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Energy Efficient Hull Forms

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ENERGY EFFICIENT HULL FORMS

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Currently, the U.S. Navy has no quick and easy to use specification for ensuring that proposed new ship designs have good energy efficient hull forms. The use of a measure of merit, Cpe that compares the bare hull resistance of the proposed design to that of the equivalent size Taylor Standard Series Ship is recommended. Cpe values are shown for over 530 historic cases in an easy to use format. The data is presented for various category hull forms such as single screw merchant ships and auxiliaries, multi screw merchant ships and auxiliaries ,destroyer/frigate type combatants, large combatants and commercial ships, aircraft carriers, and a combined grouping for trawlers, minesweepers and oceanographic vessels.

The U.S. Navy's Hull Design Database System which facilitates the quick retrieval of hull geometry and performance information on several hundred ship designs was used to generate this Cpe data base. The system can be used to easily group the Cpe historic data for hull forms that are in the neighborhood of the proposed new design in terms of length, block coefficient and other hull form characteristics. The historic data show that at high speed several hull forms have significantly better performance than the Taylor ship, but at intermediate speeds there are only a few hull forms that perform better than Taylor.

Nomenclature

Ao = Area at FP (stn. 0), sq.ft.
Ax = Section area at station of maximum area, sq.ft.
Ba = Area ratio, Ao/Ax
Bx = Beam at station of maximum area, ft.
Bx/Tx or B/T = Beam-draft ratio
C = Constant
Ca = Ship-model correlation allowance
Circle "C" = 427.1 EHP/Disp**0.67*V**3
Circle "K" = 0.5834 V/Disp**0.125
Cp = Prismatic coefficient
Cr = Residuary resistance coefficient
Cpe = Resistance coefficient. PE (ship)/PE (Taylor)
Cf = Frictional resistance coefficient

Ct = Total resistance coefficient
Ctl = Telfer Resistance Coefficient.
Cx = Maximum sectional area coefficient, Ax/LxTx
Disp. = Bare hull displacement in Long Tons (2240#)
Disp./(0.01L)**3 = Displacement-length ratio
HDDS = Hull Design Database System [2]
L = Waterline Length, ft.
Lx/Bx or L/B = Length-beam ratio
PE (ship) = Bare hull EHP for the ship, horsepower
PE (Taylor) = Bare hull EHP for an equivalent TSS ship
S = Wetted surface (bare hull), sq.ft.
TSS = Taylor Standard Series [4]
Ton = Long ton of 2240 pounds.
Tx = Draft at station of maximum area, ft.
V = Speed, knots
Vd = Design speed, knots
Vo = Fuel optimum speed, knots
V/L**0.5 = Speed-length ratio
WCF = "Worm curve factor", Cr (ship)/Cr (Taylor)

Introduction

The U.S Navy Energy Office has been pursuing many ways to reduce the fuel usage on U.S Navy ships. In a recent survey [1], several retrofit type devices were identified as potential candidates for reducing the fuel usage of existing ships, with the most cost-effective device being the stern flap. At the same time improvements to the hull form were identified as one of the most cost-effective means of reducing the propulsion fuel usage of future ships. The hull form improvements that were envisioned were small modifications to the overall shape of the hull, which at the time of new construction would involve no additional cost. It was also recognized that there is a need to avoid the use of poor fuel efficient hull forms.

The purpose herein is to provide information that can be used for the evaluation of a hull form with regard to its resistance characteristics and to provide guidance in forming a specification for energy efficient hull forms.

Hull Form Evaluation

In the current U.S. Navy ship acquisition process, bidders respond to the navy's Request for Quotation (RFQ) which is usually accompanied by a set of requirements or performance specifications regarding the proposed ship design. At the moment, there are no requirements, which ensure that the hull form design will be energy efficient. Other overall requirements on speed, endurance and the desirability to minimize first cost through the smallest engine size and life cycle cost through reduced fuel usage all tend to favor an efficient hull form design. However, a ship design with a mediocre or poor hull form can usually be made to meet speed requirements by adding more horsepower.

Furthermore, a deficiency in endurance can usually be overcome by the addition of extra fuel tank capacity. Such a design could be acceptable from the viewpoint of overall requirements on speed and power but will cost the Navy dearly in fuel bills for the life of the ship or ship class.

The fuel costs that can be saved through superior design are quite significant. For example, an arbitrary 5 percent improvement in powering for the HENRY J. KAISER, TAO 187 class ships would save $ 40 million in fuel costs * for the remainder of the life of the 16 vessels in the class. Thus there is real motivation for adopting the best possible hull form.

Of course there are many other considerations to be weighed by the designers, such as intact and damaged stability, maneuverability, sea keeping ability, radar cross-section, and specific requirements needed to meet the mission of the ship. However it is believed that having an acceptable, efficient hull form is a good first evolution, which can then be adapted to meet the ship's other requirements.

Hull Design Database System

The Hull Design Database System (HDDS) was jointly developed by the U.S and U.K. navies to enable rapid hull design and evaluation during the beginning stages of the design [2]. It is a computer based system which stores hull form geometry, propulsion data, and also various hydrodynamic performance data, both from model tests and full-scale ship trials. Currently the system has over 600 data sets that include, as a minimum, the hull geometry and the bare hull resistance model test.

The system stores the resistance data as faired model quantities, and the hull geometry is stored so that it can be instantly recalled and displayed. If necessary new hull designs can be readily developed from the stored hull forms. There is extensive search routine so that hull forms with geometric characteristics within specified ranges can be selected and rapidly displayed. The stored model test data can be quickly extrapolated to any specified scale ratio so that ship resistance, powering, motions and other hydrodynamic characteristics can be easily predicted.

Most new ship designs tend to be based on an existing hull from the designer's limited library of hull forms. Hull form resistance data is obtained only from model tests. Data which include a complete hull geometry definition and the raw model test information is difficult to obtain from general technical literature. The scarcity of this type of data makes HDDS an even more valuable resource for identifying potential good initial hull forms for any monohull design.

Hull Form Evaluation Criteria.

Throughout the development of modern naval architecture, there have been several different measures of merit for resistance that could be applied to a hull form. Many of these parameters are discussed and defined in PNA [3] and are briefly described herein. They are:

* Fuel costs based upon $37/barrell (unburdened cost. i.e. cost at the pump for an average U.S. base)

-Ct vs. Rn – Not really suitable for our purposes because of the variation in performance due to ship size,

-Circle "C" vs. Circle "K", a modified resistance to weight ratio presentation relative to speed divided by displacement to the 1/6 power. In years past these curves were produced for a standard 400-ft. long ship. Again the main shortcoming is the size and speed dependence of this coefficient.

-Ctl vs. Speed-length ratio. This is sometimes called the Telfer coefficient. This method is relatively simple to use and is good for the comparison of a number of similar hulls, but for a broad spectrum of hulls we still have speed and size variations.

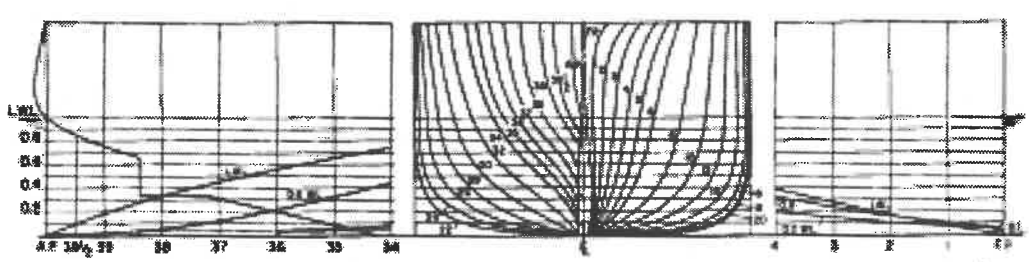
-Cr vs. Speed-length ratio. This is used during model testing to compare the performance of the ship's residual resistance to that of others of the same type. It is also a good indicator of wave making resistance effects.

-EHP/ton. This is still widely used as a comparison between ships of differing displacements. Sometimes all the vessels being compared are standardized to a 400-foot length ship. EHP can be bare hull, or fully appended. This method does not take into account major differences due to L/B, B/T and Cp, but is still a very good "first cut" on hull effectiveness.

-Worm Curve Factor (WCF). This is the comparison of the residuary resistance of the proposed ship to the residuary resistance of a Taylor Standard Series ship [4]. The shortcoming here is that this is an evaluation of predominantly the wave-making characteristic. The viscous resistance due to wetted surface is not included.

The Selected Hull Form Evaluation Criteria (Cpe).

Cpe is the comparison of bare hull resistance to that of an equivalent Taylor Standard Series Ship [4]. The advantage of this comparison is that the TSS accounts for variations in speed, length, displacement, prismatic coefficient, and beam draft ratio. Furthermore, the TSS has worldwide recognition and acceptance and the entire series has been formulated in computer code so that calculation of the TSS Ship performance is simple and quick.



Taylor Standard Series Parent Hull

The Taylor Standard Series has a parent hull (see above) based on the British vessel LEVIATHAN. Mathematical models, a total of 158 in the original series that varied beam-draft ratio, prismatic coefficient and length –beam ratio were built and tested.

Later the series was expanded to an even higher beam-draft ratio. It is recognized that the hull shapes are limited and reflect the practice of an earlier era. The importance of the TSS for our use lies not in the absolute value of the test result, but in the fact that it is a widely accepted and available database which systematically accounts for major hull parameter variations. Thus it will be simple to formulate requirement statements for the resistance of the hull relative to a TSS hull. The HDDS database can give guidance with regard to how much better the hull performance should be relative to the Taylor Standard Series ship.

In calculating Cpe, the same value of Correlation Allowance, Ca, is used for both the Taylor ship and the proposed ship under evaluation. Thus the Cpe value has the desirable characteristic of being insensitive to the value of the selected correlation allowance. In contrast, measures of merit that are based on absolute values of predicted power are always dependent to some degree on the selected correlation allowance value.

In addition, for the Cpe calculation the normal 'Froude" method of extrapolating resistance has to be used, along with the customary ITTC 1957 Ship – Model Correlation line for frictional extrapolation. Thus the burden of determining form factors for unusual hull configurations is avoided and the method can be used for hull forms that are inappropriate for the form factor method of resistance extrapolation.

Development of Curves of Cpe

At the early stages, it was decided to use the resistance coefficient Cpe to compare hull form performance. This coefficient compares the resistance of the proposed hull form to that of an equivalent "Taylor's Standard Series" hull form [4].
Since the TSS hulls were based upon a very good parent hull having a small bulb, and narrow V-shaped transom, to achieve a value better than Taylor (i.e. <1.0) is a challenge, especially considering the stability and mission requirement of modern ships, such as Ro-Ros and container vessels. To better the Taylor Standard Series by 5% to 15% will certainly indicate a very superior design.

The graphs of Cpe Vs V/L**0.5 are shown in Figures 1 - 6. These are divided into ship types (see explanation below). Each graph has three guidance curves displayed in heavy lines. These are explained as follows;

Upper Design Curve... this marks the upper limit of acceptability. To arrive at this curve, roughly 30% of the poorer designs were considered unacceptable.

Optimum Design Curve...this curve marks the lower limit, of the very best designs contained in the HDDS database. To achieve these energy efficient designs should be the goal of all ship designers.

Mean Design Curve...this curve is the mean between the Upper Design Curve and the Optimum Design Curve. Therefore it is considered a good design, although not outstanding.

Ship Types. (For Monohulls only)

For convenience, ships are grouped into six unique types. These are 1) Large Combatants, 2) Aircraft Carriers, 3) Combatants, 4) Single Screw Merchants, 5) Twin Screw Merchants, and 6) Trawlers/ Minesweepers/ Oceanographic Vessels.

1) Large Combatants/ Commercial ships. Battleships, cruisers, and generally all large vessels over 500 feet in length. (BB, CA, CG, also large commercial ships such as container vessels, Ro-Ro's and ULCC's)

2) Aircraft Carriers. Non nuclear.

3) Combatants. Destroyers, small cruisers, frigates, cutters. Generally between 250 and 600 feet in length. (DE, DD, DDG, FFG, etc)

4) Single Screw Merchants and Auxiliaries. Most single screw ships. T-ships, oilers, tankers, container ships and Ro-Ro's. (AO, AE, AF, AFS, AG, AKA, AOR, ASR, T-ships, Hospital ships)

5) Multi Screw Merchants and Auxiliaries. Most multi screw ships. T-ships, oilers, tankers, container ships and Ro-Ro's. (AO, AE, AF, AFS, AG, AKA, AOR, ASR, T-ships, Hospital ships)

6) Trawlers/ Minesweepers/ Oceanographic Vessels. (MCM, MSO, MSH, T-AGOS, T-AGOR, ARS, etc.)

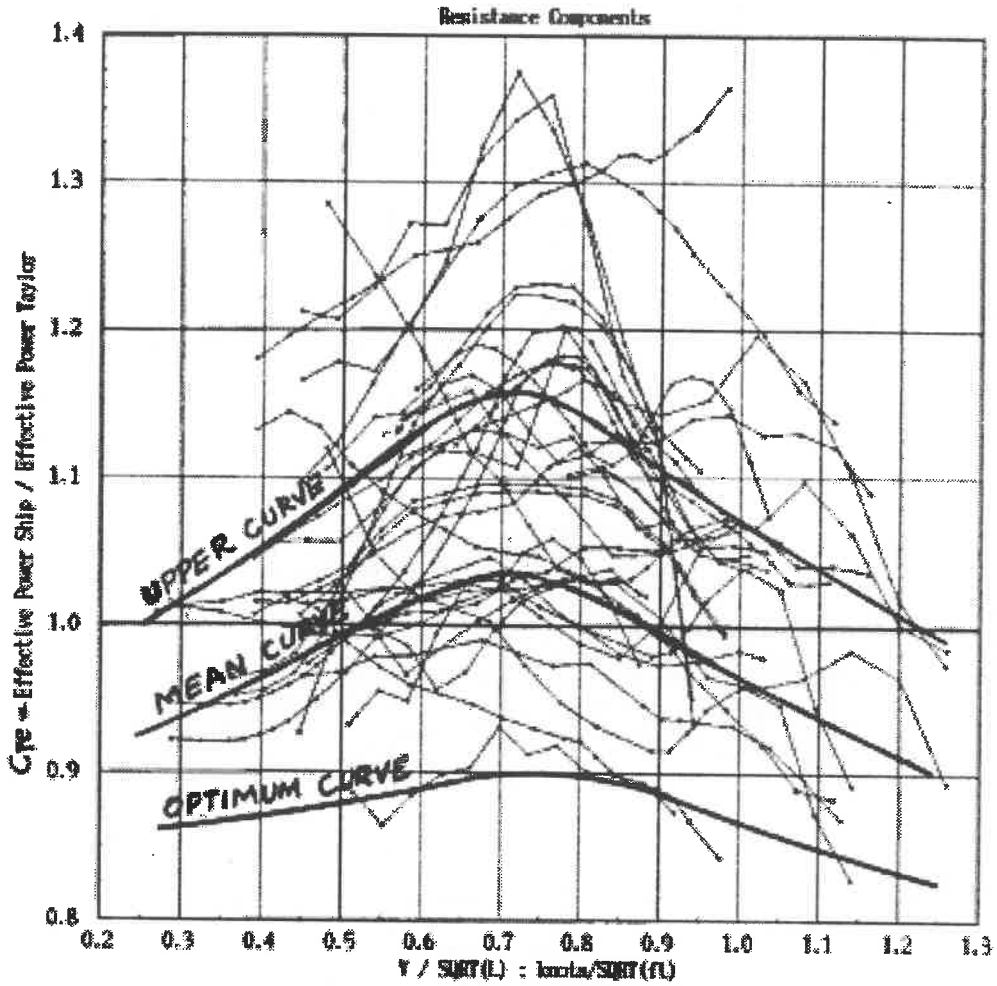


Figure 1. LARGE COMBATANTS (35 HULLFORMS)

Parameter	Range
Length (Lwl)	440 –780 feet
Beam (Bx)	63 – 106 feet
B/T	3.0 – 7.0
Disp/(0.01L)**3	40 - 194

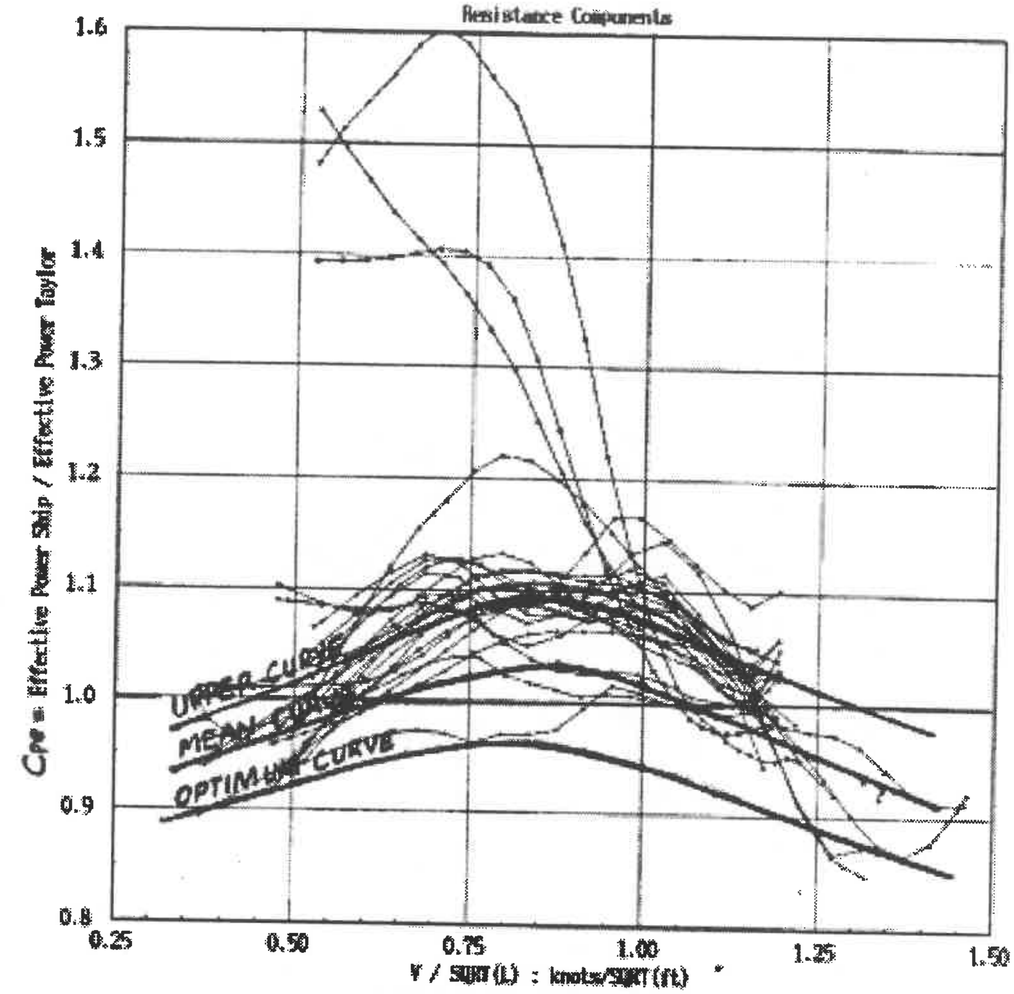


Figure 2. AIRCRAFT CARRIERS (26 HULLFORMS)

Parameter	Range
Length (Lwl)	416 – 816 feet
Beam (Bx)	70 – 105 feet
B/T	3.0 – 4.7
Disp/(0.01)**3	53 - 121

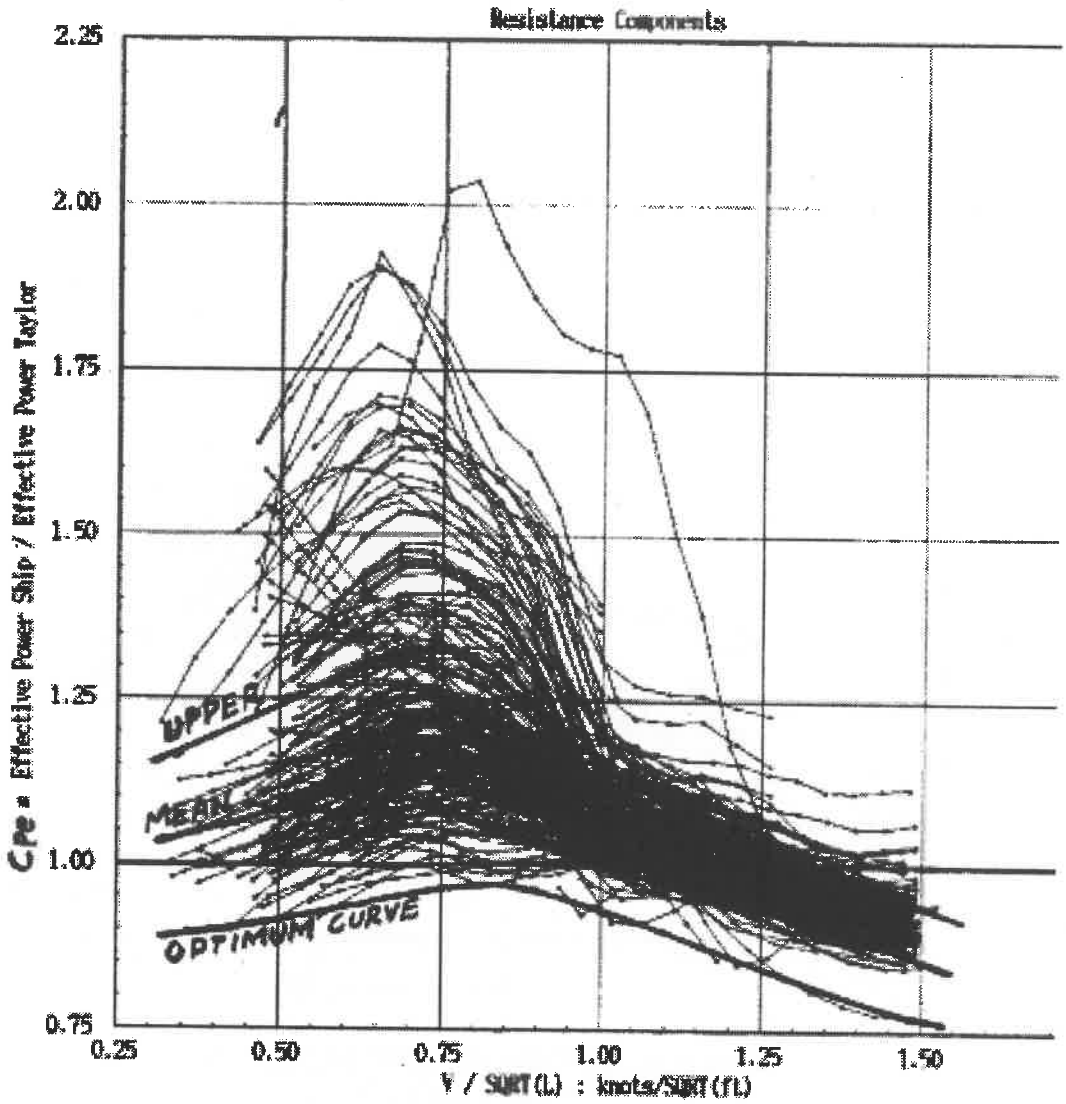


Figure 3. COMBATANTS

(246 HULLFORMS

Parameter	Range
Length (Lwl)	245 – 574 feet
Beam (Bx)	33 – 71 feet
B/T	2.0 – 4.2
Disp/(0.01L)**3	25 - 101

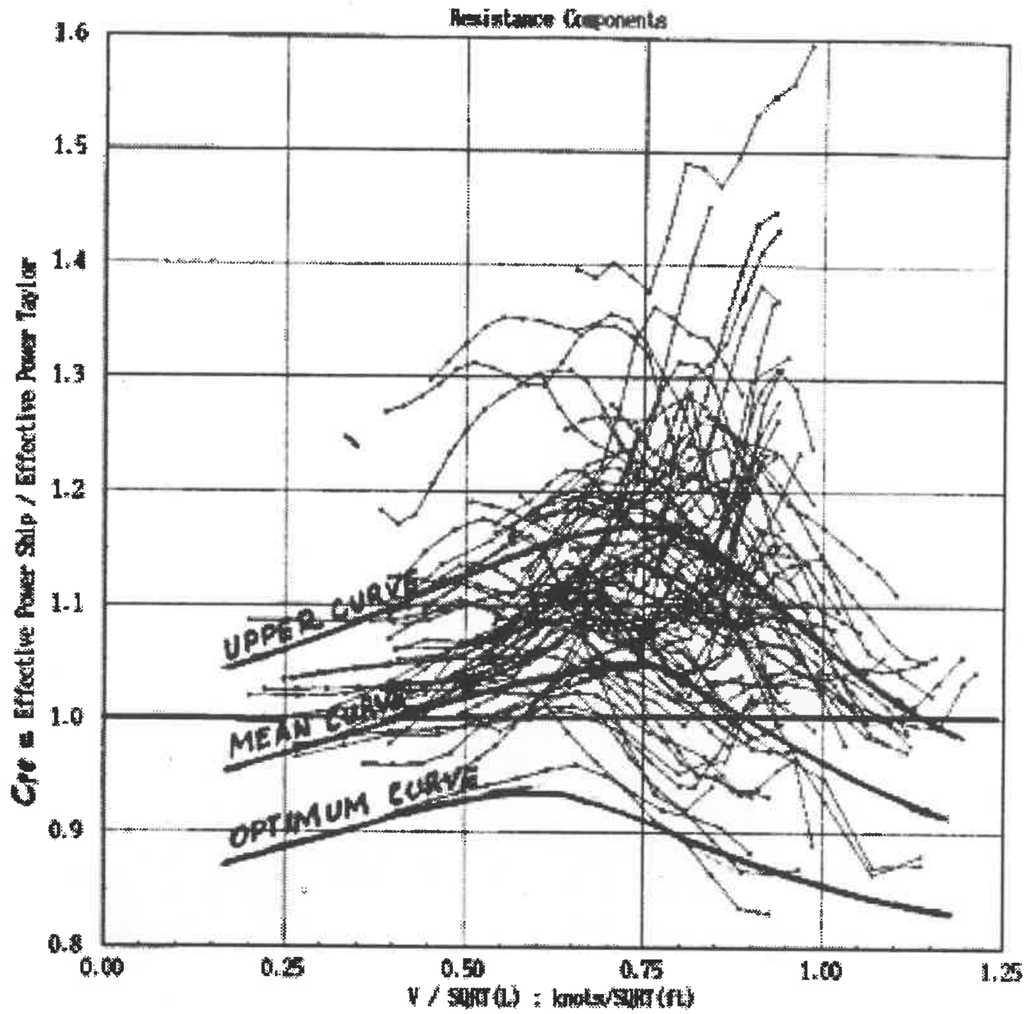


Figure 4. SINGLE SCREW MERCHANTS (101 HULLFORMS)

Parameter	Range
Length (Lwl)	300 – 790 feet
Beam (Bx)	50 –106 feet
B/T	2.3 –4.4
Disp/(0.01L)**3	80 - 230

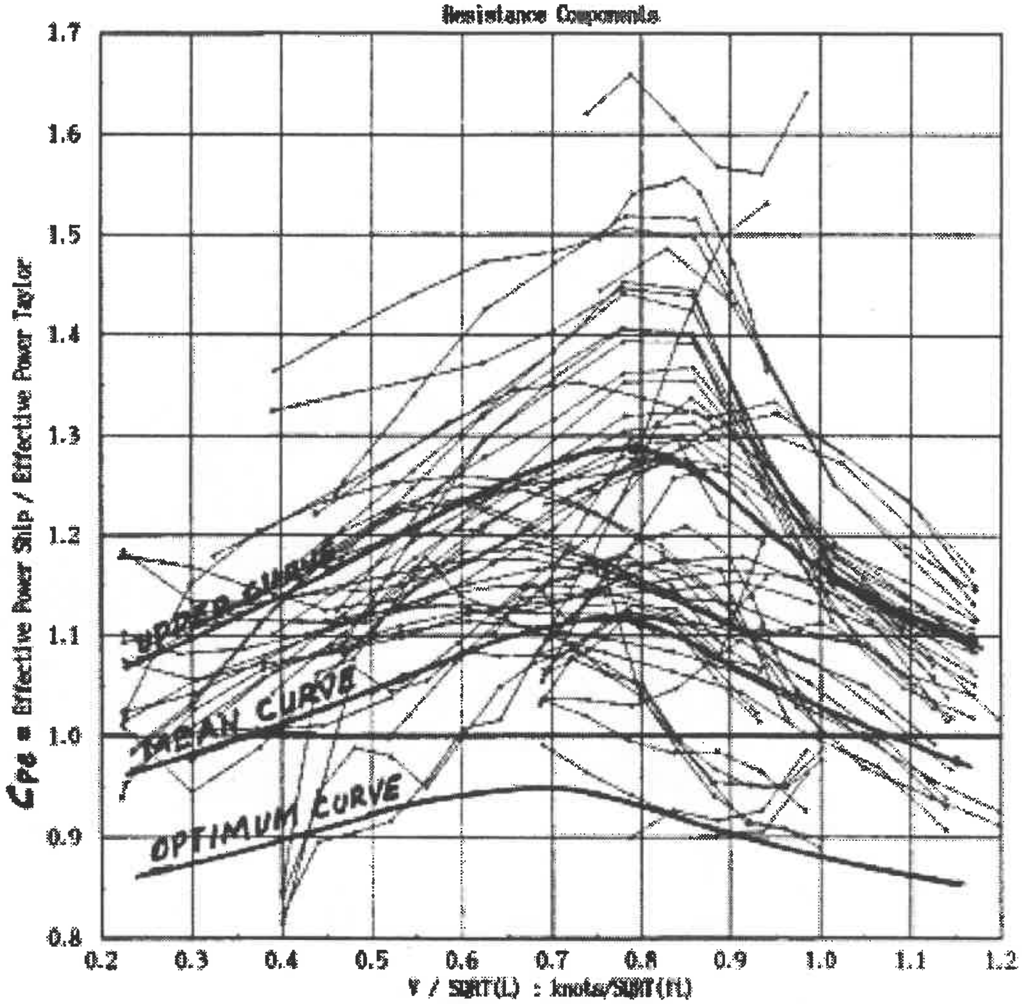


Figure 5. MULTI-SCREW MERCHANTS (74 HULLFORMS)

Parameter	Range
Length (Lwl)	300 – 930 feet
Beam (Bx)	55 – 107 feet
B/T	2.4 –4.8
Disp/(0.01L)**3	60 - 340

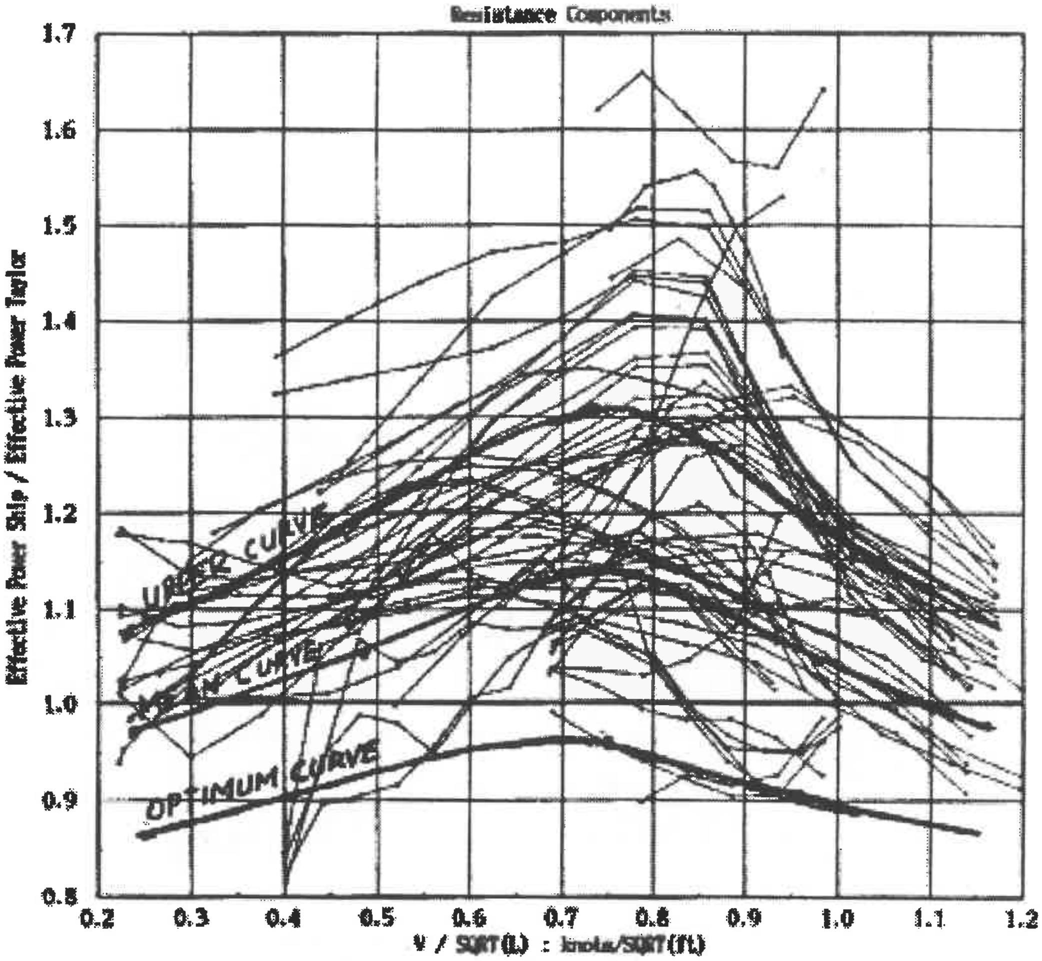


Figure 6. TRAWLERS, MINESWEEPERS, OCEANOGRAPHIC (53 HULLFORMS)

Parameter	Range
Length (Lwl)	100 – 200
Beam (Bx)	22 – 38
B/T	2.3 – 4.6
Disp/(0.01L0**3	90 - 280

Comment on the Cpe data

The data presented in figures 1 though 6 are self explanatory in the way that the resistance is presented relative to the "Taylor" ship. There is a general trend among all the figures in that for a particular ship type, the performance of the best ships in the database is better (15-20%) than that of the "Taylor" ship at high speed. At medium speeds, the performance of the best ships is only slightly (5-10%) better than the Taylor ship. This observed trend may be due to the combination of the following factors:

-The Taylor ships have narrow transoms and just a very small "Taylor " bulb or no bulb. These features tend to contribute to good medium speed performance, but do not enhance high-speed performance.

- Many ships in the database have good bulbous bows designed to current standards and some also have pram afterbodies with wide transoms. These features tend to enhance maximum speed performance, sometimes at the expense of a small penalty in medium speed performance.

The general trend of all the data is that there are many ships, which have resistance values that are significantly greater than that of the Taylor ship. This can be explained by either poor design or by other overriding naval architectural constraints, which result in increased resistance.

Proposed Use of the Cpe Curves

The following proposed usage is given to illustrate ways in which the data can be used in ship design and ship acquisition.

1) Select Characteristics of Proposed Hull Form.

The designer will select the basic hull form characteristics, such as length, beam, design draft, LCB, Cb, Cp, displacement, design speed, transom width and depth, bulbous bow, etc. These will reflect the mission of the ship, and the designer's previous experience. Often the shipyard or owner will obtain expert assistance in the design of the hull form.

2) Define V/ L**(0.5) for Two Speeds.

There are two critical speeds at which the design shall be checked.

The first is the ship's design speed, Vd, the speed for which the power plant is designed. This is normally the speed which can be attained at 80% to 90% of the engine's maximum continuous rating (MCR), with the ship at the design draft, having a clean hull in calm, deep seawater.

The second speed can be named as the "fuel optimum speed", Vo. This is the speed at which most of the ship's fuel is used, considering the mission of the ship (speed-time profile) and the fuel rate. The "fuel optimum speed" is shown below in graphical form (Fig. 7). A good approximation is 70% of the design speed, but this can vary greatly, according to the ship's mission.

For each speed, the speed-length ratio (V/ L**(0.5)) shall be calculated. Fuel optimum speed (Vo)...some examples for various types of ships:

Type of Ship	Vd (knots)	Vo (knots)	Vo/Vd
Combatants	29	14	0.48
Trawlers	12	11	0.91
Ro-Ros	20	15	0.75
Containers	22	18	0.82
Oceanographic	15	10	0.66
SS Merchants	18	15	0.83
Carriers	30+	20	0.66

The examples given above are for general guidance only, and it should be stressed that the owner should provide the naval architect with adequate guidance as to the ship's mission, loading, and operational speeds so that the values of Vo and Vd can be closely approximated.

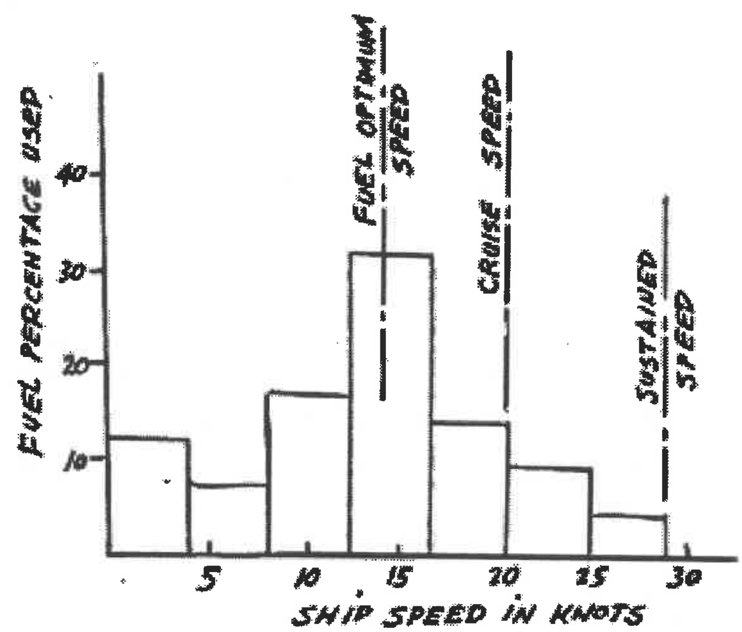


Figure 7
Typical Speed-Fuel Profile for Combatant

3) Calculate EHP (bare hull) for the Design. (PE (ship))

The designer, using the DTRC method will make an estimate of the bare hull resistance, at both of the critical speeds.

4) Calculate EHP (bare hull) for the equivalent TSS design. (PE (Taylor))
Using Reference 3, and the DTRC method, calculate the bare hull resistance for the equivalent TSS hull form (same B/T, Cp, and Disp./(0.01L)**3).

5) Calculate the Resistance Coefficient Cpe
The Resistance Coefficient is the ratio of
Ship bare hull resistance/Taylor design bare hull resistance

Or Cpe = PE (ship)/PE (Taylor)

The Cpe values shall be calculated at the two critical speeds.

6) Determine Ship Type.
Make a selection among the seven ship types, which most closely fits your design. If your ship design is multi-hull, then this procedure does not apply.

7) Compare to Cpe values for Your Specific Ship Type.
The curves given in Figures 1 through 6 show lines of "Acceptable", "Mean", and "Optimum" values of Cpe plotted on a base of V/ L**(0.5). If your calculated Cpe for each of the two critical speeds is below the "acceptable" curve, then the hull form is in the "good" range. However it would be prudent to allow a reasonable margin at this stage, since the Cpe are based upon predicted PE (bare hull), and these predictions could be optimistic at this point of the design.

If the calculated Cpe were in the "unacceptable" range, then hull form modifications would be required. Guidance for these modifications can be obtained from several sources: Historic databases (such as the navy's HDDS program [2]); expert consultants; model test facilities (such as NSWCCD), and SNAME Model Resistance Data Sheets [5]. At the end of this paper, some more detailed guidance is given, to enable the naval architect to improve the hull form.

8) Recalculate EHP (bare hull) for the Modified Design.
When this is done, then proceed through steps 3) through 7) as given above.

Typical Worked Example The following is an example of how the procedure would work in "real life". For the example we have selected to design a trawler, whose particulars are as follows:

Lwl = 180 ft (54.86m); Bx = 30.0 ft (9.11m)
Tx = 10.0 ft (3.05m); Disp.= 690 tons (701 tonnes)
Cb = 0.45, Cp = 0.59
Design Speed, Vd = 12 knots (Vd/L**0.5 = 0.89)
Fuel Optimum Speed, Vo = 11 knots (Vo/L**0.5 = 0.82)

The body plan of the proposed trawler is shown below (Fig. 8)
We have intentionally picked one of our "worst" designs in the HDDS database, to illustrate this method.

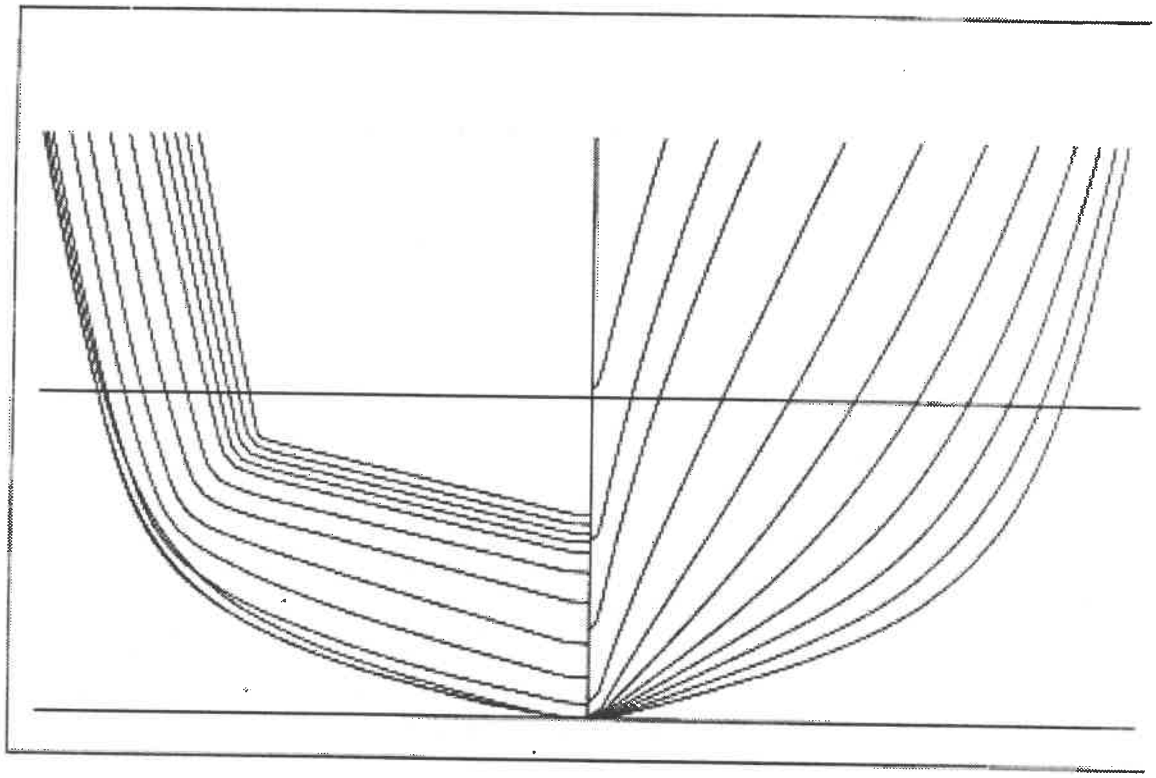


Figure 8

"Poor" Trawler Design
Body Plan

Following Step 3) of the method, and referring to fig 9, we predict:

PE (ship) = 394 HP at 12 knots (Vd)
PE (ship) = 297 HP at 11 knots (Vo)

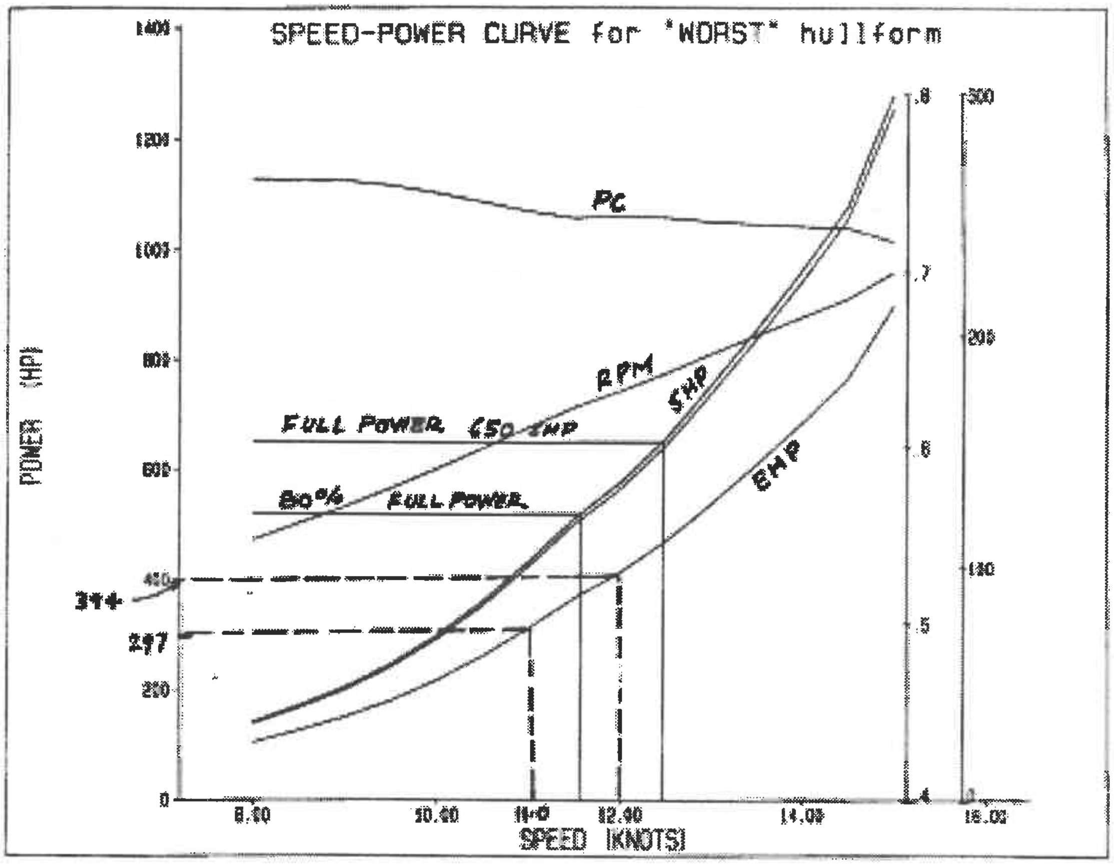


Figure 9
Speed-power curves for "Poor" Hull form

Step 4) Calculating TSS resistance, we have:

PE (Taylor) = 298 at 12 knots
PE (Taylor) = 216 at 11 knots

Step 5) Resistance coeff, Cpe = 1.32 at V/L**0.5 of 0.89
Cpe = 1.38 at V/L**0.5 of 0.82

Step 6) Checking against Fig. 6; it is apparent that both Cpe values are above the "Acceptable" curve. Thus redesign is required. Fig. 10 is the result of a search using HDDS to find a more optimal trawler hull form. Fig. 11 shows the best and worst trawler hulls discovered by this particular search. Note that both the best (good) and worst (poor) hulls in Fig. 12 meet the hull size and displacement requirements given above.

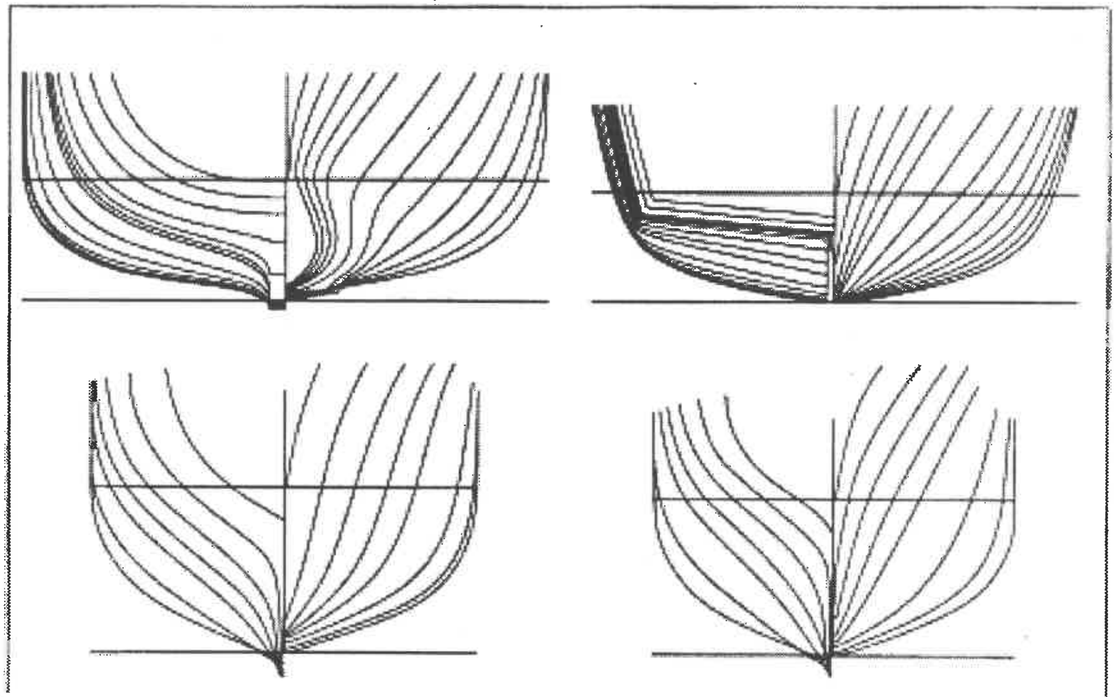


Figure 10
Sample Hull Forms from Search

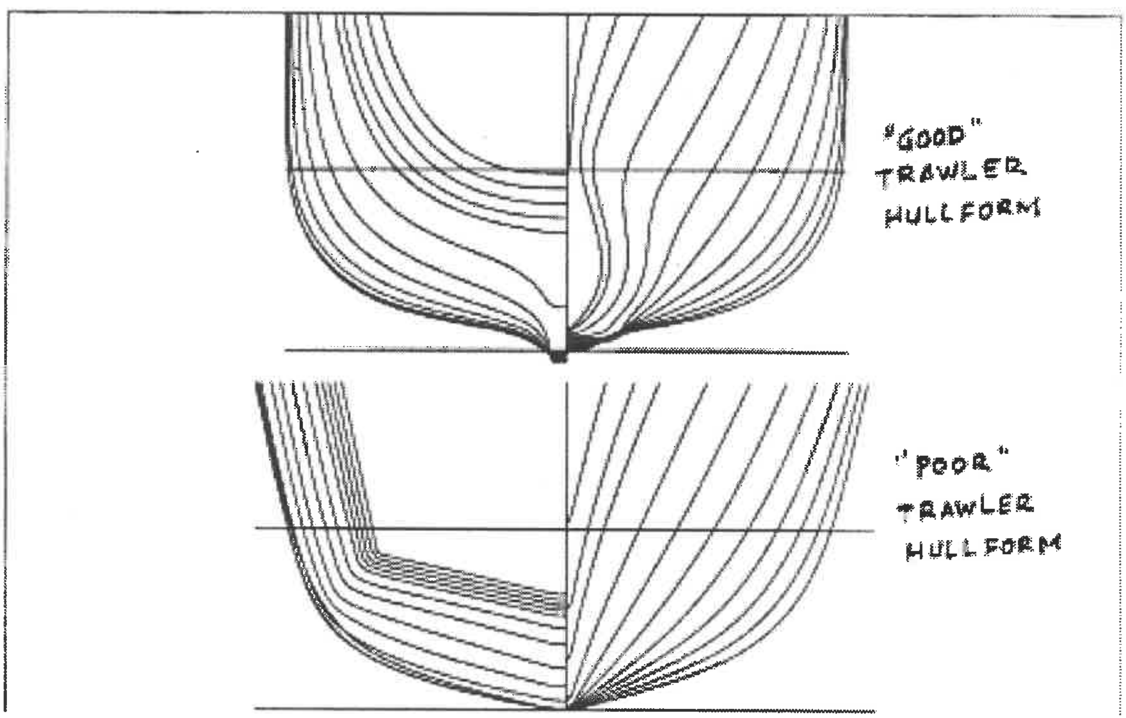


Figure 11
"Good" and "Poor" Trawler Hull Forms

The hull form differences in the above figure are significant. The poor hull has a large transom area, tight curvature at the transom, and sharp V-lines forward. Also it has a pronounced flare in all its sections. The "good" hull form has almost zero transom area, large radiussed sections, a small Taylor type bulb, and tumblehome. Note also the very fine angle of entrance at the bow.

Calculation of the PE for the "good" hull form is shown graphically in Fig. 12, and arrives at the following values

PE (ship) = 327 HP at 12 knots
PE (ship) = 235HP at 11 knots

Resistance Coeff. Cpe = 1.10 at V/L**0.5 of 0.89
Resistance Coeff. Cpe = 1.09 at V/L**0.5 of 0.82

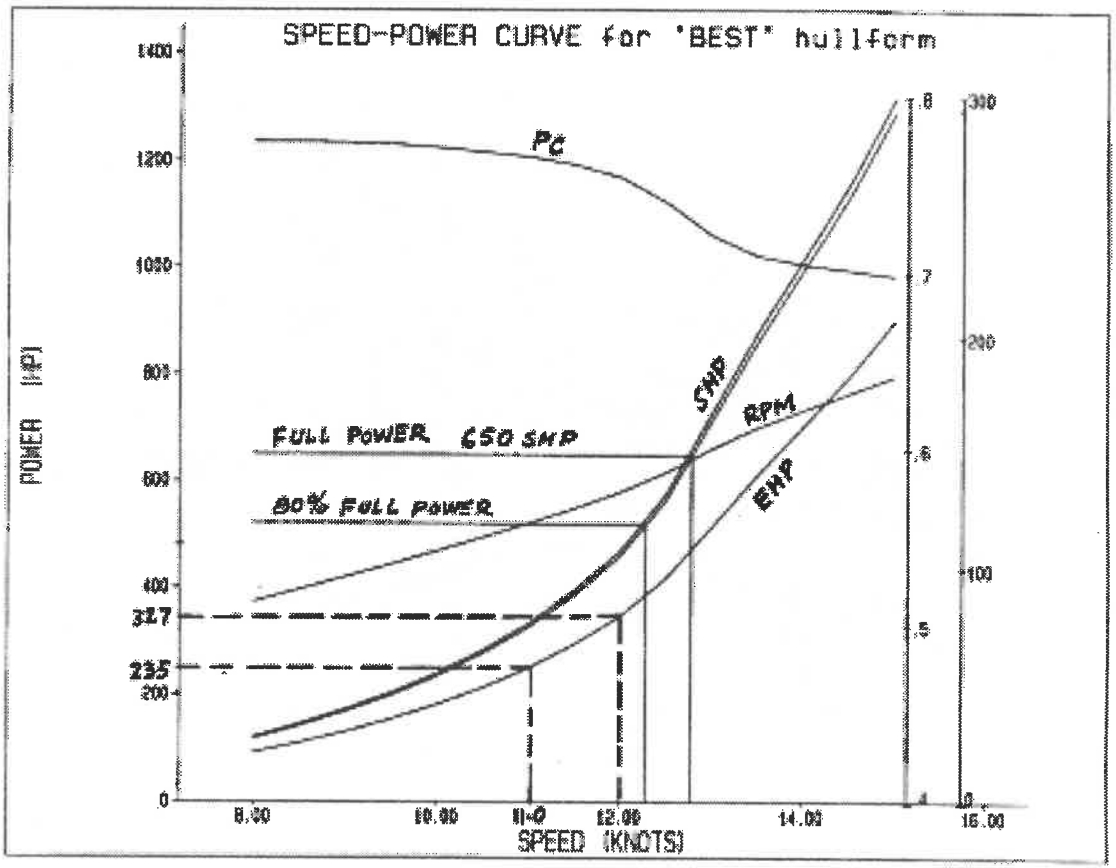


Figure 12
Speed-power curves for "good" hull form

Plotting the values of Cpe on Fig. 6, we arrive at Fig. 13, which shows the Cpe values for the redesigned trawler hull, compared to the design guidance lines. It is significant to note that, at the fuel optimum speed of 11 knots (V/L**0.5 of 0.82) the Cpe value is better than the average for the group, but not yet approaching the optimum (bottom) curve. Further improvements could still be made, but the redesigned trawler is well within the "good" design band, with a reduction in fuel of about 26% compared to the initial design. With some more careful design, and using HDDS further, a fuel savings of up to 40% could be achieved.

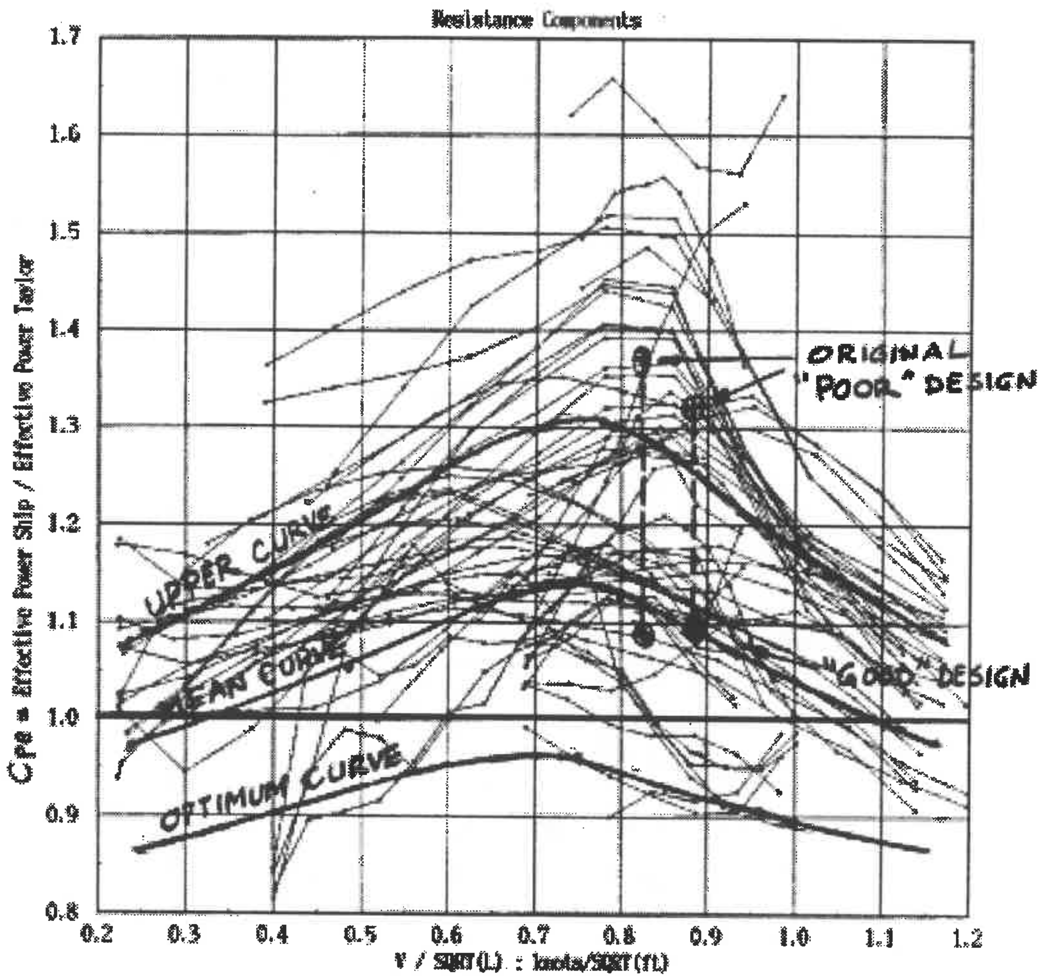


Figure 13
Plot of Cpe values for "poor" and "good" hull forms

Lessons Learned from "Best" Designs of HDDS.

Quote from 1962 PNA Vol. II, p. 106 [3]

"*..at least as much can be accomplished by careful designing and judicious choice of proportions as by introducing pronounced peculiarities*". In other words,"*Get it right the first time!*".

The "add-on" modifications to a hull form can certainly help to smooth out the flow, cancel the bow wave at certain speeds, and produce better flow into the propeller. These are all desirable, but the basic selection of the hull coefficients, such as Cp, Cx, B/T, L/B, and the volumetric coefficient are essential to good design. It is important to remember the shape of the sectional area curve should be studied carefully, so as to avoid discontinuities in the flow around the hull form.

Specific actions, which can be helpful in obtaining the optimum hull form, are as follows:

a) Use HDDS as a tool to find a good parent hull form.

The worked example given in this paper illustrates how HDDS can be used to arrive at an improved hull form. Some of the data contained within HDDS is considered proprietary. However a majority amount of the data is non-proprietary. HDDS can be accessed via NSWC, Carderock Division

b) Use regression equations to optimize certain parameters.

References [6] and [7] document the hull form regressions developed by Fung. Another good source for combatants is Aughey's regression [8]. Doust [9] was a pioneer in this field in 1959. These equations can be extremely helpful in determining bare hull resistance for the hull being considered. They can also be used to predict the effect of parametric changes, such as the reduction of transom area. The reports cited can be most helpful to determine more correct values for key design parameters.

c) Explore hull additions/appendages.

The use of bulbous bows to cancel bow waves can be effective if properly utilized. Many reference papers can be used, however Dr. Kracht's [10] is probably the most comprehensive source of model test data on bulbs. Final bulb designs should be tweaked according to recent design practices.

The use of transom wedges and flaps has been shown [11] to be effective for combatants.

d.) Use computational methods to optimize the hull

Once the parent hull has been tweaked with the assistance of data bases and published hull design data it is recommended to use modern computational methods to modify the hull slightly for improved performance. Letcher et al [12] shows the application of computational fluid dynamics to sailing yacht design. Wyatt and Chang [13] very successfully developed a low resistance fore body and bulbous bow for a high speed container ship hull form. Yang et al [14] use the same type of slender ship approximation theory for multi hull optimization.

Other free surface potential flow codes have been used to minimize hull drag . The SWIFT code has been used at NSWCCD [15,16,and17] to minimize the wave resistance. The code can be used to evaluate hull form changes and help with the design of bulbous bows. On slow, full ships, viscous flow codes are needed to minimize flow separation. In general, the combined free surface viscous flow codes are just being developed and are not yet being used in general ship design.

In the hands of experienced users, even simple flow codes can be effective in improving the performance of a hull form. In all of these optimizations, one must have an initial geometry or parent hull. HDDS and other databases can be a good source for these parent hulls. Efforts to computationally generate the parent hull from basic first principles are in their infancy and have not yet been applied to general ship design.

Typical Use of the Cpe Metric in Ship Specifications.

Based upon the guidance given in this paper, it is a relatively easy matter to provide specification guidance for shipyards, ship owners, and the U.S. and other navies, to ensure that the designs produced meet a desired level of hull performance and fuel efficiency. A few suggested "specification" formulations are given below.

For a Trawler design: "The ship shall be designed such that the following criteria are met for an efficient hull design: The values of Cpe (Effective Power, Ship/Effective Power, Taylor Std. Series) shall not exceed the value of 1.08 at a speed of 12 knots, and also not exceed 1.0 at a speed of 15 knots. These values of Cpe shall be demonstrated by model testing of the ship at the design displacement, using the NSWC method of predicting full-scale resistance ."

For a Combatant design: "The ship shall be designed such that the following criteria are met for an efficient hull design: The values of Cpe (Effective Power, Ship/Effective Power, Taylor Std. Series) shall not exceed the value of 1.05 at a speed of 14 knots, and also not exceed 0.95 at a speed of 28 knots. These values of Cpe shall be demonstrated by model testing of the ship at the design displacement, using the NSWC method of predicting full-scale resistance ."

For a Container Vessel design: "The ship shall be designed such that the following criteria are met, for an efficient hull design: The values of Cpe (Effective Power, Ship/Effective Power, Taylor Std. Series) shall not exceed 0.98 at a speed of 20 knots in the full load condition; and shall not exceed 0.95 at a speed of 22 knots in the ballast condition. These values of Cpe shall be demonstrated by model testing of the ship at the appropriate loading condition, using the NSWC method of predicting full-scale resistance."

These above examples are given to demonstrate the potential simplicity of the Cpe metric for hull form evaluation. Prior to determining a specific value of Cpe for a specification, a custom search on the HDDS could be used to determine the most appropriate Cpe value that would be appropriate for a range of ship characteristic parameters which encompass that of the expected ship design.

Future Research in Ship Optimization.

The design of an energy efficient hull form is an important first step towards achieving an integrated ship with emphasis on fuel savings. Other aspects of the total ship's hydrodynamics which need to be optimized are: appendage design; propeller design; and hull-propeller interaction. It is hoped that funding will be available to address these areas, and combine them into an integrated metric for fuel efficient ships.

Also, depending on the mission of the ship, the hull form may have to be modified due to sea keeping requirements. This can often be accomplished without diminishing the resistance too adversely. Sea keeping in ship operations, and basic design guidance for destroyer-type hulls can be found in the open literature [for example;18,19].

Conclusions and Recommendations.

Based upon the simple guidelines contained herein, it is now easier for a shipyard or naval architectural firm to demonstrate the relative effectiveness of their proposed design.

The U.S. navy, any other navy, or a shipping owner can now have a tool by which to specify an energy efficient design, or to check proposals from other sources.

The coefficient, Cpe is a simple and direct measure of the hull's effectiveness, and can be initially validated by model testing, and finally (if required) by full-scale trials.

It is recommended that the Navy adopt this method to specify the energy efficiency of future hull forms.

It is also recommended that NSWC, Carderock Division is consulted, as required, to help define the critical speeds and to help select optimum hull forms, using HDDS and other tools.

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