (kW) Example	% diff	Speed (knots)	Effective Power (kW) Program	Effective Power (kW) Example	% diff
13,082	862,609	865,012	-0,28	28,344	11685,95	11721,66	-0,30
15,262	1384,076	1392,222	-0,59	30,524	16611,45	16641,04	-0,18
17,443	2113,424	2126,736	-0,63	32,705	21978,37	21993,68	-0,07
19,623	3123,414	3142,38	-0,60	34,885	27609,01	27619,24	-0,04
21,803	4432,963	4457,049	-0,54	37,065	33243,61	33260,46	-0,05
23,983	5978,817	6020,782	-0,70	39,246	38776,35	38780,13	-0,01

3.2.11.3 Program Evaluation.

The range of validity of Fung's mathematical model encompassed all four of the vessels used for evaluation purposes.

Twin Screw Corvette. The method overestimates the effective power for the Twin Screw Corvette by about 5% over the 18-32 knot range (see Table 3.32).

Maximum under prediction of about 15% occurs at 10 knots. While appearing to be on the high side, the actual impact is minimal due to the relatively low power involved. The same is applicable to the maximum over prediction of about 13 % which occurs at 16 knots. Prediction over the entire speed range is regarded as good, erring slightly on the high side.

Table 3.32   Comparison of Effective Power -Twin Screw Corvette

Speed (knots)	Effective Power (kW)		% diff	Speed (knots)	Effective Power (kW)		% diff
	Program	Model 5281			Program	Model 5281	
10	189	224	-15,45	22	3467	3267	6,11
12	348	343	1,60	24	5272	5036	4,69
14	591	537	10,11	26	7239	6863	5,48
16	956	843	13,38	28	9163	8728	4,98
18	1415	1343	5,37	30	10923	10474	4,29
20	2153	2052	4,91	32	12628	12085	4,50

Single Screw Medium Speed Cargo Ship. Between 11 and 15 knots, the method underestimates the effective power by an average of about 4%. These values are regarded as reasonable even though they err on the low side, primary because the power involved is relatively low and the resulting effect on the speed is well below one knot in each case. Between 16-19 knots a small over prediction occurs rising to a maximum of about 13% at 22 knots (see Table 3.33). The prediction up to 20 knots is considered good. Above 20 knots, even though slightly on the high side, the difference is still considered satisfactory, primarily because the effect accounts for less than one knot and secondly because it errs on the high side.

Table 3.33   Comparison of Effective Power - Single Screw Cargo Ship

Speed (knots)	Effective Power (kW)		% diff	Speed (knots)	Effective Power (kW)		% diff
	Program	Model 3065-1011			Program	Model 3065-1011	
11	635	660	-3,72	18	3012	2970	1,43
12	823	870	-5,45	19	3649	3540	3,07
13	1053	1110	-5,09	20	4498	4190	7,34
14	1334	1390	-4,02	21	5516	4930	11,89
15	1669	1710	-2,40	22	6601	5820	13,42
16	2060	2060	0,00	23	7833	6920	13,19
17	2505	2480	1,00				

Single Screw Stern Trawler. Percentage difference is fairly consistent with an average over estimation of about 10.58% (see Table 3.34). Whilst perhaps slightly on the high side, this prediction is regarded as satisfactory. Primarily because there is less than one knot involved in each case and secondly because the error is on the positive side, thus ensuring that the vessel will meet her required design speed.

Table 3.34   Comparison of Effective Power - Stern Trawler

Speed (knots)	Effective Power (kW)		% diff	Speed (knots)	Effective Power (kW)		% diff
	Program	Model 4970			Program	Model 4970	
11,0	272	249	9,04	13,5	654	591	10,82
11,5	324	294	10,24	14,0	768	692	10,98
12,0	387	349	10,93	14,5	895	807	10,96
12,5	462	417	11,01	15,0	1045	946	10,50
13,0	552	498	10,79				

American Frigate. Examination of the results revealed a consistently high degree of under prediction averaging about 24% between 9,2 and 20,8 knots. Above this, the percentage under prediction starts to reduce reaching a minimum of 11% at 30,3 knots. However, the impact of this reduction is minimised by the increasingly high powers involved (see Table 3.35). These results are regarded as disappointing, particularly in light of the fact that this class of vessel was probably included in Fung's statistical data base.

Table 3.35   Comparison of Effective Power - American Frigate

Speed (knots)	Effective Power (kW)		% diff	Speed (knots)	Effective Power (kW)		% diff
	Program	Model 5279-1			Program	Model 5279-1	
9,2	238	299	-20,52	20,8	3137	4056	-22,67
11,9	505	665	-24,04	24,0	5262	6487	-18,89
14,8	999	1352	-26,14	27,0	9509	11169	-14,86
18,1	1927	2624	-26,54	30,3	16072	18062	-11,02

Twin Screw Corvette

(a)

Single Screw Cargo Ship

(b)

Stern Trawler

(c)

American Frigate
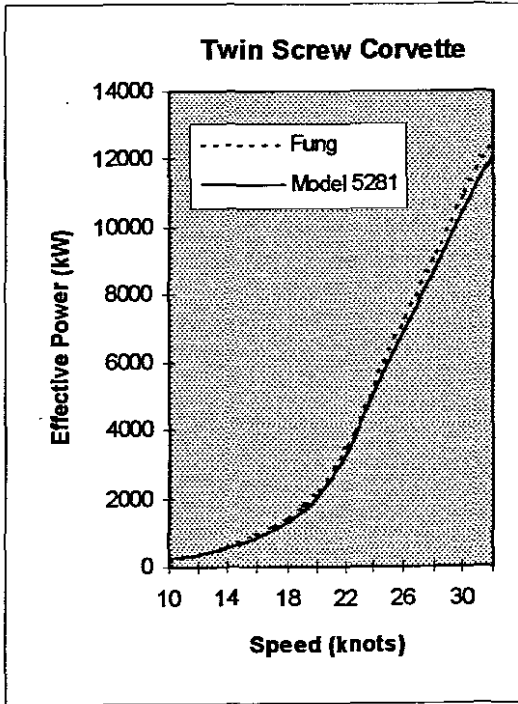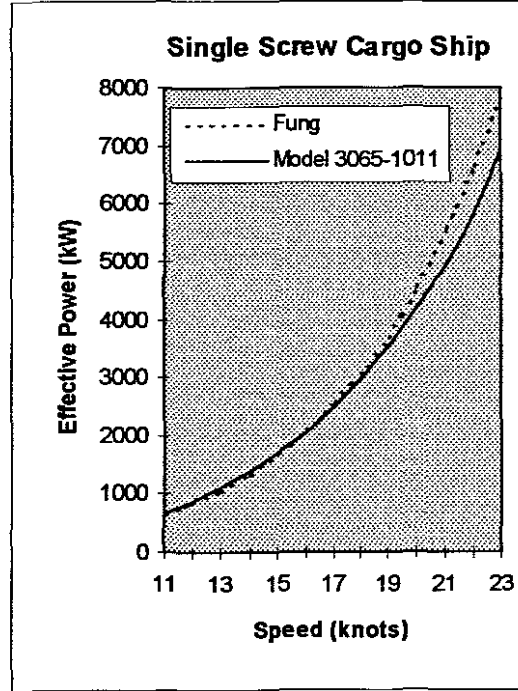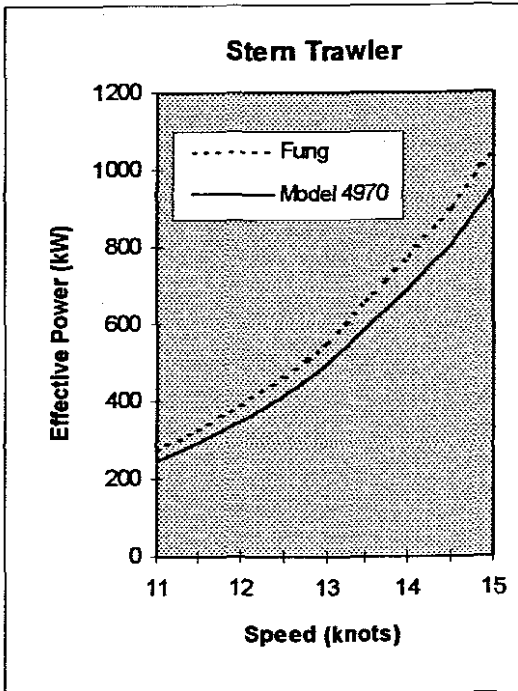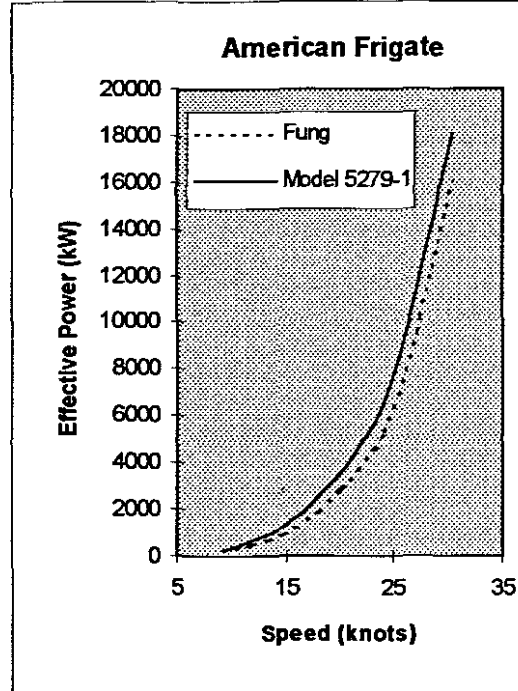
(d)

Figure 3.2　　　Comparison of Speed-Power Curves - Fung's Method

3.2.12 Empirical Equations

No program was developed using the Admiralty Coefficient. In common with the majority of empirical methods, it only provides an indication of the required installed power. As no direct indication of hull resistance is obtainable, it cannot be used as a basis of comparison with the resistance prediction methods examined.

3.2.13 Method Selected

Only the MARIN and Fung mathematical models were flexible enough to accommodate all four vessels used in the evaluation. The results obtained from both methods were not as accurate as hoped, nevertheless, based on the limited evaluation, both are considered acceptable for providing first estimates of hull resistance. The sample considered is to small to provide statistically significant results regarding the accuracy of the two methods, however, of the two methods, the MARIN method provided better approximations for three of the four vessels. Based on this, the MARIN Mathematical Model was chosen to form the core of the Power Prediction Program.

3.3 APPENDAGE RESISTANCE

3.3.1 Analysis of Methods

The choice of a suitable method for estimating appendage can be narrowed down to either:

- a percentage of total resistance based on similar ships
- the 1957 ITTC line combined with a form coefficient.

Because the model tests of the Twin Screw Corvette (model 5281) included appendage data, it was used as the basis for comparison of appendage resistance for both the ITTC line with form coefficients as supplied by Holtrop and Mennen (1982) and the statistical formula provided by Fung (1991). Results obtained ranged from 24% at 10 knots to 9,5% at 35 knots for the ITTC line using the

Holtrop and Mennen form coefficients and 27,5% at 10 knots to 13 % at 35 knots for Fung's method

3.3.2   Selection of Method

While the statistical formula provided by Fung (1991) appears to supply results of the correct order, it is considered to be restrictive as it is only applicable to twin screw ships.

The 1957 ITTC method with form coefficient is considered the most suitable as this approach allows for refinement throughout the design iteration. Typically rough estimations can be made of the wetted surface area of the appendages at *the initial design stages and these can then be altered as more information about* them becomes available

3.4   RESISTANCE DUE TO FOULING

3.4.1   Fouling

If a self polishing co-polymer (SPC) is used then there is no need to allow for added resistance due to fouling, however, if a conventional antifouling is used, some form of allowance must be made. There is little to choose between the RN and USN methods. Neither have a scientific basis, differing only in that with the RN approach, added resistance is a function of the frictional resistance, whilst in the USN approach it is a function of wetted surface area and speed. Both methods are linear with respect to time, however, in the RN method, percentage added resistance is a constant whilst in the USN method it varies over the speed range. The USN method and the original RN method (0,25% frictional resistance per day) compare favourably with one another, the USN method predicting slightly lower in the lower speed range and higher in the upper speed range (see *Figure 3.3).*
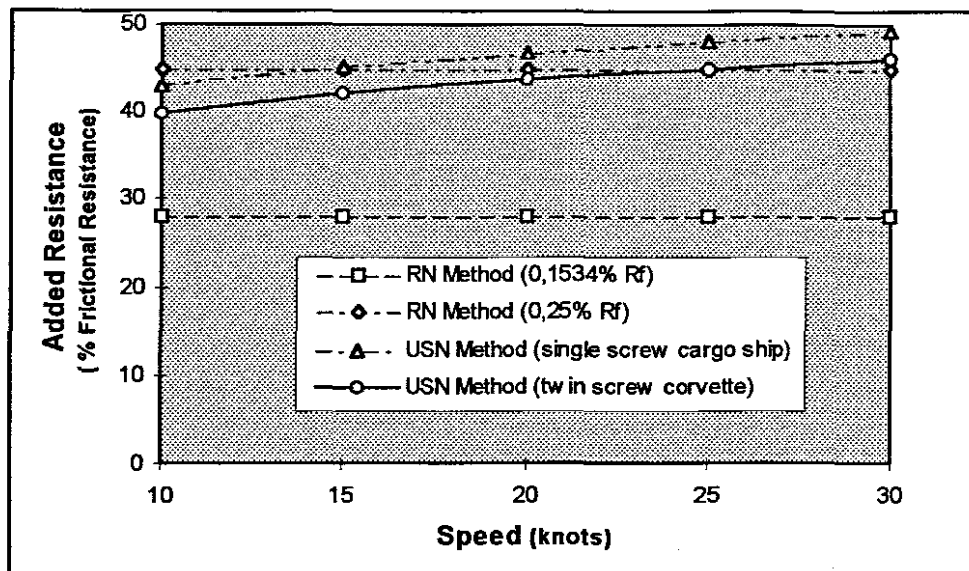
Figure 3.3 Fouling Resistance: Comparison between RN and USN Method

Newton in his discussion with Aertssen (1961) indicates that there is little doubt that the fouling component of added resistance is non-linear, following a hyperbolic trend and postulates the following formula to account for it;-

$$\% increase\ in\ skin\ friction = \frac{140d}{630+d} \quad \text{for } d \text{ days out of dock.}$$

In light of this, together with the results of the MOD trials (UCL, 1988), it was considered justifiable to modify Newton's formula so that it produced a value of 28 % six months out of dock. The new formula derived

$$\% increase\ in\ skin\ friction = \frac{90d}{405+d}$$

gives a value of 27,96% six months out of dock and provides a better account for the reduction in added resistance over a period of time. This new formula is considered the most appropriate for integration into the Power Prediction Program.
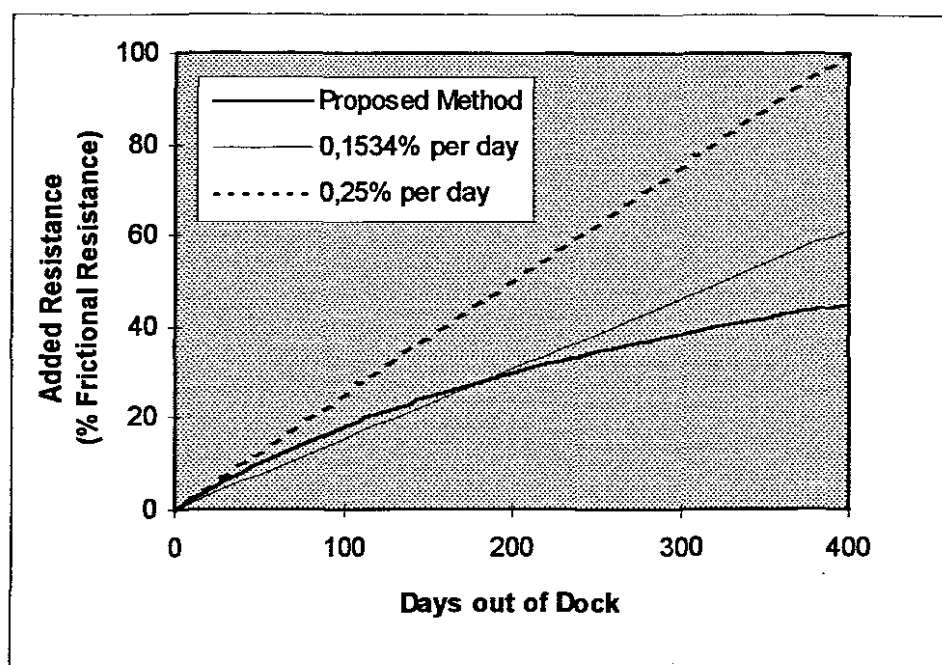
Figure 3.4   Fouling Resistance: Comparison between Proposed and RN Methods

3.5   ESTIMATING HULL ROUGHNESS.

3.5.1   Hull Roughness

For the purpose of resistance prediction a typical value must be selected which is representative of a wide spectrum on new builds. The value which at present appears to be universally acceptable is a standard hull roughness of 150 μm. This value is recommended by the ITTC (1984), Holtrop and Mennen (1982) and van Manen & van Oossanen (1988). Whilst this value is 16.3 percent higher than the mean value found by Townsin et al (1986), it is considered acceptable as it errs on the positive side.

3.5.2   Hull Roughness above 150 μm

Grigson's (1987) distrust of the ITTC formulae are justifiable, however, it is not possible to determine the quality of the topography of a concept design, neither is it considered feasible to model the topography of an actual design.

With minimal data available regarding the construction of a proposed vessel, the

1984 ITTC formula is considered the most appropriate for the purpose of predicting power increase due to hull roughness.
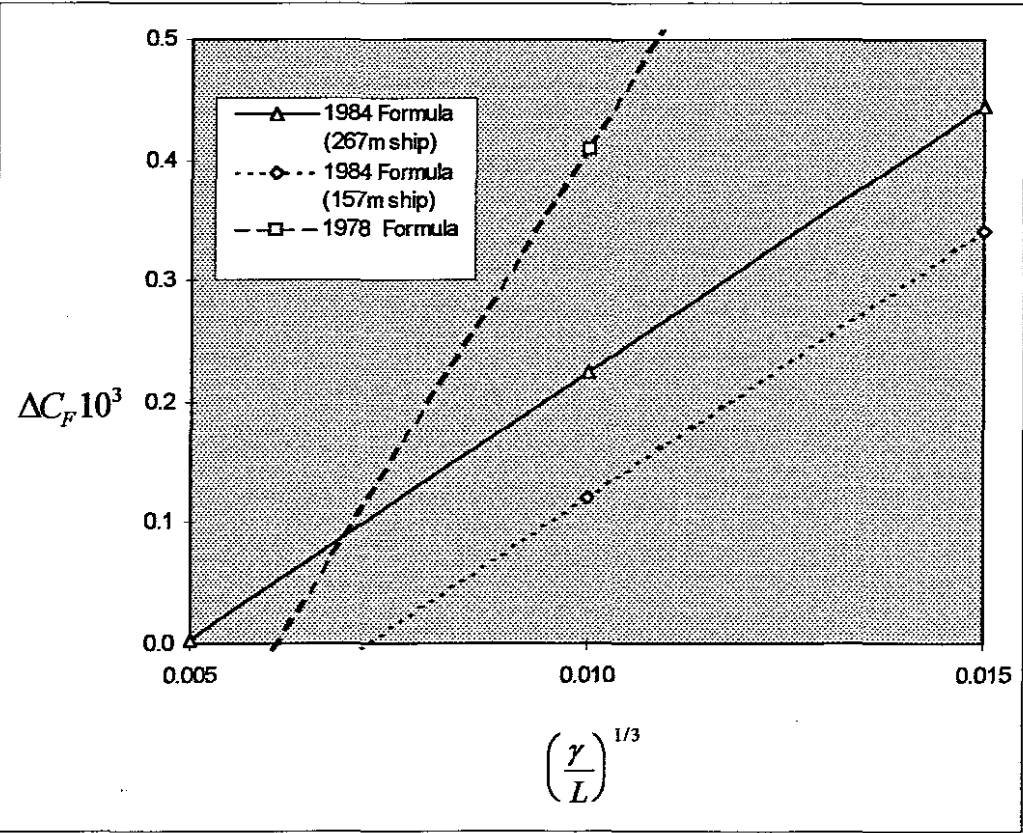
Figure 3.5   Comparison between 1978 and 1984 ITTC formula

It is interesting to note that the slope of the earlier 1978 formula is far steeper than the more recent 1984 formula (see Figure 3.5).

3.6   PROPELLER OPTIMISATION.

All the propeller series' examined in this study are available as polynomials of K_T and K_Q. The variables used in the polynomials differ from series to series, however, their basic format remains the same throughout. This enables a unified approach to be adopted in the development of the propeller prediction/optimisation programs.

The main principle around which propeller problems using K_T-K_Q-J diagrams are resolved involves the elimination of the unknown variables, i.e. those which must be optimised. This is achieved by dividing either K_T or K_Q by a power of J. The

method is easily extended to the numerical solution using K_T-K_Q polynomials. The use of K_T in solving propeller problems is referred to as the Naval Architectural approach, whilst the use of K_Q is referred to as the Marine Engineering approach. This is because the Naval Architect is generally more interested in the resistance (thrust) aspect whilst the Marine Engineer is more concerned with main engine power (torque).

i)   Optimisation of Diameter and Pitch for known Power.

By dividing K_Q by J^5 the diameter can be eliminated from the equation as shown;

$$\frac{K_Q}{J^5} = \frac{Q \times n^3}{\rho \times Va^5} \qquad \text{but} \qquad Q = \frac{P_d}{2 \times \pi \times n}$$

therefore

$$\frac{K_Q}{J^5} = \frac{P_d \times n^2}{2 \times \pi \times \rho \times Va^5}$$

Introducing relative rotational efficiency (η_R) at this point ensures that the optimum solution is for the 'behind ship' and not the 'open water' condition. Substituting the known values into the equation, a constant is obtained, i.e.

$$\frac{K_Q}{J^5} = \left(\frac{P_d \times n^2}{2 \times \pi \times \rho \times Va^5} \right) \times \eta_R = \text{constant}$$

For a range of P/D values, the value of K_Q/J^5 is evaluated from the K_Q polynomial in steps of J equal to 0,05 until the value obtained from the polynomial exceeds that of the calculated value of the constant. A 2nd degree polynomial is then generated using this and the two preceding J values (see Figure 3.6), i.e.

$$K_Q = a + bJ + cJ^2$$

If however, the number of preceding J values are less than two, the process restarts with the step value halved.
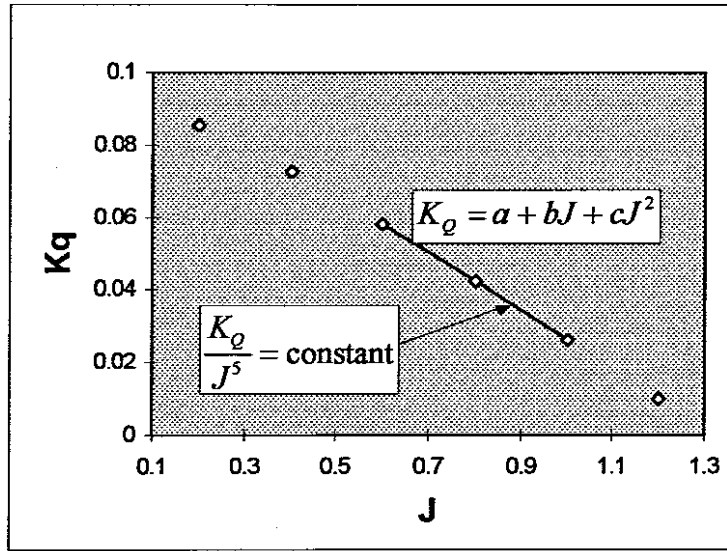
Figure 3.6   Graphical Representation of Solution for Optimum J.

The exact solution of J is at the point where the value of the constant intersects the polynomial. This is determined by firstly equating the polynomial with the constant, multiplied by J^5 and then transposing the terms so that the equation is equal to zero, i.e.

$$a + bJ + cJ^2 = \text{constant} \times J^5$$

$$0 = \left(a + bJ + cJ^2\right) - \left(\text{constant} \times J^5\right)$$

and then solving this equation using the Newton-Raphson method (Chapra & Canale, 1985:138), i.e.

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}. \qquad n = 1,2,3,\ldots\ldots$$

Thus for each P/D value, a matching J value is found. The next step of the solution now begins.

The range of P/D values covered starts at a value equal to the maximum P/D of the series and decreases in steps of 0,2. The value of K_T and K_Q is calculated from the polynomials for each solved value of J and the propeller efficiency is determined at each P/D value until the efficiency decreases (see Figure 3.7). Two 2nd degree polynomials are then generated using this and the two preceding J values, one with efficiency and the other with P/D as the dependant variable, i.e:

$$\eta_o = a + bJ + cJ^2$$

$$P/D = x + yJ + zJ^2$$

If however the number of preceding J values is less than two, the process restarts with the step value halved.
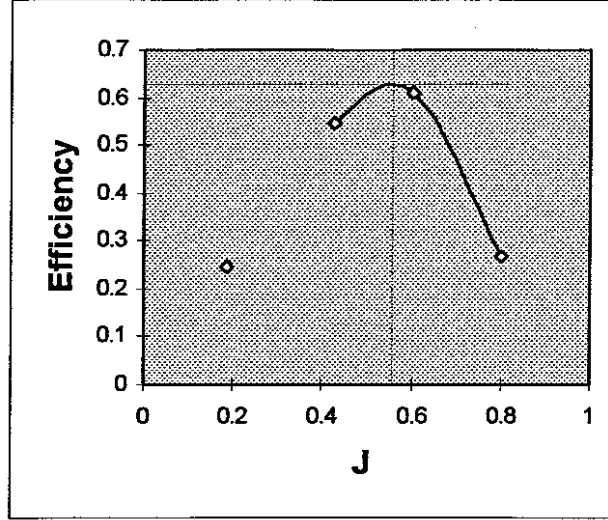
Figure 3.7   Graphical Representation of Solution for Optimum Efficiency.

Maximum efficiency occurs at the peak of the curve given by the efficiency polynomial, i.e. when the slope of the curve is equal to zero. Differentiating this polynomial and equating it to zero provides an equation which defines the J value at the point of maximum efficiency, i.e.

$$\frac{d\eta_o}{dJ} = b + 2cJ = 0$$

$$\therefore J = -\frac{b}{2c}$$

The optimum P/D can be obtained by substituting the maximum efficiency J value into the P/D polynomial and solving. Optimum diameter can be obtained by substituting the known values into the formula for J, i.e.

$$D = \frac{Va}{n \times J}$$

ii   <u>Optimisation of Diameter and Pitch for known Resistance</u>

By dividing K_T by J^4 the diameter can be eliminated from the equation;

$$\frac{K_T}{J^4} = \frac{T \times n^2}{\rho \times Va^4} \qquad \text{but} \qquad T = \frac{R}{(1-t)}$$

therefore

$$\frac{K_T}{J^4} = \frac{R \times n^2}{\rho \times Va^4 \times (1-t)}$$

The maximum efficiency and optimum pitch and diameter can now be found in a similar manner as described previously.

iii Optimisation of Rotational speed and Pitch for known Power

By dividing K_Q by J^3 the rotational speed of the propeller can be eliminated from the equation;

$$\frac{K_Q}{J^3} = \frac{Q \times n}{\rho \times Va^3 \times D^2} \qquad \text{but} \qquad Q = \frac{P_d}{2 \times \pi \times n}$$

and introducing relative rotational efficiency

$$\frac{K_Q}{J^3} = \left(\frac{P_d}{2 \times \pi \times \rho \times Va^3 \times D^2} \right) \times \eta_R$$

The maximum efficiency and optimum pitch and rotational speed can be found in a similar manner as described previously.

iv Optimisation of Rotational speed and Pitch for known Power

By dividing K_T by J^2 the rotational speed can be eliminated from the equation;

$$\frac{K_T}{J^2} = \frac{T}{\rho \times Va^4 \times D} \text{but} \qquad T = \frac{R}{(1-t)}$$

therefore

$$\frac{K_T}{J^2} = \frac{R}{\rho \times Va^4 \times D \times (1-t)}$$

The maximum efficiency and optimum pitch and rotational speed can be found in a similar manner as described previously.

3.6.1 B-Series

Using the K_T-K_Q polynomials presented by Oosterveld and van Oossanen (1975), a propeller prediction/optimisation program (BSPS.PAS) was developed using the previously defined algorithms.

Oosterveld and van Oossanen provide corrections for Reynolds number, however, giving due consideration to the advice of Loukakis and Gelegenis (1989) that the polynomials at Reynolds number $2x10^6$ tend to take into account in an approximate manner the full size propeller roughness effect, these have not been included in the computer program.

The program covers the full range of the B-Series and limits the user to entering data only within the range of the series. No check is made regarding the sensibility of the input data thus the user can enter data which will result in no valid solution.

The program allows a wide range of 'off-design calculations to be performed using an abbreviated form of the basic optimisation routine.

The minimum *BAR* required is calculated using the Keller formula. The user is provided with the opportunity of recalculating using the existing values at a new *BAR* value. Using this facility allows for a manual form of *BAR* optimisation.

3.6.1.1 Program Validation.

Oosterveld and van Oossanen supply no worked examples which could be used for validation purposes. Therefore, published example calculations based on K_T-K_Q-J, B_P-δ and the Loukakis and Gelegenis diagrams were used. Table 3.36 lists the relevant input data for each of the examples used.

Table 3.36 B-Series Examples – Input data

	Example 1 (Saunders, 1957)	Example 2 (van Manen, 1957)	Example 3 (Loukakis, 1989)	Example 4 (Wright, 1965)
Ship resistance (kN)	765,366	-	-	-
Engine Power (kW)	-	5297,400	3281,080	9805,944
Ship speed (knots)	20,500	16,600	-	16,600
Wake fraction (w)	0,261	0,240	0,050	0,394
Thrust deduction (t)	0,110	0,11	0,112	0
η_r	1	1	1,015	1
Diameter (m)	6,096	-	-	-
Rotational speed (rpm)	-	126	-	98
No of Blades	4	4	4	4
Expanded area ratio	0,400	0,550	0,770 and 0,890	0,562
Shafting efficiency (%)	100	97	100	100

The output requirements differed from example to example. When not provided, a shafting efficiency of 100% and a thrust deduction fraction of zero was used as default values. Example 1 and 2 provided an acceptable level of correlation with the K_T-K_Q-J diagram solutions (see Tables 3.37 and 3.38), the percentage difference in optimum diameter, optimum rotational speed and maximum efficiency all being less than five percent.

Table 3.37   B-Series Comparison of Results: Example 1 (Saunders, 1957)

	Saunders	Program	Difference
Optimum efficiency (%)	66,5	65,4	1,65 %
P/D ratio	1	1,046	4,60 %
Rotational speed (rpm)	109,3	106,2	2,84%

The percentage difference in optimum *P/D* ratio may be considered slightly high in Example 2 (8,9%), however, its impact on preliminary design is regarded as minimal.

Table 3.38   B-Series Comparison of Results: Example 2 (van Manen, 1957)

	van Manen	Program	Difference
Optimum efficiency (%)	62,70	63,00	0,48 %
P/D ratio	0,921	0,841	8,69 %
Diameter (m)	5,000	5,199	3,98 %

Loukakis and Gelegenis (1989) provided results for optimising both the propeller diameter and rotational speed using his diagrams. Correlation with these results is excellent, percentage differences all being less than one percent. This is to be expected as the diagrams are derived from the same K_T-K_Q polynomials used in the development of the program.

Table 3.39   B-Series Comparison of Results: Example 3 (Loukakis, 1989)

	Optimum diameter			Optimum rotational speed		
	Loukakis	Program	Difference	Loukakis	Program	Difference
Speed (knots)	16,69	16,69	-	16,65	16.65	-
Diameter (m)	2,88	2,876	0,13 %	2,80	2,80	-
N (rpm)	280	280	-	253	252,4	0,24 %
EAR	0,77	0,77	-	0,89	0,89	-
P/D ratio	0,882	0,887	0,57 %	1,068	1,075	0,66 %

Wright (1965) used B_P-δ diagrams to solve his example. The percentage differences obtained being similar to those of Example 1 and 2.

Table 3.40   B-Series Comparison of Results: Example 4 (Wright, 1965)

	Wright	Program	% diff
Optimum efficiency	56 %	54,91 %	1,95 %
P/D ratio	.0,762	0,718	5,77%
Diameter	6.834 m	7,108 m	4,01 %

It is interesting to note that differences between results obtained using the B_P-δ diagrams and those using the K_T-K_Q-J diagrams are similar. Discrepancies were expected for the following reasons

- with B_P-δ diagrams, optimum diameter is based on the 0,95δ line

- the B_P-δ diagrams are dimensional

- with B_P-δ diagrams, power corresponds to the fresh water condition

- B_P-δ diagrams hold good only for the open water conditions

Notwithstanding the small discrepancies found, the above results indicate that the program delivers results with a degree of accuracy similar to that achievable using the K_T-K_Q-J diagrams. It may be argued that, in comparison to the diagrams, a higher degree of accuracy is attainable from the program, as it does not suffer from inaccuracies generally experienced during manual graphical interpolation.

3.6.2   Newton-Rader Series

No program was developed for this series due to the published regression coefficients being suspect, probably due to typographical errors.

3.6.3   Gawn Propeller Series

Using the K_T-K_Q polynomials presented by Shen and Marchal (1995), a propeller prediction/optimisation program (GAWN.PAS) was developed using the previously defined algorithms.

Corrections for variation in Reynolds number were not accounted for as neither Shen and Marchal nor Gawn provided usable data on this topic. It may however be argued that the advice of Loukakis and Gelegenis (1989) regarding the fact that the polynomials without correction, tend to take into account in an approximate manner the full size propeller roughness effect, is applicable.

The program allows a wide range of 'off-design calculations to be performed using an abbreviated form of the basic optimisation routine.

3.6.1.1   Program Validation.

Neither Gawn nor Shen and Marchal provide a worked example which could be used for validation purposes. To validate the program, a metricated example published in Basic Ship Theory (Rawson & Tupper, 1982:408) was used. Table 3.41 lists the relevant input data from this example.

Table 3.41   Gawn Series Example - Input data

Ship resistance	1792,.972 kN	Diameter (m)	4,267m
Ship speed	28,00 Knots	No of Blades	3
Wake fraction	0,091	Expanded area ratio	0,878
Thrust deduction	0,125	Shafting efficiency (%)	100
η_r	1		

Examination of the results (see Table 3.42) show that percentage difference in optimum *P/D* ratio and rotational speed to be slightly on the large side, with *P/D* ratio underestimated by 7,4% and rotational speed overestimated by 5,5%. These values, while slightly on the high side, are considered acceptable for preliminary investigation purposes. For estimating required power, efficiency is the most important quantity and here the difference between the two values is considered negligible.

Table 3.42   Gawn-Series Comparison of Results:

	Rawson & Tupper	Program	% diff
Optimum efficiency	66,00%	66,38 %	0,58
P/D ratio	1,22	1,13	-7,38
N (revs per minute)r	217	230	5,53

Gawn (1953) provided a comparison between the Gawn Series and the B-Series. A change in trend was obtained when a similar comparison was made using the calculated results obtained from the polynomials (Figure 3.8). In the original comparison, the B-Series had higher efficiencies than the Gawn Series. The exact opposite result was found when using the polynomial results. The discrepancy is due to the lower efficiency values obtained from the B-Series polynomials and is attributable to Gawn's values been based on the earlier published results of the B-Series (pre 1968).

3.6.4   Gawn Burril Series

No suitable regressions were available for this series, consequently no computer program was developed around it.

3.6.5   Selection of Method

The results obtained from the B-Series and the Gawn series compare favourably with one another. When examining efficiencies, the Gawn propeller appears to have a slight edge over the B-Series propeller (see Figure 3.8). Additionally, the Gawn Series covers a wider range of pitch-diameters than the B-Series. Nevertheless, the B-Series propeller was selected for incorporation into the Power Prediction, primary because it covers propellers having between two and seven blades compared with three blades for the Gawn Series. Overall, this leads towards a more favourable prediction value.
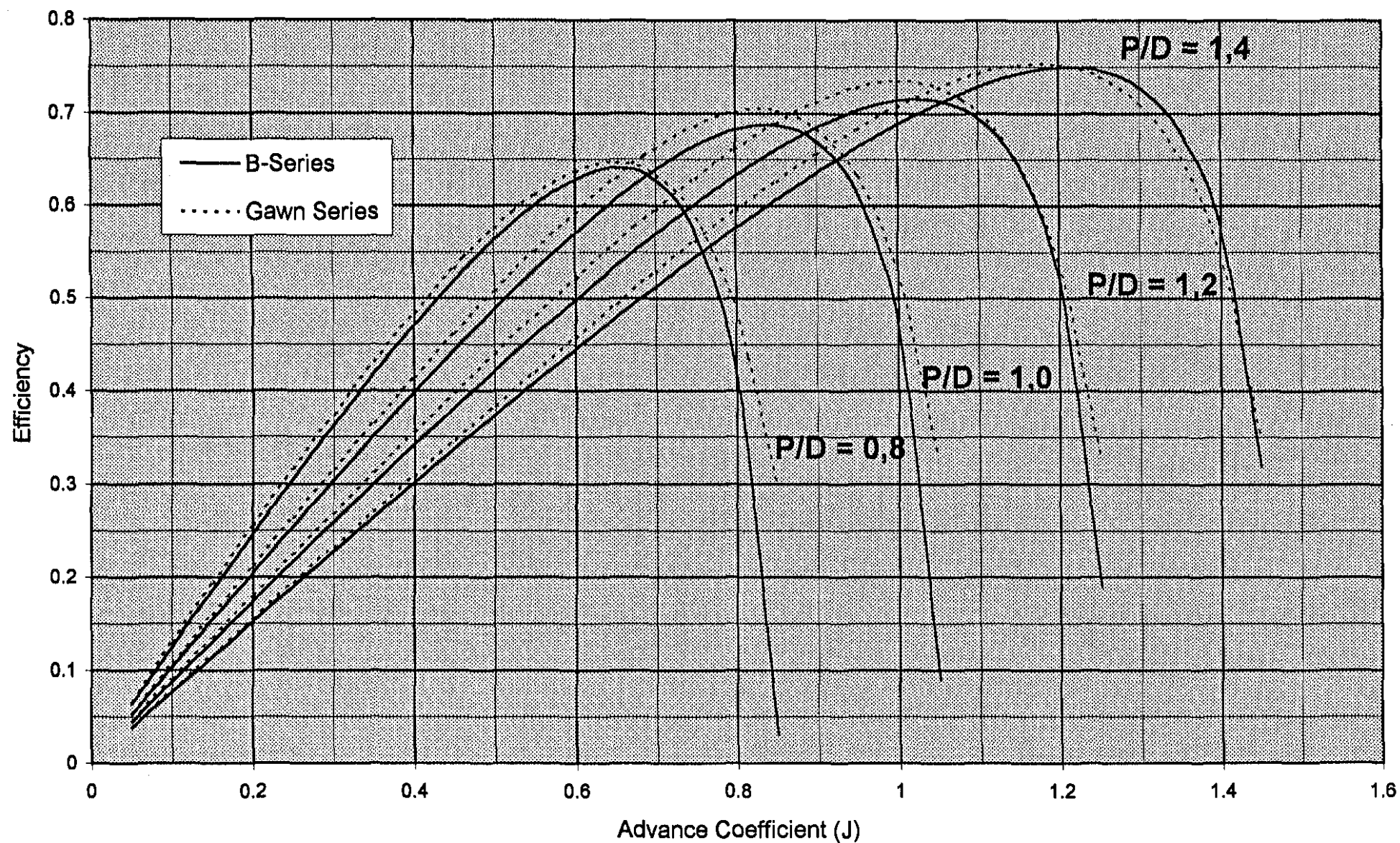
Figure 3.8 - Efficiency of B-Series compared with Gawn Series (BAR 0,65)

3.7 PROPULSION COEFFICIENTS.

3.7.1 Empirical Methods.

Only the simpler empirical equations for thrust and wake fraction were considered, as those defined earlier as more complex, require information not generally available in the early design stages (e.g. propeller rake angle, angle of bossing to horizontal, etc.).

Hadler & Cheng (1965) provided experimental wake data for 40 single screw and 19 twin screw models which included both merchant and naval types with a variety of different sterns. This data was used to in evaluating the accuracy of the more simplistic empirical equations.

3.7.1.1 Wake Fraction

When using experimental wake fraction data, it is usual to apply some form of correction to account for the higher Reynolds number of the full size ship. Typically, when comparing model results with full scale results, one would expect the full scale results to be slightly lower than those obtained from the model tests.

Using the Hadler & Cheng data, the single screw wake fraction equations of Taylor (Muckle, 1975), Hecksher (Poradnik Okretowca, 1960) and Schiffbaukalender (Poradnik Okretowca, 1960) were examined. In comparison with the Hadler & Cheng results, both the Taylor and the Hecksher equation appear to grossly overestimate the wake fraction in the lower block coefficient range. The Schiffbaukalender equation appears to provide the best all round results for single screw ships, generally with values slightly below the experimental results for clearwater/conventional stern vessels and slightly above for transom stern vessels.

Plotting the experimental wake fraction data against prismatic coefficient revealed no indication of linear correlation as implied by the Hecksher equation (r^2=0,598). Neither was there an overly high correlation between block coefficient and wake as implied by both the Taylor and Schiffbaukalender

equations (r^2=0,806). The Schiffbaukalender equation providing the closest fit with the trend line fitted to the experimental data.
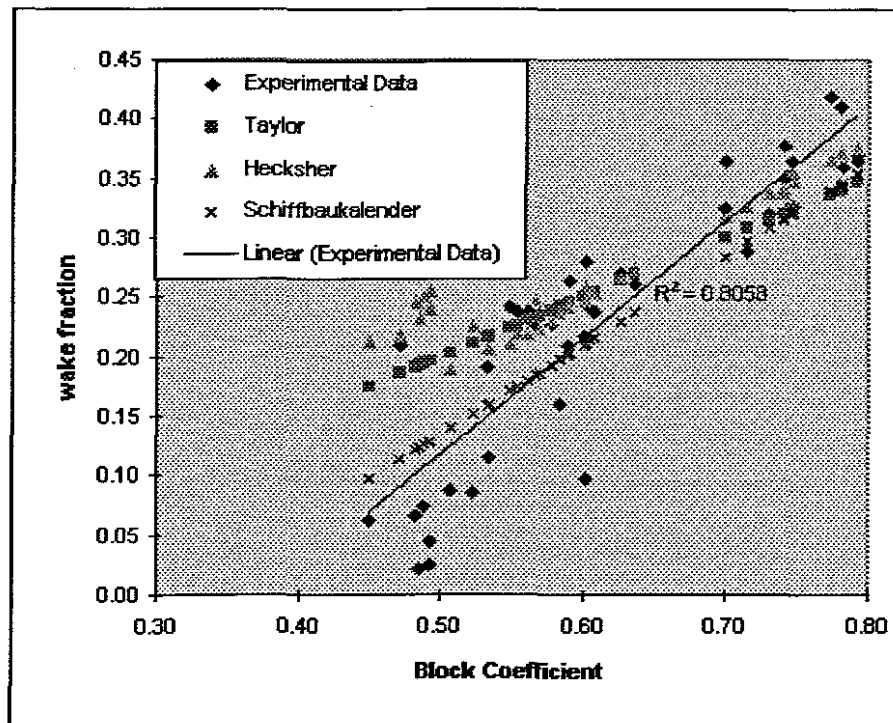
Figure 3.9 Overall Analysis of Single Screw Wake Data

A high degree of scatter was obtained when the Hadler & Cheng twin screw experimental data was plotted against block coefficient. No indication of linear correlation as implied by the Taylor equation for twin screw ships was found (r^2=0,267). A plot of the values obtained from the Taylor equation shows that it lies above the trend line fitted to the experimental data (see Figure 3.10) indicating that in general the Taylor equation will overestimate the wake fraction value in twin screw ships.
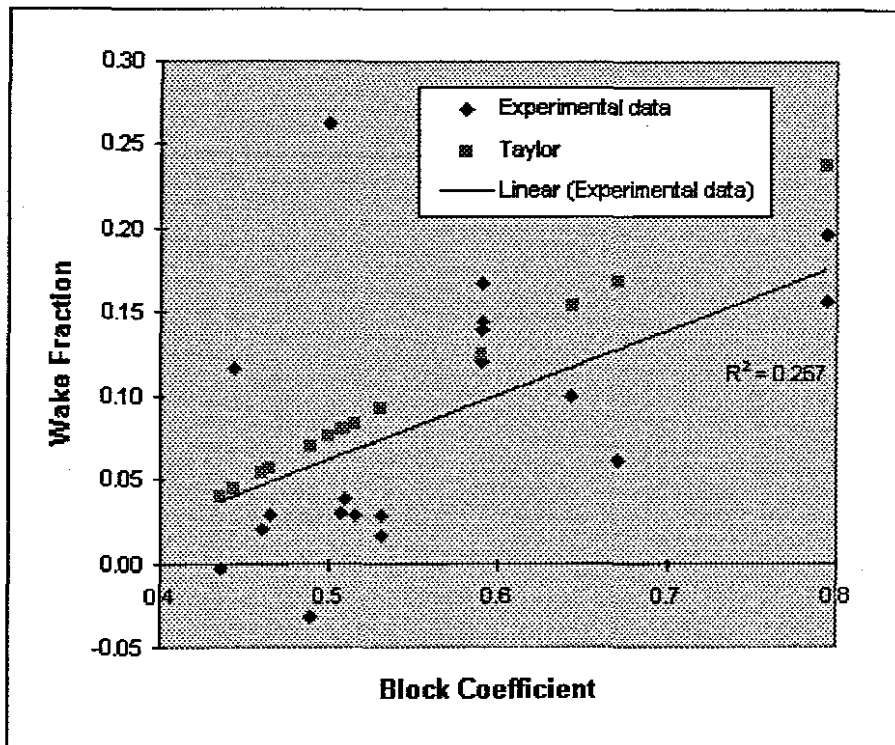
Figure 3.10   Overall Analysis of Twin Screw Wake Data

3.7.1.2 Thrust Deduction Fraction

The Hecksher equation for thrust deduction factor implies a linear relationship with prismatic coefficient whilst the Schiffbaukalender equation a linear relationship with wake fraction. To assess the validity of these implied relationships, the experimental data was plotted against both prismatic coefficient and wake fraction respectively. No correlation was found, however, examination of the data tends to indicate that the Schiffbaukalender equation will provide the better estimate of the two equations providing that the wake value used is that obtained from the corresponding Schiffbaukalender equation and not the actual value.

Both the Hecksher and Schiffbaukalender equation are valid only for single screw ships. No simple formulae for twin screw vessels was examined.
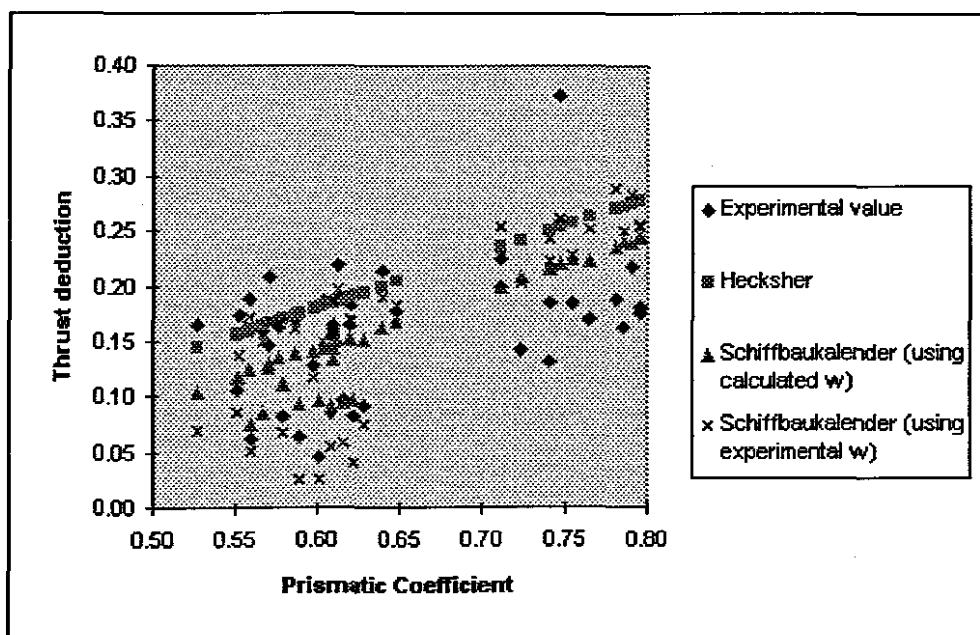
Figure 3.11   Overall Analysis of Single Screw Thrust Data

3.7.2   Statistical Methods

The propulsive coefficients obtained from the tests of the same models used in the resistance prediction evaluation were used to evaluate the statistically generated propulsive coefficient equations.   Only one speed, representing an average cruising speed, was selected for each of the models.   In all cases, the $1-w$ and $1-t$ values were used for comparison purposes.   This results in a more useful comparison, as the values are now in the same format as they would be when practically applied.   This also results in a more realistic comparison of the percentage difference between methods.

3.7.2.1   SSPA Equations.

These equations are applicable strictly to the SSPA Series and none of the vessels examined fall within this category.   However, based on the resistance results, it was hoped that the results for the Cargo ship and the Stern Trawler would be of the correct order.   This was partially the case for the Cargo ship, with an over prediction of less than 5,5% for both $1-t$ and relative rotative efficiency and an under prediction of 1,05% in $1-w$ (see Table 3.43).   Overall, the method is

considered far to inaccurate for general purpose prediction due to the comparatively poor results obtained for both the Trawler and the Corvette.

3.7.2.2 BSRA Equations.

The equations are applicable strictly to the BSRA Series and none of the vessels examined fall within this category, however, it was hoped that the results for the cargo ship would be of the correct order. This was not the case, with the results on the whole being considered far to inaccurate for general purpose prediction.

3.7.2.3 MARIN Equations.

Results obtained for both the Cargo Ship (model 3065-1011) and the Trawler (model 4970) varied between a maximum over prediction of 2,37% to a maximum under prediction of 2,71% on all coefficients. The results for the Frigate (model 5279-1) and the Corvette (model 5281) were not so promising, nevertheless, the general percentage differences obtained were consistently lower than those obtained from the other methods (see Table 3.43).

3.7.3 Miscellaneous Methods

3.7.3.1 The I.O. Series

To utilise Zborowski 's graphically supplied propulsion coefficients within the IO Series resistance prediction program linear and second order polynomials were fitted to the data lifted from the graphs. The resulting equations developed are as follows:-

$$w_t = -0.59643 + 1.09705\,m - 0.42718\,m^2$$

$$t = -0.50735 + 0.97370\,m - 0.33899\,m^2$$

$$\eta_r = 2.19006 - 1.81701\,m + 0.72319\,m^2$$

The accuracy of these equations are considered to be as good as that obtained directly from the graphs.

Table 3.43 Comparison of Propulsive Coefficients

	Model Results	MARIN Estimate	% diff	BSRA Estimate	% diff	SSPA Estimate	% diff	IO Series Estimate	% diff	Taylor Estimate	% diff	Hecksher Estimate	% diff	Schiffbaukalender Estimate	% diff
Corvette															
Speed	22	22	-	22		22		22		-	-	-	-	-	-
$(1-w)$	0,990	0,946	-4,44	0,91	-8,08	0,831	-16,06	0,905	-8,59	0,918	-7,27				
$(1-t)$	0,942	0,929	-1,38	0,792	-15,92	0,729	-22,61	0,808	-14,23	-	-	-	-	-	-
η_R	0,908	0,966	6,39	1,116	22,91	1,010	11,23	1,078	18,72	-	-	-	-	-	-
Cargo Ship															
Speed	18	18	-	18				18		-	-	-	-	-	-
w	0,760	0,778	2,37	0,827	8,82	0,752	-1,05	0,908	19,47	0,774	1,84	0,78	2,63	0,347	-54,34
t	0,808	0,82	1,49	0,756	-6,44	0,85	5,20	0,809	0,12	-	-	0,834	-43,84	0,554	-31,44
η_R	1,031	1,000	-3,01	1,080	4,75	1,010	2,04	1,085	5,24	-	-	-	-	-	-
Trawler															
Speed	13	13	-	13	-	13	-	13		-	-	-	-	-	-
w	0,799	0,792	-0,88	0,871	9,01	0,831	4,01	0,915	14,52	0,799	0,00	0,76	-4,88	0,384	-51,94
t	0,813	0,791	-2,71	0,712	-12,42	0,729	-10,33	0,81	-0,37	-	-	0,82	0,86	0,579	-28,78
η_R	1,015	1,013	-0,20	1,118	10,15	1,010	-0,49	1,098	8,18	-	-	-	-	-	-
Frigate															
Speed	20,8	20,8	-	20,8	-	20,8	-	20,8	-	-	-	-	-	-	-
w	0,958	0,888	-7,31	1,043	8,90	0,925	-3,44	0,899	-6,16	0,825	-13,88	0,769	-19,73	0,423	-55,85
t	0,870	0,85	-2,30	0,604	-30,60	0,883	1,49	0,808	-7,13	-	-	0,826	-5,06	0,605	-30,46
η_R	0,954	1,000	4,82	1,217	27,57	1,010	5,87	1,067	11,84	-	-	-	-	-	-

The original graphs are supposedly general purpose, suitable for twin screw merchant ships having a transom stern. It was therefore envisaged that they would be applicable to other vessel types having a similar stern arrangement, for example, the corvette. Due to the extremely disappointing results (see Table 3.43) the method is considered to be of limited value.

3.7.4 Selection of Method

None of the methods examined revealed results which could be regarded as conclusive. Overall, the results obtained from the MARIN equations were regarded as slightly better than the rest, therefore, they were chosen for direct implementation within the Power Prediction program.

3.8 ADDED RESISTANCE DUE TO WEATHER

3.8.1 Added Resistance Due To Wind

To account for the scale effect of wind resistance between model and full scale ship, the 1978 ITTC formula was initially considered the most appropriate due to its international acceptance. However, further examination revealed that by using relative and not absolute wind speed, the majority of wind resistance methods indirectly took this scale effect into account. Further, it was considered that the scale effect applied to both the methodical series and the mathematical models as both methods are based wholly or partially on model experiments.

3.8.1.1 Wind Resistance Formula (Isherwood, 1972).

A Pascal program (WIND.PAS) was developed around Isherwood's equations. In considering preliminary power prediction. the resistance in the fore and aft direction is of prime interest. However, in order to provide a complete program, lateral resistance and yawing moments were included. The independent variables provided by Isherwood cover only merchant ship types. Nevertheless, the method can be extended to any ship type as long as any new independent variables fall within the range of those used in the regression analysis. To

ascertain whether this was true for warships, the profiles of six proposed corvettes for the SA Navy were examined. Values of the independent variables obtained were found to lie within the range of the regression analysis, consequently their average values were included in the program. (see Table 3.44).

Table 3.44 Average Values of Independent Variables for Corvettes

$\dfrac{2A_L}{L_{OA}{}^2}$	$\dfrac{2A_T}{B}$	$\dfrac{L_{OA}}{B}$	$\dfrac{S_L}{L_{OA}}$	$\dfrac{C}{L_{OA}}$	$\dfrac{A_{SS}}{A_L}$	M
0.118	1.587	8.394	1.317	0.490	0.402	1

The results of the Isherwood equations for a head wind when compared with both the Taylor and Hughes (van Manen & van Oossanen, 1988) empirical equations, reveal values of a similar order of magnitude. This tends to indicate that with minimum ship detail, any of these three equations could be used with the same level of confidence to predict the added resistance for head wind conditions.

In the 80° to 110° range. results obtained from the Isherwood equation for resistance in the fore and aft direction, sometimes appear suspect. Typically, negative values occur in the range up to 90° with positive values above this angle. However. this can be accounted for by the standard error of the equations.

3.8.1.2 Selection of Method.

The equation provided by Todd (1967) was not considered suitable as it requires a wind direction coefficient which is not readily available in the early design stages. The Isherwood (1972) analysis provides the best insight into the effect of wind irrespective of direction. However. the main requirement during the preliminary design phase is to predict the head wind condition. Therefore, whilst the Taylor formula is somewhat crude by comparison to the other methods, it is considered the most suitable as it produces results which appear reasonable. It also has the advantage that it does not require information about the superstructure. This enhances its appeal for inclusion into the Power Prediction

program above the merits of the other methods (information regarding superstructure is generally vague during the early design stages).

3.8.2   Added Resistance Due To Sea State

Regardless of its limitations, the Moor and Murdey (1970) method has the advantage of being easily converted to computer source code and whilst not capable of accepting different sea spectra it does provide an acceptable first estimate of added resistance for single screw merchant ships with C_B lying between 0.55 and 0.88.   This limitation is not applicable to the Jinkine and Ferdinande (1974) method which encompasses both twin screw vessels and ships with finer hull forms. This method also has the advantage that it can be modified to accept different sea spectra. However, it has a major disadvantage in that it is not easy to program.

Both the Moor and Murdey and the Jinkine and Ferdinande methods require a knowledge of the longitudinal radius of gyration of the ship.   As this is not available during the early design stages, an estimate must be made. From Moor and Murdey (1968; 1970) it can be deduced that a reasonable value for longitudinal radius of gyration is one quarter length between perpendiculars. This value is therefore used as a default.

3.8.2.1   Moor and Murdey Method (1970)

A Pascal program, APSS.PAS, was written around this analysis. The program is based directly on the regression equations for added power in a head sea. Added power for the desired sea state is calculated for each of the standard ship lengths. Added power required for the actual ship length is then obtained from these *results by means of a three point interpolation routine.   No true validation of the* program was possible due to a lack of suitable data for comparison purposes. Published data generally combine the effect of both wind and waves, giving the result as a percentage power loss.

3.8.2.2 Jinkine and Ferdinande Method (1974)

A program, WAVE.PAS, comprising two main procedures was developed for determining the added resistance due to sea state. The first of these procedures is used to determine the added resistance coefficient and the second, the output spectrum. Values defining the Gospodnetic-Miles seaway spectrum are stored as an array in the program.

To facilitate the incorporation of the r_{max} curves derived by Mackay and Schmitke (1978) the data was statistically analysed and the following equations obtained:-

- V-shaped sections

$$r_{max} = 38,02Fn^{1.197}$$

(Standard error of estimate = 0.029 and r^2=0.999)

- U-shaped sections

$$r_{max} = 1034,806Fn^4 - 917,344Fn^3 + 226,563Fn^2 + 23,382Fn - 4,89$$

(Standard error of estimate = 0.343 and r^2=0.9989)

Table 3.45 compares the values obtained from these equations with the actual given values. Percentage differences are of a similar order to those obtained from the equation developed by Mackay and Schmitke (1978) for a bulbous bow.

Table 3.45   Comparison of calculated and actual values of r_{max}

Fn	V-Shaped Sections			U-Shaped Sections			Bulbous Bow		
	$r_{max.}$ act	$r_{max.}$ est.	% diff	$r_{max.}$ act	$r_{max.}$ est.	% diff	$r_{max.}$ act	$r_{max.}$ est.	% diff
0	0	0	0	0	-0.049	∞	0	0	0
0.05	1.1	1.054	4.22	1.6	1.578	1.36			
0.10	2.4	2.416	-0.65	3.5	3.741	-6.88	4.72	4.8	-1.69
0.15	3.8	3.925	-3.28	5.9	5.984	-1.42			
0.20	5.4	5.538	-2.55	8.4	8.007	4.68	10.0	9.6	4.00
0.25	7.1	7.233	-1.88	9.9	9.665	2.37			
0.30	8.9	8.998	-1.10	10.7	10.970	-2.52	14.96	14.4	3.74
0.35	10.7	10.821	-1.13	11.7	12.086	-3.30			
0.40	12.7	12.696	0.03	13.4	13.335	0.49	19.88	19.2	3.42
0.45	14.9	14.619	1.89	15.6	15.192	2.61			
0.50	17.4	16.585	4.69	18.1	18.290	-1.05	24.96	24.0	3.85

It is difficult to ascertain the accuracy of the method, due to the lack of suitable published data.

3.8.2.3 Empirical Methods

a.   ***The Aertssen Formula***   No dedicated program was written around the Aertssen empirical formula for added resistance due to weather. However, it was included in the program APSS.PAS which was based around the Moor and Murdey (1970) analysis.

b.   ***The AEW. Haslar Formula***   No dedicated program was written around the AEW empirical formula for added resistance in a head sea. However, it was also included in the program APSS.PAS. The results from this formula are generally less than 50% lower than those obtained from the Aertssen formula. This is possibly due to the effect of wind which is ignored in the AEW formula, but included in the Aertssen formula.

3.8.2.4 Selection of Method

The main distinguishing factor between the Moor and Murdey (1970) method and the Jinkine and Ferdinande (1974) method is the range of application. For this reason, the Jinkine and Ferdinande method together with the Mackay and Schmitke (1978) enhancements was selected for inclusion into the Power Prediction Program.

3.9   CONCLUSION

Results obtained from the various hull resistance prediction methods evaluated were disappointing, leading to a very limited selection of methods from which to choose.

Results from the various propeller series compared favourably with one another, however, no two series covered the same range. The B-Series was selected, primarily, because it is the only series which covers propellers having between

two and seven blades. However, the series is somewhat limited when compared to the three-bladed Gawn series as it covers a smaller range of pitch-diameter ratio. This can be construed as an advantage as the method converges to an answer quicker than the Gawn series.

The major problem encountered with estimating added resistance due to weather, is in separating the wind resistance component from the resistance component due to wave height. Selection of methods to embrace these components, has therefore being based on simplicity and range of application.

4 PROGRAM DESCRIPTION AND ANALYSIS

4.1 PROGRAM DESCRIPTION.

4.1.1 Introduction

As the various aspects of the power prediction problem were dealt with, an immediate choice was made regarding the method which provided the most acceptable solution. This was then directly incorporated into the Power Prediction Program (POWER.PAS). *The hull resistance prediction method forming the foundation for the selected modules which essentially became the building blocks.* To round off the program, screen graphics and plot file capabilities were added

4.1.2 Hull Resistance

The Power Prediction Program was developed around the MARIN mathematical model (Holtrop & Mennen, 1982 and Holtrop, 1984), which is essentially a hull resistance predictor. Apart from its relatively high degree of accuracy in comparison to many of the other methods, it also has the following advantages:

- it makes allowance for bulbous bows

- it makes allowance for a bow thruster

- it makes allowance for different stern types

- it makes allowance for different half angles of entrance (*ie*)

The mathematical model comprises of an equivalent flat plate frictional resistance to which a form factor is applied. To this is added wave-making and wave breaking resistance, the pressure resistance of the bulbous bow (if fitted) and the pressure resistance of the immersed transom stern (if fitted). Because much of the data used in the analysis was gleaned from model tests, a model ship correlation resistance is also added.

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The expression for the total bare hull resistance is simply:

$$R_{total} = R_F(1+k_1) + R_W + R_B + R_{TR} + R_A$$

Typical of many hull resistance prediction methods, use was made of the 1957 ITTC correlation line for determining the equivalent flat plate frictional resistance, i.e.

$$C_F = 0.075 / (Log_{10}Rn - 2)^2$$

and

$$R_F = C_F 0.5\rho Sv^2$$

The following equation is used to estimate the form factor $(1+k_1)$

$$1+k_1 = c_{13}\left\{0.93 + c_{12}(B/L_R)^{0.92497}(0.95 - C_P)^{-0.521448}(1 - C_P + 0.0225lcb)^{0.6906}\right\}$$

Where the coefficient c_{13} is a function of stern type, c12 is a function of draught-length ratio and L_R is a parameter reflecting the length of run.

Resistance due to wavemaking and wavebreaking is calculated from the following equation:

$$R_W / \nabla\rho g = c_1 c_2 c_3 \exp\left\{mFn^d + m_1 cos(\lambda Fn^{-2})\right\}$$

where the coefficients c_n, m_n and λ are hull dependent coefficients. Equations for these coefficients are provided for two speed range, namely $Fn<0.4$ and $Fn>0.55$. Between these two speed ranges, linear interpolation is used to estimate the wavemaking and wavebreaking resistance.

The additional resistance due to a bulbous bow is determined from

$$R_B = 0.11\exp(-3P_B^{-2})Fn_i^3 A_{BT}^{1.5}\rho g / (1 + Fn_i^2)$$

where Fn_i is the Froude number based on the immersion of the bow, P_B is a measure of the emergence of the bow and A_{BT} is the transverse area of the bulb.

The additional pressure resistance due to the immersed transom is determined from

$$R_{Tr} = 0.5\rho V^2 A_T c_6$$

Where the coefficient c_6 is a function of Froude number based on transom immersion.

The model ship correlation resistance is calculated from the following equation:-

$$C_a = 0,006(L+100)^{-0,16} - 0,00205 + 0,003\sqrt{L/7,5}C_B^4 c_2(0,04 - c_4)$$

Where coefficient c_4 is a function of the forward draft-length ratio.

The previously developed program (HM.PAS), which was based on these equations, was renamed POWER.PAS and together with its various procedures formed the foundation of the Power Prediction Program

Holtrop and Mennen provide guidance values for the various factors and coefficients used throughout the model. These have been included in the program as default values, however, allowance is made to overwrite them if so desired. Also included in the method are regression equations for estimating the value of items such as wetted surface area and half angle of entrance. Again, these can be overridden if so desired.

The input data is written to a text file which is subsequently read by the program. This method was selected over an interactive approach as it proved to be more flexible, allowing for modification of the data for subsequent runs.

4.1.3   Appendage Resistance

Appendage resistance is estimated using the method advocated by MARIN (Holtrop & Mennen, 1978, 1982). Essentially, in this method the appendage is treated as a 2-D flat plate of similar surface area. Frictional resistance of the flat plate is obtained using the 1957 ITTC line. This value is then corrected for 3-D effects by applying a form coefficient $(1+k_2)$.

$$R_{app} = 0,5\rho V^2 S_{app}(1 + k_2)_{eq} C_F$$

Where

$$\left(1+k_2\right)_{eq} = \frac{\sum\left(1+k_2\right)S_{app}}{\sum S_{app}}$$

Holtrop and Mennen provide $1+k_2$ values for a variety of streamlined, flow orientated appendages. Unless stipulated, these coefficients form the default value for any appendage defined. Appendages are simply defined by stipulating their wetted surface area

4.1.4 Fouling Resistance

Added resistance due to fouling is estimated from a modified version of the equation proposed by Newton (Aertssen, 1961), i.e.

$$\% \textit{increase in skin friction} = \frac{140d}{630+d} \quad \text{for } d \text{ days out of dock.}$$

The equation produces a value of 28% increase in frictional resistance six months out of dock. The method differs from most others in that it is hyperbolic in nature as opposed to the more general linear function.

The program automatically calculates results for both the clean and fouled ship condition. If days out of dock are not stipulated, a default of six months out of dock is used

4.1.5 Hull Roughness

The program assumes a minimum value of 150 μm for hull roughness. If hull roughness is greater than this minimum value, then the additional drag due to this roughness is calculated from the 1984 ITTC formula, i.e.

$$\Delta C_F 10^3 = 44\left[\left(\frac{\gamma}{L}\right)^{1/3} - 10Rn^{-1/3}\right] + 0,125$$

4.1.6 Propeller Efficiency

The program makes use of the Wageningen B-Screw Propeller Series for estimating propeller open water efficiency and rate of rotation. A separate Pascal unit, OPTEFF.PAS was written using routines developed for the previously described B-Series Propeller Optimisation Program, BSPS.PAS.

Use is made of the Oosterveld and van Oossanen (1975) $K_T K_Q$ polynomials, i.e.

$$K_T, K_Q = \sum_{s,t,u,v} \left[C_{stuv}(J)^s . (P/D)^t . (A_E/A_O)^u . (z)^v \right]$$

where C_{stuv} are regression coefficients

No allowance is made for correcting for the effects of Reynolds number.

The minimum BAR value required at design speed is estimated from the Keller formula (Oosterveld & van Oossanen, 1975)

$$\frac{A_E}{A_O} = \frac{(1,3 + 0,3Z)}{(P_o - P_V).D^2} + K$$

Where K = 0   for fast twin-screw ships

         = 0,20   for single-screw ships.

4.1.7 Propulsion Coefficients

For determining the propulsion coefficients, the MARIN equations were selected as they appeared to provide slightly better results compared to the other methods investigated.

For following equations were used for estimating the propulsive coefficients of single screw ships (Holtrop, 1984);

$$w = c_9\left(1 + 0,015 C_{stern}\right) C_V \frac{L}{T_A}\left(0,050776 + 0,934505 C_{11} \frac{C_V}{\left\{1 - \left(1,45 C_P - 0,315 - 0,0225\ lcb\right)\right\}}\right)$$

$$+ \left\{0,27915 C_{20} \sqrt{\frac{B}{L\left\{1 - \left(1,45 C_P - 0,315 - 0,0225\ lcb\right)\right\}}} + C_{19}\left(1 + 0,015 C_{stern}\right)\right\}$$

where C_n are hull dependant coefficients.

$$t = 0,25014\left(\frac{B}{L}\right)^{0,28956}\left\{\frac{\left(\frac{\sqrt{BT}}{D}\right)^{0,2624}}{\left(1 - C_P + 0,0225\ lcb\right)^{0,01762}}\right\} + 0,0015 C_{stern}$$

$$\eta_R = 0,9922 - 0,05908\left(\frac{A_E}{A_O}\right) + 0,07424\left(C_P - 0,0225\ lcb\right)$$

For vessels having two or more propellers, the following equations were used (Holtrop & Mennen, 1982):

$$w = 0,3095 C_B + 10 C_V C_B - 0,23\left(\frac{D}{\sqrt{BT}}\right)$$

$$t = 0,3095 C_B - 0,1885\left(\frac{D}{\sqrt{BT}}\right)$$

$$\eta_R = 0,9737 + 0,111\left(C_P - 0,0225\ lcb\right) - 0,06325\frac{P}{D}$$

4.1.8   Weather Conditions

To reduce the amount of input data required while at the same time providing a rough indication of related factors, the wind-wave relationship proposed by the 11th ITTC was incorporated into the Power Prediction program. This allows wind speed to be estimated from wave height and was achieved by the

development of the following equation, which provides a reasonable approximation of the ITTC curve

$$V_R = 5,53Hs - 0,093Hs^2 \ knots$$

A single input value, sea state, determines the factors which influence wind and wave height. In both instances, only the head condition is considered.

4.1.8.1 Wind Resistance

The program uses the following simple empirical equation developed by Taylor for estimating wind resistance. (van Manen & van Oossanen, 1988):-

$$R_{AA} = 0,208 \times 0,5B^2 \times V_R{}^2$$

As previously stated, the wind speed is estimated from the significant wave height.

4.1.8.2 Resistance due to sea state

For predicting added resistance due to sea state, the method of superposition is used, i.e. the average added resistance of a ship in an irregular sea is predicted from the mean response curve $R(\omega_e)$ and the energy spectrum of the sea $S_\zeta(\omega_e)$, typically;

$$\overline{R}_{AW} = 2\int_0^\infty R(\omega_e) \ S_\zeta(\omega_e) \ d\omega_e$$

The non-dimensional added resistance coefficient is determined using the Jinkine and Ferdinande (1974) empirical equations, i.e.

$$\frac{\sigma_{AW}}{r_{max}} = \left(\frac{\omega}{\omega_{max}}\right)^b \exp\left\{\frac{b}{d}\left[1 - \left(\frac{\omega}{\omega_{max}}\right)^d\right]\right\}$$

where

$$b = \begin{cases} 11 & \omega \leq \omega_{max} \\ -8,5 & \omega > \omega_{max} \end{cases}$$

$$d = \begin{cases} 14 & \omega \leq \omega_{max} \\ -14 & \omega > \omega_{max} \end{cases}$$

$$r_{max} = 3600(k_{yy} / L)^2 Fn^{1,5} \exp(-3,5Fn)$$

For predicting the non dimensional added resistant coefficient (σ_{AW}), use is made of the Mackay and Schmitke (1978) equation for ω_{max}

$$\omega_{max} \sqrt{L / g} = 2,79 - 1,18Fn$$

The r_{max} curve for bulbous bow vessels was approximated by the linear equation

$$r_{max} = 48Fn$$

For V and U shaped hull sections, the regression equations developed from the Mackay and Schmitke (1978) curves were used, namely;

for V-shaped sections

$$r_{max} = 38,02Fn^{1,197}$$

and for U-shaped sections

$$r_{max} = 1034,806Fn^4 - 917,344Fn^3 + 226,563Fn^2 + 23,382Fn - 4,89$$

The procedures developed for the previously described program WAVE.PAS were directly integrated into the Power Prediction Program to provide the capability of estimating the added resistance due to sea state.

4.2   PROGRAM ANALYSIS

4.2.1   Introduction.

Analysis of the program occurred in two stages, firstly an analysis of the of the propeller routines after integration into the program and secondly an analysis of the total program.

4.2.2   B-Series Routines.

With the integration of the propeller efficiency routines into the Power Prediction Program it was decided to review the merits of these routines in their new context. The results obtained from the propulsion experiments of the vessels defined in Table 3.1 were used for this exercise. The values used as input into the routines being those generated by the Power Prediction Program (i.e. the MARIN method) and not those given in the model tests. This provides for a more meaningful result regarding the overall accuracy of the Power Prediction program.

With the exception of the Frigate, the program tended to under estimate propeller speed by less than 4,5% (see Table 4.1). The slightly higher under estimation of propeller speed for the Frigate (4,73% to 7,21%) is attributed to the characteristics of the highly skewed propeller with which it is fitted.

With the exception of the Corvette, the program tends to underestimate the open water efficiency by less than 4,5% (see Table 4.2). The program substantially overestimates the open water efficiency for the corvette at the lower end of the speed range. This could be attributed to the slope of the shafts.

Considering the slightly higher efficiency values obtainable from the Gawn Series (see Figure 3.8), it is probable that the small discrepancies obtained using the B-Series could be minimised if a different propeller series was chosen.

Table 4.1 Comparison of Propeller Speed (rpm)

Twin Screw Corvette Model 5281				Single Screw Cargo Ship Model 3065-101				Stern Trawler Model 4970				American Frigate Model 5279-1			
Speed	rpm		% diff	Speed	rpm		% diff	Speed	rpm		% diff	Speed	rpm		% diff
knots	Program	Model		knots	Program	Model		knots	Program	Model		knots	Program	Model	
10	91,79	95,00	-3,38	11	91,46	93,00	-1,66	11,0	169,74	177,70	-4,48	9,2	42,31	45,24	-6,47
15	140,80	145,00	-2,90	13	108,42	111,20	-2,50	12,0	189,93	196,70	-3,44	14,8	68,76	74,10	-7,21
20	193,31	197,00	-1,87	15	126,15	129,30	-2,44	13,0	212,11	218,00	-2,70	20,8	99,24	105,84	-6,23
25	262,63	261,00	0,63	17	145,16	147,80	-1,79	14,0	233,68	242,80	-3,76	24,0	117,24	123,06	-4,73
30	324,73	315,00	3,09	19	165,74	167,10	-0,81	15,0	256,09	266,70	-3,98	27,0	137,23	144,60	-5,10
				21	186,09	188,10	-1,07					30,3	158,16	167,94	-5,83

Table 4.2 Comparison of Open Water Efficiency (η_o)

Twin Screw Corvette Model 5281				Single Screw Cargo Ship Model 3065-101				Stern Trawler Model 4970				American Frigate Model 5279-1			
Speed	η_o		% diff	Speed	η_o		% diff	Speed	η_o		% diff	Speed	η_o		% diff
knots	Program	Model		knots	Program	Model		knots	Program	Model		knots	Program	Model	
10	0,729	0,654	11,54	11	0,630	0,640	-1,56	11,00	0,630	0,636	-0,97	9,20	0,747	0,774	-3,49
15	0,723	0,673	7,48	13	0,630	0,642	-1,87	12,00	0,623	0,629	-0,94	14,80	0,745	0,769	-3,12
20	0,714	0,676	5,57	15	0,629	0,645	-2,48	13,00	0,613	0,619	-0,89	20,80	0,734	0,762	-3,67
25	0,679	0,676	0,37	17	0,628	0,646	-2,79	14,00	0,604	0,605	-0,20	24,00	0,724	0,757	-4,36
30	0,665	0,688	-3,41	19	0,625	0,646	-3,25	15,00	0,596	0,589	1,19	27,00	0,707	0,738	-4,20
				21	0,622	0,643	-3,27					30,30	0,694	0,721	-3,74

4.2.3 Final Analysis.

Extracts from the model test results, ship estimates and observations at sea of the cross-channel ship, the 'Reine Astrid' as reported by Aertssen (1961) were used to evaluate the complete Power Prediction program. Principal particulars of the 'Reine Astrid' are given in Table 4.3

Table 4.3   Principal Particulars - Reine Astrid

Length between perpendiculars	108,555 m	Wetted Surface Area	1477,56 m^2
Beam on waterline	14,201 m	Half angle of entrance	8,5°
Draught	3,479	Propeller Diameter	2,896 m
Displacement Volume	2997,6 m^3	No of Propellers	2
Midship Section Coefficient	0,919	No of Blades	4
Prismatic Coefficient	0,574	Pitch-Diameter ratio	1,245
LCB from amidships	-1,13 m	Blade Area Ratio	0,8758

Initial comparison between the full scale ship based on the model test results and the program yielded differences of a similar order of magnitude for both effective power and shaft power. In both cases, maximum over prediction occurred at 17 knots and maximum under prediction at 24,5 knots (see Table 4.4). Neither method made use of a correlation allowance. The overall magnitude of the percentage differences were generally lower than those obtained in the comparisons with the earlier mentioned model tests.

Table 4.4   Comparison of Power Estimates for 'Reine Astrid'

Speed (knots)	Effective Power (kW) Model	Effective Power (kW) Program	% Diff	Shaft Power (kW) Model	Shaft Power (kW) Program	% Diff
14,5	798.91	786.24	-1.59	1183.43	1174.47	-0.76
17,0	1347.71	1447.22	7.38	2057.39	2177.69	5.85
19,5	2222.47	2336.96	5.15	3419.03	3534.47	3.38
22,0	3590.81	3666.69	2.11	5482.39	5588.87	1.94
24,5	6866.85	6264.96	-8.77	10646.36	9783.77	-8.10

Values of propeller open water efficiency were not provided for the speeds investigated, however, values for the quasi propulsive coefficient (QPC) and

propeller speed were. In both cases, reasonably good correlation was found with QPC being over predicted by only 1,69% and propeller speed under predicted by only 3,01% (see Table 4.5).

Table 4.5   Comparison of QPC and Propeller Speed for 'Reine Astrid'

Speed (knots)	QPC		% Diff	Propeller Speed (rpm)		% Diff
	Model	Program		Model	Program	
14,5	0.675	0.669	-0.89	140	140.8	0.54
17,0	0.655	0.665	1.53	165.5	169.1	2.20
19,5	0.650	0.661	1.69	194.5	196.6	1.08
22,0	0.655	0.656	0.15	226.5	225.8	-0.30
24,5	0.645	0.640	-0.78	271.5	263.3	-3.01

To evaluate the remainder of the Power Prediction program, comparisons were made with data obtained during the programme of sea trials on the Reine Astrid. The Power Prediction program considers added resistance only in the head wind and wave condition, therefore, observations for the comparison were limited to those where wind and wave direction was 35 degrees or less from the bow.

Wind velocity and wave height are normally estimated within the program based on the stipulated sea state. In an attempt to validate the accuracy of the methods used within the program to predict the combined effect of wind and waves, the program was modified to accept actual wind velocity and wave height values.

All estimates were based on an eight months out of dock period to coincide with the actual condition of the ship at the time of the observations.

For all observations the sea was described as 'rather rough' with the exception of observation 28 where it was described as a 'very high sea' with heavy pitching and slamming experienced. It is noteworthy that this is the only condition where delivered power and propeller speed was underestimated (see Table 4.6). The reason for the under prediction of

power is attributed to a greater power being required to 'drive' the ship out of the waves when her bow is deeply submerged. The higher propeller speed experienced onboard is attributed to the 'racing' of the propeller as it breaks clear of the water.

It is difficult to ascertain what component is responsible for the relatively high over prediction of delivered power by the program for observations 42 and 84 especially when one considers the relatively close result obtained for observation 18. One possibility is that the measured wind speed is slightly on the high side for the particular sea state, particularly when one compares the values with those estimated from the 11th ITTC wind-wave relationship. Another possibility, is that the method used to estimate wind resistance is too simplistic.

Propeller speed from the program correlates reasonably well with that measured. The slightly higher speeds given by the program are linked directly to its higher power estimates.

Table 4.6 **Comparison of Actual Measured Data for 'Reine Astrid' with Estimate from Power Prediction Program**

Observation No	18	28	42	84
Ship Speed (knots)	17.9	18.5	21.5	21.2
Sig. Wave Height (m)	2.438	4.023	2.743	1.463
Wind Speed (knots)	25.1	31.5	25.5	19.8
Actual Pd (kW)	4280	6160	7121	6286
Estimated Pd (kW)	4435	5424	7975	7137
Difference in Pd (%)	3.62	-11.95	11.99	13.54
Actual Shaft rpm	192	213	231	223
Estimated Shaft rpm	198	209	240	233
Difference in rpm (%)	3.13	-1.88	3.90	4.48

5   CONCLUSIONS AND RECOMMENDATIONS

5.1   GENERAL COMMENTS

5.1.1.   Resistance Prediction

When selecting a resistance prediction method, it is preferable to select one that tends to err slightly on the high side. This ensures that the vessel, when built, will be able to meet its trial speed. No one method examined satisfied this criteria, typically, they all under predicted, over predicted or partially under predicted and partially over predicted.

All methods examined were highly sensitive to use outside their specified range. This was particularly evident with regression equations fitted to standard series data. This highlights the danger of using regression equations beyond their valid range.

Based on the validation of the YP Series, it is concluded that the method is circumspect and due caution should be exercised when using it. Validation of the various resistance prediction methods indicate that generally each method has merit only when applied strictly to vessels of similar form to those used during its development. It follows that satisfying the range of application without ensuring that the hull form is similar to that which the series is based on, can lead to unacceptable results.

The only methods which appear suitable for general purpose resistance prediction are those based on random data regression analysis, typically, Fung and MARIN.

5.1.2   Appendage Resistance.

Only the ITTC line with form coefficients has the flexibility to allow for improvement of the appendage resistance estimations over the whole design cycle. All other methods examined required either an unduly high degree of form

geometry (which does not guarantee an equivalent level of accuracy) or are based on values obtained from similar ships.

A further advantage of this method is that it enables the influence of parametrical variations of each appendage to be studied.

5.1.3   Fouling Resistance.

Antifouling paint should be toxic to any forms of sea life which attempts to attach itself to the hull of a vessel, whilst at the same time it must be environmentally safe. These two requirements are contradictory. It is inevitable that sometime in the future there will be a total ban on antifouling paints containing tributyltin. *Ongoing research may result in the development of an environmentally acceptable product having qualities similar or better than the SPC's containing tributyltin,* but until that time, the requirement for a method to estimate resistance due to fouling remains. The only method which appears to approximate the fouling resistance trend is that provided by Newton. It is therefore recommended, dependant on future developments in the field of antifouling paints, that this formula be modified as necessary to keep it in line with such developments.

5.1.4   Hull Roughness.

The general trend indicates that the mean hull roughness of new ships is on the decline, albeit slowly. Hull roughness is a function of material quality and workmanship, therefore a value will eventually be reached beyond which there will be no further reduction.

5.1.5   Propeller Optimisation

Based on the limited comparisons, polynomial representations of K_T and K_Q appear to be able to predict propeller performance with a degree of accuracy comparable to that obtained from model tests using stock propellers, particularly if the correct choice is made regarding the propeller series.

5.1.6 Propulsion Coefficients

Overall, statistical methods appear to be able to provide a better indication of the propulsion coefficients when compared with their empirical counterparts whose results tend to be far to inaccurate to be meaningful.

Of the methods examined, the MARIN regression equations provide the best overall estimates of the propulsion coefficients and their use is recommended over that of empirical and other methods.

5.1.7 Wind Resistance

Isherwood's equations provide valuable insight into the effect of wind regardless of direction. In preliminary design work, the condition most relevant is that which provides the greatest resistance, i.e. wind between 0 and 30 degrees off the bow. The simple Taylor formula provides a reasonable estimate for this condition without requiring a detailed knowledge of the vessel geometry.

5.1.8 Wave Resistance

Providing a ship does not experience excessive pitching and heaving, the Jinkine and Ferdinande method can provide a reasonable first estimate of added resistance due to waves in a head sea. Excessive pitching and heaving will adversely effect the estimates obtained from any method using the principle of linear superposition. In practice, the sea spectrum used in the method should be modified to one which best fits the envisaged area of operation

5.2 RECOMMENDATIONS FOR FURTHER WORK

Further work is required in the analysis of the results obtained from using random data base regression equations. A wider variety of vessel types not forming part of the original data should be analysed in order to determine the most accurate overall method.

In the event that the focus of the program shifts from preliminary power prediction to that of voyage analysis, then consideration should be given to incorporating the Isherwood wind resistance equations in the program. Additionally, the program should be modified to allow the user to choose the sea spectrum which best suits the envisaged area of operation, e.g. Jonswop, Pierson Moskowitz, etc.

An area which still requires research and investigation is that of voluntary speed reduction in a heavy sea. Whilst it was intended to incorporate this facet into the Power Prediction Program, the literature study failed to deliver a suitable method which did not require fairly extensive hull definition.

At present the program only caters for the B-Series propeller. It is recommended that the program be extended to include the option of a number of the other propeller series.

5.3   CONCLUSION

Overall accuracy of the Power Prediction Program is similar if not better than that experienced from methodical series and borders on that achievable from model results. The program should not be seen as a replacement for model tests, but rather as a tool to reduce design iterations and ensure that the hull form which is tank tested is as close to the final hull as possible. Typically it could be used to qualitatively compare the merits of a series of hull forms, however, it should be remembered that the output from the program will only be as good as the input.

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POWER PREDICTION PROGRAM

This appendix contains the user guide for running the program *POWER*.

POWER PREDICTION PROGRAM - *POWER*

USER GUIDE.

1. INTRODUCTION

Program *POWER* enables the user to rapidly evaluate the preliminary power requirements of a displacement hull during the early design stages. *Input data requirements consists primarily of the vessel's principal dimensions and form coefficients*

In order to determine the propulsion power requirement, the program estimates hull resistance, appendage resistance, propeller efficiency, propulsion coefficients, and added resistance due to hull roughness, fouling and sea state (i.e. waves and wind).

The program has the ability to estimate unknown data such as wetted surface area, half angle of entrance, correlation allowance, etc. Where possible, default values have been included. These cover items such as stern factor and appendage $1+k_2$ coefficients for a wide range of appendages.

Input data is in the form of an ASCII text file. Output data is presented in both tabular and graphical formats.

2 PROGRAM DESCRIPTION

The core of the program is based on the MARIN regression equations coefficients (Holtrop & Mennen, 1982; Holtrop, 1984) which encompass both hull resistance and propulsion. The valid range of the method is as follows;-

Ship Type	Fn	C_P		L/B		B/T	
	max	min	max	min	max	min	max
Tankers, bulk carriers (ocean)	0,24	0,73	0,85	5,1	7,1	2,4	3,2
Trawlers, coasters, tugs	0,38	0,55	0,65	3,9	6,3	2,1	3,0
Container ships, destroyer types	0,45	0,55	0,67	6,0	9,5	3,0	4,0
Cargo liners	0,30	0,56	0,75	5,3	8,0	2,4	4,0
Ro-Ro's, car ferries	0,35	0,55	0,67	5,3	8,0	3,2	4,0

Appendage resistance is calculated using the 1957 ITTC line with form coefficient $(1+k_2)$. The $1+k_2$ values provided by Holtrop and Mennen (1982) for a range of appendages are used as default values, however, they can be overridden in the input file.

Propeller efficiency is calculated from the B-Series regression equations (Oosterveld & van Oossanen, 1975). The range of application of this method is as follows:-

No of blades	A_E/A_o
2	0,30 - 0,38
3	0,35 - 0,80
4	0,40 - 1,00
5	0,45 - 1,05
6	0,50 - 0,80
7	0,55 - 0,85

A hyperbolic function based on Newton (Aertssen , 1961) is used to determine the fouling resistance after the stipulated number of days out of dock. If no time period is given, a default value of six-months is used.

A standard hull roughness of 150 µm is assumed. Added resistance for hulls with a roughness greater than this is calculated using the formula proposed by the 1984 ITTC.

To calculate the added resistance due to weather (i.e. wind and waves), the program extracts wave height from the sea state given in the input file. Using the wind speed-wave height relationship proposed by the 11th ITTC, this value is then used to determine wind speed and thereafter wind resistance using the Taylor empirical equation (van Manen & van Oossanen, 1988).

Added resistance due wave height in the given sea state is calculated using the method of superposition from an empirically estimated response curve and the Godspodnetic-Miles energy spectrum (Mackay & Schmitke, 1978).

The program caters for a maximum of ten speeds, if a greater number is stipulated, it will automatically default to the first ten.

3.   OPERATING INSTRUCTIONS

3.1   Input Data File.

Data required by the program must be in the form of an ASCII text file. This can be created using any ASCII type editor (e.g. the MSDOS text editor EDIT). The format of the data must be as shown in the INPUT DATA SHEET (see Section 4). Values must be separated by one or more spaces, **not commas**. A sample input data file is shown in Section 5.1. Comments can be added to any line after all mandatory input values for that line have been entered. This can be used to facilitate identification of the values within the input data file (see Section 5.2). Any file name can be used so long as it complies with the MSDOS naming requirements.

3.2   Running Instructions.

Once the input data file has been compiled, the program can be run.   The program should be run from within the directory where the various program components lie. On the command line type **POWER**⏎

Dependant on the computer's hardware, either a graphical (see Figure A1) or text (see Figure A2) introductory screen will be displayed. Hit any key to continue.
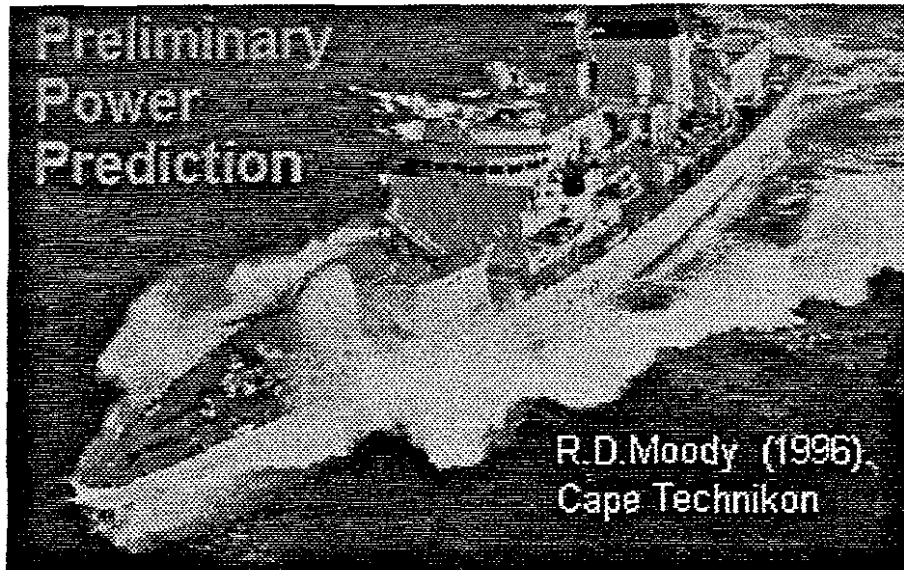
Figure A1 - Graphical Introductory Screen
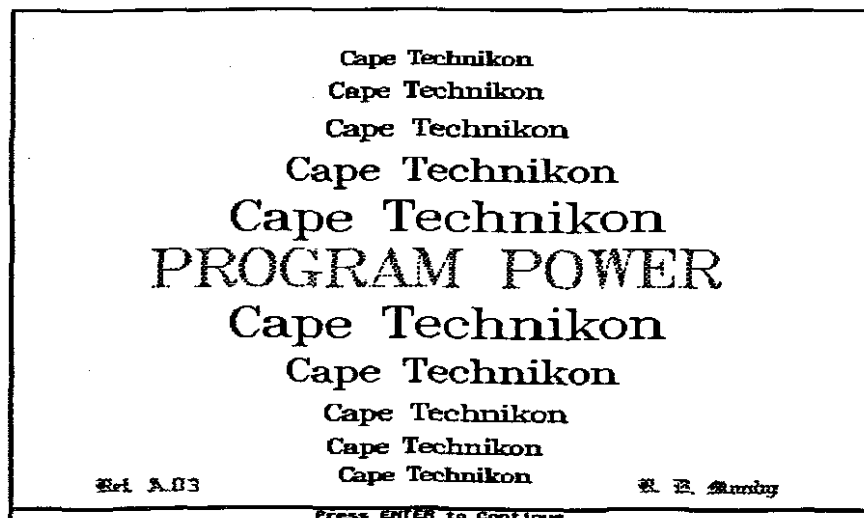
Figure A2 - Text Introductory Screen

The next screen which appears allows the user to interactively enter the name of the input file to be used, the output file name (again any file name that complies with the MSDOS naming convention) and whether brake power is required in addition to effective power (see Figure A3). The user also can select whether graphic output is required and whether it should be directed to the screen, plotfile or both.

RESISTANCE and POWER PREDICTION	
Enter input file name	DKB.DAT
Enter output file name	DKB.OUT
Brake Power required (Y or N)	Y
Plot Effective Power Graph to Screen	Y
Effective Power Plot File Required (Y or N)	Y
Enter Effective Power plot file name	DKB1.HPL
Plot Brake Power Graph to Screen (Y or N)	Y
Brake Power Plot File Required (Y or N)	Y
Enter Brake Power plot file name	DKB2.HPL

Figure A3 - Interactive Input Screen

3.3   Program Output.

To assist in selection of the most favourable attributes from a powering viewpoint, the resistance of each component is provided in the tabulated output data (see Section 6). Essentially, the tabulated data comprises four pages. The first summarises the input data and values that have been estimated. This facilitates the checking of the Input File. The second page covers Resistance and Effective Power estimates over the stipulated speed range and the third, Predicted Brake Power and Propulsion Efficiency. The last page is a summary of the values at the Design Speed.. This summary also contains the full wording of all abbreviations used in the previous pages.

If screen graphics were selected, the program will automatically display these at the end of its calculation phase. These screens may be captured if the program is run from within MS-Windows, however, under DOS they are automatically cleared when a key is pressed. An example of a screen capture is shown in Figure A4.

The plot files generated can be plotted directly to a HP 7550A or compatible plotter. Alternatively, they may be read into a word processor (e.g. MS Word for Windows). NOTE: the newer HPGL-2 commands are not supported. Examples of these plots can be seen in Section 6.
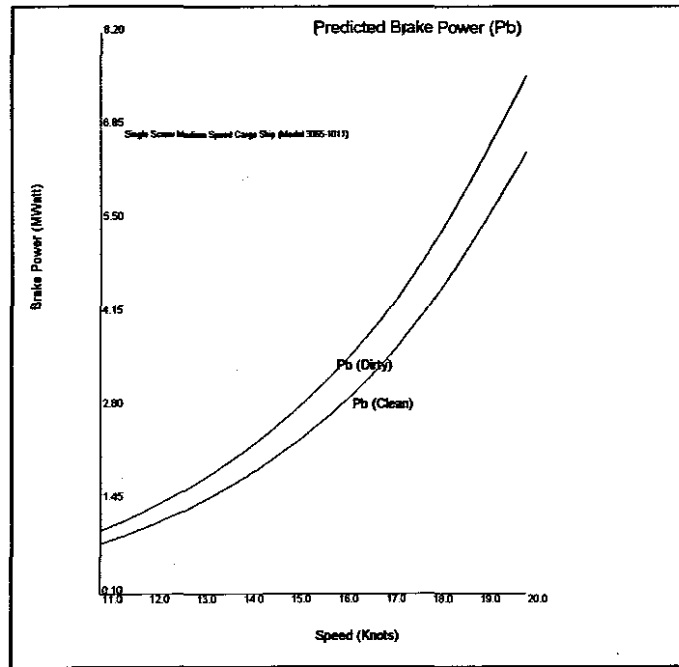
Figure A4 - Screen Capture Example

3.4   Warnings and General Notes..

Whilst every effort has been made to ensure error trapping of non-valid data, isolated incidents of this may still occur, specifically if the propeller input data violates the parameters of the B-Series.

No error trapping exists with regard to the format of the input file.   Generally a 'Runtime error 106 at 0000:XXXX' will indicate a fault of this nature   XXXX is a hexadecimal number and will vary depending on where and what the fault is.

4. DATA INPUT SHEET

Title (80 characters)

LWL (m)	Lpp (m)	Beam (m)	Draught-Fwd (m)	Draught-Aft (m)

∇ (m³)	C_M	C_{WP}

LCB relative to 0,5 Lpp (%)	Half angle of entrance (deg) (0 = Calculated)	Wetted Surface Area (m²) (0 = Calculated)

LCB Position
Forward = Plus
Aft   = Minus

Ca switch 1=Calculated 2= Default 0,0004 3=User supplied	Hull roughness (kss) (0 =default of 150 µm)

IF Ca switch =3 then

Ca

Bulbous bow fitted 0 = No, 1 = Yes

If Bulbous bow fitted = 1 then

Transverse bulb area (m²)	Height of bulb from keel line (m)

Bowthruster fitted 0 = No, 1 = Yes

If Bowthruster fitted = 1 then

Tunnel Diameter (m)	Opening coefficient (0.003 to 0.012)

Transom immersed area (m^2)	Stern Coefficient (*CStern*)	Bow Coefficient (*CBow*)

Afterbody Form	*CStern*
Pram with Gondola	-25
V-Shaped Sections	-10
Normal Section Shape	0
U-Shaped Sections with Hogner Stern	10

Forebody Form	*Cbow*
V-Shaped Sections	0
U-Shaped Sections	1

Rudder Wetted Surface area (m^2)	Rudder Form coefficient (0 = Default value)	Rudder Position 1= behind skeg 2= behind stern 3=twin, balanced

Appendage	Wetted Surface Area (m^2)	Form Coefficient (0 = Default value)
Shafts		
Shaft Brackets		
Stabiliser Fins		
Bilge Keels		
Skeg		
Strut Bossings		
Hull Bossings		
Sonar Dome		

Sea State (1-5)	Days out of Dock 0= Six months

Design Speed (knots)	Min. Speed (knots)	Max Speed (knots)	Speed increment (knots)

(Maximum of 10 speeds)

Number of Propellers	Propeller Diameter (m)	Number of Blades	Clearance between propeller and Keel (m)

Shafting Efficiency (%)

Blade Area Ratio	Pitch Diameter Ratio

NOTE:

a) data is to be separated by at least one space

b) dimensions are in meters

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5. EXAMPLE INPUT FILE

5.1 Input File

Single Screw Medium Speed Cargo Ship (Model 3065-1011)

136.00	133.048	19.5	6.0	6.0
8776	0.9567	0.6702		
-1.50	0	2839		
3	0			
0.0001				
1				
6.38	2			
1				
2.0	0.008			
0	0	0		
36	0	1		
0	0			
0	0			
0	0			
0	0			
0	0			
0	0			
0	0			
0	0			
5	0			
16	11	22	1	
1	4.75	4	1.2	
100				
0.75	0.630			

5.2 Commented Input File

Single Screw Medium Speed Cargo Ship (Model 3065-1011)

136.00	133.048	19.5	6.0	6.0	Lwl	Lpp	B	Tf	Ta
8776	0.9567	0.6702			VDisp	Cm	Cwp		
-1.50	0	2839			LCB	ie	S		
3	0				Ca switch	kss			
0.0001					Ca				
1					Bulbous bow switch				
6.38	2				Bulb area	Bulb height			
1					Bow thruster switch				
2.0	0.008				Tunnel Dia.		Opening Coeff		
0	0	0			At	CStern	CBow		
36	0	1			Rudder	WSA	Coeff	Pos	
0	0				Shaft		SApp	1+k2	
0	0				Shaft Brackets		"	"	
0	0				Stab Fins		"	"	
0	0				Bilge keel		"	"	
0	0				Skeg		"	"	
0	0				Strut Bossings		"	"	
0	0				Hull Bossings		"	"	
0	0				Sonar Dome		"	"	
5	0				Sea State		Days out of dock		
16	11	22	1		VDes	VMin	VMax	VInc	
1	4.75	4	1.2		n	Dia	Z	Clear	
100					Shafting eff				
0.75	0.630				P/D	BAR			

A8

6. EXAMPLE OUTPUT FILE

```
-----------------------------------------------------------------------
11/11/1996                                               22:38:12
                 PRELIMINARY RESISTANCE/POWER PREDICTION
                      List of Input/Estimated Data
By R.Moody                                            Release 1.00
-----------------------------------------------------------------------
```

Ship Name: Single Screw Medium Speed Cargo Ship (Model 3065-1011)

Length on Waterline [LWL]	136.000 m
Length between Perpendiculars [Lpp]	133.048 m
Beam [B]	19.500 m
Draught forward [Tf]	6.000 m
Draught aft [Ta]	6.000 m

Displacement volume	8776.000 m^3
Displacement mass	8995.400 tonne

Block Coefficient on LWL [Cb]	0.552
Prismatic Coefficient on LWL [Cp]	0.576
Midship Coefficient [Cm]	0.957
Waterplane Coefficient [Cw]	0.823
Prismatic Waterplane Coefficient [Cwp]	0.670

Centre of Buoyancy [Lcb] (relative to 0.5 Lpp) -1.500 %

Half angle of entrance [Ie]   8.555 degrees

Wetted Surface Area [S]	2839.000 m^2
Hull Roughness	150.000 micron
Days out of Dock	182.500 days

Transom immersed area [At]	0.000 m^2
After body shape factor [CStern]	0.000

Number of propellers [N]	1
Propeller Diameter [D]	4.750 m
Number of blades [Z]	4
Blade Area Ratio [BAR]	0.630
Pitch Diameter Ratio	0.750
Clearance between propeller and Keel	1.200 m

Mechanical Efficiency [Ns]   100.000 %

Transverse bulb area [Abt]	6.380 m^2
Height of bulb from keel line [Hb]	2.000 m

Thruster tunnel diameter [Dbt]	2.000 m
Thruster opening coefficient [Cbto]	0.008

Appendage	(1+k2)	SApp
Rudder	1.750	36.000
Shafts	2.000	0.000
Shaft Brackets	3.000	0.000
Stabilizer Fins	2.800	0.000
Bilge Keels	1.400	0.000
Skeg	1.750	0.000
Strut Bossings	3.000	0.000
Hull Bossings	2.000	0.000
Sonar Dome	2.700	0.000

(1+k2)equivalent	1.750	Total Sapp	36.000 m^2

Sea State	5
Estimated Wave Height [Hs]	3.700 m
Estimated energy averaged wave period [Ts]	9.241 sec
Estimated wind speed [Vwind]	19.188 knots

PRELIMINARY RESISTANCE/POWER PREDICTION
Resistance and Effective Power

By R.Moody   Release 1.00

Ship Name: Single Screw Medium Speed Cargo Ship (Model 3065-1011)

Resistance Coefficients

v (Knots)	v (m/s)	Fn	v/L²2	Cf	Cr	Ca
16.00	8.236	0.225	0.757	0.001542	0.000394	0.000100
17.00	8.751	0.240	0.805	0.001530	0.000494	0.000100
18.00	9.266	0.254	0.852	0.001520	0.000619	0.000100
19.00	9.781	0.268	0.899	0.001509	0.000752	0.000100
20.00	10.295	0.282	0.947	0.001500	0.000863	0.000100
21.00	10.810	0.296	0.994	0.001491	0.000946	0.000100
22.00	11.325	0.310	1.042	0.001483	0.001026	0.000100
23.00	11.840	0.324	1.089	0.001475	0.001136	0.000100
24.00	12.354	0.338	1.136	0.001467	0.001298	0.000100
25.00	12.869	0.352	1.184	0.001460	0.001528	0.000100

Resistance Components (kN)

V (Knots)	Rf	Rf(1+k1)	Rapp	Rw	Rb	Rtr	Ra
16.00	152.188	174.404	10.370	28.494	0.000	0.000	9.870
17.00	170.516	195.408	11.678	43.321	0.000	0.000	11.143
18.00	189.818	217.528	13.063	64.263	0.000	0.000	12.492
19.00	210.088	240.757	14.523	90.184	0.000	0.000	13.919
20.00	231.321	265.089	16.060	117.067	0.000	0.000	15.422
21.00	253.509	290.517	17.672	143.226	0.000	0.000	17.003
22.00	276.650	317.035	19.360	172.175	0.000	0.000	18.661
23.00	300.736	344.638	21.124	210.499	0.000	0.000	20.396
24.00	325.765	373.321	22.963	265.337	0.000	0.000	22.208
25.00	351.732	403.078	24.878	343.304	0.000	0.000	24.097

Resistance(kN) and Effective Power (kW)

V (Knots)	Rwind	Rwave	Rt	Pe	Rt Dirty	Pe Dirty
16.00	48.965	42.630	314.73	2592.25	357.28	2942.69
17.00	51.788	45.419	358.76	3139.52	406.43	3556.70
18.00	54.690	48.031	410.07	3799.61	463.13	4291.34
19.00	57.670	50.516	467.57	4573.13	526.30	5147.59
20.00	60.730	52.871	527.24	5428.14	591.91	6093.96
21.00	63.869	55.110	587.40	6349.86	658.27	7116.03
22.00	67.087	57.240	651.56	7378.86	728.90	8254.78
23.00	70.384	59.244	726.28	8599.01	810.36	9594.47
24.00	73.761	61.129	818.72	10114.85	909.79	11240.04
25.00	77.216	62.853	935.43	12038.23	1033.76	13303.73

Propulsion data

V (Knots)	w	tdf	nh	Thrust(kN) Clean	Min BAR	Thrust(kN) Dirty	Min BAR
16.00	0.222	0.180	1.055	383.756	0.544	435.635	0.591
17.00	0.222	0.180	1.054	437.433	0.593	495.560	0.645
18.00	0.222	0.180	1.054	499.994	0.649	564.700	0.707
19.00	0.222	0.180	1.053	570.108	0.712	641.724	0.776
20.00	0.221	0.180	1.053	642.864	0.777	721.718	0.848
21.00	0.221	0.180	1.053	716.214	0.843	802.632	0.921
22.00	0.221	0.180	1.053	794.446	0.913	888.752	0.998
23.00	0.221	0.180	1.052	885.561	0.995	988.077	1.000
24.00	0.221	0.180	1.052	998.265	1.000	1109.314	1.000
25.00	0.220	0.180	1.052	1140.566	1.000	1260.466	1.000

NOTE: Min BAR gives an indication of value to avoid cavitation.
      Actual BAR used in calculations is 0.630

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Ship Name: Single Screw Medium Speed Cargo Ship (Model 3065-1011)

Brake Power of clean ship (fitted with Wageningen B Series Propeller)

V (Knots)	Thrust (kN)	Speed (rpm)	no	nr	nh	QPC	ns
16.000	383.756	146.810	0.614	1.000	1.055	0.647	1.000
17.000	437.433	156.367	0.613	1.000	1.054	0.646	1.000
18.000	499.994	166.379	0.612	1.000	1.054	0.645	1.000
19.000	570.108	176.660	0.610	1.000	1.053	0.643	1.000
20.000	642.864	186.906	0.609	1.000	1.053	0.641	1.000
21.000	716.214	196.784	0.608	1.000	1.053	0.641	1.000
22.000	794.446	206.725	0.607	1.000	1.053	0.639	1.000
23.000	885.561	217.234	0.606	1.000	1.052	0.638	1.000
24.000	998.265	228.751	0.603	1.000	1.052	0.635	1.000
25.000	1140.566	241.741	0.599	1.000	1.052	0.630	1.000

V (Knots)	Pe (kW)	PC	Pb (kW)	J	Kt	Kq
16.000	2592.252	0.6471	4005.657	0.551	0.123	0.018
17.000	3139.517	0.6462	4858.204	0.550	0.123	0.018
18.000	3799.615	0.6447	5893.957	0.547	0.125	0.018
19.000	4573.125	0.6428	7114.714	0.544	0.126	0.018
20.000	5428.143	0.6414	8462.522	0.542	0.127	0.018
21.000	6349.862	0.6405	9913.909	0.541	0.128	0.018
22.000	7378.860	0.6395	11538.820	0.539	0.128	0.018
23.000	8599.008	0.6378	13482.831	0.536	0.129	0.018
24.000	10114.850	0.6347	15936.982	0.531	0.132	0.018
25.000	12038.230	0.6302	19101.308	0.525	0.135	0.019

Brake Power of dirty ship (fitted with Wageningen B Series Propeller)

V (Knots)	Thrust (kN)	Speed (rpm)	no	nr	nh	QPC	ns
16.000	435.635	151.674	0.604	1.000	1.055	0.637	1.000
17.000	495.560	161.481	0.604	1.000	1.054	0.637	1.000
18.000	564.700	171.721	0.602	1.000	1.054	0.635	1.000
19.000	641.724	182.219	0.601	1.000	1.053	0.633	1.000
20.000	721.718	192.686	0.600	1.000	1.053	0.632	1.000
21.000	802.632	202.796	0.599	1.000	1.053	0.631	1.000
22.000	888.752	212.966	0.598	1.000	1.053	0.630	1.000
23.000	988.077	223.680	0.597	1.000	1.052	0.628	1.000
24.000	1109.314	235.365	0.594	1.000	1.052	0.625	1.000
25.000	1260.466	248.473	0.590	1.000	1.052	0.621	1.000

V (Knots)	Pe (kW)	PC	Pb (kW)	J	Kt	Kq
16.000	2942.690	0.6374	4616.702	0.534	0.131	0.018
17.000	3556.698	0.6365	5587.735	0.533	0.131	0.018
18.000	4291.339	0.6349	6758.606	0.530	0.132	0.019
19.000	5147.593	0.6330	8131.580	0.528	0.133	0.019
20.000	6093.961	0.6317	9646.283	0.526	0.134	0.019
21.000	7116.030	0.6308	11280.236	0.525	0.135	0.019
22.000	8254.778	0.6299	13105.879	0.523	0.135	0.019
23.000	9594.470	0.6282	15273.983	0.521	0.136	0.019
24.000	11240.042	0.6251	17982.465	0.516	0.138	0.019
25.000	13303.730	0.6206	21435.355	0.510	0.141	0.019

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Ship Name: Single Screw Medium Speed Cargo Ship (Model 3065-1011)

Design Speed   [v]   16.00 knots
                                                     8.236 m/s

Froude Number   [Fn]   0.225
Taylor Speed Length Ratio   [v/L^2]   0.757

RESISTANCE COEFFICIENTS
Frictional resistance coefficient   [Cf]   0.001542
Residuary resistance coefficient   [Cr]   0.000394
Model ship correlation coefficient   [Ca]   0.000100

HULL RESISTANCE COMPONENTS
Friction resistance according to 1957 ITTC   [Rf]   152.188 kN
Friction resistance with form factor correction [Rf(1+k1)] 174.404 kN
Resistance of appendages   [Rapp]   10.370 kN
Wave making and wave breaking resistance   [Rw]   28.494 kN
Pressure resistance of bulbous bow near water surface [Rb]   0.000 kN
Pressure resistance of immersed transom   [Rtr]   0.000 kN
Model ship correlation resistance   [Ra]   9.870 kN

RESISTANCE COMPONENTS DUE TO ENVIRONMENTAL FACTORS
Added resistance due to 19.2 knot head wind   [Rwind]   48.965 kN
Added resistance due to 3.70m waves ie Sea State 5 [Rwave] 42.630 kN

TOTAL RESISTANCE (Clean Hull)   [Rt]   314.734 kN
Added resistance due to hull fouling 183 days out of dock 42.548 kN
TOTAL RESISTANCE after 183 days out of dock   [Rtdirty] 357.282 kN

PROPULSION COEFFICIENTS
Taylor wake fraction   [w]   0.222
Thrust deduction fraction   [tdf]   0.180
Hull efficiency   [nh]   1.055
Relative rotative efficiency   [nr]   1.000
Shafting efficiency   [ns]   100.000 %

PROPULSION DATA FOR SHIP IN CLEAN CONDITION
Thrust coefficient   [Kt]   0.123
Torque coefficient   [Kq]   0.018
Propeller advance coefficient   [J]   0.551
Propeller speed   [Speed]   146.810 rpm
Open water efficiency   [no]   61.353 %
Quasi-propulsion coefficient   [QPC]   0.647
Propulsion coefficient   [PC]   0.647
Thrust   [Thrust] 383.756 kN
Effective Power   [Pe]   2592.252 kW
Brake Power   [Pb]   4005.657 kW

PROPULSION DATA FOR SHIP 183 DAYS OUT OF DOCK
Thrust coefficient   [Kt]   0.123
Torque coefficient   [Kq]   0.018
Propeller advance coefficient   [J]   0.551
Propeller speed   [Speed]   146.810 rpm
Open water efficiency   [no]   60.429 %
Quasi-propulsion coefficient   [QPC]   0.637
Propulsion coefficient   [PC]   0.637
Thrust   [Thrust] 435.635 kN
Effective Power   [Pe]   2942.690 kW
Brake Power   [Pb]   4616.702 kW

A12

Predicted Effective Power (Pe)

Single Screw Medium Speed Cargo Ship (Model 3065-1011)

Y-axis: Effective Power (MWatt) — 1.00, 3.14, 5.28, 7.42, 9.56, 11.70, 13.84

X-axis: Speed (Knots) — 16.0, 17.0, 18.0, 19.0, 20.0, 21.0, 22.0, 23.0, 24.0, 25.0

Pe (Dirty)

Pe (Clean)

A13
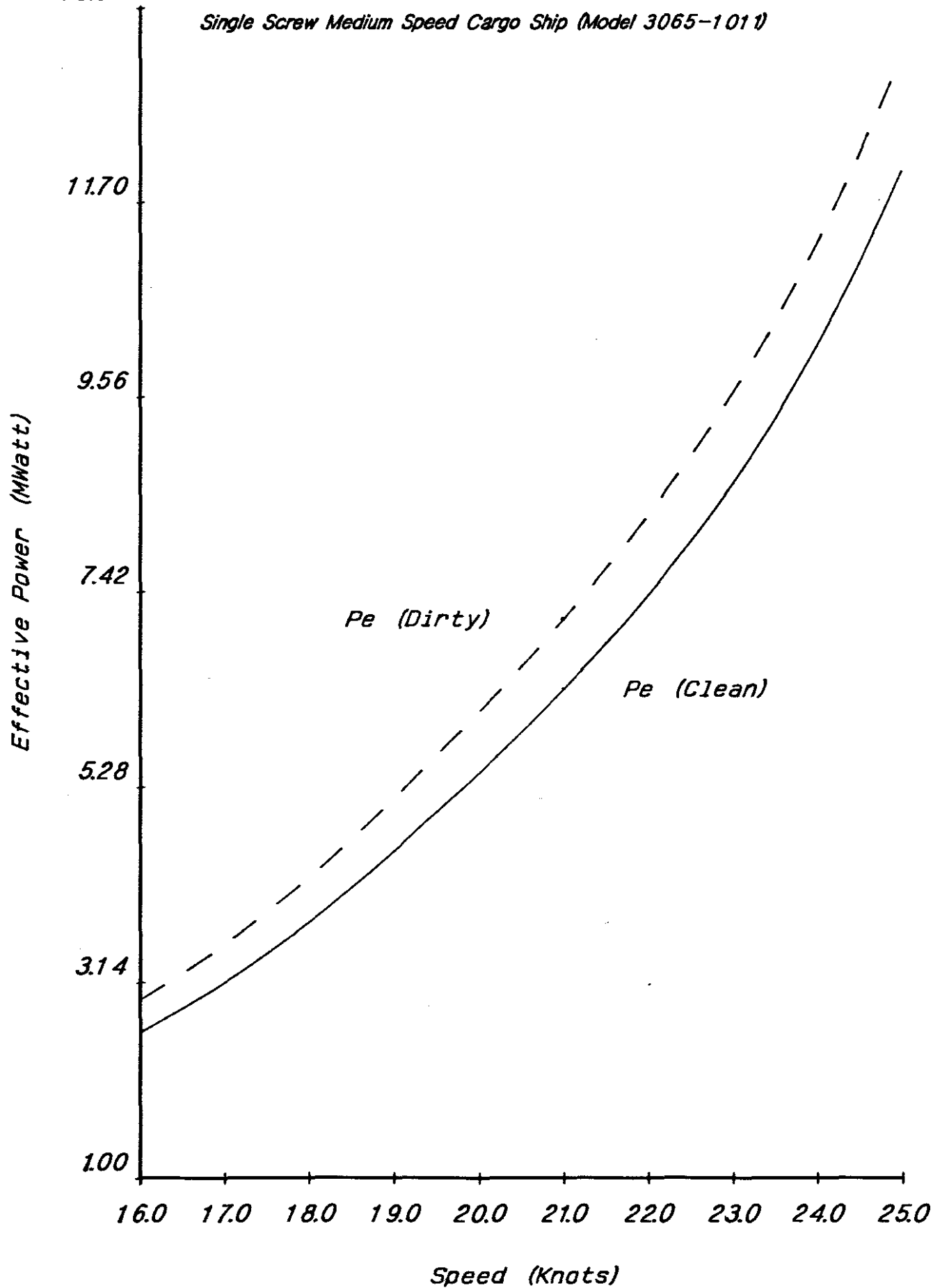
Predicted Brake Power (Pb)

Single Screw Medium Speed Cargo Ship (Model 3065-1011)

Brake Power (MWatt)

Speed (Knots)

Pb (Dirty)

Pb (Clean)

A14
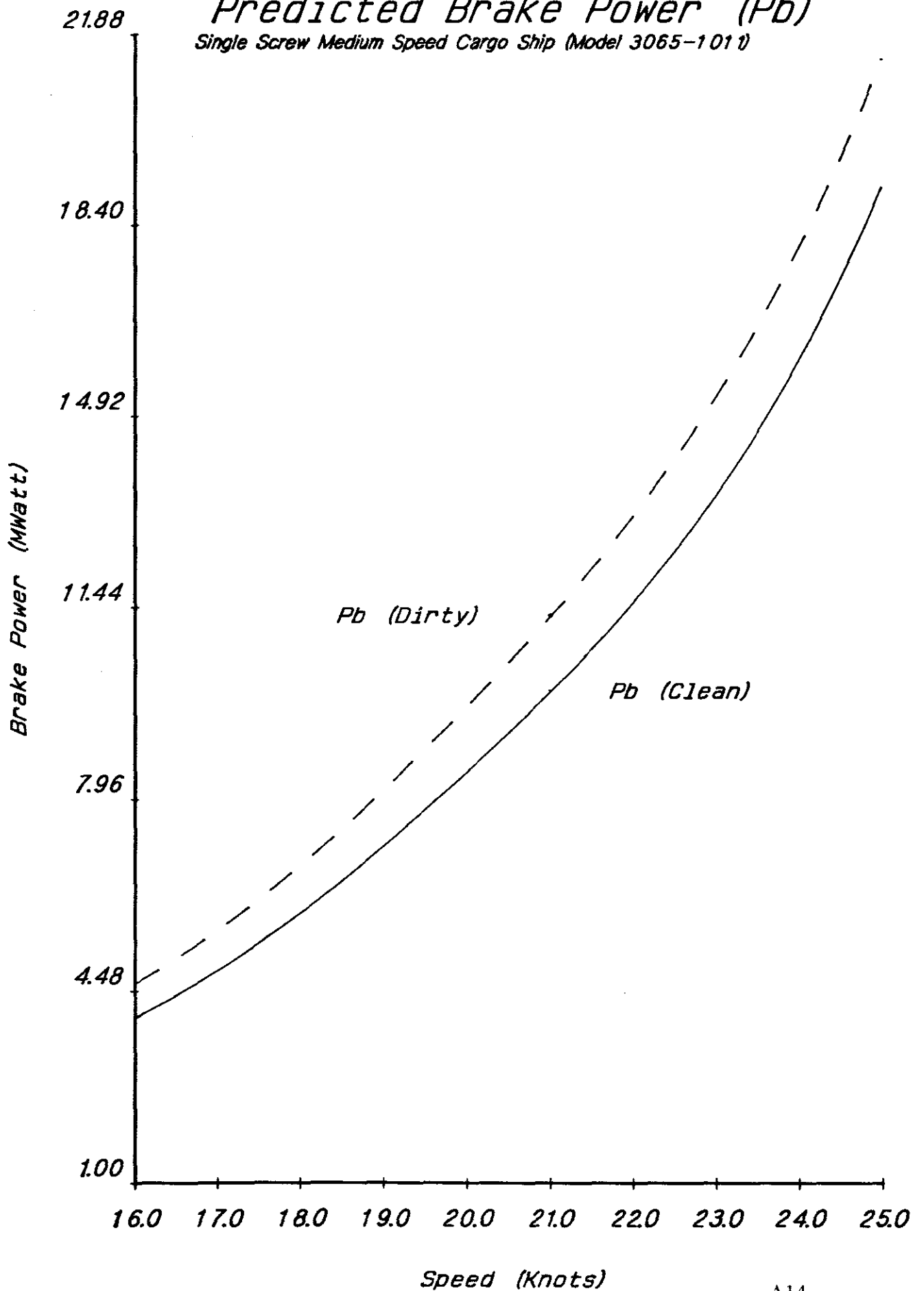
7. PROGRAM LISTING

```
PROGRAM POWER;

{ ------------------------MAIN REFERENCES  ---------------------- }
{ Resistance prediction
      1:    An Approximate Power Prediction Method
            By J. Holtrop and G.G.J. Mennen
            International Shipbuilding Progress. Vol. 29,1982


      2:    A Statistical Re-Analysis of Resistance and Propulsion Data
            By J. Holtrop
            International Shipbuilding Progress. Vol.31, 1984


  Brake power prediction
      3:    Further Computer-Analysed Data of the Wageningen B-Screw
            Series
            By M. Oosterveld and P. van Oossanen.
            International Shipbuilding Progress. Vol. 22, 1974


  Wind Resistance (Taylor Formula)
      4:    Resistance.  Principles of Naval Architecture Vol II
            By van Manen and van Oossanen
            Society of Naval Architects and Marine Engineers.


  Wave Resistance
      5:    PHHS. A Fortran Program for Ship Pitch, Heave and
            Seakeeping Prediction
            By M. Mackay and R. Schmitke.
            DREA Technical Memorandum 78/B.


                              Program author: R.D. Moody.
                                        Oct. 1996    }

{ -------------------------DEFINE VARIABLES --------------------}
  USES Dos,CRT,Graph,Plotter,ScGraph,Logos,OptEff,Border;
  VAR
      FileInp  : String[30];      FilePlot1: String[30];
      FileOut  : String[30];      FilePlot2: String[30];
      FileTemp : String[30];      FilePlot3: String[30];


      Name     : String[80];      FileVar  : Text;
      F        : File;


      LWL, Lpp, B, Ta, Tf, VDisp, LCB, Abt, Hb, S, Mass      : REAL;
      Cm, Cwp, Cb, Cp, D, CProp, Fact, PDRat, Pe, BARc,BARd  : REAL;
      RTot, TForm2, TSApp, T, Form1, Rn, Rf, RfAct, tdf, ns  : REAL;
      Rt, Rb, Rtr, Ra, Rbt, RApp, Rw, Rw_a, Rw_b,Rw_c        : REAL;
      At, CStern, Lr, Lamda, Ie, M1, M3, w, Thrustc, Thrustd: REAL;
      nh, K, Dbt, Cbto, V, VMin, VMax, VInc, Vm,SLRat        : REAL;
      Fn, Fn1, Cf, Cr, Ca, C1, C2, C5, C7, C15, C16, C17     : REAL;
      DeltaCa, ks, RfDirty, RtDirty, PeDirty, Days, BAR      : REAL;
      Noptc, PDc, RPMc, Ktc, Jc, nr1c, nh1, QPCc, PCc, Pbc   : REAL;
      Noptd, PDd, RPMd, Ktd, Jd, nr1d,  QPCd, PCd, Pbd, Kqd  : REAL;
      Hs, Vwind, Rwind, Ts, Spectrum, Wd, VDes, Kqc          : REAL;
      Year, Month, Day, DayOfWeek, Hour, Min, Sec, Sec100    : WORD;


      N1, N2, N3, N4, I, NI, N, Z, CBow, SS           : INTEGER;
      PFR, PSR, OBPS, OBPP, BPS, BPP, BPO             : CHAR;


      A00    : ARRAY [ 1..80] of REAL;
      A10    : ARRAY [ 1..80] of REAL;
      A11    : ARRAY [ 1..80] of REAL;
      A20    : ARRAY [ 1..80] of REAL;
      A01    : ARRAY [ 1..80] of REAL;
      A02    : ARRAY [ 1..80] of REAL;
      A0     : ARRAY [ 1..80] of REAL;
      WW     : ARRAY [ 1..25] of REAL;
      Sapp   : ARRAY [ 1..9] of REAL ;
      Form2  : ARRAY [ 1..9] of REAL ;
      SState : ARRAY [ 0..9] of REAL ;

CONST
      Title  = '  PROGRAM POWER   ';
      Version = 'Release 1.00';
```

A15

```pascal
        Rho     = 1.025;   {Density of Sea water}
        g       = 9.807;   {gravitational accelaration}
        Pic_Name = 'PPP.PCX';
{$I Lib.inc}


{-------------------- GET SYSTEM DATE AND TIME --------------------}
PROCEDURE Date;   {Get system date and time}
BEGIN
     GetDate(Year, Month, Day, DayOfWeek);
     GetTime(Hour, Min, Sec,Sec100);
END;


{-------------------- SET HIDDEN FILES TO ARCHIVE ---------------}
PROCEDURE Temp_Init;
BEGIN
   ASSIGN  (F,'HM1.TMP');
   SetFAttr(F, Archive);
   ASSIGN  (F,'HM2.TMP');
   SetFAttr(F, Archive);
   ASSIGN  (F,'HM3.TMP');
   SetFAttr(F, Archive);
END;


{-------------------- SET TEMP FILES TO HIDDEN ------------------}
PROCEDURE Temp_Fin;
BEGIN
   ASSIGN  (F, 'HM1.TMP');
   SetFAttr(F, Hidden);
   ASSIGN  (F, 'HM2.TMP');
   SetFAttr(F, Hidden);
   ASSIGN  (F, 'HM3.TMP');
   SetFAttr(F, Hidden);
END;

{-------------------- GET INPUT AND OUTPUT FILENAME --------------}
PROCEDURE File_Names;
LABEL 1, 2, 3, 4, 5, 6;

 BEGIN  {Get name of input and output file}
   {Initialise variables}
     OBPS := 'N';
     OBPP := 'N';
     BPO  := 'N';
     BPS  := 'N';
     BPP  := 'N';
     TextBackGround(Blue);
  {Variable initilisation complete}

     HighVideo;
     TextColor(14);
1:     GotoXY(1,2);
     Writeln('  Enter input file name    ');
     GotoXY(57,2);ClrEol;
     Readln (FileInp);
     Assign (FileVar, FileInp);
     {$i-} Reset (FileVar);{$i+}
     IF IoResult <> 0 THEN
       BEGIN
       Write ('This File does not exist, enter valid file name');
       Goto 1;
       END;

     GotoXY(1,3);ClrEol;

     GotoXY(1,4);
     Writeln('  Enter output file name   ');
     GotoXY(57,4);ClrEol;
     Readln (FileOut);

2:    GotoXY(1,6);
     Writeln('  Brake Power required (Y or N) ');
     GotoXY(57,6); ClrEol;
     Readln (BPO);
     IF BPO = 'y' THEN BPO :='Y';
     IF BPO = 'n' THEN BPO :='N';
     IF (BPO<>'Y') AND (BPO<>'N')THEN GOTO 2;
```

A16

```
3:      GotoXY(1,8);
        WriteLn(' Plot Effective Power Graph to Screen (Y or N)');
        GotoXY(57,8);ClrEol;
        ReadLn(PSR);
        IF PSR = 'y' THEN PSR :='Y';
        IF PSR = 'n' THEN PSR :='N';
        IF (PSR<>'Y') AND (PSR<>'N')THEN GOTO 3;


4:      GotoXY(1,10);
        Writeln(' Effective Power Plot File Required (Y or N)');
        GotoXY(57,10);ClrEol;
        Readln (PFR);
        IF PFR = 'y' THEN PFR := 'Y';
        IF PFR = 'n' THEN PFR := 'N';
        IF (PFR<>'Y') AND (PFR<>'N')THEN GOTO 4;
        IF PFR = 'Y' THEN
          BEGIN
            GotoXY(1,12);
            Writeln(' Enter Effective Power plot file name ');
            GotoXY(57,12);ClrEol;
            Readln (FilePlot1);
          END;

        IF BPO = 'Y' THEN
          BEGIN
5:          GotoXY(1,14); ClrEol;
            WriteLn(' Plot Brake Power Graph to Screen (Y or N)');
            GotoXY(57,14);ClrEol;
            ReadLn(BPS);
            IF BPS = 'y' THEN BPS :='Y';
            IF BPS = 'n' THEN BPS :='N';
            IF (BPS<>'Y') AND (BPS<>'N')THEN GOTO 5;

6:          GotoXY(1,16); ClrEol;
            Writeln(' Brake Power Plot File Required (Y or N)');
            GotoXY(57,16);ClrEol;
            Readln (BPP);
            IF BPP = 'y' THEN BPP := 'Y';
            IF BPP = 'n' THEN BPP :='N';
            IF (BPP<>'Y') AND (BPP<>'N')THEN GOTO 5;
            IF BPP = 'Y' THEN
              BEGIN
                GotoXY(1,18); ClrEol;
                Writeln(' Enter Brake Power plot file name ');
                GotoXY(57,18);ClrEol;
                Readln (FilePlot3);
              END;
          END;

      NormVideo;
END;   {Procedure File}

{------------------- READ DATA FROM INPUT FILE -------------------}

PROCEDURE Dat_Inp;  {Data input from user defined input file}
VAR
    Form22 :  ARRAY [ 2..9] of REAL ;
BEGIN {Assign default values to Form22 ie. (1+K2) }
    Form22[2] := 2.00;
    Form22[3] := 3.00;
    Form22[4] := 2.80;
    Form22[5] := 1.40;
    Form22[6] := 1.75;
    Form22[7] := 3.00;
    Form22[8] := 2.00;
    Form22[9] := 2.70;


    SState[0] :=  0   ;  SState[1] := 0.08;  SState[2] :=  0.42;
    SState[3] := 1.10;   SState[4] := 2.25;  SState[5] :=  3.70;
    SState[6] := 5.60;   SState[7] := 8.40;  SState[8] := 13.00;
    SState[9] := 21.20;


{Initialise variables}
    Abt        := 0;    Dbt    := 0;
    Cbto       := 0;    Hb     := 0;
    Form2[2] := 0;      PDRat := 0;
```

A17

```
      Rb       := 0;   CBow  := 0;
      SS       := 0;

   ASSIGN (FileVar,FileInp);    {Open input file and read in data}
       RESET (FileVar);
       Readln (FileVar,Name);
       Readln (FileVar,LWL,Lpp,B,Tf,Ta);
       Readln (FileVar,VDisp, Cm, Cwp);
       Readln (FileVar,LCB, Ie, S);

       Readln (FileVar,N4,Ks);  {N4- Correlation coefficient 3=user supplied}
                               {ks- hull surface roughness}
               IF N4 = 3  THEN   { if =1 read in Ca.}
               Readln (FileVar,Ca);
               IF N4 = 2 THEN Ca := 0.0004;
               IF N4 = 1 THEN Ca := 9999;
               IF N4 > 3 THEN Ca := 0;

       Readln (FileVar,N1);      { Bulb fitted 1=Yes 0=No}
               IF N1=1  THEN  { if fitted read in bulb data. }
               Readln (FileVar,Abt,Hb);

       Readln (FileVar,N2);        { Bowthruster fitted 1=Yes 0=No }
               IF N2 = 1 THEN             { if fitted read in tunnel data.}
               Readln (FileVar,Dbt,Cbto);

       Readln (FileVar,At,CStern,CBow);
       Readln (FileVar,SApp[1],Form2[1],N3);

       BEGIN    {Rudder data input}
           IF SApp[1] <> 0 THEN      { Rudder wsa given 0=No }
               IF Form2[1] = 0 THEN   { 1+K2 given      0=No }
                 IF N3 = 1 THEN Form2[1] := 1.75 ELSE {Rudder behind Skeg}
                 IF N3 = 2 THEN Form2[1] := 1.40 ELSE {Rudder behind Stern}
                 IF N3 = 3 THEN
                     BEGIN  {Rudder data :-two rudders and two shafts}
                        Form2[1] := 2.80;  {Twin-screw balanced rudders}
                         Form22[2] := 4.00; { 1+K2 for twin shafts}
                      END;   { Twin rudder data }
       END;     {Rudder data}


       Readln (FileVar,SApp[2],Form2[2]);   {Shaft data}

       FOR I := 3 TO 9 DO   {Get WSA of appendage and 1+K2 factor}
       BEGIN                {else use default 1+K2 factor.        }
             Readln (FileVar,SApp[I],Form2[I]);
             IF Form2[I] = 0 THEN Form2[I] := Form22[I];
       END;      {WSA of appendages and 1+K2 factor}

       ReadLn (FileVar,SS, Days);        {Sea State, No days out of Dock}
       IF SS > 9  THEN  SS := 9;         {Set max sea state}
       IF Days = 0  THEN  Days := 182.5;  {Default 6 months out of Dock}

       Readln (FileVar,VDes,VMin,VMax,VInc);   {Min and max speed and increment}
       Readln (FileVar,N, D, Z, CProp);   {Propeller Data}


       ReadLn (FileVar,ns); {Shafting Efficiency}
             IF ns > 100  THEN ns := 100;
             IF ns <= 0 THEN ns := 100;
             ns := ns/100;

       Readln (FileVar,PDRat, BAR); {Data required for Brake Power}

       IF Form2[2] = 0 THEN         {Default (1+k2) = 4.0 (twin screw)  }
          Begin                     {              = 2.0 (Single screw)}
             IF N >1 THEN Form2[2] := 4.00 ELSE Form2[2] := 2.00
          End;
   CLOSE(FileVar); {Close Input file}

END; {Procedure Dat_Inp}

{----------ASSIGN SEA SPECTRUM VALUES TO VARIABLE ARRAYS----------}
PROCEDURE VarAssign;
 BEGIN
    A00[1 ] :=  0.00000;   A01[1 ] :=  0.00000;   A11[1 ] :=  0.00000;
    A00[2 ] :=  0.00000;   A01[2 ] :=  0.00000;   A11[2 ] :=  0.00000;
```

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A00[3 ] :=  0.00001;    A01[3 ] :=  0.00001;    A11[3 ] :=  0.00000;
A00[4 ] :=  0.00018;    A01[4 ] :=  0.00003;    A11[4 ] :=  0.00002;
A00[5 ] :=  0.00133;    A01[5 ] :=  0.00000;    A11[5 ] :=  0.00020;
A00[6 ] :=  0.00324;    A01[6 ] := -0.00067;    A11[6 ] :=  0.00041;
A00[7 ] :=  0.00709;    A01[7 ] := -0.00240;    A11[7 ] :=  0.00077;
A00[8 ] :=  0.01325;    A01[8 ] := -0.00558;    A11[8 ] :=  0.00112;
A00[9 ] :=  0.02618;    A01[9 ] := -0.00822;    A11[9 ] :=  0.00146;
A00[10] :=  0.05336;    A01[10] := -0.01065;    A11[10] :=  0.00103;
A00[11] :=  0.11641;    A01[11] := -0.01169;    A11[11] := -0.00103;
A00[12] :=  0.25030;    A01[12] := -0.01241;    A11[12] := -0.00667;
A00[13] :=  0.49430;    A01[13] := -0.00664;    A11[13] := -0.01387;
A00[14] :=  0.83054;    A01[14] :=  0.01278;    A11[14] := -0.02494;
A00[15] :=  1.23195;    A01[15] :=  0.03974;    A11[15] := -0.02849;
A00[16] :=  1.59871;    A01[16] :=  0.06999;    A11[16] := -0.01366;
A00[17] :=  1.79955;    A01[17] :=  0.08177;    A11[17] :=  0.01256;
A00[18] :=  1.76253;    A01[18] :=  0.05580;    A11[18] :=  0.02414;
A00[19] :=  1.56762;    A01[19] :=  0.01841;    A11[19] :=  0.02513;
A00[20] :=  1.30231;    A01[20] :=  0.00270;    A11[20] :=  0.01785;
A00[21] :=  1.07908;    A01[21] := -0.00276;    A11[21] :=  0.01365;
A00[22] :=  0.91784;    A01[22] := -0.01522;    A11[22] :=  0.01369;
A00[23] :=  0.77733;    A01[23] := -0.03524;    A11[23] :=  0.01287;
A00[24] :=  0.66816;    A01[24] := -0.03485;    A11[24] :=  0.01190;
A00[25] :=  0.57326;    A01[25] := -0.03189;    A11[25] :=  0.00914;
A00[26] :=  0.49269;    A01[26] := -0.03983;    A11[26] :=  0.00604;
A00[27] :=  0.43533;    A01[27] := -0.03554;    A11[27] :=  0.00441;
A00[28] :=  0.38482;    A01[28] := -0.03005;    A11[28] :=  0.00222;
A00[29] :=  0.33183;    A01[29] := -0.02822;    A11[29] := -0.00303;
A00[30] :=  0.28287;    A01[30] := -0.02864;    A11[30] := -0.00754;
A00[31] :=  0.25230;    A01[31] := -0.02787;    A11[31] := -0.00807;
A00[32] :=  0.23205;    A01[32] := -0.02231;    A11[32] := -0.00403;
A00[33] :=  0.21658;    A01[33] := -0.01716;    A11[33] := -0.00067;
A00[34] :=  0.20370;    A01[34] := -0.01219;    A11[34] :=  0.00046;
A00[35] :=  0.19481;    A01[35] := -0.01098;    A11[35] :=  0.00026;
A00[36] :=  0.18371;    A01[36] := -0.01213;    A11[36] := -0.00081;
A00[37] :=  0.17350;    A01[37] := -0.01061;    A11[37] := -0.00096;
A00[38] :=  0.16129;    A01[38] := -0.01317;    A11[38] := -0.00310;
A00[39] :=  0.14752;    A01[39] := -0.02021;    A11[39] := -0.00798;
A00[40] :=  0.14327;    A01[40] := -0.00812;    A11[40] := -0.00544;
A00[41] :=  0.13558;    A01[41] :=  0.00344;    A11[41] := -0.00238;
A00[42] :=  0.12091;    A01[42] :=  0.00783;    A11[42] := -0.00232;
A00[43] :=  0.10697;    A01[43] :=  0.01083;    A11[43] := -0.00222;
A00[44] :=  0.09764;    A01[44] :=  0.01190;    A11[44] := -0.00222;
A00[45] :=  0.09052;    A01[45] :=  0.01113;    A11[45] := -0.00281;
A00[46] :=  0.08372;    A01[46] :=  0.01021;    A11[46] := -0.00349;
A00[47] :=  0.07646;    A01[47] :=  0.00988;    A11[47] := -0.00324;
A00[48] :=  0.06884;    A01[48] :=  0.00930;    A11[48] := -0.00292;
A00[49] :=  0.05932;    A01[49] :=  0.01115;    A11[49] := -0.00199;
A00[50] :=  0.05156;    A01[50] :=  0.01152;    A11[50] := -0.00146;
A00[51] :=  0.04350;    A01[51] :=  0.01164;    A11[51] := -0.00011;
A00[52] :=  0.03660;    A01[52] :=  0.01193;    A11[52] := -0.00094;
A00[53] :=  0.03037;    A01[53] :=  0.01243;    A11[53] := -0.00047;
A00[54] :=  0.02363;    A01[54] :=  0.01189;    A11[54] := -0.00007;
A00[55] :=  0.01831;    A01[55] :=  0.01054;    A11[55] :=  0.00031;
A00[56] :=  0.01466;    A01[56] :=  0.00913;    A11[56] :=  0.00056;
A00[57] :=  0.01117;    A01[57] :=  0.00785;    A11[57] :=  0.00019;
A00[58] :=  0.00829;    A01[58] :=  0.00674;    A11[58] := -0.00028;
A00[59] :=  0.00561;    A01[59] :=  0.00554;    A11[59] := -0.00073;
A00[60] :=  0.00395;    A01[60] :=  0.00475;    A11[60] := -0.00075;
A00[61] :=  0.00283;    A01[61] :=  0.00422;    A11[61] := -0.00059;
A00[62] :=  0.00225;    A01[62] :=  0.00403;    A11[62] := -0.00010;
A00[63] :=  0.00143;    A01[63] :=  0.00345;    A11[63] := -0.00016;
A00[64] :=  0.00057;    A01[64] :=  0.00256;    A11[64] := -0.00055;
A00[65] :=  0.00006;    A01[65] :=  0.00184;    A11[65] := -0.00054;
A00[66] := -0.00041;    A01[66] :=  0.00129;    A11[66] := -0.00030;
A00[67] := -0.00032;    A01[67] :=  0.00124;    A11[67] :=  0.00030;
A00[68] := -0.00012;    A01[68] :=  0.00120;    A11[68] :=  0.00048;
A00[69] := -0.00005;    A01[69] :=  0.00109;    A11[69] :=  0.00036;
A00[70] := -0.00032;    A01[70] :=  0.00093;    A11[70] :=  0.00016;
A00[71] := -0.00059;    A01[71] :=  0.00073;    A11[71] := -0.00002;
A00[72] := -0.00077;    A01[72] :=  0.00051;    A11[72] := -0.00010;
A00[73] := -0.00097;    A01[73] :=  0.00027;    A11[73] := -0.00011;
A00[74] := -0.00080;    A01[74] :=  0.00021;    A11[74] := -0.00005;
A00[75] := -0.00047;    A01[75] :=  0.00023;    A11[75] :=  0.00006;
A00[76] := -0.00032;    A01[76] :=  0.00021;    A11[76] :=  0.00013;
A00[77] := -0.00022;    A01[77] :=  0.00017;    A11[77] :=  0.00015;
A00[78] := -0.00014;    A01[78] :=  0.00013;    A11[78] :=  0.00014;
A00[79] := -0.00008;    A01[79] :=  0.00007;    A11[79] :=  0.00009;
A00[80] := -0.00003;    A01[80] :=  0.00004;    A11[80] :=  0.00005;
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A02[1 ]  :=   0.00000;      A20[1 ]  :=   0.00000;      A10[1 ]  :=   0.00000;
A02[2 ]  :=   0.00000;      A20[2 ]  :=   0.00000;      A10[2 ]  :=   0.00000;
A02[3 ]  :=   0.00000;      A20[3 ]  :=   0.00000;      A10[3 ]  :=  -0.00001;
A02[4 ]  := -0.00004;       A20[4 ]  :=   0.00000;      A10[4 ]  :=  -0.00004;
A02[5 ]  := -0.00021;       A20[5 ]  :=   0.00000;      A10[5 ]  :=  -0.00043;
A02[6 ]  := -0.00016;       A20[6 ]  :=   0.00005;      A10[6 ]  :=  -0.00134;
A02[7 ]  :=   0.00027;      A20[7 ]  :=   0.00009;      A10[7 ]  :=   0.00255;
A02[8 ]  :=   0.00140;      A20[8 ]  :=   0.00016;      A10[8 ]  :=   0.00387;
A02[9 ]  :=   0.00193;      A20[9 ]  :=   0.00035;      A10[9 ]  :=  -0.00543;
A02[10]  :=   0.00188;      A20[10]  :=   0.00033;      A10[10]  :=  -0.00475;
A02[11]  :=   0.00082;      A20[11]  :=   0.00022;      A10[11]  :=  -0.00017;
A02[12]  :=   0.00042;      A20[12]  :=   0.00079;      A10[12]  :=   0.00901;
A02[13]  := -0.00032;       A20[13]  :=   0.00172;      A10[13]  :=   0.02629;
A02[14]  :=   0.00428;      A20[14]  :=   0.00417;      A10[14]  :=   0.04993;
A02[15]  :=   0.00436;      A20[15]  :=   0.00481;      A10[15]  :=   0.06652;
A02[16]  := -0.00858;       A20[16]  :=   0.00119;      A10[16]  :=   0.06000;
A02[17]  := -0.02142;       A20[17]  :=  -0.00660;      A10[17]  :=   0.03906;
A02[18]  := -0.01770;       A20[18]  :=  -0.00935;      A10[18]  :=   0.00467;
A02[19]  := -0.01166;       A20[19]  :=  -0.00604;      A10[19]  :=  -0.03727;
A02[20]  := -0.00411;       A20[20]  :=  -0.00044;      A10[20]  :=  -0.06926;
A02[21]  :=   0.00016;      A20[21]  :=   0.00188;      A10[21]  :=  -0.07963;
A02[22]  :=   0.00259;      A20[22]  :=   0.00049;      A10[22]  :=  -0.06424;
A02[23]  :=   0.00845;      A20[23]  :=   0.00021;      A10[23]  :=  -0.05265;
A02[24]  :=   0.00818;      A20[24]  :=  -0.00021;      A10[24]  :=  -0.04332;
A02[25]  :=   0.00924;      A20[25]  :=  -0.00030;      A10[25]  :=  -0.03261;
A02[26]  :=   0.01304;      A20[26]  :=  -0.00107;      A10[26]  :=  -0.01857;
A02[27]  :=   0.01044;      A20[27]  :=  -0.00137;      A10[27]  :=  -0.01263;
A02[28]  :=   0.00776;      A20[28]  :=  -0.00081;      A10[28]  :=  -0.00911;
A02[29]  :=   0.00819;      A20[29]  :=   0.00131;      A10[29]  :=  -0.00801;
A02[30]  :=   0.00995;      A20[30]  :=   0.00251;      A10[30]  :=  -0.00336;
A02[31]  :=   0.00943;      A20[31]  :=   0.00183;      A10[31]  :=   0.00342;
A02[32]  :=   0.00585;      A20[32]  :=   0.00020;      A10[32]  :=   0.00539;
A02[33]  :=   0.00222;      A20[33]  :=  -0.00063;      A10[33]  :=   0.00458;
A02[34]  := -0.00011;       A20[34]  :=  -0.00076;      A10[34]  :=   0.00400;
A02[35]  := -0.00139;       A20[35]  :=  -0.00087;      A10[35]  :=   0.00652;
A02[36]  := -0.00171;       A20[36]  :=  -0.00060;      A10[36]  :=   0.00907;
A02[37]  := -0.00314;       A20[37]  :=  -0.00050;      A10[37]  :=   0.00923;
A02[38]  := -0.00183;       A20[38]  :=   0.00013;      A10[38]  :=   0.01084;
A02[39]  :=   0.00268;      A20[39]  :=   0.00108;      A10[39]  :=   0.01613;
A02[40]  := -0.00207;       A20[40]  :=   0.00050;      A10[40]  :=   0.01451;
A02[41]  := -0.00614;       A20[41]  :=  -0.00001;      A10[41]  :=   0.01063;
A02[42]  := -0.00630;       A20[42]  :=   0.00023;      A10[42]  :=   0.00839;
A02[43]  := -0.00615;       A20[43]  :=   0.00042;      A10[43]  :=   0.00592;
A02[44]  := -0.00599;       A20[44]  :=   0.00046;      A10[44]  :=   0.00532;
A02[45]  := -0.00532;       A20[45]  :=   0.00045;      A10[45]  :=   0.00714;
A02[46]  := -0.00432;       A20[46]  :=   0.00052;      A10[46]  :=   0.00877;
A02[47]  := -0.00360;       A20[47]  :=   0.00030;      A10[47]  :=   0.01007;
A02[48]  := -0.00290;       A20[48]  :=   0.00017;      A10[48]  :=   0.01077;
A02[49]  := -0.00300;       A20[49]  :=  -0.00002;      A10[49]  :=   0.01001;
A02[50]  := -0.00267;       A20[50]  :=  -0.00015;      A10[50]  :=   0.00923;
A02[51]  := -0.00211;       A20[51]  :=  -0.00011;      A10[51]  :=   0.00750;
A02[52]  := -0.00171;       A20[52]  :=   0.00002;      A10[52]  :=   0.00467;
A02[53]  := -0.00145;       A20[53]  :=   0.00011;      A10[53]  :=   0.00175;
A02[54]  := -0.00095;       A20[54]  :=   0.00008;      A10[54]  :=   0.00034;
A02[55]  := -0.00043;       A20[55]  :=  -0.00012;      A10[55]  :=   0.00066;
A02[56]  := -0.00001;       A20[56]  :=  -0.00028;      A10[56]  :=   0.00106;
A02[57]  :=   0.00051;      A20[57]  :=  -0.00012;      A10[57]  :=   0.00095;
A02[58]  :=   0.00094;      A20[58]  :=   0.00011;      A10[58]  :=   0.00090;
A02[59]  :=   0.00126;      A20[59]  :=   0.00036;      A10[59]  :=   0.00102;
A02[60]  :=   0.00134;      A20[60]  :=   0.00040;      A10[60]  :=   0.00091;
A02[61]  :=   0.00133;      A20[61]  :=   0.00035;      A10[61]  :=   0.00068;
A02[62]  :=   0.00118;      A20[62]  :=   0.00013;      A10[62]  :=   0.00036;
A02[63]  :=   0.00108;      A20[63]  :=   0.00027;      A10[63]  :=   0.00050;
A02[64]  :=   0.00104;      A20[64]  :=   0.00054;      A10[64]  :=   0.00077;
A02[65]  :=   0.00090;      A20[65]  :=   0.00058;      A10[65]  :=   0.00093;
A02[66]  :=   0.00078;      A20[66]  :=   0.00040;      A10[66]  :=   0.00073;
A02[67]  :=   0.00062;      A20[67]  :=  -0.00003;      A10[67]  :=   0.00027;
A02[68]  :=   0.00050;      A20[68]  :=  -0.00014;      A10[68]  :=   0.00018;
A02[69]  :=   0.00044;      A20[69]  :=  -0.00010;      A10[69]  :=   0.00015;
A02[70]  :=   0.00043;      A20[70]  :=   0.00001;      A10[70]  :=   0.00003;
A02[71]  :=   0.00036;      A20[71]  :=   0.00014;      A10[71]  :=  -0.00009;
A02[72]  :=   0.00029;      A20[72]  :=   0.00020;      A10[72]  :=  -0.00013;
A02[73]  :=   0.00025;      A20[73]  :=   0.00022;      A10[73]  :=  -0.00013;
A02[74]  :=   0.00022;      A20[74]  :=   0.00015;      A10[74]  :=  -0.00009;
A02[75]  :=   0.00018;      A20[75]  :=   0.00004;      A10[75]  :=  -0.00006;
A02[76]  :=   0.00014;      A20[76]  :=  -0.00001;      A10[76]  :=  -0.00003;
A02[77]  :=   0.00008;      A20[77]  :=  -0.00003;      A10[77]  :=  -0.00001;
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A20

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         A02[78] := 0.00004;    A20[78] := -0.00003;    A10[78] := -0.00001;
         A02[79] := 0.00002;    A20[79] := -0.00002;    A10[79] :=  0.00000;
         A02[80] := 0.00001;    A20[80] := -0.00001;    A10[80] :=  0.00000;
END;


{---------FUNCTION TO DETERMINE ADDED RESISTANCE COEFFICIENT---------}
FUNCTION RAW(W,XL,PRG,FR,CM :REAL; CBow :Integer) :REAL;
  VAR
        A, B, D, WM, RM, DF         :REAL;
        UB, VB   :  ARRAY [ 1..11] of REAL;
        IK   :INTEGER;
  CONST
     g = 9.807;

  LABEL
   1, 2, 3, 4, 5, 6, 7;

BEGIN
     UB[1 ] :=  0.00;      VB[1 ] :=  0.00;
     UB[2 ] :=  1.60;      VB[2 ] :=  1.10;
     UB[3 ] :=  3.50;      VB[3 ] :=  2.40;
     UB[4 ] :=  5.90;      VB[4 ] :=  3.80;
     UB[5 ] :=  8.40;      VB[5 ] :=  5.40;
     UB[6 ] :=  9.90;      VB[6 ] :=  7.10;
     UB[7 ] := 10.70;      VB[7 ] :=  8.90;
     UB[8 ] := 11.70;      VB[8 ] := 10.70;
     UB[9 ] := 13.40;      VB[9 ] := 11.70;
     UB[10] := 15.60;      VB[10] := 14.90;
     UB[11] := 18.10;      VB[11] := 17.40;


     IF FR > 0 THEN GOTO 1;
     RAW := 0;
     GOTO 6;
  1: A := SQR(PRG);
     B := SQRT(XL/g);
     IF CM < 0.9 THEN GOTO 2;
     RM := 3600 * A * RAISE(FR,1.5) * EXP(-3.5*FR);
     WM := 1.17 * RAISE(FR,(-1/7)) * RAISE(A,(-1/3))/B;
     GOTO 5;
  2: WM := (2.79-1.18*FR)/B;
     IF C1 <2  THEN GOTO 3;
     RM := 48.0*FR;
     IF FR > 0.5 THEN  RM := 24.0 + 32.0 * (FR-0.5);
     GOTO 5;
  3: IK := TRUNC(FR/0.05+1);
     DF := FR-(IK-1)*0.05;
     IF C1 < 1 THEN GOTO 4;
     RM := UB[IK] + DF*(UB[IK+1]-UB[IK])/0.05;
     GOTO 5;
  4: { RM := 38.02 * RAISE(FR,1.197);
     WriteLn ('HELP');             }
     RM := VB[IK]+DF*(VB[IK+1]-VB[IK])/0.05;
  5: WM := W/WM;
     B := 11;
     D := 14;
     IF WM < 1.0 THEN GOTO 7;
     B := -8.5;
     D := -14.0;
  7: RAW := RM*EXP(B * (1.0 - RAISE(WM,D))/D)*RAISE(WM,B);

  6: END;

{---------------------FUNCTION TO DETERMINE SEASTATE--------------}
FUNCTION SEAST(HH,TT,WW:REAL) :REAL ;
{All units metric - output spectrum units =m^2/(Rad/sec)}
  VAR
     F                    : ARRAY [ 1..2] of REAL;
     H, T, W, S           : REAL;
     M, N, IJ             : INTEGER;

LABEL
  1, 2, 3, 4;

  BEGIN
     VarAssign;
     H := HH - 4.016;
```

```
            T := TT - 9.159;
            W := WW * TT/6.283185;
            IF W > 0.05 THEN GOTO 2;
            SEAST := 0;
            GOTO 4;
         2: IF W <4 THEN  GOTO 3;
            SEAST := 0;
            GOTO 4;
         3: N := TRUNC(W/0.05);
            FOR IJ := 1 to 2 DO
            BEGIN
               M := N+IJ-1;
               F[IJ] := A00[M]+A10[M]*H+A01[M]*T+A20[M]*H*H+A11[M]*H*T+A02[M]*T*T;
            END;
            S := F[1]+(F[2]-F[1])*(W-N*0.05)*20;
            SEAST := S * SQR(HH) * TT/9.398;
      4: END;


{------------------- DETERMINE FORM COEFFICIENTS----------------}

PROCEDURE Form_Coeff;
BEGIN
      T := ((Tf + Ta)/2);            {Determine average draught}
      Cb := (VDisp / (LWL * B * T));  {Determine  Block Coefficient (Cb)}
      Cp := (Cb / Cm );               {Determine Prismatic Coefficient (Cp)}
      Mass:= VDisp * Rho;             {Determine mass displacement in tonne}
END;


{------------------- DETERMINE SPEED RANGE FOR LOOPS--------------}

PROCEDURE Incr;  {Determine speed range for loop}
VAR
    VTest, DecTest    :REAL;

BEGIN

      VTest:= ( 0.032 * SQRT(9.81 * LWL))/0.51477;
      IF VTest > VMin THEN
            BEGIN
                DecTest :=  VMin/INT(VMin);
                IF DecTest = 1
                     THEN VMin := INT(VTest) + 1
                     ELSE VMin := ROUND(VTest) + 0.5;
            END;

      NI :=  (Round((VMax - VMin) / VInc) + 1);
      IF NI >10 THEN
                 Begin
                    NI := 10;
                    VMax := VMin + (9 * VInc);
                 End;
      V   := VMin - VInc;
END;


{------- DETERMINE SPEED INDEPENDANT WAVEMAKING VARIABLES -----------}

PROCEDURE Constant; {Calculate speed independant wavemaking variables}
LABEL
   1, 2, 3, 4, 5, 6;
VAR
C3, Ax, Bx, Cx      :REAL;
BEGIN

      C5 := 1 - 0.8*At/(B*T*Cm);

      BEGIN  {C17    Fn > 0.55}
         Ax := 6919.3*RAISE(Cm,-1.3346)* RAISE((VDisp/RAISE(LWL,3)),2.00977);
         Bx := RAISE((LWL/B - 2),1.40692);
         C17 := Ax * Bx;
      END; {C17}

      {M3    Fn > 0.55}
      M3 := -7.2035 * RAISE((B/LWL),0.326869) * RAISE((T/B),0.605375);

      BEGIN   {Lamda }
```

```pascal
            IF (LWL/B) < 12 THEN
                        Lamda := 1.446 * Cp - 0.03 * LWL / B
                    ELSE
                        Lamda := 1.446 * Cp - 0.36;
        END; {Lamda}

        BEGIN {C15 Fn > 0.55}
                Cx := RAISE(LWL,3) / VDisp;
                IF Cx < 512     THEN GOTO 1;
                IF Cx > 1726.91 THEN GOTO 2;
                C15 := - 1.69385 + (LWL/(RAISE(VDisp,(1/3)))) - 8 ) / 2.36;
                GOTO 3;
            1: C15 := -1.69385;
                GOTO 3;
            2: C15 := 0;
        3: END; {C15}

        BEGIN {C16  Fn < 0.4}
          IF Cp < 0.8 THEN
            C16 := 8.07981*Cp - 13.8673*SQR(Cp) + 6.984388*RAISE(Cp,3)
                      ELSE
            C16 := 1.73014 - 0.7067 * Cp;
        END; {C16}

        BEGIN {M1  Fn < 0.4}
          Ax := (0.0140407 * LWL / T) - (1.75254 * RAISE(VDisp,(1/3)) /LWL);
          Bx := -(4.79323 * B / LWL) - C16;
          M1 :=  Ax + Bx;
        END; {M1}

        BEGIN { C7  Fn < 0.4}
            Ax := B/LWL;
            IF Ax > 0.25 THEN GOTO 4;
            IF Ax < 0.11 THEN GOTO 5;
            C7 := Ax;
            GOTO 6;
         4: C7 := 0.5 - 0.0625 * LWL / B;
            GOTO 6;
         5: C7 := 0.229577 * RAISE((B/LWL),0.33333);
         6: END; {C7}


        BEGIN { C2 }
          Ax := 0.56 * RAISE(Abt,1.5);
          Bx := B * T * (0.31*SQRT(Abt) + Tf - Hb);
          C3 := Ax / Bx;

          C2 := EXP(-1.89 * SQRT(C3));
        END;  {C2}

        BEGIN { C1  Fn < 0.4}
          Ax := 2223105 * RAISE(C7,3.78613) * RAISE((T/B),1.07961);
          Bx := RAISE((90 - Ie),-1.37565);
          C1 := Ax * Bx;
        END; {C1}


{Significant Wave Height as a function of Sea State}
    Hs  := SState[SS];

{Energy averaged wave period as function of sig. wave height}
    IF SS = 0 THEN Ts := 0 ELSE
    Ts  := 6.17 + 5* SQRT(Hs/g);

{Wind speed as a function of significant wave height}
    Vwind := 5.53*Hs -0.093*SQR(Hs);

END; {Procedure Constant}

{-----------------Determine Hull Form Factor 1+K1 (Form1----------}
PROCEDURE Factor;
 VAR
   C14, Ax, Bx, Cx              :REAL;
 BEGIN
    C14    := 1 + 0.011 * CStern;
    Lr     := LWL * (1-Cp+((0.06*Cp*LCB)/(4*Cp-1)));
    Ax     := 0.487118*C14*(RAISE((B/LWL),1.06806))*(RAISE((T/LWL),0.46106));
```

```pascal
        Bx    := RAISE((LWL/Lr),0.121563)*RAISE((RAISE(LWL,3)/VDisp),0.36486);
        Cx    := RAISE((1-Cp),-0.604247);
        Form1 := 0.93 + (Ax*Bx*Cx);
END; {Procedure Factor}


{---------------Determine wetted surface area of hull--------------}
PROCEDURE WSA;
  VAR
    Ax, Bx              :REAL;
  BEGIN
      Ax:= LWL * (2*T + B) * SQRT(Cm);
      Bx:= (0.453 + 0.4425*Cb - 0.2862*Cm - 0.003476 * B/T + 0.3696*Cwp);
      S := Ax * Bx + (2.38 * Abt/Cb);
END; {Procedure WSA}


{---------------Determine half angle of entrance in degrees--------}
PROCEDURE Entrance;
  VAR
    Ax, Bx, Cx          :REAL;
  BEGIN
      Ax := RAISE((LWL/B),0.80856) * RAISE((1-Cwp),0.30484);
      Bx := RAISE((1-Cp-0.0225*LCB),0.6367) * RAISE((Lr/B),0.34574);
      Cx := RAISE((100*VDisp/RAISE(LWL,3)),0.16302);
      Ie := 1 + 89*EXP(-Ax * Bx * Cx);
END; {Procedure Enrance}


{-----------------Calculate Appendage Resistance-------------------}
PROCEDURE Appendage;
  VAR
    SForm2          :REAL;
  BEGIN
      TSApp  :=0; SForm2 :=0;   {Initialise variables}
      FOR I := 1 TO 9 DO
        BEGIN
            TSApp := SApp[I] + TSApp;
            SForm2 := (SApp[I] * Form2[I]) + SForm2;
        END;
      IF TSApp <> 0 THEN TForm2 := SForm2/TSApp ELSE TForm2 := 0;
END;


{-------Calculate Correlation Coefficient and Hull Rougness--------}
PROCEDURE Correl_Coeff;
LABEL 1;
  VAR
    Ax, Bx, C4    : REAL;
  BEGIN

    IF Ca = 9999 THEN
      BEGIN
        IF (Tf/LWL) <= 0.04 THEN C4 := (TF/LWL) ELSE C4 := 0.04;
        Ax := 0.006*RAISE((LWL+100),-0.16) - 0.00205 ;
        Bx := (0.003 * SQRT(LWL/7.5) * RAISE (Cb,4) * C2*(0.04 - C4));
        Ca := Ax + Bx;
      END;


    IF ks <> 0 THEN
      DeltaCa := (0.105 * RAISE((ks*1e-6),(1/3)) - 0.005579)/RAISE(LWL,(1/3))
      ELSE DeltaCa :=0;
    Ca := Ca + DeltaCa;
END;  {Procedure Correl_Coeff}


{--------------Resistance due to friction and Fouling-------------}
PROCEDURE Frict_Resist;  {Frictional Resistance}
BEGIN
      Rn := Vm * LWL / 1.18831E-6;           {15 deg C, nu = 1.18831E-6}
      Cf := 0.075 /SQR(LOG (Rn) -2 );        {1957 ITTC Line}
      Rf := Cf * 0.5 * Rho * S * SQR(Vm);
      RfAct:= Form1 * Rf;                     { RfAct = Rf(1+K1) }


{Frictional resistance due to fouling - Newton proposal modified}
      RfDirty := RfAct + (Rf * (90*Days)/(405+days)/100);

END;  {Frict_Resist}

{----------------------------------------------------------------}
PROCEDURE Appen_Resist;
```

```pascal
BEGIN
     Rbt:=0;
     IF N2 = 1 THEN Rbt := Rho * SQR(Vm) * (22/7) * SQR(Dbt) * Cbto;

     Rapp  := (0.5 * Rho * SQR(Vm) * TSApp * TForm2 * Cf) + Rbt;
END; {Appen_Resist}


{---------------------------------------------------------------------}
PROCEDURE  Bulb_Resist;  {Resistance due to bulbous bow}
 VAR
    FnI, Pb, Ax, Bx  :REAL;
BEGIN
    Fni := Vm / SQRT(9.81*(Tf-Hb-SQRT(ABT)/4) + 0.15*SQR(Vm));  {Fn based on   }
                                                                {bow immersion.}
    Pb  := 0.56*SQRT(Abt) / (Tf - 1.5*Hb);          { Measure of bow emergence.}

    {Resistance due to bulb}
    Ax := 0.11 * EXP(-3 * RAISE(Pb,-2)) * RAISE(Fni,3) * RAISE(Abt,1.5) ;
    Bx := 1 + SQR(Fni);
    Rb := Ax * Rho * 9.81/ Bx;
END; {Bulb_Resist}


{---------------------------------------------------------------------}
PROCEDURE Trans_Resist;  {Resistance due to transom}
 VAR
    Fnt, C6      :REAL ;
 BEGIN
   IF At = 0 THEN Rtr := 0 ELSE
     BEGIN
        Fnt := Vm / SQRT(2 * 9.81 * At/(B + B*Cwp));  {Fn based on transom }
                                                      {        immersion.}
        IF Fnt >= 5 THEN C6 := 0  ELSE C6 := 0.2 * (1 - 0.2*Fnt);
        Rtr := 0.5 * Rho * SQR(Vm) * At * C6;   {Transom resistance}
     END;
END; {Trans_Resist}


{---------------------------------------------------------------------}
PROCEDURE Correlat_Resist;
BEGIN
   Ra := (0.5 * Rho * S * (Ca) * SQR(Vm));
END; {Correlat_Resist}


{---------------------------------------------------------------------}
PROCEDURE Wave3_Resist;
VAR
   M4, Ax, Bx     :REAL;

BEGIN
   M4 := (C15 * 0.4) * EXP(-0.034 * RAISE(Fn,-(3.29)));

   Ax   := C17 * C2 * C5 * VDisp * Rho * 9.81;
   Bx   := M3 * RAISE(Fn,-0.9)  + M4 * COS(Lamda * RAISE(Fn,-2));
   Rw_c := EXP(Bx) * Ax;
END; {Wave3_Resist}


{---------------------------------------------------------------------}
PROCEDURE Wave1_Resist;    {For Fn < 0.4 }
VAR
   {M4          :EXTENDED;  ---Only use if coprocessor fitted}
    Ax, Bx, M4    :REAL;

BEGIN
   M4 := C15 * 0.4 * EXP(-0.034 * RAISE(Fn,-3.29));

   Ax  := C1 * C2 * C5 * VDisp * Rho * 9.81;
   Bx  := M1 * RAISE(Fn,-0.9)  + M4 * COS(Lamda * RAISE(Fn,-2));
   Rw_a:= EXP(Bx) * Ax;
END; {Wave1_Resist}


{---------------------------------------------------------------------}
PROCEDURE Wave2_Resist;
BEGIN
    Rw_b := Rw_a + (10 * Fn - 4)*(Rw_c - Rw_a) / 1.5;
END; {Wave2_Resist}

{--------------Estimate Wind Resistance using Taylor's Formula-------}
PROCEDURE WindCalc;
```

```
BEGIN
   Rwind := (0.208 * 0.5 * SQR(B) * SQR(Vwind+V)/1000);
END;


{------Intermediate Wave Frequencies for use with Sea State Calc------}
PROCEDURE Frequent;
VAR
NN                    :INTEGER;
wMin, wMax            :REAL;
WInc                  :ARRAY [1..25] OF REAL;

BEGIN
   wMin    := 0.2 + (SQR(0.2) * V * 0.51444 / g);
   wMax    := 2   + (SQR(2)   * V * 0.51444 / g);
   wD      := (wMax - wMin) / 24;
   WW[1 ] := 0.2000;
   WW[25] := 2.0000;
   WInc[1] := wMin;
   WInc[25]:= wMax;
   FOR NN  := 2 to 24 DO
   BEGIN
      Winc[NN] := WInc[NN-1] + wD;
      WW[NN]   := (-1+SQRT(1+4*V*0.51444/g * WInc[NN]))/(2*V*0.5144/g);
   END;
END;


{---------------Perform Added Resistance Calculation---------------}
PROCEDURE SSTATE_CALC;
VAR
  S_State : REAL;
  RCoef   : ARRAY [1..25] OF REAL;
  KK      : INTEGER;
BEGIN
   Spectrum :=0;
   FOR KK := 1 to 25 DO
   BEGIN
     Rcoef[KK]:= RAW(WW[KK],Lpp,0.25,Fn,Cm, CBow) ;
     S_State  := SEAST(Hs,Ts,WW[KK]);
     X1       := S_State /(1 + 2 * (V*0.51444) * WW[KK]/g);
     Spectrum        := Spectrum + X1*RCoef[KK];
   END;
   Spectrum :=   (Spectrum * (95.3286 * g * B * B/Lpp) * WD)/1000;
END;


{-------------------------------------------------------------------}
PROCEDURE BAreaRat(Thrust:REAL; VAR BAR :REAL);
VAR
   Kx, Thrust1    :REAL;
BEGIN
  {Clean}
  IF N > 1 THEN Kx:=0.0 ELSE Kx:= 0.2;
  IF N > 1 THEN Thrust1:=(Thrust/2) ELSE Thrust1:=Thrust;
  {Blade Area Ratio :- Keller formula}
  BAR:=Kx+(1.3+0.3*Z)*Thrust1/(SQR(D)*(99.047+(Rho*9.81*(Ta-CProp-(D/2)))));

{Default minimum and maximum BAR's to comply with range of polynomials}
  IF Z = 2 THEN
  Begin
    IF BAR < 0.30 THEN BAR := 0.30;
    IF BAR > 0.38 THEN BAR := 0.38;
  End;

  IF Z = 3 THEN
  Begin
    IF BAR < 0.35 THEN BAR := 0.35;
    IF BAR > 0.80 THEN BAR := 0.80;
  End;

  IF Z = 4 THEN
  Begin
    IF BAR < 0.40 THEN BAR := 0.40;
    IF BAR > 1.00 THEN BAR := 1.00;
  End;

  IF Z = 5 THEN
  Begin
    IF BAR < 0.45 THEN BAR := 0.45;
    IF BAR > 1.05 THEN BAR := 1.05;
```

```
    End;

    IF Z = 6 THEN
    Begin
      IF BAR < 0.50 THEN BAR := 0.50;
      IF BAR > 0.80 THEN BAR := 0.80;
    End;

END;

{---------------------------------------------------------------------------}
PROCEDURE Sing_Prop; {Determine propulsion coefficients for single screw ship}
VAR
    Ax, Bx, C8, C9, C11, C19, C20, Cp1, Cv         :REAL;

  BEGIN
  {Determine wake fraction}
      IF (B/Ta) < 5 THEN C8 :=(B*S / (LWL*D*Ta))
                ELSE  C8 :=S *( 7*B/Ta -25)/(LWL*D*(B/Ta-3));
      IF C8 < 28    THEN C9 := C8
                ELSE  C9 :=32-(16/(C8-24));
      IF (Ta/D) < 2 THEN C11:=(Ta/D)
                ELSE  C11:=0.0833333*RAISE((Ta/D),3)+1.333333;
      IF Cp < 0.7   THEN C19:=0.12997/(0.95-Cb)-0.11056/(0.95-Cp)
                ELSE  C19:=0.18567/(1.3571-Cm)-0.71276+0.38648*Cp;
      C20:= 1 + 0.015*CStern;
      Cp1:= 1.45*Cp-0.315-0.0225*LCB;
      Cv := Form1*Cf + Ca;

      w := C9*C20*Cv*(LWL/Ta)*(0.050776+0.93405*C11*Cv/(1-Cp1))
           + 0.27915*C20 * SQRT(B/(LWL*(1-Cp1))) + C19 * C20;

  {Determine thrust deduction factor}
      Ax := 0.25014*RAISE((B/LWL),0.28956)*RAISE((SQRT(B*T)/D),0.2624);
      Bx := RAISE((1-Cp+0.0225*LCB),0.01762);

      tdf := Ax / Bx + 0.0015*CStern;

  {Determine Hull efficiency}
      nh := (1 - tdf) / ( 1- w);

  {Determine Thrust}
      Thrustc:=Rt/(1-tdf);
      Thrustd:=Rtdirty/(1-tdf);

  {Determine Blade Area ratio (BAR)}
      BAreaRAT(Thrustc, BARc);    {Thrust in clean condition (BARc)}
      BAreaRAT(Thrustd, BARd);    {Thrust in dirty condition (BARd)}
  END;

{---------------------------------------------------------------------------}

PROCEDURE Twin_Prop; {Determine propulsion coefficients for twin screw ship}
VAR
    Cv :REAL;
BEGIN
    Cv:=Form1*Cf + Ca;

{Determine wake fraction}
    w := 0.3095*Cb + 10*Cv*Cb-0.23*D/SQRT(B*T);

{Determine thrust deduction factor}
    tdf:=0.325*Cb- 0.1885*D/SQRT(B*T);

{Determine Thrust}
    Thrustc:=Rt/(1-tdf);
    Thrustd:=Rtdirty/(1-tdf);

{Determine Hull efficiency}
    nh := (1 - tdf) / ( 1- w);

{Determine Blade Area ratio (BAR)}
    BAreaRAT(Thrustc, BARc);    {Thrust in clean condition (BARc)}
    BAreaRAT(Thrustd, BARd);    {Thrust in dirty condition (BARd)}

END;

{---------------------------------------------------------------------------}
```

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```
PROCEDURE File1; {Write data to output file}
 BEGIN
 ASSIGN(FileVar,FileOut);
 REWRITE(FileVar);
   WriteLn (FileVar,'---------------------------------------------------------------------
-');
                         Writeln      (FileVar,Day,'/',        Month,'/',        Year,'
,
   ,Hour,':',Min:2,':',Sec:2);
   Writeln (FileVar,'          PRELIMINARY RESISTANCE/POWER PREDICTION              ');
     Writeln  (FileVar,'                                  List  of  Input/Estimated  Data
');
   Writeln (FileVar,'By R.Moody                                          ',Version);
   WriteLn (FileVar,'---------------------------------------------------------------------
-');
   Writeln (FileVar);
   Writeln (FileVar);
   Writeln (FileVar,' Ship Name:  ',Name);
   Writeln (FileVar);
   Writeln (FileVar,' Length on Waterline [LWL]           ', LWL:10:3,' m');
   Writeln (FileVar,' Length between Perpendiculars [Lpp]  ', Lpp:10:3,' m');
   Writeln (FileVar,' Beam [B]                            ',  B:10:3,' m');
   Writeln (FileVar,' Draught forward [Tf]                ', Tf:10:3,' m');
   Writeln (FileVar,' Draught aft [Ta]                    ', Ta:10:3,' m');
   Writeln (FileVar);
   Writeln (FileVar,' Displacement volume                 ',VDisp:10:3,' m^3');
   Writeln (FileVar,' Displacement mass                   ', Mass:10:3,' tonne');
   Writeln (FileVar);
   Writeln (fileVar,' Block Coefficient on LWL [Cb]        ',  Cb:10:3);
   Writeln (FileVar,' Prismatic Coefficient on LWL [Cp]    ',  Cp:10:3);
   Writeln (FileVar,' Midship Coefficient [Cm]             ',  Cm:10:3);
   Writeln (FileVar,' Waterplane Coefficient [Cw]          ', (Cb/Cwp):10:3);
   Writeln (FileVar,' Prismatic Waterplane Coefficient [Cwp]  ',  Cwp:10:3);
   Writeln (FileVar);
   Writeln (FileVar,' Centre of Buoyancy [Lcb] (relative to 0.5 Lpp) ', Lcb:5:3,' %');
   Writeln (FileVar);
   Writeln (FileVar,' Half angle of entrance [Ie]          ',  Ie:10:3,' degrees');
   Writeln (FileVar);
   Writeln (FileVar,' Wetted Surface Area [S]              ',  S:10:3,' m^2');
   IF ks <> 0 THEN
   Writeln (FileVar,' Hull roughness                      ',  ks:10:3,' microns')
   ELSE
   Writeln (FileVar,' Hull Roughness                       150.000 micron');
   Writeln (FileVar,' Days out of Dock                    ',  Days:10:3,' days');
   Writeln (FileVar);
   Writeln (FileVar,' Transom immersed area [At]          ',  At:10:3,' m^2');
   Writeln (FileVar,' After body shape factor [CStern]    ',CStern:10:3);
   Writeln (FileVar);
   Writeln (FileVar,' Number of propellers [N]            ',  N:6);
   Writeln (FileVar,' Propeller Diameter [D]              ',  D:10:3,' m');
   Writeln (fileVar,' Number of blades [Z]                ',  Z:6);
   WriteLn (FileVar,' Blade Area Ratio [BAR]          -   ',  BAR:10:3);
   Writeln (fileVar,' Pitch Diameter Ratio                ',PDRat:10:3);
   Writeln (fileVar,' Clearance between propeller and Keel  ',CProp:10:3,' m');
   WriteLn (FileVar);
   Writeln (fileVar,' Mechanical Efficiency [Ns]           ',(Ns*100):10:3,' %');
   IF N1 = 1 THEN
   BEGIN
     Writeln (FileVar);
     Writeln (FileVar,' Transverse bulb area  [Abt]         ', Abt:10:3,' m^2');
     Writeln (FileVar,' Height of bulb from keel line [Hb]  ', Hb:10:3,' m');
   END;
   IF N2 = 1 THEN
   BEGIN
     Writeln (FileVar);
     Writeln (FileVar,' Thruster tunnel diameter [Dbt]      ', Dbt:10:3,' m');
     Writeln (FileVar,' Thruster opening coefficient [Cbto]  ', Cbto:10:3);
   END;
   Writeln (FileVar);
   Writeln (FileVar,' Appendage              (1+k2)              SApp');
   Writeln (FileVar,' Rudder         ',Form2[1]:12:3, SApp[1]:22:3);
   Writeln (FileVar,' Shafts         ',Form2[2]:12:3, SApp[2]:22:3);
   Writeln (FileVar,' Shaft Brackets ',Form2[3]:12:3, SApp[3]:22:3);
   Writeln (FileVar,' Stabilizer Fins ',Form2[4]:12:3, SApp[4]:22:3);
   Writeln (FileVar,' Bilge Keels    ',Form2[5]:12:3, SApp[5]:22:3);
   Writeln (FileVar,' Skeg           ',Form2[6]:12:3, SApp[6]:22:3);
   Writeln (FileVar,' Strut Bossings ',Form2[7]:12:3, SApp[7]:22:3);
   Writeln (FileVar,' Hull Bossings  ',Form2[8]:12:3, SApp[8]:22:3);
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```pascal
      Writeln (FileVar,' Sonar Dome           ',Form2[9]:12:3, SApp[9]:22:3);
      Writeln (FileVar);
      Writeln (FileVar,' (1+k2)equivalent    ',TForm2:12:3,'    Total Sapp ',TSapp:7:3,' m^2');
      Writeln (FileVar);
      Writeln (FileVar);
      Writeln (FileVar,' Sea State                                    ', SS:6);
      IF SS <> 0 THEN
      BEGIN
      Writeln (FileVar,' Estimated Wave Height [Hs]                   ', Hs:10:3,' m');
      Writeln (FileVar,' Estimated energy averaged wave period [Ts]', Ts:10:3,' sec');
      Writeln (FileVar,' Estimated wind speed [Vwind]                 ', Vwind:10:3,' knots');
      END;
      Writeln (FileVar);
      WriteLn (FileVar,'------------------------------------------------------------------------');
CLOSE(FileVar);
END;


{------------------------------------------------------------------------}
PROCEDURE Calc; {Calculate Resistance data and write to temporary file}
  LABEL
     1, 2, 3;
  BEGIN
    ASSIGN (FILEVAR,'HM1.TMP');
    REWRITE (FileVar);
    FOR I := 1 TO NI DO
      BEGIN;
        V := V + VInc;
        Vm:= V * 0.51477;                    {Speed in m/sec}
        SLRat:= V/SQRT(LWL/(0.0254*12));     {Taylor speed/length ratio}
        Fn:= Vm/SQRT(9.81 * LWL);           {Froude Number}

        Frict_Resist;                        {Rf  }
        Appen_Resist;                        {Rapp}
        IF N1 = 1 THEN bulb_Resist;          {Rb  }
        Trans_Resist;                        {Rtr }
        Correlat_Resist;                     {Ra  }
        Frequent;
        SState_Calc;
        WindCalc;                            {RWind}


        BEGIN;                               {Rw  }
          IF Fn < 0.4 THEN GOTO 1;
          IF Fn > 0.55 THEN GOTO 2;
          BEGIN
            Fn1 := Fn;                {Set Froude Number to 0.4}
            Fn := 0.4;
            Wave1_Resist;
            Fn := 0.55;               {Set Froude Number to 0.55}
            Wave3_Resist;
            Fn := Fn1;
            Wave2_Resist;             {Interpolation between Fn 0.4 and 0.55}
            Rw := Rw_b;
            GOTO 3;
          END;
        1: Wave1_Resist;
          Rw := Rw_a;
          GOTO 3;

        2: Wave3_Resist;
          Rw := Rw_c;

      3: END; {Rw}

        Rt := RfAct + Rw + Rapp + Rb + Rtr + Ra + Spectrum + Rwind; {Total Resistance}
        RtDirty := Rt - RfAct + RfDirty;    {Dirty condition - out of dock}
        Pe := Rt * Vm;                      {Effective Power }
        PeDirty :=RtDirty * Vm;
        Cr := (Rtr + Rb + Rw + Rapp)/(Rho/2 * S * SQR(Vm));

        IF N > 1  THEN Twin_prop ELSE Sing_Prop;

        Writeln(FileVar,V:11:3,Vm:11:3,Fn:11:3,SLRat:15:3,Cf:15:7,Cr:15:7);
        Writeln(FileVar,Rf:11:3,RfAct:11:3,Rapp:15:3,Rw:15:3,Rb:15:3,
                Rtr:15:3,Ra:15:3, Rwind:15:3, Spectrum:15:3);
        Writeln(FileVar,Rt:11:3,Pe:18:3,w:11:3,tdf:11:4,nh:8:4,BARc:8:4,
                Thrustc:11:3);
        Writeln(FileVar,RtDirty:11:3,PeDirty:15:3,BARd:8:4,Thrustd:11:3);
```

```
      END;
        Close (FileVar);
    END; {Procedure Calc}

{----------------------------------------------------------------------}

    PROCEDURE DESIGN; {Calculate Resistance data at design speed and write
                        to temporary file}
    LABEL
      1, 2, 3;
    BEGIN
      ASSIGN (FILEVAR,'HM1.TMP');
      APPEND (FileVar);
          V := VDes;
          Vm:= V * 0.51477;                 {Speed in m/sec}
          SLRat:= V/SQRT(LWL/(0.0254*12));   {Taylor speed/length ratio}
          Fn:= Vm/SQRT(9.81 * LWL);         {Froude Number}

          Frict_Resist;                     {Rf  }
          Appen_Resist;                     {Rapp}
          IF N1 = 1 THEN bulb_Resist;       {Rb  }
          Trans_Resist;                     {Rtr }
          CorreTat_Resist;                  {Ra  }

          FREQUENT;

          SState_Calc;

          BEGIN;                            {Rw  }
            IF Fn < 0.4 THEN GOTO 1;
            IF Fn > 0.55 THEN GOTO 2;
            BEGIN
              Fn1 := Fn;                {Set Froude Number to 0.4}
              Fn := 0.4;
              Wave1_Resist;
              Fn := 0.55;               {Set Froude Number to 0.55}
              Wave3_Resist;
              Fn := Fn1;
              Wave2_Resist;             {Interpolation between Fn 0.4 and 0.55}
              Rw := Rw_b;
              GOTO 3;
            END;
          1: Wave1_Resist;
             Rw := Rw_a;
             GOTO 3;

          2: Wave3_Resist;
             Rw := Rw_c;

        3: END; {Rw}

          Rt := RfAct + Rw + Rapp + Rb + Rtr + Ra + Spectrum + Rwind; {Total Resistance}
          RtDirty := Rt - RfAct + RfDirty;      {x months out of dock}
          Pe := Rt * Vm;                        {Effective Power }
          PeDirty :=RtDirty * Vm;
          Cr := (Rtr + Rb + Rw + Rapp)/(Rho/2 * S * SQR(Vm));

          IF N > 1  THEN Twin_prop ELSE Sing_Prop;

          Writeln(FileVar,V:11:3,Vm:11:3,Fn:11:3,SLRat:15:3,Cf:15:7,Cr:15:7);
          Writeln(FileVar,Rf:11:3,RfAct:11:3,Rapp:15:3,Rw:15:3,Rb:15:3,
                  Rtr:15:3,Ra:15:3, Rwind:15:3, Spectrum:15:3);
          Writeln(FileVar,Rt:11:3,Pe:18:3,w:11:3,tdf:11:4,nh:8:4,BARc:8:4,
                  Thrustc:11:3);
          Writeln(FileVar,RtDirty:11:3,PeDirty:15:3,BARd:8:4,Thrustd:11:3);

        Close (FileVar);
    END; {Procedure Design }

{----------------------------------------------------------------------}

PROCEDURE File2; {Write page 2 of data to output  file}
VAR
     V      : ARRAY[1..11] of REAL;      BARc   : ARRAY[1..11] of REAL;
     Vm     : ARRAY[1..11] of REAL;      BARd   : ARRAY[1..11] of REAL;
     SLRat  : ARRAY[1..11] of REAL;      Fn     : ARRAY[1..11] OF REAL;
```

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```
      Cf     : ARRAY[1..11] of REAL;      Noptc  : ARRAY[1..11] OF REAL;
      Cr     : ARRAY[1..11] of REAL;      PDc    : ARRAY[1..11] OF REAL;
      Rf     : ARRAY[1..11] of REAL;      RPMc   : ARRAY[1..11] OF REAL;
      RfAct  : ARRAY[1..11] of REAL;      Ktc    : ARRAY[1..11] OF REAL;
      Rapp   : ARRAY[1..11] of REAL;      Kqc    : ARRAY[1..11] OF REAL;
      Rw     : ARRAY[1..11] of REAL;      Jc     : ARRAY[1..11] OF REAL;
      Rb     : ARRAY[1..11] of REAL;      nr1c   : ARRAY[1..11] OF REAL;
      Rtr    : ARRAY[1..11] of REAL;      nh1    : ARRAY[1..11] OF REAL;
      Ra     : ARRAY[1..11] of REAL;      QPCc   : ARRAY[1..11] OF REAL;
      Rt     : ARRAY[1..11] of REAL;      PCc    : ARRAY[1..11] OF REAL;
      RtDirty: ARRAY[1..11] of REAL;      Pb     : ARRAY[1..11] OF REAL;
      Pe     : ARRAY[1..11] of REAL;      Noptd  : ARRAY[1..11] OF REAL;
      PeDirty: ARRAY[1..11] of REAL;      PDd    : ARRAY[1..11] OF REAL;
      Thrustc: ARRAY[1..11] of REAL;      RPMd   : ARRAY[1..11] OF REAL;
      Thrustd: ARRAY[1..11] of REAL;      Ktd    : ARRAY[1..11] OF REAL;
      W      : ARRAY[1..11] of REAL;      Kqd    : ARRAY[1..11] OF REAL;
      Tdf    : ARRAY[1..11] of REAL;      Jd     : ARRAY[1..11] OF REAL;
      Nh     : ARRAY[1..11] of REAL;      nr1d   : ARRAY[1..11] OF REAL;
      Nr_p   : ARRAY[1..11] of REAL;      QPCd   : ARRAY[1..11] OF REAL;
      PCd    : ARRAY[1..11] OF REAL;      Rwind  : ARRAY[1..11] OF REAL;
      PbDirty: ARRAY[1..11] OF REAL;      Rwave  : ARRAY[1..11] OF REAL;


BEGIN
    ASSIGN(FileVar,'HM1.TMP');
    RESET(FileVar);
     FOR I:= 1 TO NI+1 DO
       BEGIN
          Readln(FileVar,V[I],Vm[I],Fn[I],SLRat[I],Cf[I],Cr[I]);
          Readln(FileVar,Rf[I],RfAct[I],Rapp[I],Rw[I],Rb[I],Rtr[I],Ra[I],Rwind[I],Rwave[I]);
          Readln(FileVar,Rt[I],Pe[I],W[I],Tdf[I],Nh[I],BARc[I],Thrustc[I]);
          Readln(FileVar, RtDirty[I],PeDirty[I],BARd[I],Thrustd[I]);
       END;
    CLOSE(FileVar);

{---Write design speed data to temporary file HM3.TMP----------------}
    ASSIGN(FileVar,'HM3.TMP');
    REWRITE(FileVar);
    Writeln(FileVar,V[NI+1],Vm[NI+1],Fn[NI+1],SLRat[NI+1],Cf[NI+1],Cr[NI+1]);

Writeln(FileVar,Rf[NI+1],RfAct[NI+1],Rapp[NI+1],Rw[NI+1],Rb[NI+1],Rtr[NI+1],Ra[NI+1],Rwind[NI
+1],Rwave[NI+1]);
    Writeln(FileVar,Rt[NI+1],Pe[NI+1],W[NI+1],Tdf[NI+1],Nh[NI+1],BARc[NI+1],Thrustc[NI+1]);
    WriteLn(FileVar, RtDirty[NI+1],PeDirty[NI+1],BARd[NI+1],Thrustd[NI+1]);
    CLOSE(FileVar);

{----------------------------------------------------------------------}

    ASSIGN(FileVar,FileOut);
    APPEND(FileVar);
     Writeln (FileVar,CHR(12));
     WriteLn (FileVar,'-------------------------------------------------------------
----');
                                      Writeln    (FileVar,Day,'/',    Month,'/',    Year,'
'
      ,Hour,':',Min:2,':',Sec:2);
     Writeln (FileVar,'          PRELIMINARY RESISTANCE/POWER PREDICTION');
     Writeln (FileVar,'             Resistance and Effective Power');
                                      Writeln      (FileVar,'By         R.Moody
',Version);
     WriteLn (FileVar,'-------------------------------------------------------------
----');
     Writeln (FileVar);
     Writeln (FileVar,'Ship Name:   ',Name);
     Writeln (FileVar);
     Writeln (FileVar,'Resistance Coefficients');
     Writeln (FileVar);
     Writeln(FileVar,' v (Knots)  v (m/s)   Fn    v/L^2      Cf         Cr         Ca');
     FOR I := 1 TO NI DO
        BEGIN;

Writeln(FileVar,V[I]:7:2,Vm[I]:10:3,Fn[I]:8:3,SLRat[I]:8:3,Cf[I]:12:6,Cr[I]:12:6,Ca:12:6);
     END;
     Writeln(FileVar);
     Writeln(FileVar);
     Writeln(FileVar,'Resistance Components (kN)');
     Writeln(FileVar);
```

```
        Writeln(FileVar,' V (Knots)    Rf        Rf(1+k1)    Rapp       Rw         Rb         Rtr
Ra');
      FOR I := 1 to NI DO
        BEGIN;

Writeln(filevar,V[I]:7:2,Rf[I]:10:3,RfAct[I]:10:3,Rapp[I]:9:3,Rw[I]:9:3,Rb[I]:9:3,Rtr[I]:9:3,
Ra[I]:9:3);
      END;
        Writeln(FileVar);
        Writeln(FileVar);
        Writeln(FileVar,'Resistance(kN) and Effective Power (kW)');
        Writeln(FileVar);
        Writeln(FileVar,' V (Knots)  Rwind       Rwave         Rt        Pe       Rt Dirty    Pe
Dirty ');
      FOR I := 1 to NI DO
      BEGIN;

Writeln(filevar,V[I]:7:2,Rwind[I]:10:3,Rwave[I]:10:3,Rt[I]:10:2,Pe[I]:12:2,RtDirty[I]:10:2,Pe
Dirty[I]:13:2);
      END;
        Writeln(FileVar);
        Writeln(FileVar);
        Writeln(FileVar,'Propulsion data');
        Writeln(FileVar);
        BEGIN
          Writeln(FileVar,'V (Knots)  w         tdf        nh        Thrust(kN)  Min       Thrust(kN)
Min');
          Writeln(FileVar,'                                                     Clean   BAR       Dirty   BAR
');
        FOR I := 1 to NI DO

Writeln(filevar,V[I]:7:2,w[I]:8:3,tdf[I]:8:3,nh[I]:8:3,Thrustc[I]:12:3,BARc[I]:8:3,Thrustd[I]
:12:3,BARd[I]:8:3);
      END;
        WriteLn (FileVar);
        WriteLn (FileVar,' NOTE: Min BAR gives an indication of value to avoid cavitation.');
        WriteLn (FileVar,'       Actual BAR used in calculations is ',BAR:3:3);
        WriteLn (FileVar,'-------------------------------------------------------------------
—');

      CLOSE(FileVar);
END; {File2}


{--------------------------------------------------------------}

PROCEDURE SUMMARY;
VAR
  V_s,Vm_s,Fn_s,SLRat_s,Cf_s,Cr_s                           :REAL;
  Rf_s,RfAct_s,Rapp_s,Rw_s,Rb_s,Rtr_s,Ra_s,Rwind_s,Rwave_s  :REAL;
  Rt_s,Pe_s,W_s,Tdf_s,Nh_s,BARc_s,Thrustc_s                 :REAL;
  RtDirty_s,PeDirty_s,BARd_s,Thrustd_s                      :REAL;
  Jc_s, Ktc_s, Kqc_s, Effc_s, Revsc_s, QPCc_s, PCc_s, BPc_s :REAL;
  Jd_s, Ktd_s, Kqd_s, Effd_s, Revsd_s, QPCd_s, PCd_s, BPd_s :REAL;

BEGIN
    ASSIGN(FileVar,'HM3.TMP');
    RESET(FileVar);
        Readln(FileVar,V_s,Vm_s,Fn_s,SLRat_s,Cf_s,Cr_s);
        Readln(FileVar,Rf_s,RfAct_s,Rapp_s,Rw_s,Rb_s,Rtr_s,Ra_s,Rwind_s,Rwave_s);
        Readln(FileVar,Rt_s,Pe_s,W_s,Tdf_s,Nh_s,BARc_s,Thrustc_s);
        Readln(FileVar, RtDirty_s,PeDirty_s,BARd_s,Thrustd_s);
        ReadLn(FileVar, Jc_s, Ktc_s, Kqc_s, Effc_s, Revsc_s, QPCc_s, PCc_s, BPc_s);
        ReadLn(FileVar, Jd_s, Ktd_s, Kqd_s, Effd_s, Revsd_s, QPCd_s, PCd_s, BPd_s);
    Close(FileVar);

    ASSIGN(FileVar,FileOut);
    APPEND(FileVar);
      Writeln (FileVar,CHR(12));
      WriteLn (FileVar,'-------------------------------------------------------------------
------');
                                  Writeln    (FileVar,Day,'/',     Month,'/',     Year,'
                                          ,Hour,':',Min:2,':',Sec:2);
      Writeln (FileVar,'          PRELIMINARY RESISTANCE/POWER PREDICTION');
      Writeln (FileVar,'          Resistance and Effective Power at Design Speed');
                                      Writeln      (FileVar,'By        R.Moody
',Version);
```

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```
        WriteLn (FileVar,'-----------------------------------------------------------------
----');
        Writeln (FileVar);
        Writeln (FileVar,' Ship Name: ',Name);
        Writeln (FileVar);
        Writeln (FileVar,' Design Speed                                        [v] ',
V_s:9:2,' knots');
        Writeln (FileVar,'                                                         ',
Vm_s:10:3,' m/s');
        Writeln (FileVar);
        Writeln (FileVar,' Froude Number                                       [Fn] ',
Fn_s:10:3);
        Writeln (FileVar,' Taylor Speed Length Ratio                       [v/L^2] ',
SLRat_s:10:3);
        Writeln(FileVar);
        Writeln(FileVar, ' RESISTANCE COEFFICIENTS');
        Writeln (FileVar,' Frictional resistance coefficient                  [Cf] ',
Cf_s:13:6);
        Writeln (FileVar,' Residuary resistance coefficient                   [Cr] ',
Cr_s:13:6);
        Writeln (FileVar,' Model ship correlation coefficient                 [Ca] ',
Ca:13:6);
        Writeln(FileVar);
        Writeln(FileVar, ' HULL RESISTANCE COMPONENTS');
        Writeln (FileVar,' Friction resistance according to 1957 ITTC         [Rf] ',
Rf_s:10:3,' kN');
        Writeln (FileVar,' Friction resistance with form factor correction [Rf(1+k1)] ',
RfAct_s:10:3,' kN');
        Writeln (FileVar,' Resistance of appendages                         [Rapp] ',
Rapp_s:10:3,' kN');
        Writeln (FileVar,' Wave making and wave breaking resistance           [Rw] ',
Rw_s:10:3,' kN');
        Writeln (FileVar,' Pressure resistance of bulbous bow near water surface [Rb] ',
Rb_s:10:3,' kN');
        Writeln (FileVar,' Pressure resistance of immersed transom           [Rtr] ',
Rtr_s:10:3,' kN');
        Writeln (FileVar,' Model ship correlation resistance                  [Ra] ',
Ra_s:10:3,' kN');
        Writeln(FileVar);
        Writeln(FileVar, ' RESISTANCE COMPONENTS DUE TO ENVIRONMENTAL FACTORS');
        Writeln (FileVar,' Added resistance due to ',Vwind:5:1,' knot head wind      [Rwind]
', Rwind_s:10:3,' kN');
        Writeln (FileVar,' Added resistance due to ',Hs:5:2,'m waves ie Sea State ',SS:1,'
[Rwave] ', Rwave_s:10:3,' kN');
        Writeln(FileVar);
        Writeln (FileVar,' TOTAL RESISTANCE (Clean Hull)                      [Rt] ',
Rt_s:10:3,' kN');
        Writeln (FileVar,' Added resistance due to hull fouling ',Days:4:0,' days out of dock
', (RtDirty_s-Rt_s):10:3,' kN');
        Writeln (FileVar,' TOTAL RESISTANCE after ',Days:4:0,' days out of dock      [Rtdirty]
', Rtdirty_s:10:3,' kN');
        Writeln(FileVar);
        Writeln(FileVar);
        Writeln(FileVar, ' PROPULSION COEFFICIENTS');
        Writeln (FileVar,' Taylor wake fraction                                [w] ',
w_s:10:3);
        Writeln (FileVar,' Thrust deduction fraction                         [tdf] ',
tdf_s:10:3);
        Writeln (FileVar,' Hull efficiency                                    [nh] ',
nh_s:10:3);
        Writeln (FileVar,' Relative rotative efficiency                       [nr] ',
nr:10:3);
        Writeln (FileVar,' Shafting efficiency                                [ns] ',
(ns*100):10:3,' %');
        Writeln(FileVar);
        Writeln(FileVar, ' PROPULSION DATA FOR SHIP IN CLEAN CONDITION');
        Writeln (FileVar,' Thrust coefficient                                 [Kt] ',
Ktc_s:10:3);
        Writeln (FileVar,' Torque coefficient                                 [Kq] ',
Kqc_s:10:3);
        Writeln (FileVar,' Propeller advance coefficient                       [J] ',
Jc_s:10:3);
        Writeln (FileVar,' Propeller speed                                 [Speed] ',
Revsc_s:10:3,' rpm');
        Writeln (FileVar,' Open water efficiency                              [no] ',
(effc_s*100):10:3,' %');
        Writeln (FileVar,' Quasi-propulsion coefficient                      [QPC] ',
QPCc_s:10:3);
```

```pascal
        Writeln (FileVar,' Propulsion coefficient                              [PC]  ',
PCc_s: 10:3);
        Writeln (FileVar,' Thrust                                          [Thrust]  ',
Thrustc_s:10:3,' kN');
        Writeln (FileVar,' Effective Power                                      [Pe]  ',
Pe_s:10:3,' kW');
        Writeln (FileVar,' Brake Power                                          [Pb]  ',
Bpc_s:10:3,' kW');
        Writeln(FileVar);
        Writeln(FileVar, ' PROPULSION DATA FOR SHIP',Days:4:0,' DAYS OUT OF DOCK');
        Writeln (FileVar,' Thrust coefficient                                   [Kt]  ',
Ktc_s:10:3);
        Writeln (FileVar,' Torque coefficient                                   [Kq]  ',
Kqc_s:10:3);
        Writeln (FileVar,' Propeller advance coefficient                         [J]  ',
Jc_s:10:3);
        Writeln (FileVar,' Propeller speed                                   [Speed]  ',
Revsc_s:10:3,' rpm');
        Writeln (FileVar,' Open water efficiency                                [no]  ',
(effd_s*100):10:3,' %');
        Writeln (FileVar,' Quasi-propulsion coefficient                        [QPC]  ',
QPCd_s:10:3);
        Writeln (FileVar,' Propulsion coefficient                              [PC]  ',
PCd_s: 10:3);
        Writeln (FileVar,' Thrust                                          [Thrust]  ',
Thrustd_s:10:3,' kN');
        Writeln (FileVar,' Effective Power                                      [Pe]  ',
PeDirty_s:10:3,' kW');
        Writeln (FileVar,' Brake Power                                          [Pb]  ',
Bpd_s:10:3,' kW');
        Writeln(FileVar);
        WriteLn (FileVar,'---------------------------------------------------------------
-------');
      CLOSE(FileVar);

    END;
{----------------------------------------------------------------------------}

BEGIN  { Main Program}
  INTRO256(Pic_Name);
  Date;
  Box;
  WINDOW(2,4,78,23);
  Temp_Init;
  File_Names;
  VarAssign;
  Dat_Inp;
  Form_Coeff;
  Factor;
  IF  S = 0 THEN WSA;
  IF Ie = 0 THEN Entrance;
  Constant;
  Appendage;
  Correl_Coeff;
  Incr;
  File1;
  Calc;
  Design;
  File2;
  IF BPO = 'Y' THEN
    BEGIN
      BPower (Cp, lcb, BAR, PDRat, D, ns, NI, Z, N, FilePlot3,
                              FileOut, Name, Version);
    END;

  Summary;

  IF PFR  = 'Y' THEN Plot('1', NI, FilePlot1, Name);
  IF OBPP = 'Y' THEN Plot('2', NI, FilePlot2, Name);
  IF BPP  = 'Y' THEN Plot('3', NI, FilePlot3, Name);

  IF PSR  = 'Y' THEN Graphics('1',  NI, Name );
  IF OBPS = 'Y' THEN Graphics('2',  NI, Name);
  IF BPS  = 'Y' THEN Graphics('3',  NI, Name);

  Temp_Fin;
  ClrScr;
END.
```

```
{$F+}
UNIT SPLINET;
INTERFACE
VAR
  C                        :Array[1..15] of Real;
  X                        :Array[1..15] of Array[1..15] of Real;
  N, I, J                  :Integer;
  xx,xx1 :real;
     FileInp  : String[30];
     FileOut  : String[30];
     FileVar  : Text;


PROCEDURE COEFFICIENTS(VAR P,Q; N : Integer);

IMPLEMENTATION

{$I lib.inc}
PROCEDURE COEFFICIENTS(VAR P,Q; N : Integer);
TYPE
 Array1 = Array[1..15] of Real;
 Array2 = Array[1..15] of Real;

VAR
  X1 : Array1 Absolute P;
  Y  : Array2 Absolute Q;

{-----------------------CONVERT INITIAL 1 DIM ARRAY --------------}
Procedure Initialise;
BEGIN
        For I := 1 TO N DO
         BEGIN
         X[I,2] := X1[I];
         END;
END; {Procedure Initialise}

{-----------------------SET UP THEILHEIMER MATRIX----------------}
Procedure Set_Up;
BEGIN
   For I := 1 to N DO
      BEGIN
        X[I,1] := 1;
        X[I,3] := (X[I,2] * X[I,2]);
        X[I,4] := (X[I,2] * X[I,3]);
      END;
      FOR I:= 1 to N DO
       BEGIN
        FOR J := 5 to (N+1) DO
        BEGIN
          IF I <=(J-2) THEN  X[I,J] := 0
            ELSE
              BEGIN
                IF X[I,2] > X[(J-2),2]
                 THEN
                  X[I,J] :=RAISE((X[I,2]-X[(J-2),2]),3)
                 ELSE
                  X[I,J] := 0
              END
        END;
      END;
END;


{-------------SOLVE MATRIX USING GAUSS ELIMINATION--------------}

Procedure GAUSS;
VAR
  K, II, JJ, KK, LL, NN, PP         :Integer;
  Okay                              : Boolean;
  YY                                :Array[1..15] of Real;
  XX                                :Array[1..15,1..15] of Real;
LABEL
  1, 2;

{Create a working copy of the X matrix}
 BEGIN;
 FOR J := 1 TO  N DO
  BEGIN
```

```pascal
        FOR I:= 1 TO N DO
          BEGIN
            XX[I,J] := X[I,J]
          END;
      END;


    K := N-1;
      FOR II := 1 TO K DO
        BEGIN
        IF XX[II,II] <> 0.0 THEN GOTO 2;

{Carry out row swapping}
          FOR NN := (II+1) TO N DO
            Begin
              KK := NN;
              IF XX[NN,II] <> 0.0 THEN NN := N;
              IF NN > N THEN WriteLn('Singular matrix - No solution possible!')
            End;

          FOR PP := II TO N DO
            Begin
              YY[PP] := XX[KK,PP];
              XX[KK,PP] := XX[II,PP];
              XX[II,PP] := YY[PP];
            End;
            YY[N+1] := Y[KK];
            Y[KK] := Y[II];
            Y[II] := YY[N+1];

2:{Elimination Process}
            LL := II+1;
            For JJ := LL TO N DO
              BEGIN
              If XX[JJ,II] = 0 THEN GOTO 1;
              For KK := LL TO N DO
              BEGIN
                XX[JJ,KK] := XX[JJ,KK] - XX[II,KK] * XX[JJ,II]/XX[II,II];
              End;
              Y[JJ] := Y[JJ] - Y[II] * XX[JJ,II]/XX[II,II];
1:      End;
      End;

{Carry out back substitution}
      Y[N] := Y[N] / XX[N,N];

      FOR II:= 1 TO K DO
        Begin
          KK := N - II;
          LL := KK + 1;
              FOR JJ := LL TO N DO
                Begin
                  Y[KK]:= Y[KK] - Y[JJ] * XX[KK,JJ]
                End;
            Y[KK] := Y[KK]/XX[KK,KK]
        End;
End;

{------------------------MAIN PROGRAM----------------------}
BEGIN
 Initialise;
 Set_up;
 Gauss;
END;
END.
```

```
{$F+}
UNIT SCGRAPH;
INTERFACE

   USES Graph, Crt, GrDrivers, GrFonts;
Const
   FileName  = 'HM1.tmp';
   FileName1 = 'HM2.tmp';
VAR
   GraphDriver, GraphMode, OrigMode      : Integer;
   K, PxInc, IncK, NI_5, I               : Integer;
   xx, yy, xx1, yy1, S1, S2, Dummy       : Real;
   s1diff, s1inc, s2diff, s2inc, J, K1   : Real;
   FileVar                               : Text;
   x1, y1                  :Array [1..10] of integer;
   vt, Pxt                 :Array [1..10] of string[4];
   P                       :Boolean;
   Ch                      :Char;
   v,  Px, PxDirty         :Array [1..10] of real;

PROCEDURE GRAPHICS(A{, OPD}:Char;
                         NI:Integer;
                       Name:String);


IMPLEMENTATION

{-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --}
PROCEDURE GRAPHICS(A{, OPD} :Char;
                         NI :Integer;
                       Name:String);
{-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --}
   Procedure Initialise;
      BEGIN
         Graphdriver := Detect;
         InitGraph( GraphDriver, GraphMode, '');
         IF NOT (graphdriver in [ega,HercMono,vga,cga,att400,mcga,pc3270]) THEN
            BEGIN
               RestoreCrtmode;
               Writeln ('Error : Requires video graphics display');
               Halt
            END; {if}
         SetbkColor (blue);
         SetColor (white);
      END; {Procedure Initialise}

{-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --}
   PROCEDURE LABEL1;
   BEGIN
      MoveTo(X1[I],Y1[I]);
      SetUserCharSize(1,5,1,5);
      SetTextStyle(DefaultFont,HorizDir,UserCharSize);
      SetTextJustify(RightText,BottomText);
      {SetTextStyle(DefaultFont,VertDir,1);}
      IF A = '1' THEN OutText('Effective Power (Dirty)');
      IF A = '2' THEN OutText('Optimum Brake Power (Dirty)');
      IF A = '3' THEN OutText('Brake Power (Dirty)');
   END;  {PROCEDURE LABEL1}

{-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --}
   PROCEDURE LABEL2;
   BEGIN
      MoveTo(x1[I],y1[I]);
      SetUserCharSize(1,5,1,5);
      SetTextStyle(DefaultFont,HorizDir,UserCharSize);
      SetTextJustify(LeftText,TopText);
      {SetTextStyle(DefaultFont,VertDir,1);}
      IF A ='1' THEN OutText('Effective Power (Clean)');
      IF A ='2' THEN OutText('Optimum Brake Power (Clean)');
      IF A ='3' THEN OutText('Brake Power (Clean)');
   END;  {PROCEDURE LABEL2}

{-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --}
   PROCEDURE TICKS;
   BEGIN

   {Place ticks and V on the X axis}
      SetTextStyle(DefaultFont,HorizDir,1);
      FOR I:= 1 to NI DO
```

```pascal
        BEGIN
           line(x1[i],round(GetmaxY+1-yy1),x1[i],round(getmaxy+1-yy1+5));
           moveto(x1[i],round(GetmaxY+1-yy1+8));
           SetTextJustify(CenterText,TopText);
           OutText(vt[i]);
        END;

   {Place ticks on the Y axis}
      SetTextStyle(DefaultFont,VertDir,1);
      K:=0;
      FOR I :=1 TO NI DO
      BEGIN
         line(round(xx1),round(y1[1]-K),round(xx1-5),round(y1[1]-K));
         K:= K + round(S2Inc);
      END;

   {Px on every second tick of Y axis.}
      K:=0;   P:=false;
      FOR I :=1 TO NI DO
      BEGIN
         MoveTo(round(xx1-8),round(y1[1]-K));
         SetTextJustify(bottomText,centerText);
         IF P THEN OutText(Pxt[I]);
         IF P THEN P:= False ELSE P:=true;
         K:= K + round(S2Inc) ;
      END;
   END;


{-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --}
PROCEDURE SETUP;
    BEGIN
        xx:=(0.8*GetMaxX);   yy:=(0.8 * GetMaxY);
        xx1:=(0.1*GetMaxX);   yy1:=(0.1*GetMaxY);
        S1Diff:=v[NI]-v[1];
        S1 :=XX / S1Diff;
        S1Inc := XX / (NI-1);
        S2Diff :=PxDirty[NI]-Px[1];
        S2 := yy / S2Diff;
        S2Inc := yy / (NI-1);
        PxInc := Round(S2Diff/(NI-1));

        K1 := 0;
        For I := 1 to NI do
        BEGIN
           J := (Px[1] + (PxInc * K1))/1000;
           Str(v[i]:3:1,vt[i]);
           Str(J:0:1,Pxt[I]);
           K1 := K1 + 1;
        END;

        SetTextStyle(TriplexFont,Horizdir,2);
        MoveTo(150,20);
        IF A = '1' THEN OutText('      Predicted Effective Power');
        IF A = '2' THEN OutText('    Predicted Optimum Brake Power');
        IF A = '3' THEN OutText('         Predicted Brake Power');
        MoveTo(120,60);
        SetTextStyle(DefaultFont,HorizDir,1);
        OutText(Name);
        SetTextStyle(DefaultFont,VertDir,1);
        Moveto(round(0.5*XX1),round(getmaxY/2));
        SetTextJustify(CenterText,CenterText);

        IF A = '1' THEN OutText('Effective Power  (MWatt)')
                ELSE OutText('Brake Power  (MWatt)');

        SetTextStyle(DefaultFont,HorizDir,1);
        SetTextJustify(CenterText,TopText);
        MoveTo(round(GetMaxX/2),round(GetMaxY-YY1+0.5*YY1));
        OutText('SPEED (Knots)');

        MoveTo(Round(GetMaxX-100),round(GetmaxY-15));
        SetUserCharSize(1,3,1,3);
        SetTextStyle(TriplexFont,HorizDir,UserCharSize);
        OutText ('R. D. Moody');
    END;

{-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --}
  PROCEDURE AXIS; {Draw X and Y axis}
```

A38

```pascal
  BEGIN
    Line (round(xx1),round(yy1),round(xx1),round(getmaxy-yy1));
    Line(round(xx1),round(getmaxy-yy1),round(getmaxx-xx1),round(getmaxy-yy1));
  END;

{-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --}
  PROCEDURE DIRTY; {Draw Px Dirty curve}
    BEGIN
       SetColor(Yellow);
       NI_5 := round ((NI+1)/2);
       FOR I :=1 to (NI-1) DO
       BEGIN;
         x1[i]   :=round(xx1 + v[i]*s1 - v[1]*s1);
         y1[i]   :=round(yy1 + yy +(Px[1]-pxDirty[I])*s2);
         x1[i+1] :=round(xx1 + v[i+1]*s1 -v[1]*s1 );
         y1[i+1] :=round(yy1 + yy +(Px[1]-PxDirty[I+1])*s2) ;
         LINE(x1[I],y1[I],x1[I+1],y1[I+1]);
         IF I = NI_5 THEN LABEL1;
       END;
       SetColor(White);
    END;

{-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --}
PROCEDURE CLEAN; {Draw Px Clean curve}
  BEGIN

       SetColor (Green);
       FOR I :=1 to (NI-1) DO
       BEGIN;
         x1[i]   :=round(xx1 + v[i]*s1 -v[1]*s1 );
         y1[i]   :=round(yy1 + yy +(Px[1]-Px[I])*s2);
         x1[i+1] :=round(xx1 + v[i+1]*s1 - v[1]*s1);
         y1[i+1] :=round(yy1 + yy +(Px[1]-Px[I+1])*s2) ;
         LINE(x1[I],y1[I],x1[I+1],y1[I+1]);
         IF I = NI_5 THEN LABEL2;
       END;
       SetColor(White);
  END;

{-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --}
{-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --}
PROCEDURE DATA_GRAPH1;
  BEGIN
   ASSIGN (FILEVAR,FileName);
   RESET(filevar);
     FOR I := 1 TO NI DO
     BEGIN
        Readln(FileVar,v[i]);
        Readln(FileVar,DUMMY);
        Readln(FileVar,DUMMY,Px[I]);
        Readln(FileVar,DUMMY,PxDirty[I]);
(*       IF OPD = 'Y' THEN
         BEGIN
           Readln(FileVar,DUMMY);
           Readln(FileVar,DUMMY);
         END; *)
     END;
   CLOSE(FILEVAR);
END;

{-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --}
PROCEDURE DATA_GRAPH2;
  BEGIN
   ASSIGN (FILEVAR,FileName);
   RESET(filevar);
     FOR I := 1 TO NI DO
     BEGIN
        Readln(FileVar,v[i]);
        Readln(FileVar,DUMMY);
        Readln(FileVar,DUMMY);
        Readln(FileVar,DUMMY);
(*       IF OPD = 'Y' THEN
         BEGIN
           Readln(FileVar,Px[I]);
           Readln(FileVar,PxDirty[I]);
         END; *)
     END;
   CLOSE(FILEVAR);
```

```pascal
    END;
{--  --  --  --  --  --  --  --  --  --  --  --  --  --  --  --  --  --  --}

PROCEDURE DATA_GRAPH3;
  BEGIN

    ASSIGN (FILEVAR,FileName);                    {Get array of speeds}
    RESET(filevar);
      FOR I := 1 TO NI DO
      BEGIN
          Readln(FileVar,v[i]);
          Readln(FileVar,DUMMY);
          Readln(FileVar,DUMMY);
          Readln(FileVar,DUMMY);
(*          IF OPD = 'Y' THEN
          BEGIN
              Readln(FileVar,DUMMY);
              Readln(FileVar,DUMMY);
          END; *)
      END;
    CLOSE(FILEVAR);

    ASSIGN (FILEVAR,FileName1);                   {Get arrays of powers }
    RESET(filevar);
      FOR I := 1 TO NI DO
      BEGIN
          Readln(FileVar,DUMMY,DUMMY,DUMMY,DUMMY,DUMMY,DUMMY,DUMMY,Px[I]);
          Readln(FileVar,DUMMY,DUMMY,DUMMY,DUMMY,DUMMY,DUMMY,DUMMY,PxDirty[I]);
      END;
    CLOSE(FILEVAR);
  END;


{--  --  --  --  --  --  --  --  --  --  --  --  --  --  --  --  --  --}
 BEGIN    {PROCEDURE GRAPHICS}

   IF A = '1' THEN DATA_GRAPH1;
   IF A = '2' THEN DATA_GRAPH2;
   IF A = '3' THEN DATA_GRAPH3;
   INITIALISE;
   SETUP;
   AXIS;
   DIRTY;
   CLEAN;
   TICKS;
     BEGIN
       Repeat
       CH := Readkey
       Until Ch = Chr(13);
     END;
 RestoreCrtmode;
 CloseGraph;
 TextMode(LastMode)
 END;

END.
```

```
UNIT PLOTTER;

INTERFACE

USES SPLINET;

VAR
    Dummy, Test, Tmp1, Tmp2, Tmp3, Tmp4      :REAL;
    TmpA, TmpB, Vinc, XX, YAxisB, YAxisT     :REAL;
    y1, y2, y3, Z, z1, z2, z3                :REAL;
    P, Param1, Param2, Px, PxDirty, V, Y     :ARRAY [1..15] of REAL;
    FileVar                                  :TEXT;
    I, J, K, NI2                             :INTEGER;

PROCEDURE Plot ( A               :CHAR;
                 NI              :INTEGER;
                 FilePlot, Name  :STRING   );

IMPLEMENTATION
{$I LIB.INC}

{=================== PLOTTING PROCEDURE ====================}

PROCEDURE Plot ( A               :CHAR;
                 NI              :INTEGER;
                 FilePlot, Name  :STRING   );

{------------Read Effective Power Data Arrays from File------------}

PROCEDURE Input1;
BEGIN
{Read in data from file}
   ASSIGN (FILEVAR,'HM1.TMP');
   RESET(filevar);
     FOR I := 1 TO NI DO
     BEGIN
       Readln(FileVar,v[I]);
       Readln(FileVar,DUMMY);
       Readln(FileVar,DUMMY,Px[I]);
       Readln(FileVar,DUMMY,PxDirty[I]);
  (*       IF OPD = 'Y' THEN
         BEGIN
            Readln(FileVar,DUMMY);
            Readln(FileVar,DUMMY);
         END; *)
     END;
   CLOSE(FILEVAR);
End;


{------------Read Optimum Brake Power Data Arrays from File--------------}

PROCEDURE Input2;
BEGIN
{Read in data from file}
   ASSIGN (FILEVAR,'HM1.TMP');
   RESET(filevar);
     FOR I := 1 TO NI DO
     BEGIN
       Readln(FileVar,v[I]);
       Readln(FileVar,DUMMY);
       Readln(FileVar,DUMMY);
       Readln(FileVar,DUMMY);

 (*       IF OPD = 'Y' THEN
         BEGIN
            Readln(FileVar,Px[I]);
            Readln(FileVar,PxDirty[I]);
         END; *)
     END;
   CLOSE(FILEVAR);
END;


{-------------Read Brake Power Data Arrays from File-------------}

PROCEDURE Input3;
BEGIN
```

```
{Read in data from file}
    ASSIGN (FILEVAR,'HM1.TMP');
    RESET(filevar);
      FOR I := 1 TO NI DO
      BEGIN
          Readln(FileVar,v[I]);
          Readln(FileVar,DUMMY);
          Readln(FileVar,DUMMY);
          Readln(FileVar,DUMMY);
(*            IF OPD = 'Y' THEN
          BEGIN
              Readln(FileVar,Dummy);
              Readln(FileVar,Dummy);
          END; *)
      END;
    CLOSE(FILEVAR);

    ASSIGN (FILEVAR,'HM2.TMP');
    RESET(filevar);
      FOR I := 1 TO NI DO
      BEGIN
        Readln(FileVar,Dummy,Dummy,Dummy,Dummy,Dummy,Dummy,Dummy,Px[I]);
        Readln(FileVar,Dummy,Dummy,Dummy,Dummy,Dummy,Dummy,Dummy,PxDirty[I]);
      END;
    CLOSE(FILEVAR);
 END;


{----------------Set up PxClean data array for transfer----------}

PROCEDURE Px_Clean;
BEGIN
     FOR I := 1 TO NI DO
     BEGIN
         P[I] := Px[I];
     END;
END;

{----------------Set up PxDirty data array for transfer----------}

PROCEDURE Px_Dirty;
BEGIN
     FOR I := 1 TO NI DO
     BEGIN
         P[I] := PxDirty[I];
     END;
END;


{----------------Obtain polynomial coefficients ---------------}

PROCEDURE Theilheim;
BEGIN
   For I := 1 to NI Do
     BEGIN
        Param1[I] := V[I];
        Param2[I] := P[I];
     END;

   Coefficients(Param1,Param2,NI);

   For I := 1 to NI Do
     BEGIN
        Y[I] := Param2[I];
     END;
END;

{----------------Interpolate and draw Curves---------------}

PROCEDURE Draw;
BEGIN
   VInc := (V[2] - V[1])/10;
   Z := V[1] - VInc;
   J := 1;

   While J < NI DO
   BEGIN
       FOR K:= 1 to 10 DO
```

A42

```
        BEGIN
            Z := Z + VInc;
            XX := y[1];
            FOR I := 2 TO 4 DO
                BEGIN
                    XX := XX + Y[I]*Raise(Z,(I-1));
                END;
                FOR I := 5 TO NI DO
                    BEGIN
                        IF    Z > X[(I-2),2]
                        THEN  XX := XX + Y[I]*Raise((Z-X[(I-2),2]),3);
                    END;
                    WriteLn (FileVar,'PA',Z:0:3,XX:14:3);
            END;
                J := J + 1;
    END;
    Z := Z + VInc;
    XX := y[1];
    FOR I := 2 TO 4 DO
        BEGIN
            XX := XX + Y[I]*Raise(Z,(I-1));
        END;
    FOR I := 5 TO NI DO
        BEGIN
            IF    Z > X[(I-2),2]
            THEN  XX := XX + Y[I]*Raise((Z-X[(I-2),2]),3);
        END;
        WriteLn (FileVar,'PA',Z:0:3,XX:14:3);
END;


{------------------------------------------------------------------}

BEGIN    {Main Routine}

IF A = '1' THEN Input1;
IF A = '2' THEN Input2;
IF A = '3' THEN Input3;

{Determine distance between ticks on Y Axis 'Tmp3'}
    Tmp1 := Int((PxDirty[NI]-Px[1])/(5*10));
    Tmp2 := Round((Frac((PxDirty[NI]-Px[1])/(5*10) + 0.5))-0.5);
    Tmp3 := (Tmp1 + (Tmp2))*10;

{Determine distance between ticks on X Axis 'Tmp4'}
    Tmp4 := ((V[NI] - V[1])/(NI-1));

{Determine lower value of Y axis:- YAxisB}
    TmpA := 1;
    REPEAT
        TmpA := TmpA * 10;
    UNTIL (Px[1] < TmpA);
    YAxisB := TmpA/10;
    IF YAxisB = 1 THEN YAxisB := 0;

{Determine upper value of Y axis:- YAxisT}
    YAxisT := YAxisB;
    REPEAT
        YAxisT := YAxisT + Tmp3;
        For I := 1 to 100  do begin; end;
    UNTIL (YAxisT > PxDirty[NI]);

    NI2 := NI * 2 DIV 3;

    ASSIGN(FileVar,FilePlot);
    REWRITE(FileVar);

{Initialise P1 and P2, Rotate 90 deg. and Scale Axis}
    Writeln (FileVar,'IN;IP1500,1200,7250,10000;');
    Writeln (FileVar,'R090');
    Writeln (FileVar,'SC',V[1]:0:2,V[NI]:6:2,YAxisB:14:3,YAxisT:14:3);

{Label Title}
{- Select pen, move to origin,}
    Writeln (FileVar,'SP1; PA',((V[1]+V[NI])/2):0:2,YAxisT:14:3);

{- Select character size, slant and label origin, Write label}
    Writeln (FileVar,'SI.3,.5;SL.4;L014');
```

A43

```
        IF A = '1' THEN
            WriteLn (FileVar,'LBPredicted Effective Power (Pe)'+ chr(3));
        IF A = '2' THEN
            WriteLn (FileVar,'LBPredicted Optimum Brake Power (Pb)'+ chr(3));
        IF A = '3' THEN
            WriteLn (FileVar,'LBPredicted Brake Power (Pb)'+ chr(3));

        Writeln (FileVar,'PU',((V[1]+V[NI])/2):0:2,YAxisT:14:3);
        Writeln (FileVar,'SI.2,.35;SL.4;L016');
        WriteLn (FileVar,'LB(                      )'+ chr(3));

{Draw in Axis}
        Writeln (FileVar,'PA',V[1]:0:2,YAxisT:14:3);
        Writeln (FileVar,'PD',V[1]:0:2,YAxisB:14:3,V[NI]:6:2,YAxisB:14:3);

{Reset character size, set tick length}
        Writeln (FileVar,'PU;SI.2,.3;TL.5,.5;');

{Label Y axis }
        TmpB := YAxisB - Tmp3;
        WHILE (TmpB < YAxisT) DO
            BEGIN
                TmpB := TmpB + Tmp3;
                WriteLn (FileVar,'PA',V[1]:0:2,TmpB:14:3,';YT');
                WriteLn (FileVar,'L017; LB ',(TmpB/1000):0:2,'  ', + chr(3));
            END;
        Writeln (FileVar,'PU; PA',(V[1]-(1.25*Tmp4)):0:2,((YAxisT+YAxisB)/2):14:3);
        Writeln (FileVar,'SI;DIO,1;L014');

        IF A = '1' THEN
            WriteLn (FileVar,'LB Effective Power (MWatt)'+ chr(3),'PU');
        IF A = '2' THEN
            WriteLn (FileVar,'LB Optimum Brake Power (MWatt)'+ chr(3),'PU');
        IF A = '3' THEN
            WriteLn (FileVar,'LB Brake Power (MWatt)'+ chr(3),'PU');
{Reset character size, and direction, Label X axis}
        Writeln (FileVar,'SI.2,.3;DI1,0');
        TmpB := V[1] - Tmp4;
        WHILE (TmpB < V[NI]) DO
            BEGIN
                TmpB := TmpB + Tmp4;
                WriteLn (FileVar,'PA',TmpB:0:2,(YAxisB-(Tmp3/10)):14:3,';XT');
                WriteLn (FileVar,'L016; LB ',(TmpB):0:1, + chr(3));
            END;
        Writeln (FileVar,'PU; PA',((V[NI]+V[1])/2):0:2,(YAxisB-(Tmp3/2)):14:3);
        Writeln (FileVar,'SI;L05');
        WriteLn (FileVar,'LB Speed (Knots)'+ chr(3));

{Draw in the clean power curve}
        Writeln (FileVar,'SP2;PU',V[1]:0:3,Px[1]:14:3,';PD');
        Px_Clean;
        Theilheim;
        Draw;

{Draw in the dirty power curve}
        Writeln (FileVar,'SP3; PU',V[1]:0:3,PxDirty[1]:14:3,';PD');
        Px_Dirty;
        Theilheim;
        Draw;

{Label the dirty  power curve}
        Writeln (FileVar,'PU',V[NI2]:0:3,PxDirty[NI2]:14:3,';PD');
        IF A = '1' THEN
            Writeln (FileVar,'L018;LBPe (Dirty)      '+chr(3))
        ELSE
            Writeln (FileVar,'L018;LBPb (Dirty)      '+chr(3));

{Label the clean power curve}
        Writeln (FileVar,'SP2; PU',V[(NI2)]:0:3,Px[NI2]:14:3,';PD');

        IF A = '1' THEN
            Writeln (FileVar,'L012;LB     Pe (Clean) '+chr(3))
        ELSE
            Writeln (FileVar,'L012;LB     Pb (Clean) '+chr(3));

{User Title}
        Writeln (FileVar,'SI.17,.25; SP1; PU',
                        (V[1]+(Tmp4/2)):0:3,(Px[NI-1]+Tmp3):14:3);
```

```
        Writeln (FileVar,'L012;LB',Name +chr(3));
        Writeln (FileVar,'PU');

{Return Pen, send plotter not ready signal}
        WriteLn (FileVar,'SP0; NR');

{Write Blank Lines to File}
        WriteLn (FileVar,'                                              ');
        WriteLn (FileVar,'                                              ');
        WriteLn (FileVar,'                                              ');
        WriteLn (FileVar,'                                              ');
        WriteLn (FileVar,'                                              ');
        WriteLn (FileVar,'                                              ');
        WriteLn (FileVar,'                                              ');
        Close (FileVar);
        End;
End.
```

```pascal
{$F+}
UNIT OPTEFF;
INTERFACE
USES Dos;

VAR
    A, B, C, Xn, X,  Dummy, Kt, Kq, Ku, nr       :REAL;
    J, D, BAR, Z, PD, Y1, Y2, Y3, X1, X2         :REAL;
    X3, Ya, Yb, Eff, revs, Thrust, Vx, QPC       :REAL;
    PC, BP                                       :REAL;
    Pe, PeDirty, Thrustc, Thrustd, V, Vk, nh     :ARRAY [1..11] of REAL;
    Jc, Jd, Ktc, Ktd, Kqc, Kqd, Revsc, Revsd     :ARRAY [1..11] of REAL;
    Effc, Effd, w, tdf, QPCc, PCc, QPCd, Pcd     :ARRAY [1..11] of REAL;
    BPc, BPd                                     :ARRAY [1..11] of REAL;
    Q                                            :ARRAY [0..50] of REAL;
    FileVar                                      :TEXT;
    I, J1, K, cl, KK                             :INTEGER;
    Year, Month, Day, DayOfWeek, Hour, Min       :WORD;
    Sec, Sec100                                  :WORD;

  CONST
    PI = 3.14159;
    Rho = 1.025;

PROCEDURE BPower (Cp, lcb, BAR, PD, D, ns            :REAL;
                  NI, Z, N                           :INTEGER;
                  FilePlot, FileOut, Name, Version   :STRING);
              (*  OPD                                :CHAR *)

IMPLEMENTATION
{$I LIB.INC}

{=================== POWERING PROCEDURE ===================}

PROCEDURE BPower (Cp, lcb, BAR, PD, D, ns            :REAL;
                  NI, Z, N                           :INTEGER;
                  FilePlot, FileOut, Name, Version   :STRING);
              (*OPD                                   :CHAR*)


{------------------- GET SYSTEM DATE AND TIME ------------------}

PROCEDURE Date;  {Get system date and time}
BEGIN
    GetDate(Year, Month, Day, DayOfWeek);
    GetTime(Hour, Min, Sec,Sec100);
END;
{-------------Read Thrust Data Arrays from File------------}
PROCEDURE Input;
BEGIN
{Read in data from file}
  ASSIGN (FILEVAR,'HM1.TMP');
  RESET(filevar);
    FOR I := 1 TO (NI+1)  DO
    BEGIN
        Readln(FileVar,Vk[I] ,V[I]);
        Readln(FileVar,DUMMY);
        Readln(FileVar,DUMMY,Pe[I],w[I],Tdf[I],nh[I],DUMMY,Thrustc[I]);
        Readln(FileVar,DUMMY,PeDirty[I],DUMMY,Thrustd[I]);
    (*    IF OPD = 'Y' THEN
        BEGIN
         Readln(FileVar,DUMMY);
         Readln(FileVar,DUMMY);
        END;  *)

    END;
  CLOSE(FILEVAR);
End;

{---------------------Kt Polynomials------------------------}
PROCEDURE KtCalc;
BEGIN
    KT :=     8.80496E-03;
    KT := KT - 0.204554*J;
    KT := KT + 0.166351*PD;
    KT := KT + 0.158114*PD*PD;
    KT := KT - 0.147581*J*J*BAR;
    KT := KT - 0.481497*J*PD*BAR;
```

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```
KT := KT + 0.415437*PD*PD*BAR;
KT := KT + 0.0144043*Z;
KT := KT - 0.0530054*J*J*Z;
KT := KT + 0.0143481*PD*Z;
KT := KT + 0.0606826*J*PD*Z;
KT := KT - 0.0125894*BAR*Z;
KT := KT + 0.0109689*J*BAR*Z;
KT := KT - 0.133698*PD*PD*PD;
KT := KT + 6.38407E-03*RAISE(PD,6);
KT := KT - 1.32718E-03*J*J*RAISE(PD,6);
KT := KT + 0.168496*J*J*J*BAR;
KT := KT - 0.0507214*BAR*BAR;
KT := KT + 0.0854559*J*J*BAR*BAR;
KT := KT - 0.0504475*J*J*J*BAR*BAR;
KT := KT + 0.010465*J*RAISE(PD,6)*BAR*BAR;
KT := KT - 6.48272E-03*J*J*RAISE(PD,6)*BAR*BAR;
KT := KT - 8.417281E-03*PD*PD*PD*Z;
KT := KT + 0.0168424*J*PD*PD*PD*Z;
KT := KT - 1.02296E-03*J*J*J*PD*PD*PD*Z;
KT := KT - 0.0317791*PD*PD*PD*BAR*Z;
KT := KT + 0.018604*J*BAR*BAR*Z;
KT := KT - 4.10798E-03*PD*PD*BAR*BAR*Z;
KT := KT - 6.06848E-04*Z*Z;
KT := KT - 0.0049819*J*Z*Z;
KT := KT + 0.0025983*J*J*Z*Z;
KT := KT - 5.60528E-04*J*J*J*Z*Z;
KT := KT - 1.63652E-03*J*PD*PD*Z*Z;
KT := KT - 3.28787E-04*J*RAISE(PD,6)*Z*Z;
KT := KT + 1.16502E-04*J*J*RAISE(PD,6)*Z*Z;
KT := KT + 6.90904E-04*BAR*Z*Z;
KT := KT + 4.21749E-03*PD*PD*PD*BAR*Z*Z;
KT := KT + 5.65229E-05*J*J*J*RAISE(PD,6)*BAR*Z*Z;
KT := KT - 1.46564E-03*PD*PD*PD*BAR*BAR*Z*Z;
END;


{-------------------------Kq Polynomials-------------------------}
PROCEDURE KqCalc;
 BEGIN
  KQ := 3.79368E-03;
  KQ := KQ + 8.86523E-03 * J * J;
  KQ := KQ - 0.032241 * J * PD;
  KQ := KQ + 3.44778E-03 * PD * PD;
  KQ := KQ - 0.0408811 * PD * BAR;
  KQ := KQ - 0.108009 * J * PD * BAR;
  KQ := KQ - 0.0885381 * J * J * PD * BAR;
  KQ := KQ + 0.188561 * PD * PD * BAR;
  KQ := KQ - 3.70871E-03 * J * Z;
  KQ := KQ + 5.13696E-03 * PD * Z;
  KQ := KQ + 0.0209449 * J * PD * Z;
  KQ := KQ + 4.74319E-03 * J * J * PD * Z;
  KQ := KQ - 7.23408E-03 * J * J * BAR * Z;
  KQ := KQ + 4.38388E-03 * J * PD * BAR * Z;
  KQ := KQ - 0.0269403 * PD * PD * BAR * Z;
  KQ := KQ + 0.0558082 * J * J * J * BAR;
  KQ := KQ + 0.0161886 * PD * PD * PD * BAR;
  KQ := KQ + 3.18086E-03 * J * PD * PD * PD * BAR;
  KQ := KQ + 0.015896 * BAR * BAR;
  KQ := KQ + 0.0471729 * J * BAR * BAR;
  KQ := KQ + 0.0196283 * J * J * J * BAR * BAR;
  KQ := KQ - 0.0502782 * PD * BAR * BAR;
  KQ := KQ - 0.030055 * J * J * J * PD * BAR * BAR;
  KQ := KQ + 0.0417122 * J * J * PD * PD * BAR * BAR;
  KQ := KQ - 0.0397722 * PD * PD * PD * BAR * BAR;
  KQ := KQ - 3.50024E-03 * RAISE(PD,6) * BAR * BAR;
  KQ := KQ - 0.0106854 * J * J * J * Z;
  KQ := KQ + 1.10903E-03 * J * J * J * PD * PD * PD * Z;
  KQ := KQ - 3.13912E-04 * RAISE(PD,6) * Z;
  KQ := KQ + 0.0035985 * J * J * J * BAR * Z;
  KQ := KQ - 1.42121E-03 * RAISE(PD,6) * BAR * Z;
  KQ := KQ - 3.83637E-03 * J * BAR * BAR * Z;
  KQ := KQ + 0.0126803 * PD * PD * BAR * BAR * Z;
  KQ := KQ - 3.18278E-03 * J * J * PD * PD * PD * BAR * BAR * Z;
  KQ := KQ + 3.34268E-03 * RAISE(PD,6) * BAR * BAR * Z;
  KQ := KQ - 1.83491E-03 * J * PD * Z * Z;
  KQ := KQ + 1.12451E-04 * J * J * J * PD * PD * Z * Z;
  KQ := KQ - 2.97228E-05 * J * J * J * RAISE(PD,6) * Z * Z;
  KQ := KQ + 2.69551E-04 * J * BAR * Z * Z;
  KQ := KQ + 8.3265E-04 * J * J * BAR * Z * Z;
```

```
            KQ := KQ + 1.55334E-03 * PD * PD * BAR * Z * Z;
            KQ := KQ + 3.02683E-04 * RAISE(PD,6) * BAR * Z * Z;
            KQ := KQ - 0.0001843 * BAR * BAR * Z * Z;
            KQ := KQ - 4.25399E-04 * PD * PD * PD * BAR * BAR * Z * Z;
            KQ := KQ + 8.69243E-05 * J * J * J * PD * PD * PD * BAR * BAR * Z * Z;
            KQ := KQ - 0.0004659 * RAISE(PD,6) * BAR * BAR * Z * Z;
            KQ := KQ + 5.54194E-05 * J * RAISE(PD,6) * BAR * BAR * Z * Z;
       END;
{------------Approximate Intersection Kt/J^2 and Ku---------------}

PROCEDURE Straddle;
LABEL 1,2;

BEGIN
     REPEAT
     J := J1/C1;
     IF J > PD THEN WriteLn('Out of Range');
     KtCalc;
     Q[J1] := Kt;
     IF Kt = 0 THEN Y2 := Ku
               ELSE Y2 := (Ku * J * J);
      J1 := J1 +1;
       UNTIL Kt < Y2;                  {Note value of J1 to use is J1-1}
End;


{---------------Accurate Intersection Kt/J^2 and Ku----------------}
PROCEDURE Intersect;
BEGIN
        C1 := 20;
        Ku := Thrust/(Rho * Vx * Vx * D * D);
        J1:=0;
        Straddle;
        IF J1 < 2  THEN
                BEGIN
                  C1 :=40;
                  J1 := 0;
                  Straddle;
                END;

{Determine coefficients of parabola    :- Y = A + BX + CX^2}
        Y1 := Q[J1-3];
        Y2 := Q[J1-2];
        Y3 := Q[J1-1];
        X1 := (J1-3)/C1;
        X2 := (J1-2)/C1;
        X3 := (J1-1)/C1;
        C := ((Y1-Y2)/(X1- X2)-(Y1-Y3)/(X1- X3))/(X2- X3);
        B := (Y1-Y2)/(X1- X2)- C*(X1+ X2);
        A :=  Y1 - (B*X1) - (C*X1* X1);

{Find intersection using Newton Raphson method}
        Xn := X2;
        REPEAT
        X := Xn;
        Ya := (A + B*X + C*X*X);
        Yb :=  (Ku * X * X);
        Xn :=  X -((Ya-Yb)/(B + 2*X*(C-Ku)));
        Until ABS((Ya-Yb)/Ya) <= 0.00001;
        J := Xn;
        KtCalc;
        KqCalc;
        Eff := J * Kt/(2*Pi*Kq);
{Find Revs/Min}
        Revs :=SQRT( THRUST /(Rho*D*D*D*D *Kt))*60 ;
End;


{---------------Determine Relative Rotational Efficiency-----------}
PROCEDURE RELATIVE;
BEGIN

IF N >= 2 THEN
        nr :=0.9737 + 0.111*(Cp-0.0225*lcb)-0.06325*PD    {Twin Prop}
   ELSE
        nr := 0.9922-0.05908*BAR+0.07424*(Cp-0.0225*LCB); {Single prop}

END;


{-------------------------DETERMINE PROPULSION COEFFICIENTS----------------}
```

```
Procedure PropCoeff;
  Begin
        QPC := nh[I] * nr * Eff;
        PC := QPC * ns;
  End;


{-----------------------Determine Brake Power-----------------------}
PROCEDURE BPower(Pex: REAL);
BEGIN
  BP := Pex / PC
END;


{-----------------------Read Data from temporary file-----------------------}
PROCEDURE TEMP;
BEGIN
    ASSIGN (FILEVAR,'HM2.TMP');
    RESET (FileVar);
    FOR I := 1  TO (NI+1) DO
      BEGIN
        READLn (FileVar, Jc[I], Ktc[I], Kqc[I], Effc[I], Revsc[I], QPCc[I], PCc[I], BPc[I]);
        READLn (FileVar, Jd[I], Ktd[I], Kqd[I], Effd[I], Revsd[I], QPCd[I], PCd[I], BPd[I]);
      END;
    CLOSE(FileVar);

{---}
    ASSIGN (FILEVAR,'HM3.TMP');
    APPEND (FileVar);
    WriteLn(FileVar, Jc[NI+1], Ktc[NI+1], Kqc[NI+1], Effc[NI+1], Revsc[NI+1], QPCc[NI+1],
PCc[NI+1], BPc[NI+1]);
    WriteLn(FileVar, Jd[NI+1], Ktd[NI+1], Kqd[NI+1], Effd[NI+1], Revsd[NI+1], QPCd[NI+1],
PCd[NI+1], BPd[NI+1]);
    CLOSE(FileVar);
{---}

END;


{-----------------------Read Data from temporary file-----------------------}
PROCEDURE OUTPUT;
BEGIN
    ASSIGN (FILEVAR,FileOut);
    APPEND (FileVar);
    Writeln (FileVar,CHR(12));
    WriteLn (FileVar,'-------------------------------------------------------
-');
                                Writeln     (FileVar,Day,'/',        Month,'/',        Year,'
',Hour,':',Min:2,':',Sec:2);
      Writeln (FileVar,'                      PRELIMINARY  RESISTANCE/POWER  PREDICTION
');
      Writeln (FileVar,'                Predicted  Brake  Power  and  Propeller  Efficiency
');
    Writeln (FileVar,'By R.Moody                                              ',Version);
    WriteLn (FileVar,'-------------------------------------------------------
-');
    Writeln (FileVar);
    Writeln (FileVar,'Ship Name:   ',Name);
    Writeln (FileVar);
      Writeln (FileVar,'Brake  Power  of  clean  ship    (fitted  with  Wageningen  B  Series
Propeller)');
    Writeln (FileVar);
    Writeln(FileVar,'   V        Thrust     Speed      no       nr       nh       QPC       ns
');
    Writeln(FileVar,'(Knots)      (kN)       (rpm)                                           ');
    Writeln (FileVar,'-------   --------   ------   ------   ------   ------   ------   ------
');
    FOR I := 1 to NI DO
        BEGIN
          Writeln(FileVar,Vk[I]:7:3, Thrustc[I]:12:3,
          Revsc[I]:10:3, Effc[I]:9:3,nr:8:3,nh[I]:8:3,QPCc[I]:8:3,ns:8:3);
        END;
    Writeln (FileVar);
    Writeln(FileVar,'   V           Pe          PC          Pb           J       Kt      Kq ');
    Writeln(FileVar,'(Knots)       (kW)                     (kW)                            ');
    Writeln(FileVar,'-------   -----------   ------   -----------   -----   -----   -----');
    FOR I := 1 to NI DO
        BEGIN
                                Writeln(FileVar,Vk[I]:7:3,Pe[I]:15:3,PCc[I]:9:4,BPc[I]:15:3,
Jc[I]:9:3,Ktc[I]:8:3,Kqc[I]:8:3);
```

```pascal
            END;
     WriteLn (FileVar,'-----------------------------------------------------------------
—');
     Writeln (FileVar);
        Writeln (FileVar,'Brake Power of dirty ship    (fitted with Wageningen B Series
Propeller)');
     Writeln (FileVar);
     Writeln(FileVar,'    V         Thrust    Speed      no      nr      nh      QPC     ns ');
     Writeln(FileVar,'(Knots)       (kN)      (rpm)                                         ');
     Writeln (FileVar,'-----         ------     -----    ------  ------  ------   ------  ------
');
     FOR I := 1 to NI DO
         BEGIN
            Writeln(FileVar,Vk[I]:7:3, Thrustd[I]:12:3,
            Revsd[I]:10:3, Effd[I]:9:3,nr:8:3,nh[I]:8:3,QPCd[I]:8:3,ns:8:3);
         END;

     Writeln (FileVar);
     Writeln(FileVar,'    V          Pe         PC          Pb         J       Kt      Kq ');
     Writeln(FileVar,'(Knots)       (kW)                   (kW)                            ');
     Writeln(FileVar,'-----         -------     -----    ---------     -----   -----  -----');
        FOR I := 1 to NI DO
          BEGIN
             Writeln(FileVar,Vk[I]:7:3, PeDirty[I]:15:3, PCd[I]:9:4, BPd[I]:15:3, Jd[I]:9:3,
             Ktd[I]:8:3,Kqd[I]:8:3);
          END;

        WriteLn(FileVar,'-----------------------------------------------------------------
—');
        CLOSE(FileVar);
END;


{---------------------------MAIN PROGRAM---------------------------}

BEGIN
    Date;
    Input;

    Relative;
    ASSIGN (FILEVAR,'HM2.TMP');
    REWRITE (FileVar);

    For I := 1 to (NI+1) DO
       BEGIN
         Vx := V[I] * (1 - w[I]);
         THRUST := Thrustc[I]/N;
         Intersect;       {Calculate Data for clean condition}
         PropCoeff;
         BPower(Pe[I]);
                WriteLn(FileVar,J:11:6,Kt:11:6,Kq:11:6,Eff:11:6,Revs:20:4,   QPC:11:6,   PC:11:6,
BP:20:4);
         THRUST := Thrustd[I]/N;
         Intersect;       {Calculate data for dirty condition}
         PropCoeff;
         BPower(PeDirty[I]);
                WriteLn(FileVar,J:11:6,Kt:11:6,Kq:11:6,Eff:11:6,Revs:20:4,   QPC:11:6,   PC:11:6,
BP:20:4);
       END;

    Close (FileVar);
    Temp;
    Output;

End;
END.
```

```
{$F+}
UNIT LOGOS;
INTERFACE

USES Graph, Crt, GrDrivers, GrFonts, overlay;
VAR
    GraphDriver, GraphMode, K, I, N, xx1, yy1, xx2, yy2, X11, Y11 : Integer;
    M, P, xx, yy                                                  : Real;
    CH   : char;
    Title : string[30];

CONST
{   TitleB = '    Naval Engineering Bureau    ';}
    TitleB = '           Cape Technikon       ';
    Author = 'R. D. Moody';
    Version = 'Rel. 1.0';

PROCEDURE LOGO (Title :String);

IMPLEMENTATION

{-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --}
{-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --}
PROCEDURE   LOGO (Title :String);
{-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --}
    Procedure Initialise;
      BEGIN
        Graphdriver := Detect;
        InitGraph( GraphDriver, GraphMode, '');
        IF NOT (graphdriver in [ega,HercMono,vga,cga,att400,mcga,pc3270]) THEN
          BEGIN
            RestoreCrtmode;
            Writeln ('Error : Requires video graphics display');
            Halt
          END; {if}
        SetbkColor (blue);
        SetColor (white);
      END; {Procedure Initialise}

{-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --}
    Procedure Box;
      BEGIN
        SetViewPort(0, 0, GetmaxX, GetMaxY-(TextHeight('A')+4)-1,ClipOn);
        Rectangle(0, 0, GetMaxX-1, (GetmaxY-(TextHeight('A')+4)-1)-1);
      END { PROCEDURE BOX };

    Procedure Message;
      BEGIN
        SetTextStyle(DefaultFont, HorizDir, 1);       .
        SetTextJustify(CenterText, TopText);
        SetLineStyle(SolidLn, 0, NormWidth);
        SetFillStyle(EmptyFill, 0);
        Bar(0, GetMaxY-(TextHeight('A')+4), GetMaxX, GetMaxY);
        Rectangle(0, GetMaxY-(TextHeight('A')+4), GetMaxX, GetMaxY);
        MoveTo(GetMaxX div 2, GetMaxY-(TextHeight('A')+2));
        OutText('Press ENTER to Continue');
        Box;
      END { PROCEDURE MESSAGE};

    Procedure Text;
      BEGIN
        xx:=GetMaxX;   yy:= GetMaxY;
        x11 :=round(xx/2);    y11:=round(yy/8);
        yy1 :=round(yy/2);
        K := round( (yy1-y11)/7);
        M:=1;
        N:=1;
        P:=1;
        SetColor (Green);
        MoveTo (Round(GetmaxX*0.1),Round(GetmaxY*0.9));
        SetTextJustify(LeftText,TopText);
        SetTextStyle(Gothicfont,Horizdir,(1));
        OutText(Version);
        MoveTo (Round(GetmaxX*0.9),Round(GetmaxY*0.9));
        SetTextJustify(RightText,TopText);
        SetTextStyle(Gothicfont,Horizdir,(1));
        OutText(Author);
        SetColor (white);
```

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```
            MoveTo(Xx1,yy1);
            y11 :=y11 -k -10;
            For I := 1 to 5  do
               BEGIN
                  y11 := y11 + round(p*k);
                  MoveTo(x11,(y11));
                  SetTextStyle(TriplexFont,Horizdir,(N));
                  SetTextJustify(CenterText,BottomText);
                  OutText(TitleB);
                  M:= M + 1;
                  P := P+0.20;
                  N := Round(M);
               END;
            For I := 1 to 6  do
               BEGIN
                  y11 := y11 + round(p*k);
                  MoveTo(x11,y11);
                  SetTextStyle(TriplexFont,Horizdir,(N));
                  SetTextJustify(CenterText,BottomText);
                  IF I = 1 THEN
                     BEGIN
                        SetColor(Yellow);
                        OutText(Title);
                        SetColor(White);
                     END
                  ELSE
                  OutText(TitleB);
                  M:=M-1;
                  P := P-0.20;
                  N := Round(M);
               END;
            END;  {Procedure Text}

{-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --}
      BEGIN    {PROCEDURE LOGO}
         Initialise;
         Text;
         Message;
            BEGIN
               Repeat
               CH := Readkey
               Until Ch = Chr(13);
            END;
         RestoreCrtmode;
         CloseGraph;
         TextMode(LastMode);
      END; {PROCEDURE LOGO}
{-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --}
{-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --}
END.
```

```pascal
{$F+}
UNIT Border;
INTERFACE
 USES Crt, DOS, PCX, Graph, GRDrivers, Logos;
 VAR
  I, K, J, e : Integer;
  blackpal: array[0..255] of RGBrec;
  sec, Hour, min, sec100 :Word;
  seca, secb :REAL;
  sec1, sec2 :String[8];
  ch : char;
  p : Pointer;

PROCEDURE Box;
PROCEDURE INTRO256(Pic_Name: String);

IMPLEMENTATION

PROCEDURE Box;

 BEGIN
   ClrScr;
   WINDOW(1,1,80,25);
   TextBackground(Blue);
   FOR I := 1 TO 24 DO
   BEGIN
   FOR K:= 1 to 80 DO
   Write (CHR(255));                    {Blank Character}
   END;


   GoToXY(1,1); Write(Chr(201));        {Top left corner of box}
   gotoxy(2,1);
   FOR I := 1 to 78 DO
    begin
      Write (CHR(205));                      {Top line of box}
    end;
   GoToXY(80,1); Write(Char(187));      {Top right corner of box}
   GoToXY(1,24);Write(chr(200));        { Bottom left corner of box}
   GoToXY(2,24);
   FOR I := 1 to 78 do
    BEGIN
      Write(Chr(205));                     { Bottom line of box}
    END;
   gotoxy(80,24);write(chr(188));       {Bottom right corner of box}
   FOR I := 2 to 23 do
    begin
      GOTOXY(1,I);

      IF I = 3 THEN                                 {Begin IF THEN ELSE}
       BEGIN
         GoToXY(1,3); Write(chr(199));
         GoToXY(2,3);
         FOR K := 1 to 78 DO
          BEGIN
            Write (CHR(196));
          END;
         gotoxy(80,3);write(chr(182));
       END
       ELSE
     write(chr(186));gotoxy(80,I);write(chr(186));
    end;                                            {End IF THEN ELSE}

   HighVideo;
      GotoXY(26,2);
      TextBackGround(White);
      TextColor(Blue);
      Write('RESISTANCE and POWER PREDICTION ');
      TextBackGround(Blue);
   NormVideo;
 END;

PROCEDURE INTRO256(Pic_Name: String);
 begin
      pcxfilename:= Pic_Name;
      setmode($13);                          { Initialize graphics }
         fillchar(blackpal, 768, 0);             { Set all colors to black }
      setregisters(blackpal);
      read_pcx256(Pic_Name);                { Put image into display memory }
```

```pascal
      if file_error then
      begin
           setmode(3);
           Logo('  PROGRAM POWER  ');
      end;
setregisters(RGB256);                   { Show true colors }

GetTime(Hour, Min, Sec,Sec100);
seca:=sec;

REPEAT
GetTime(Hour, Min, Sec,Sec100);
secb:=sec;
UNTIL  (secb-seca > 8) or (keypressed);
If keypressed Then ch := readkey;

setmode(3);                             { Restore text mode }
end;
END.
```

8. REFERENCES

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