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METHODS FOR THE NEW ANALYSIS OF THE ORIGINAL DATA FOR THE TAYLOR STANDARD SERIES

By

Morton Gertler

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NOTATION

The notation used in connection with the hydrodynam of ship powering has been subject to many changes in recent years. Accordingly, the tentative notation of the "Model Resistance Data Explanatory Notes," Project No. 2 of the Hydr mechanics Sub-Committee of the Technical and Research Committ of the Society of Naval Architects and Marine Engineers, March 1948, is followed, wherever possible.

Symbol	Description	Dimensions in Ma Length-Time Syst
L	Waterline length	L
B_M	Beam at midlength measured at the waterline	L
H	Draft measured at midlength	L
S	Wetted Surface Area	L^2
∇	Immersed Volume	L^3
A_M	Area of a transverse section at midlength	L^2
B_M/H	Beam/draft ratio	
C_P	Longitudinal Prismatic Coefficient	
C_V	Volumetric Coefficient	
C_S	Wetted Surface Coefficient	
C_M	Midship section coefficient	
v	Speed	LT^{-1}
V	Speed expressed in knots	
ρ	Mass density	ML^{-3}
ν	Kinematic viscosity	LT^{-2}
R_t	Total resistance	MLT^{-2}
R_f	Frictional resistance	MLT^{-2}
R_r	Residual resistance	MLT^{-2}

bol	Description	Dimensions in Mass Length-Time System
	Effective horsepower	
	Reynolds number	
	Total-resistance coefficient	
	Frictional-resistance coefficient	
	Residual-resistance coefficient	
	Roughness-allowance coefficient	
	Hydraulic radius of a channel	L
	Ratio of the ordinate at the forward perpendicular of the sectional area curve extended to the ordinate at the midship section.	
	Slope of the sectional area curve at the forward perpendicular	

METHODS FOR THE NEW ANALYSIS OF THE ORIGINAL DATA FOR THE TAYLOR STANDARD SERIES

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INTRODUCTION

Early in 1948 the David Taylor Model Basin started work on a new analysis of the original data for the Taylor Standard Series. This action was prompted by the decision of the American Towing Tank Conference (1)* to adopt the Schoenhe frictional-resistance formulation for use in predicting the effective horsepower of ships from model resistance test data. This decision, it was realized, would result in effective hors powers that were no longer directly comparable with those calculated from the existing Taylor Standard Series contours (2), and thus would diminish the value of the Taylor Standard Serie This would be unfortunate, since that series has been widely used for many years by naval architects for preliminary estimates of effective horsepower of ships and also as a criterior of the performance of proposed and existing ship designs.

To distinguish between the existing contours of residual-resistance per ton given in Reference (2) and the new presentation of resistance data, the former is referred to as the Original Standard Series and the latter as the Revised Standard Series throughout the remainder of this paper.

It has been known for some time that the Original Standard Series is subject to a number of errors due to the failure to compensate for changes in resistance caused by the variation in towing basin water temperature, for transitional flow occurring at the lower Reynolds numbers, and for restricted channel effects. Consequently, a complete revision of the Taylor Standard Series could be accomplished only by reanalyzi the original test data and not by directly converting the faired residual-resistance per ton contours.

The purposes of this paper are to describe the techniques which are being used to analyze the original data for the Taylor Standard Series, the significant parameters being used, and the proposed methods of presenting the data.

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* Numbers in parentheses indicate references on page 21 of this report.

A brief history of the Taylor Standard Series is given to acquaint the reader with the background and scope of the original work. The geometry of the vessels in the series is then discussed with special reference to the non-dimensional parameters which describe the overall characteristics of the vessels. The methods of precisely reproducing the offsets of the vessels lying within the range covered by these parameters are also discussed. Methods are presented for analyzing the original data and the proposed methods of presenting the resistance data for use by the profession are given. Finally, a method of converting the Revised Standard Series for use with other frictional-resistance formulations is given in an effort to anticipate future changes in the art.

HISTORY OF THE TAYLOR STANDARD SERIES

The original parent lines of the Taylor Standard Series were derived in 1906 from the sectional area curve, the waterline curve, and the profile of the British armored cruiser LEVIATHAN of the Drake Class together with a body plan derived from Taylor's mathematical lines (2). This parent was used to construct 38 models, designated Series 18, to investigate how the resistance of ships is affected by changes in longitudinal prismatic coefficient C_p, displacement-length ratio, and section area curve endings. The first alteration of the parent was accomplished by eliminating the bulbous ram bow. Twenty-five additional models, designated Series 19, were constructed from this parent and tested to determine how the resistance of ships is affected at various longitudinal prismatic coefficients and displacement-length ratios when a ram type of bow is used. The parent was finally altered by dropping the forefoot to the baseline, adopting a 3 per cent bulb, and moving the maximum section to midlength. This parent formed the basis of Series 20, 21, and 22. Series 20 consisted of 38 models with a constant beam/draft ratio B_M/H of 2.92 and varied C_p and displacement-length ratio. The series was tested in 1906 and the results of the tests were never published. Series 21 and 22 with B_M/H of 3.75 and 2.25, respectively, were then designed. These two series originally consisted of 80 models, which were tested in 1907. The results of these tests were made available in the first edition of Taylor's "Speed and Power of Ships", which was published in 1910. The scope of Series 21 and 22 was extended in 1913 and 1914 through the tests of 40 additional models. The results of the extended series were first published in the 1933 edition of Taylor's "Speed and Power of Ships" and are now familiar to the profession as the Taylor Standard Series Contours.

From the preceeding account it can be seen that the contours of residual-resistance per ton that form the Original Standard Series are based upon concepts existing in 1910. At that time the old Experimental Model Basin data from the 20-foot friction plane were used for the reduction of data in the model range, and the Tideman frictional resistance constants were used to predict the effective horsepower of the full-scale vessel.

In 1923, the Taylor Model Basin began to use the Gebe[illegible] frictional-resistance formulation for the calculation of fricti[illegible] al resistance in both the model and the ship ranges. This prac[illegible] tice continued through 1947. However, the validity of comparis[illegible] with the Standard Series was maintained through an empirical fac[illegible] denoted G, which brought the effective horsepowers calculated w[illegible] Gebers formula into agreement with those derived by the EMB-Tideman method. The present use of the Schoenherr formula make[illegible] no attempt at such an arbitrary factor and so the resulting effective horsepowers disagree considerably with those calculat[illegible] by the EMB-Tideman Method.

THE GEOMETRY OF THE STANDARD SERIES

Each model or prototype which forms a component part of a series and which is derived from a common set of parent lines must of a necessity be related geometrically to all of the other components. Consequently, before any attempt is made to analyze the resistance data for such a series, the geometric[illegible] properties of all members of the series must be consistent. Furthermore, the value of the series is greatly enhanced if the user can, with little effort, reproduce the offsets or lines of the vessel which corresponds to the resistance data in which he is interested. These rules have been strictly observed in the new analysis of the Standard Series data, and the results of these studies are described in detail.

Treatment of Geometrical Parameters

The geometrical parameters which are used to relate the resistance data in the original Taylor Series are: the longitudinal coefficient, C_P, the displacement-length ratio, beam/draft ratio, B_M/H, and the wetted-surface coefficient. In order to eliminate confusion new nondimensional coefficients were substituted for the displacement-length ratio and Taylor's wetted-surface coefficient. The displacement-length ratio is defined (2) as

$$\frac{\Delta}{\left(\frac{L}{100}\right)^3}$$

where Δ is the displacement in tons and applies to salt water whether the model or the full-scale ship is under consideration and

L is the waterline length in feet.

The displacement-length ratio therefore has the dimension of density. The parameter which has been chosen to replace the displacement-length ratio is termed the volumetric coefficient, C_V, and is defined as

$$\frac{\nabla}{L^3}$$

where ∇ is the immersed volume and

L is the waterline length.

The displacement-length ratio has been used for many years by members of the profession and consequently they are apt to associate numerical values of this ratio with certain types of vessels. The relation of the displacement-length ratio to the volumetric coefficient, C_V, is given in Figure 1 to provide an easy comparison of numerical values.

The Taylor wetted-surface coefficient is defined (2) as

$$\frac{S}{\sqrt{\Delta L}}$$

where S is the wetted-surface area in square feet,

Δ is the displacement in tons and applies to salt water whether the model or the full-scale ship is under consideration, and

L is the waterline length in feet.

Thus it has the dimension of the square root of the density. The proposed wetted surface coefficient, C_S, is defined as

$$\frac{S}{\sqrt{\nabla L}}$$

where S is the wetted-surface area,

∇ is the immersed volume, and

L is the length.

The numerical values of the Taylor wetted-surface coefficient with the proposed wetted-surface coefficient, C_S, are related Figure 1.

The values of the geometrical parameters for each mo composing the Standard Series were calculated from the dimensi given on the original displacement and wetted-surface calculat sheets. The values of C_P, midship section coefficient C_M, and B_M/H, were checked for consistency on each model and then were cross-faired with the values for all of the other models. The volumetric coefficient, C_V, was taken as a base in the cross-fairing, since each model was tested at a definite displacemen and consequently the immersed volume was constant except for a negligible change due to the temperature of the water. After the faired values of C_P were obtained, the values of wetted-surface coefficient, C_S, were faired on C_P and C_V for each B_M/H. The results of these fairings were prepared for final presentation as contours of C_S plotted on an abscissa of C_V and an ordinate of C_P, as shown in Figures 2, 3, and 4. A separate set of contours was prepared for each of the three B_M/H of 2.25, 2.92, and 3.75. The C_S for any Standard Series vessel within the scope of the contours can be obtained to an accuracy of four significant figures. The contours are especially enlightening as to the change in frictional resistance that can result from a change in form parameter, since the frictional resistance is a direct function of the wetted area of a vessel. Thus, from the standpoint of frictional resistan alone, it can be seen that for a given C_V an optimum C_P and B_M/H can be obtained.

Presentation of Lines or Offsets

The defined set of geometrical parameters is not sufficient to describe completely a ship shape, and thus an infinite number of sets of ship lines can be made according to prescribed values of C_P, C_V, and B_M/H. The given form can be precisely defined if the lines or offsets of the vessel are given. The method of obtaining the lines for the offspring of a given parent is suggested in Reference (2). This procedure, however, is tedious and is subject to much error. Furthermore the offsets given in Reference (2) which serve as the basis for reproducing vessels of other prismatic coefficients are not those of the finally revised parent used for the construction of the series models.

The objective of accurately reproducing the lines or offsets of any Standard Series vessel can be most satisfactori reached through the use of mathematical lines. Once a mathema ical fit has been made to sectional area curves, waterline curves, or body plan lines, interpolations can be made with a high degree of accuracy. It is known that the body lines of the parent of the Standard Series were mathematically derived (2). However, no mention has ever been made of the derivation of the sectional area curves which were used to accomplish the C_p variation in the series. Consequently it was considered worthwhile to obtain a fit to the offsets of the sectional area curves given in Reference (2) by the use of Taylor's mathematical lines. These lines are derived from the general equation of a fifth-degree parabola (3).

$$y = tx + ax^2 + bx^3 + cx^4 + dx^5 \qquad [1]$$

where t is the tangent at the forward of after perpendicular. If x and y, the nondimensional abscissa and ordinate, are taken to be unity at the half waterline length and half maximum area, respectively, then at unity the arbitrary constants a, b, c, and d can be evaluated to obtain the following equation:

$$\begin{aligned} y = &- 30x^2 + 100x^3 + 105x^4 + 36x^5 \\ &+ p\,(60x^2 - 180x^3 + 180x^4 + 60x^5) \\ &+ t\,(x - 6x^2 + 12x^3 - 10x^4 + 3x^5) \\ &+ \alpha_1\left(-\frac{x^2}{2} + 2x^3 - \frac{5x^4}{2} + x^5\right) \end{aligned} \qquad [2]$$

where p is the longitudinal prismatic coefficient and α_1 is the second derivative of the sectional area curve at $x = 1$.

Equation [2] may be rewritten as

$$y = C_y + pC_p + tC_t + \alpha_1 C_{\alpha_1} \qquad [3]$$

In Equation [3], C_y, C_p, C_t, and C_{α_1} are functions of x only and independent of the parameters p, t, and α_1. Consequently, tables can be prepared for a number of values of x for the bow half and the stern half of the sectional area curves. Then for a given value of longitudinal prismatic coefficient and selected values of t and α_1 the offset of the sectional areas curve, y, can be obtained at each tabulated value of x by solving Equation [3].

Since the values of t are known for each of the prismatic coefficients used for the Taylor series models (2) then the only unknown is α_1. Equation [3] can be used in solving for the values of α_1, first by considering α_1, as zero and then subtracting the values of y thus obtained from the ordinates of the sectional area curves listed in Referenc (2). The differences are equal to $\alpha_1 C_{\alpha_1}$ and since C_{α_1} is known for each value of x, a mean value of α_1 can be obtained which will give the best fit to the bow or stern half of the sectional area curve under consideration.

The sectional area curves have been defined by the preceding process with very good success. Agreement has been obtained generally within 1 in the third significant figure. This, for all practical purposes, represents the plottable accuracy of the sectional area curves from which the offsets (2) of the curves were originally obtained. The sectional area curve obtained from the mathematical lines is compared in Figure 5 with that given in Reference (2). Wherever the deviations are too small to be shown, they are indicated num ically on the curve.

Another property of the sectional area curve which is considered significant by many naval architects is the location of points of inflection. These can be accurately determined from the mathematically defined sectional area curve by Equation [4].

$$-x = \frac{42 - 72p + \alpha_1 + 4t}{36 - 60p + \alpha_1 + 3t}$$

The offsets of a Standard Series vessel of given prismatic coefficient from a parent with a different prismatic coefficient need no longer be obtained by the inaccurate graph ical method. Solutions can be accomplished algebraically by taking the values of y at each even value of x for the parent and solving for x in Equation [2], using the appropriate t and α_1 for the desired prismatic coefficient. The values of x thus obtained correspond to the stations whose body lines are the same as those of the chosen even stations of the parent. This calculation can be performed very easily on a production basis with the IBM calculating machines at the Taylor Model Basin. It is intended, therefore, to tabulate the offsets for each primatic coefficient between 0.48 and 0.86 in increments of 0.01 when the Revised Standard Series is finally presented.

ANALYSIS OF THE ORIGINAL RESISTANCE DATA

The original data from model resistance tests were reduced to nondimensional form by the method of Reference (4). The procedure is as follows:

The total resistance coefficient is defined as

$$C_t = \frac{R_t}{\rho/2\ Sv^2} \qquad [5]$$

where C_t is the total-resistance coefficient,
R_t is the total resistance,
ρ is the mass density, and
v is the speed.

It is calculated for each of the test values of resistance versus speed. The frictional-resistance coefficient is obtained from the Schoenherr formula

$$\frac{0.242}{\sqrt{C_f}} = \log_{10}(R_e \cdot C_f) \qquad [6]$$

where C_f is the frictional-resistance coefficient,
R_e is the Reynolds number, equal to $\frac{vL}{\nu}$,
v is the speed,
L is the waterline length, and
ν is the kinematic viscosity.

This coefficient is subtracted from the total-resistance coefficient to obtain the residual-resistance coefficient, or

$$C_t - C_f = C_r = \frac{R_r}{\rho/2\ Sv^2} \qquad [7]$$

where C_r is the residual-resistance coefficient and
R_r is the residual resistance.

It should be emphasized that the residual-resistance coefficient is defined as that which remains after the frictional-resistance coefficient of a flat plate is subtracted from the total-resistance coefficient of a vessel. Therefore, it is possible that this quantity may include not only wave-making resistance and eddy-making resistance but also the difference between the true frictional resistance of the vessel and the frictional resistance of the flat plate. As long as the frictional resistance coefficient versus Reynolds number curve for the vessel is parallel to that for the flat plate this need be of no concern when effective horsepowers are finally compared. However, when residual-resistance coefficients of two dissimilar vessels are directly compared the possibility of discrepancies due to the differences in frictional resistance should be considered, although it is believed at the present time that such discrepancies are of a small order of magnitude.

Because the procedure for calculating C_r had to be performed on the data from tests of 158 models, the necessary constants were supplied to the Computing Section at the David Taylor Model Basin and the calculations were made with an IBM card-punch computing machine. The residual-resistance co efficients thus calculated were plotted against speed-length ratio.

Temperature Corrections

One of the largest errors in the original Taylor Se is due to the failure to account for the effects of the basin water temperature. Since C_f computed from Equation [6] is a function of Reynolds number which in turn is affected by the kinematic viscosity of the water, it is necessary to know the temperature of the water. The basin-water temperature was not recorded on the data sheets of all the tests which were run prior to 1913. Consequently, it was necessary to make an estimate of the temperature. To accomplish this, a chart of water temperature in the Experimental Model Basin versus date was prepared and is shown in Figure 6. The chart, which cove a five year period begining with the time when the temperatur was first recorded at the Experimental Model Basin, or from about 1913 to 1918, indicates the maximum and minimum tempera tures by width of line. It can be seen that, although the temperatures ranged from 53F to 80F during a given year, the temperatures at a given annual date were generally repeated within 3F. Therefore, by weighting the averages, the assigne values of temperature are, in most cases, believed to be accurate to within 1F.

The temperature differential of 53F to 80F will, according to the Schoenherr Formula, cause a change in fricti al resistance of approximately 7 per cent on a 20-foot model. When it is considered that the frictional resistance on slow-speed vessels amounts to approximately 80 per cent of the total resistance, it can be readily seen that an attempt to cross-fair the remainder or residual resistance would become complicated and large distortion might result.

The temperature of the basin water will also affect the nature of the flow about the model, that is, whether or not appreciable laminar flow would exist. This is discussed in connection with the corrections for the effect of transitional flow upon resistance.

Transitional Flow Corrections

At the time when the original contours of the Taylor Series were prepared, no consideration was given to the problem of whether adequate turbulence existed in the boundary layer of a given model. Even at a comparatively recent date, it was believed that with a 20-foot model and the average basin water temperatures, Reynolds numbers which were high enough for adequate turbulence were attained. Recent studies have shown, however, that the resistance is affected by transitional flow on even larger models, especially at Reynolds numbers below 6×10^6. Consequently, in reanalyzing the original data, an attempt was made to correct for this effect. The procedure was as follows: The C_r is plotted against speed-length ratio as shown in Figure 7. An assumption is then made that the C_r is constant at low speeds. This assumption is considered valid since the residual resistance is largely eddy-making resistance, which apparently varies as the square of the speed beyond transition. The question then becomes: where does the constant portion of the curve begin? Fortunately, in most cases, the transitional portion of the curves approaches the turbulent curve asymptotically and a short length of the constant portion of the curve still remains. This short length of curve is then drawn horizontally to the lower speed-length ratios.

As seen in Figure 7, curve A apparently needs no alteration since it continues to be constant at low speed-length ratios. This indicates that turbulent flow was attained with this model owing to one or more of the variables: the higher water temperature, the shape of the model, the initial turbulence in the basin, etc. Curve B, however, drops off considerably below a speed-length ratio of 0.55, which corresponds to a Reynolds number of 8.3×10^6 for the test. Consequently the value which occurs at the speed-length ratio of 0.55 is continued at the lower speeds as shown by the broken line. This procedure serves as a good approximation of the resistance that would have been obtained with turbulent flow. The procedure was used on a number of recent tests of 20-foot models which were towed with and without a turbulence device. Excellent agreement with the faired residual-resistance coefficient curve and that resulting with the turbulence device was attained in nearly every case. Furthermore, since the residual-resistance coefficient curves for each model in the series are related to the curves for all of the other models, the constant value of each curve can be more precisely determined by cross-fairing.

Restricted Channel Corrections

It has long been suspected that the U. S. Experimental Model Basin was not large enough in cross section for towing full-bodied 20-foot models without getting some restricted-channel effect. To compensate for this, the faired C_r curves were corrected by the semi-empirical method of Reference (5). This procedure was developed for the general case and is too cumbersome for application to a large mass of data. Consequen the following new procedure, which greatly simplifies the restricted channel corrections, was developed.

The corrections for restricted-cahnnel effect are based upon two assumptions (5), which may be summarized as follows:

1. The theoretical assumption that the wave-making resistance at Schlichting's intermediate shallow-water speed, v_d, is equal to the wave-making resistance at a corresponding speed in deep water, v_∞. The relation between v_d and v_∞ is given from the wave theory by the formula

$$\left(\frac{v_d}{v_\infty}\right)^2 = \tanh\left(\frac{gd}{v_\infty^2}\right) \qquad [8]$$

where d is the depth of the channel and
g is the acceleration due to gravity.

2. The empirical assumption that the change in displacement flow around the ship hull due to limitations in dept or width of the channel necessitates a correction to the inter mediate speed, v_d, to give the speed v of the ship relative to the channel. This connection is derived from tests in restric channels and is given as an empirical curve of the form

$$\frac{v}{v_d} = \phi\left(\frac{\sqrt[3]{A_M L}}{r}\right) \qquad [9]$$

where A_M is the midship section area of the vessel,
L is the waterline length, and
r is the hydraulic radius and is equal to

$$\frac{wd - A_M}{w + 2d + p}$$

where w is the width of the channel and
p is the wetted girth of the vessel at the midship secti

The first assumption may now be restated as follows:

$$R = R_{t_\infty} - R_{f_\infty} + R_{fd} \qquad [10]$$

where R is the total resistance in the restricted channel,
R_{fd} is the frictional resistance in the restricted channel at a Reynolds number based on the intermediate speed, v_d,
R_{t_∞} is the total resistance in an unrestricted channel, and
R_{f_∞} is the frictional resistance in an unrestricted channel.

By substitution,

$$R_r + R_f = R_{r_\infty} + R_{fd} \qquad [11]$$

where R_r is the residual resistance in the restricted channel,
R_f is the frictional resistance in the restricted channel, and
R_{r_∞} is the residual resistance in an unrestricted channel, and

$$R_{r_\infty} = R_r + R_f - R_{fd} \qquad [12]$$

since

$$R_{r_\infty} = \rho/2\ S\ v_\infty^2 \ x\ C_{r_\infty} = K\ v_\infty^2 \ x\ C_{r_\infty},$$

$$R_r = \rho/2\ S\ v^2\ x\ C_r = K\ v^2\ x\ C_r,$$

$$R_f = \rho/2\ S\ v^2\ x\ C_f = K\ v^2\ x\ C_f, \text{ and}$$

$$R_{fd} = \rho/2\ S\ v_d^2\ x\ C_{fd} = K\ v_d^2\ x\ C_{fd}$$

where the subscript on the residual and frictional-resistance coefficients denotes the speed upon which the coefficient is based, then from Equation [12]

$$Kv_\infty^2\ C_{r_\infty} = K\ v^2\ C_r + K\ v^2\ C_f - K\ v_d^2\ C_{fd} \qquad [13]$$

and rearranging

$$C_{r_\infty} = C_r\left(\frac{v}{v_\infty}\right)^2 + C_f\left(\frac{v}{v_\infty}\right)^2 - C_{f_d}\left(\frac{v_d}{v_\infty}\right)^2 \qquad [14]$$

or

$$C_{r_\infty} = C_r\left(\frac{v}{v_\infty}\right)^2 + C_f\left(\frac{v}{v_\infty}\right)^2 - C_{f_d}\left(\frac{v_d}{v_\infty}\right)^2\left(\frac{v_\infty}{v}\right)^2\left(\frac{v}{v_\infty}\right)^2 \qquad [15]$$

and

$$C_{r_\infty} = \left\{C_r + \left[C_f - C_{f_d}\left(\frac{v_d}{v}\right)^2\right]\right\}\left(\frac{v}{v_\infty}\right)^2 \qquad [16]$$

$$= \left(C_r + \Delta C_r\right)\left(\frac{v}{v_\infty}\right)^2 \qquad [17]$$

If now the data are taken to apply to a model of constant length or 20.51 feet in the case of the Standard Series models, a set of contours of speed-length ratio plotted against ΔC_r and $\frac{\sqrt[3]{A_M L}}{r}$ can be prepared as shown in Figure 8a. Furthermore, the cross section of the U. S. Experimental Model Basin in which the tests were made is constant. Consequently contours of $\frac{\sqrt[3]{A_M L}}{r}$ plotted against speed speed-length ratio and $\left(\frac{V}{V_\infty}\right)^2$ may be formed as shown in Figure 8b.

In addition to the change in magnitude of C_r due to restricted-channel effect, a change in speed related to that shown in formulas [8] and [9] , is indicated in Figure 8c.

The procedure for correcting the faired C_r versus speed-length ratio data from the Experimental Model Basin is shown in the following numerical example:

If the speed-length ratio of the model operating in the restricted channel is taken to be 1.0, then C_r taken from curve A in Figure 7 for illustrative purposes, is 1.620×10^{-3}. From Figure 8a, $\Delta C_r = 0.022 \times 10^{-3}$. for an assumed value of 0.3 $\frac{\sqrt[3]{A_M L}}{r}$. The sum $C_r + \Delta C_r = 1.620\times10^{-3} + 0.022\times10^{-3} = 1.642\times10^{-3}$ when multiplied by $\left(\frac{V}{V_\infty}\right)^2$ 0.992 which is obtained from Figure 8b yields a $C_{r_\infty} = 1.629\times10^{-3}$. The value of C_{r_∞} , the residual-resistance coefficient in an unrestricted channel would then normally be plotted on the adjusted value of $\frac{V_\infty}{\sqrt{L}}$ obtained from Figure 8c which in this case is equal to $\frac{V}{\sqrt{L}}$.

Since the U. S. Experimental Model Basin is of trapezoidal cross section, the depth, d, was taken as the perpendicular distance from the centerline of the basin to the nearest side of the basin. This gave a value of 13.6 feet as compared to the full 14.0-foot depth of the basin. From this value of depth, the restricted channel corrections of the Standard Series data were generally found to be very small. The largest correction obtained amounted to approximately 2 per cent based on the resistance of a 400-foot vessel operating in salt water at a temperature of 59F.

Cross-Fairing of Resistance Data

After the C_r versus speed length ratio curves were faired with corrections for transitional flow and restricted channel effect, it remained to cross-fair the C_r against the other parameters C_p, C_V and B_M/H. Since there were only three values of B_M/H, most of the cross-fairing had to be performed on the variations of C_p and C_V. The procedure was as follows: For each even speed-length ratio, a curve of C_r versus C_p was plotted and faired for the given values of C_V, as shown in Figure 9. Then for each of the same speed length ratios cross curves of C_r versus C_V were plotted for even values of C_p, using the faired values, as shown in Figure 10. Minor adjustments were made until the data were faired in both of these views. The finally faired values were checked back on the faired C_r versus speed-length ratio curves to assure fairness in this view.

It should be mentioned that in this fairing process special effort was made to adhere strictly to the original data which were corrected according to the procedures given in the preceding paragraphs. This was especially true for the high-speed data where the C_r values were very stable. At low speed-length ratios, since the C_r forms such a small precentage of the total resistance, the cross-fairing after corrections could of necessity only introduce small-order changes.

FINAL PRESENTATION OF DATA

It seems only fitting that in dealing with a comprehensive work such as the Standard Series a special effort should be made to present the data in a form which will be most convenient and useful to the members of the profession. The methods of presenting these data are numerous, and it seems worthwhile to present the same data in several different forms for the convenience of specialized groups.

The first method of presenting the data was chosen because it is, with the exception of the speed-length ratio, a nondimensional presentation and thus can be universally applied.

Although the speed-length ratio operates like a nondimensional coefficient, it is not a true one since it requires the use of specified english units. It has been retained, however, in the Revised Standard Series because it can be plotted on a convenient scale and can be converted easily to speed in knots. The Froude number, $\frac{V}{\sqrt{gL}}$, is recommended for international use and its numerical value can be attained readily by multiplying the speed-length ratio by 0.2978 if a value of g for the North Atlantic Ocean is used. The presentation consists of contours of even values of C_V on an abscissa of speed-length ratio and an ordinate of C_r. These contours are given for even values of Cp in increments of 0.01 for each of the three values of B_M Samples of the contours for a C_p of 0.58 are given in Figures 11, 12, and 13. The C_r values for speed length ratios above 1 are given in an insert in order to retain a scale which would permit accuracy of reading. Some advantages of this method of presentation are as follows:

1. It requires reference to only two pages for a given case when an interpolation on B_M/H is required and only one page when such interpolation is not required.

2. The increments of prismatic coefficient are smal enough to give an accuracy in reading to the nearest five in tl third significant figure without interpolation.

3. Interpolation on a given set of contours is alon the ordinate and not normal to the contours, as in the origina Standard Series.

4. The values of C_r are read on the fine cross sect of the ordinate, permitting a closer reading.

5. The shape of the C_r curves showing such features as humps and hollows can be directly seen.

6. Values of C_r can be directly read at speed-lengt ratios corresponding to even speeds on the full-scale vessel.

7. The C_r curves of other vessels can be directly compared to the Standard Series for analytical purposes.

The objection has been raised to the use of C_r as a parameter of residual resistance since it contains wetted surfa instead of the two-thirds power of the volume in the denominat This objection is based on the premise that the residual resist ance is a function of volume or displacement and not wetted su face. It is somewhat academic, however, when it is realized that the wetted surface or volume term serves only to render the coefficient dimensionless and has no other physical signifi cance. Furthermore, reference to the wetted surface coefficie of Figures 2, 3, and 4 shows that the values of C_r at various values of C_v do not converge by the substitution of volume to the two-thirds power for wetted surface in the definitions of C_r. On the other hand, it is desirable to retain the form of C_r based on wetted surface since it facilitates the calculatio of effective horsepower. In this calculation, the C_r can be added directly to values of C_f, which are single functions of Reynolds number. A C_r based on volume would require a separate calculation for vessels of different immersed volume even though their Reynolds numbers were equal.

Other methods of presenting C_r are shown in Figures 9 and 10. Contours of C_r on C_p and C_V for even speed-length ratios similar to those for the original Standard Series could be prepared. They are not considered desirable since minor discrepancies result in distorted contours at low speed-length ratios.

In addition to the C_r values, it is necessary to have the C_f values to complete the calculation of effective horsepower for a given vessel. The C_f calculated from the Schoenherr formula are generally given in tables as a function of the Reynolds number (4). Since Reynolds numbers in the ship range are required for the Standard Series calculations, it is possible to prepare a specialized chart of C_f values. Taking the International Standard of salt water of 59°F, which makes the value of the kinematic viscosity constant, the values of C_f can be expressed as a function of length for even speed-length ratios, as shown in Figure 14. Furthermore, if the standard roughness allowance of the American Towing Tank Conference of 0.0004 is used, the frictional-resistance coefficient including the roughness allowance can be read directly from the appropriate scale in Figure 14.

In addition to presenting data in the form of C_r which permits direct computation of the effective horsepower of a Standard Series vessel of any size, it is desirable also to present "merit curves". The merit curves tend to immediately apprise the user as to the advantage to be gained by altering form parameters such as C_p and B_M/H. The C_r curves do not provide such a ready comparison when the wetted surface coefficient of the vessel under consideration differs materially from that of the Standard Series. The method chosen to present merit relationships is exemplified in Figure 15. In these curves the effect of the variation in C_p for each of the three B_M/H is shown for a constant C_V at several even speed-length ratios. The changes are shown as ratios to the minimum effective horsepower in each group of three curves. The effective horsepowers were calculated for a 400-foot vessel operating in salt water of a temperature of 59°F. The ratios apply, however, with reasonable accuracy to vessels ranging from 100 to 1000 feet in length. Thus by the use of these merit curves, the actual percentage increase or decrease of effective horsepower due to a change in C_p or B_M/H at a given C_V can be immediately seen.

The merit curves are also useful in the preliminary design stage for quickly reproducing the effective horsepower of a vessel of prescribed coefficients if they are used in conjunction with curves of the type given in Figure 16. The curves given in this figure are the minimum Standard Series EHP plotted against the length for each of a number of even speed-length ratios. A set of these contours could be prepare for each of a number of values of C_V which would be sufficient to permit an accurate linear interpolation.

CALCULATION OF THE EFFECTIVE HORSEPOWER WITH THE REVISED STANDARD SERIES

Several methods of presenting the resistance data of the Revised Standard Series have been presented in the previous sections. The following discussion will demonstrate the effectiveness of these methods in actual application.

The Standard Series data are used primarily as a criterion of the performance of proposed and existing ship designs for which model test or full-scale test data are availal The procedure for this application can be best demonstrated b a numerical example. For the illustration the dimensions and coefficients for a typical cargo vessel are given in Table 1.

TABLE 1

Particulars for a 495-foot Cargo Vessels

Dimensions

	Model	Prototype
Length, feet	20.00	495.0
Beam, feet	3.094	70.0
Draft, feet	1.118	27.67
Displacement	2473 pounds	17140 tons
Wetted Surface, sq.ft.	73.83	45220

Coefficients

Longitudinal Prismatic Coefficient,	C_P	0.641
Volumetric Coefficient,	C_V	4.959×10^{-3}
Wetted-Surface Coefficient,	C_S	2.621
Midship Section Coefficient,	C_M	0.967
Beam/ Draft Ratio,	B_M/H	2.53

At an assumed even ship speed of 20.00 knots, the speed-length ratio of the given vessel is $\frac{20.00}{\sqrt{495}} = 0.899$.

Since the C_p for this vessel is 0.64 and the C_V is 4.96×10^{-3}, Figures 11 and 12 can be entered and the values of C_r at a speed-length ratio of 0.899 can be obtained. These values of C_r correspond to Standard Series vessels with C_p and C_V equal to those of the vessel in question but with B_M/H of 2.25 and 2.92 respectively. A linear interpolation is then applied to obtain the C_r for a Standard Series vessel with a B_M/H of 2.53 as follows:

$$C_r = 1.400 \times 10^{-3} \text{ for } B_M/H = 2.92$$

$$C_r = \underline{1.380 \times 10^{-3}} \text{ for } B_M/H = 2.25$$

$$\Delta C_r = 0.020 \times 10^{-3}$$

$$\text{Interpolation factor} = \frac{2.53 - 2.25}{2.92 - 2.25} = \frac{0.28}{0.67}$$

$$\text{Then } C_r \text{ for } B_M/H \text{ of } 2.53 = \frac{0.28}{0.67} \times 0.020 \times 10^{-3} + 1.380 \times 10^{-3} = 1.388 \times 10^{-3}$$

The practice in the past has been to compute the effective horsepower of a "phantom" vessel from the Standard Series data. The "phantom" vessel is defined as one which has a residual resistance equal to that of the corresponding Standard Series vessel but with a frictional resistance equal to that of the subject vessel. Accordingly, it is necessary to convert the C_r based on the wetted surface of the Standard Series vessel to a new C_r, denoted $C_{r'}$, which is based on the wetted surface of the subject vessel. For this conversion, the wetted surface coefficiant of the Standard Series vessel with a B_M/H of 2.53 is obtained by a linear interpolation between Figures 2 and 3 which have been entered at the appropriate values of C_p and C_V. The C_r is then multiplied by the ratio of the wetted surface coefficients of the Standard Series and the subject vessel to obtain $C_{r'}$, or

$$1.388 \times 10^{-3} \times \frac{2.549}{2.621} = 1.350 \times 10^{-3}$$

The $C_f + \Delta C_f$ is read from Figure 14 at a ship length of 495 feet and a speed-length ratio of 0.899 and added to $C_{r'}$ to obtain C_t as follows:

$$C_f + \Delta C_f + C_{r'} = 1.350 \times 10^{-3} + 1.881 \times 10^{-3} = 3.231 \times 10^{-3}.$$

Then since

Power = resistance x speed

$$\text{the EHP} = \frac{C_t \times \rho/2\ Sv^3}{550\ \text{ft - lb/sec}}$$

$$= \frac{3.231\times10^{-3} \times \frac{1.991}{2} \times 45220 \times (20.00)^3 \times (1.689)^3}{550}$$

$$= 1018$$

where the density is obtained from the Table of Density of Water (4) adopted by the American Towing Tank Conference in 1942 for salt water at a temperature of 59°F. The figure 1.689 is the conversion factor of knots to feet per second. When the conversion of C_t to effective horsepower is set up for routine calculations, then C_t is merely multiplied by AV^3 where

$$A = \frac{\rho/2s \times (1.689)^3}{550} = 0.004380\ \rho\ s$$

and V is the speed in knots

It is pointed out that when the effective horsepower of the subject vessel has been calculated according to the procedure given in Reference (4), the speed-length ratio, the $C_f + \Delta C_f$, and the AV^3 are already available. Consequently the calculation is accomplished simply by substituting the C_r' for the C_r of the subject vessel and carrying out the remaining cal culations.

The effective horsepower for the phantom vessel obtained from the Revised Standard Series is compared in Figure 17 to the effective horsepower predicted from tests of a 20-foot model of the subject cargo vessel. The effective horsepow for the phantom vessel derived from the Original Standard Serie is also shown. It can be seen that the two Standard Series cu do not agree very well. Approximately half of the discrepancy is due to the disagreement between the results obtained with the EMB-Tideman frictional constants and the Schoenherr Formula which includes a roughness allowance of 0.0004 and is calculate at a Reynolds numbers using the kinematic viscosity of salt water at a temperature of 59°F. The remainder of the discrepan is due to the omission in the Original Standard Series of the corrections which were described in previous sections and also to the requirement in the Original Standard Series of a linear interpolation from $B_M/H = 2.25$ to $B_M/H = 3.75$ instead of betwee 2.25 and 2.92.

The Standard Series data are also used for the purpose of making estimates of effective horsepower in the preliminary design stage. Here the procedure used in the calculations is similar to that given above. The wetted surface area of the proposed vessel may not be known, however, and consequently, for this purpose the wetted surface of the Standard Series vessel can be directly used. This would eliminate the step of converting C_r to C_r'.

As mentioned previously, the effective horsepower for preliminary design purposes can be calculated in a simpler manner. To demonstrate this simplification, it is assumed that the vessel contemplated has a length of 500 feet, a Cp of 0.58, a C_V of 1.5×10^{-3}, and a B_M/H of 2.92. Then at a speed-length ratio of 1.5 it is found from Figure 15 that the Standard Series vessel of the given coefficients has an effective horsepower which is 1.08 times higher than the Standard Series vessel of equal C_V with the minimum effective horsepower. Then referring to Figure 16, minimum effective horsepower for the 500-foot vessel is 35,500. The desired EHP = 1.08x35,500 = 38,300

CONVERSION OF REVISED STANDARD SERIES FOR USE WITH OTHER FRICTIONAL-RESISTANCE FORMULATIONS

The question as to whether the work with the original data would have to be repeated if a new frictional-resistance formulation were adopted can be answered in the negative. As long as such a formulation is a function of Reynolds number, the change can be simply accomplished. Since all of the tests were conducted with models of approximately the same length, namely 20.51 feet, the difference between the frictional-resistance coefficients can be expressed as functions of speed and temperature. Taking for example, the possibility of the use of Gebers frictional resistance formula. A chart of differences between the Schoenherr and the Gebers frictional-resistance coefficients can be prepared. Since these differences are reflected in the residual-resistance coefficient as a ΔC_r, a set of curves of the form shown in Figure 18 can be applied to perform the conversion. Thus, at a speed-length ratio of 1.0, for example, a ΔC_r correction of 0.140×10^{-3} would have to added to the Revised Standard Series Contours if the model was tested in water at 70°F. To find the effective horsepower, the Gebers frictional-resistance coefficient in the full-scale range would have to be added to the corrected C_r and the rest of the calculation would be the same as that given in the previous section.

Acknowledgements

The author is indebted to William Kopko and John L. Beveridge, both of the Staff of the David Taylor Model Basin, who assisted materially in the calculations and in the preparation of the figures in this paper.

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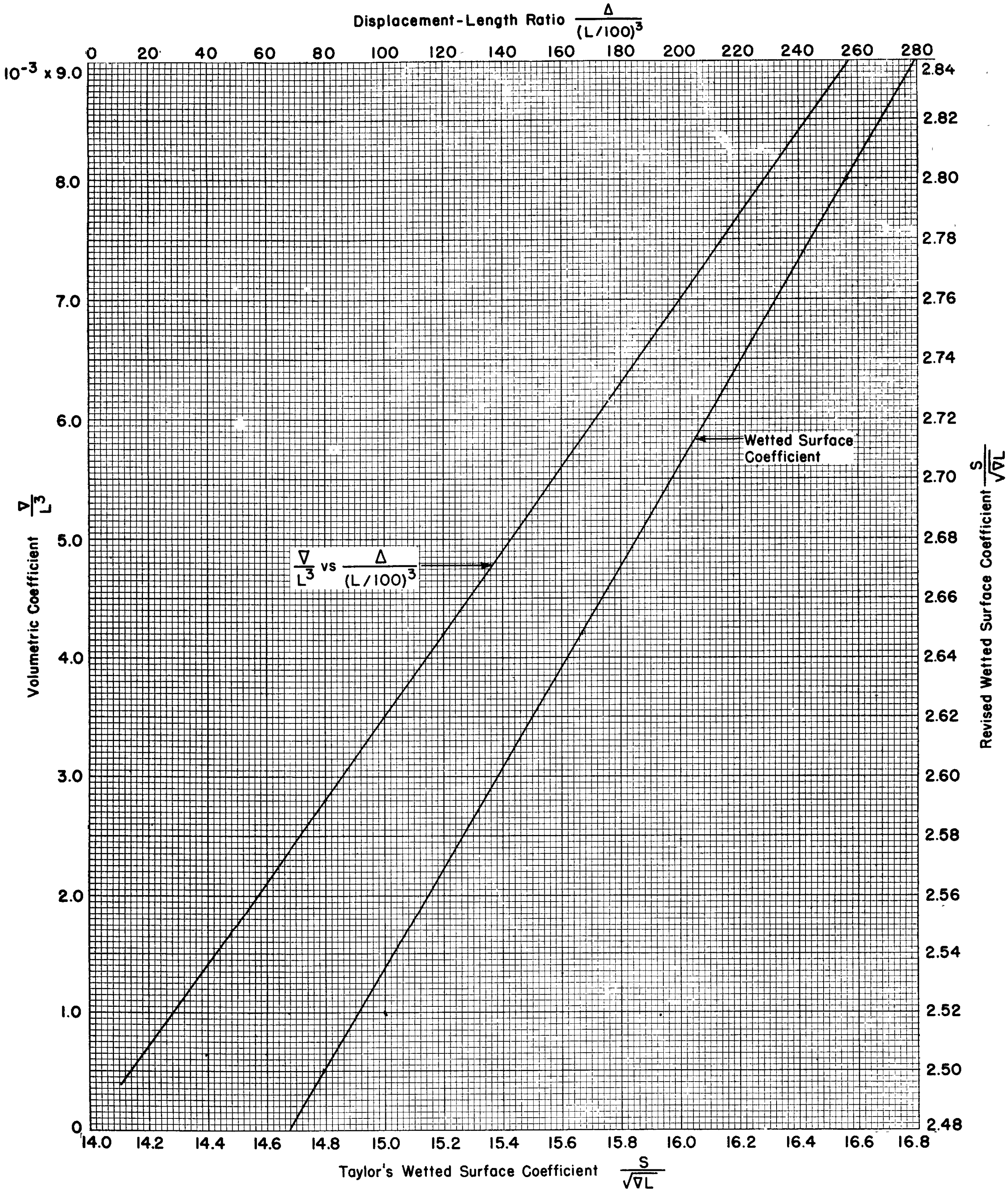


Figure 1 - Comparison of Geometric Parameters

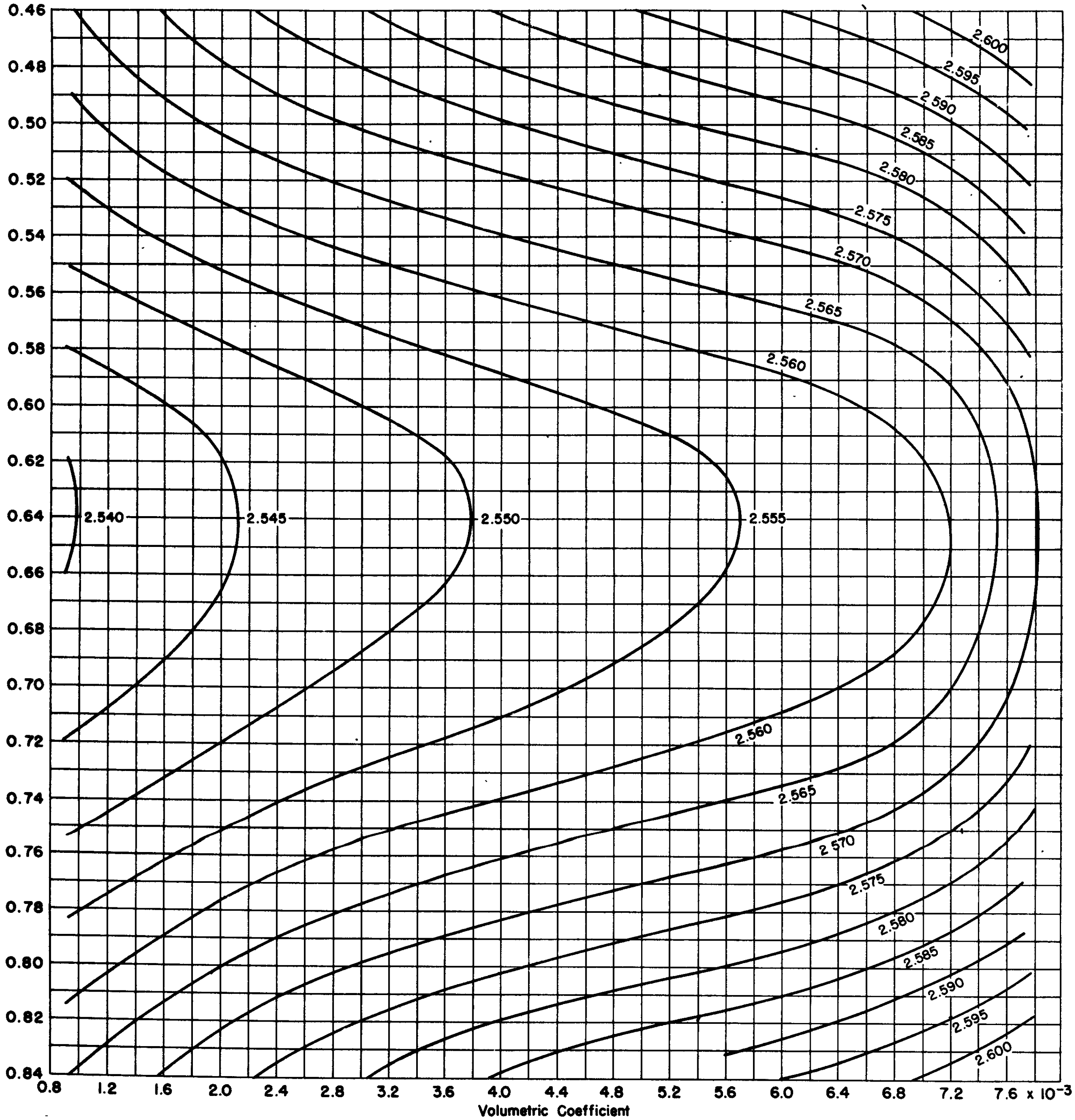


Figure 2 - Contours of Wetted Surface Coefficient, $B_M/H = 2.25$

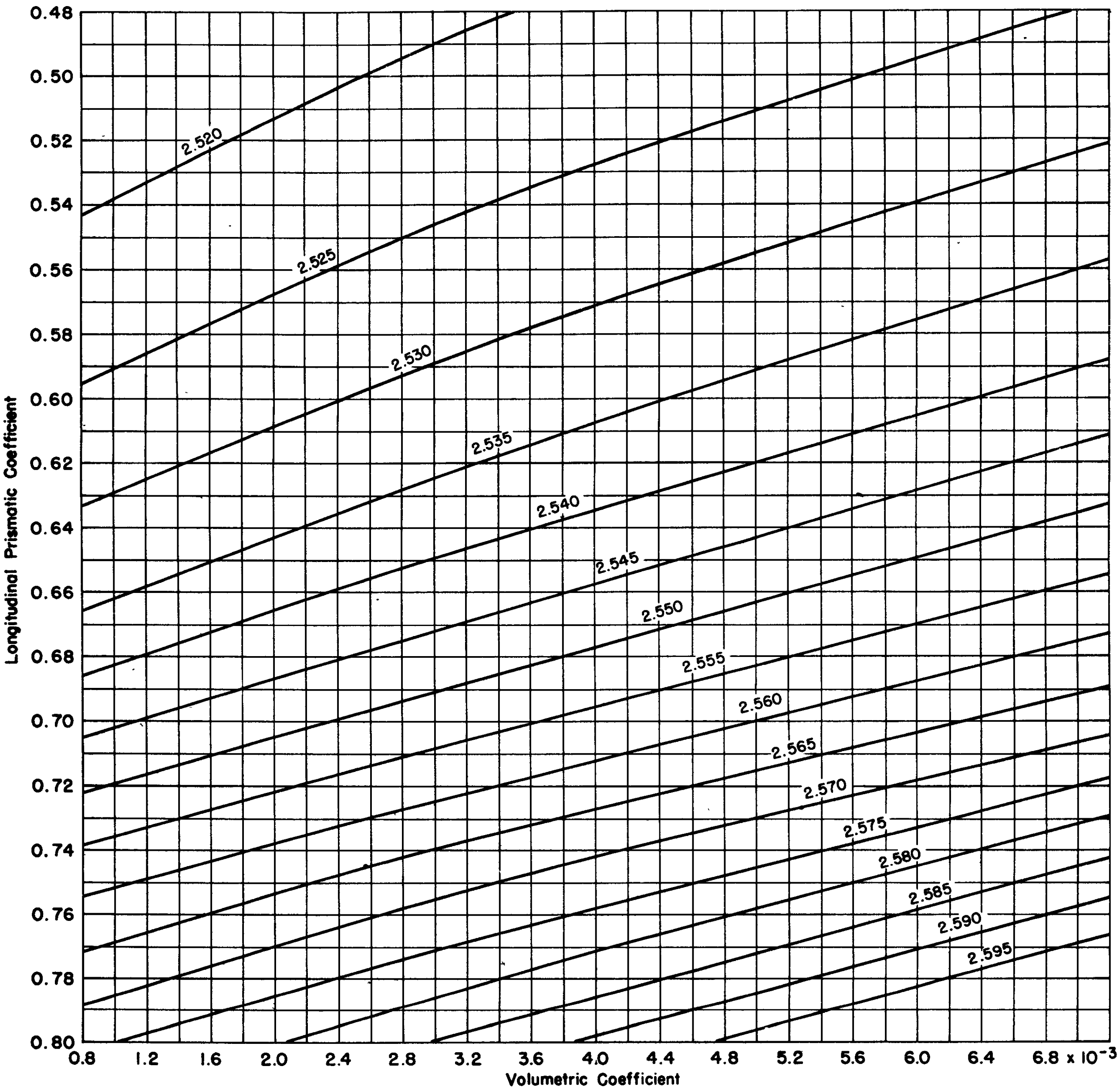


Figure 3 - Contours of Wetted Surface Coefficient, $B_M/H = 2.92$

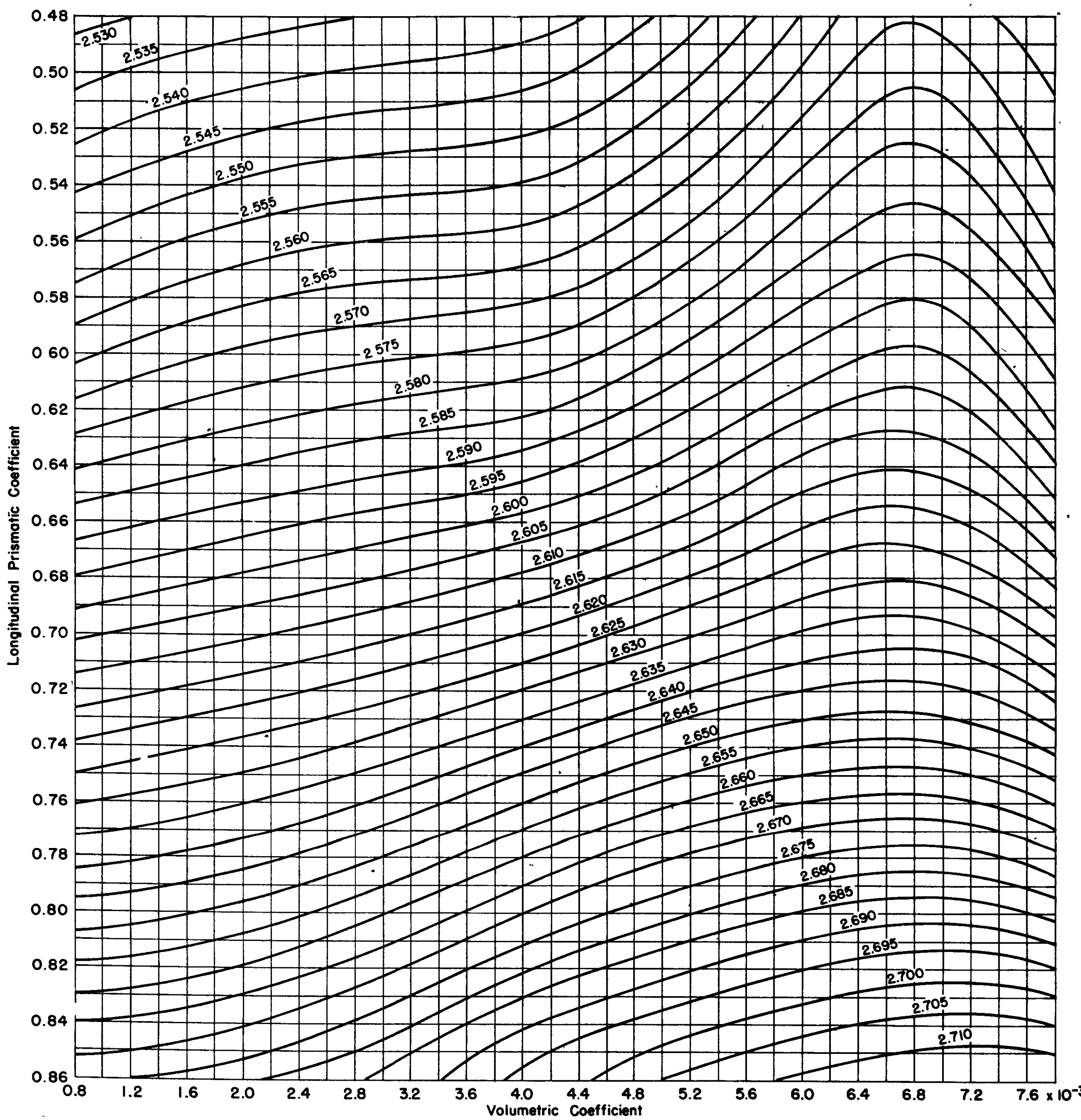


Figure 4 - Contours of Wetted Surface Coefficient, $B_M/H = 3.75$

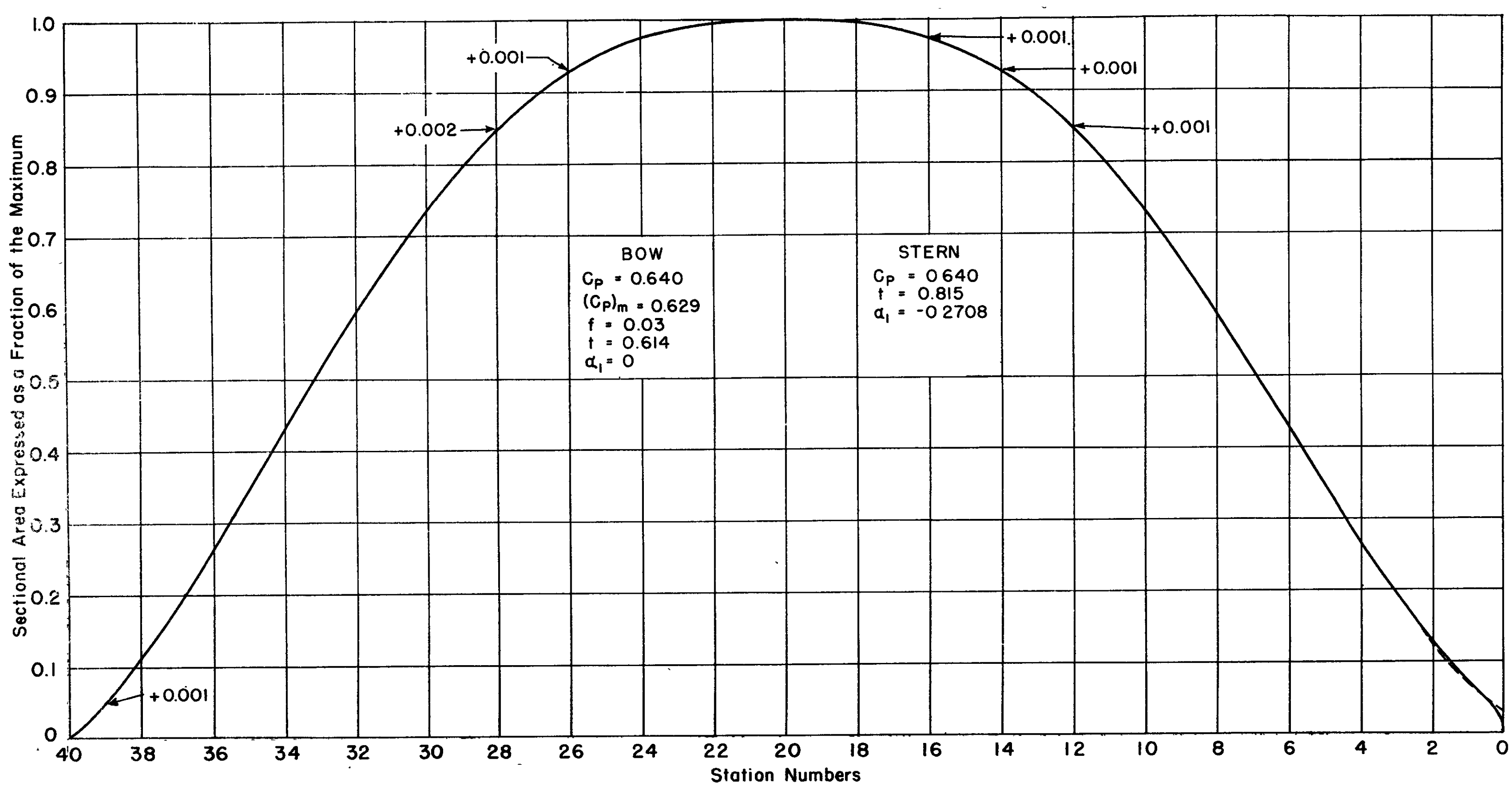


Figure 5 - Comparison of a Mathematically Derived Sectional Area Curve with the Corresponding Sectional Area Curve Given in Taylor's "Speed and Power of Ships"

The numeral indicates the difference between the offsets of the two curves.

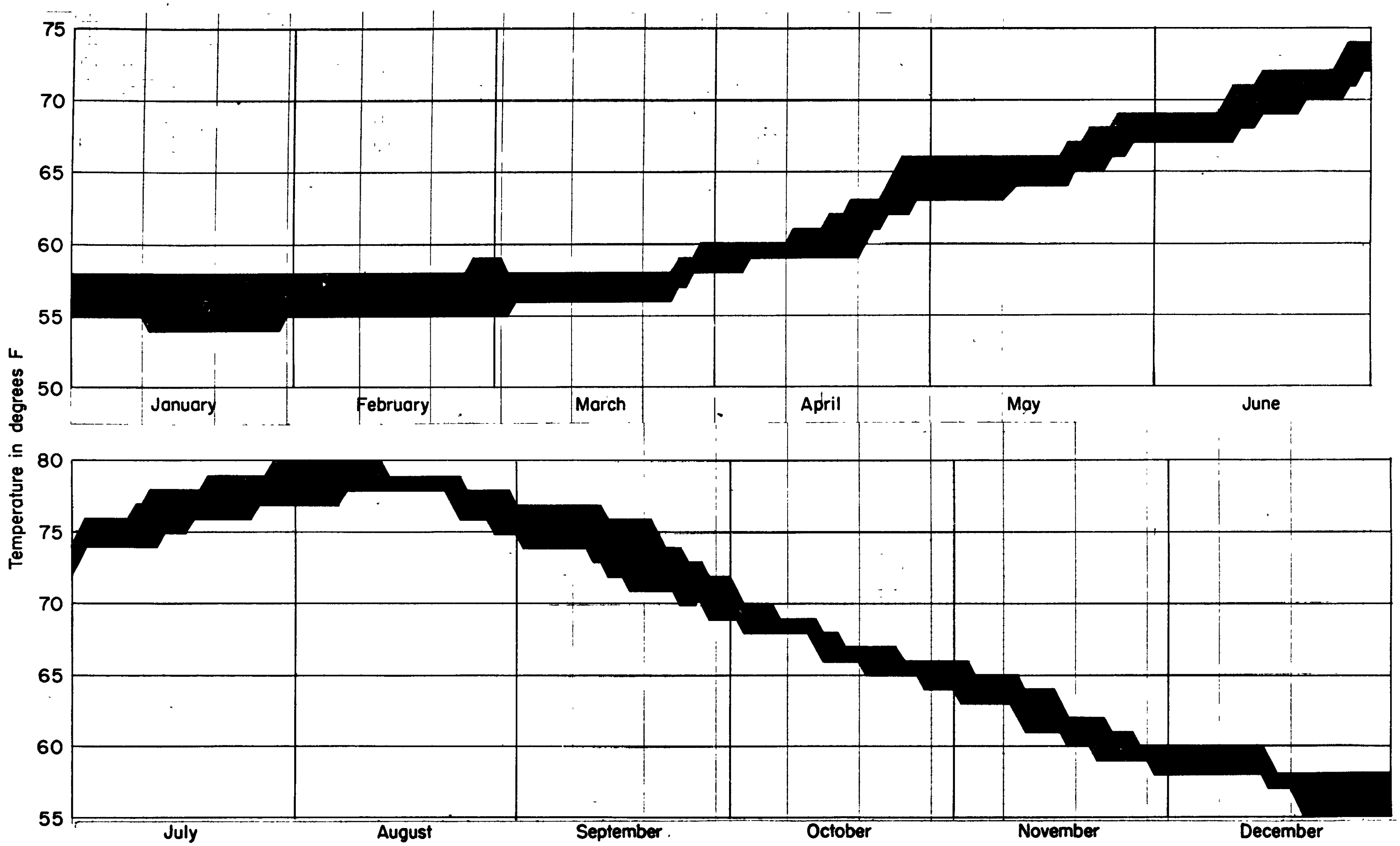


Figure 6 - Water Temperatures in the U.S. Experimental Model Basin During the Years of 1913 to 1918

The width of the line indicates the variation in temperature from year to year.

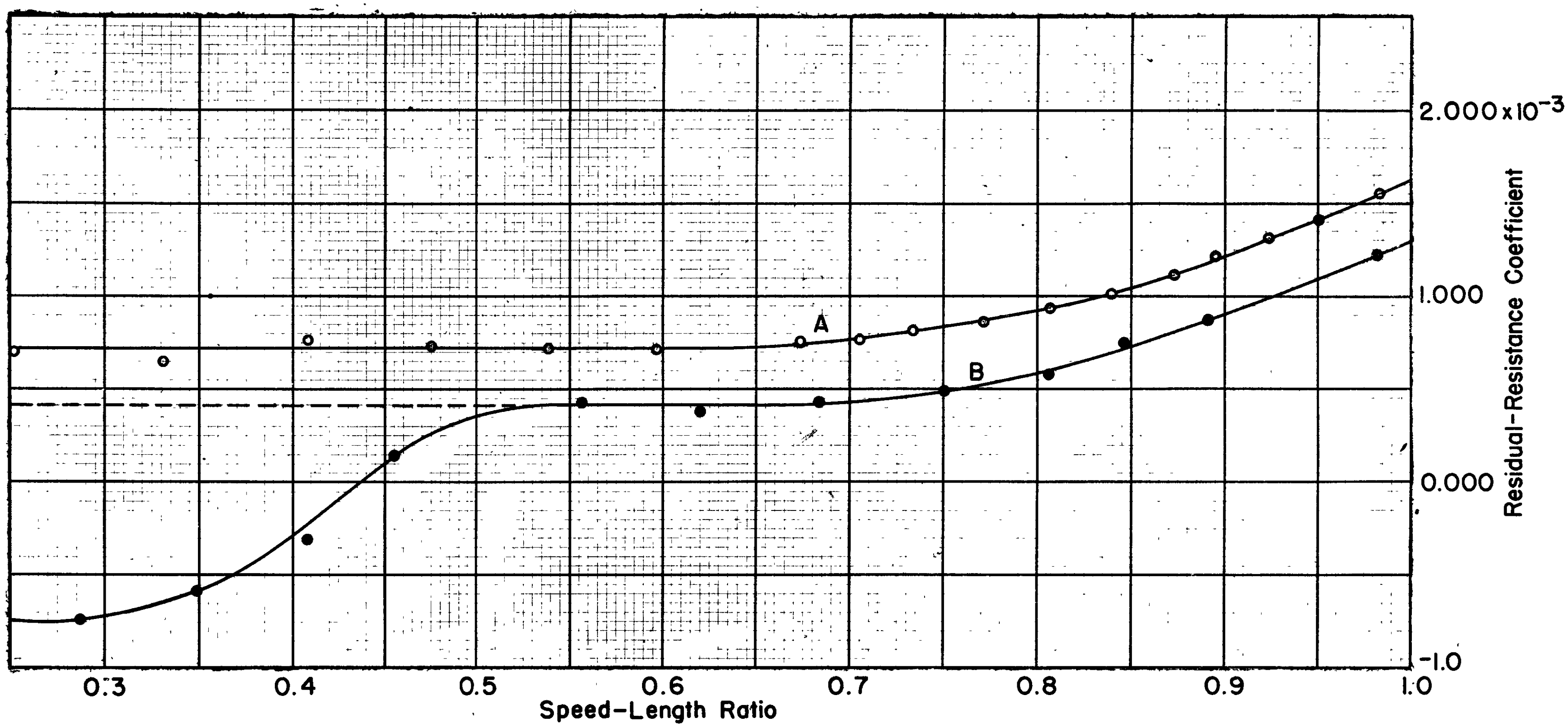


Figure 7 - Curves of Residual-Resistance Coefficient Showing Typical Data Spots

Curve A is for a Standard Series vessel with $C_P = 0.56$, $B_M/H = 2.25$, and $C_V = 7.76 \times 10^{-3}$. Curve B is for a Standard Series vessel with $C_P = 0.56$, $B_M/H = 2.25$, and $C_V = 5.58 \times 10^{-3}$.

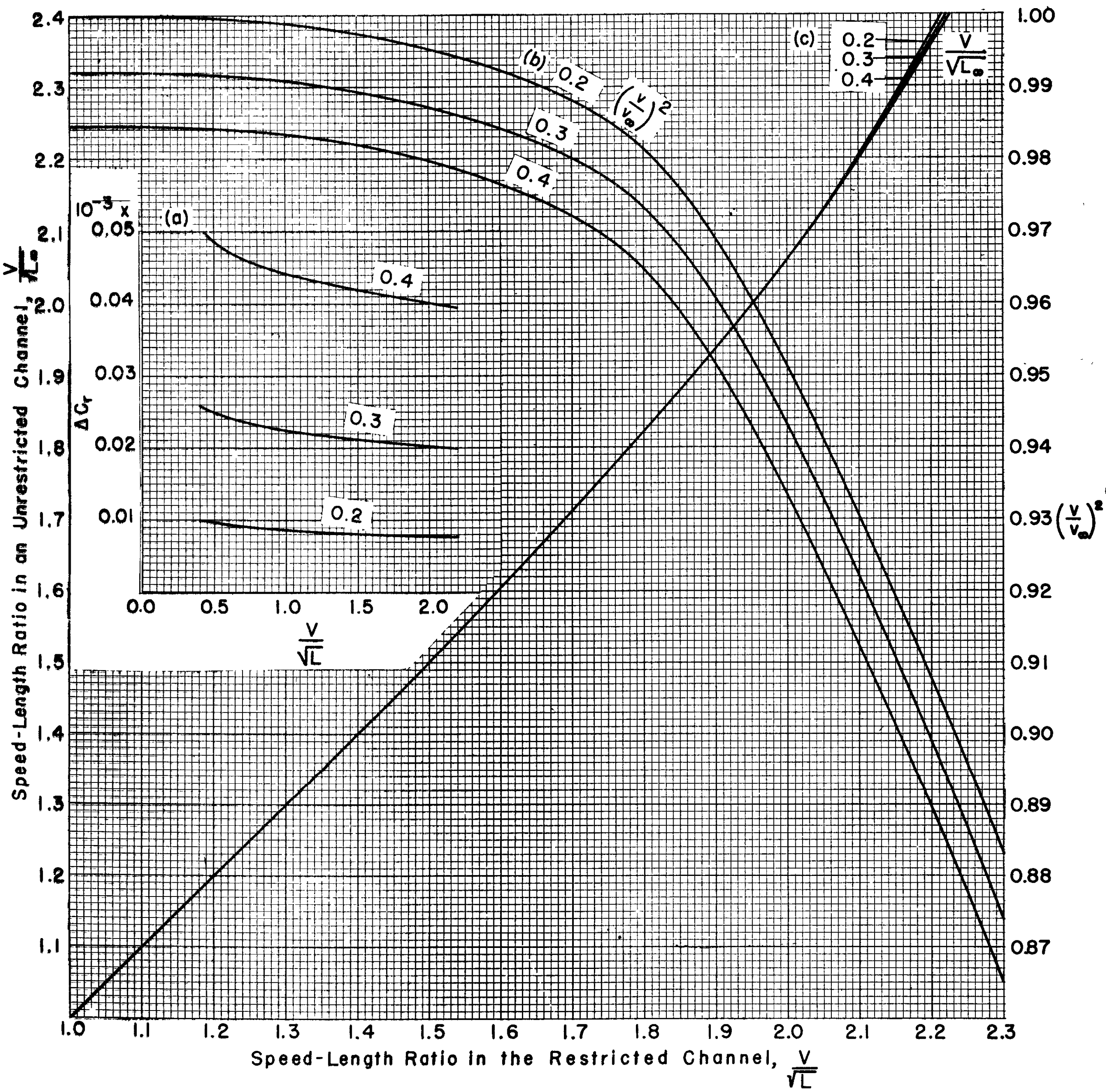


Figure 8 - Restricted Channel Corrections for Standard Series Models Tested in the U.S. Experimental Model Basin

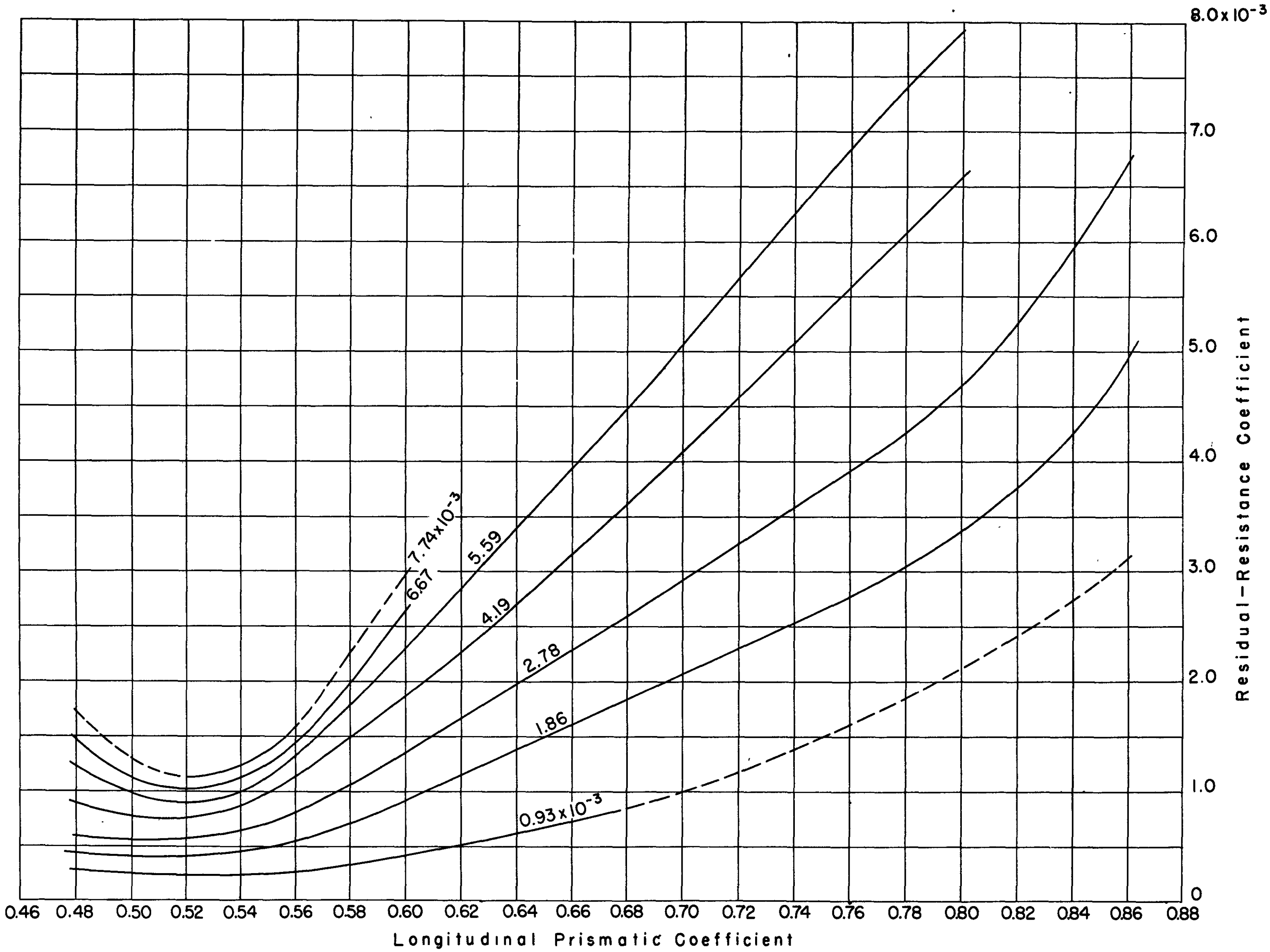


Figure 9 - Contours of Volumetric Coefficient, $B_M/H = 2.25$,
Speed-Length Ratio = 1.0

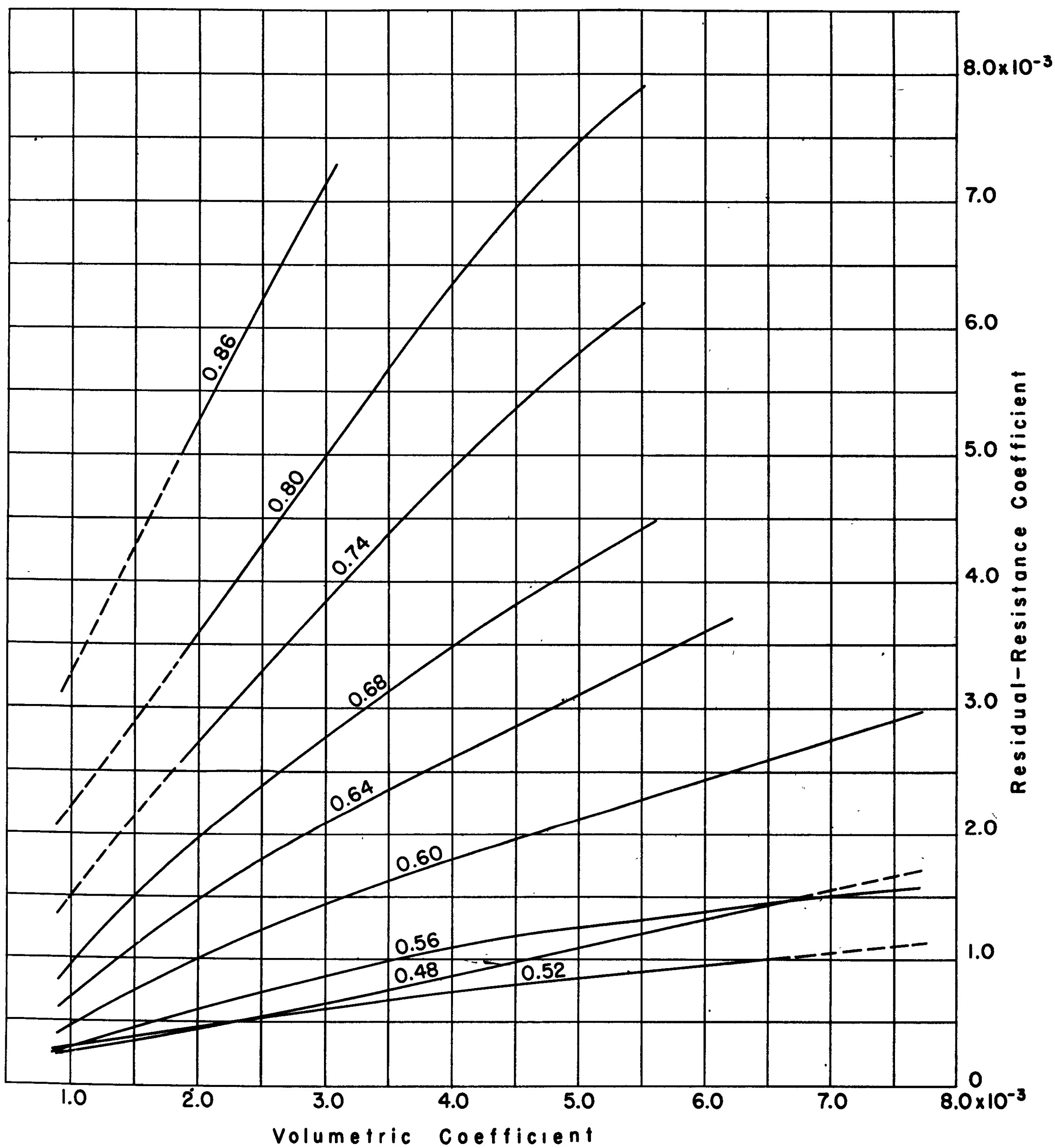
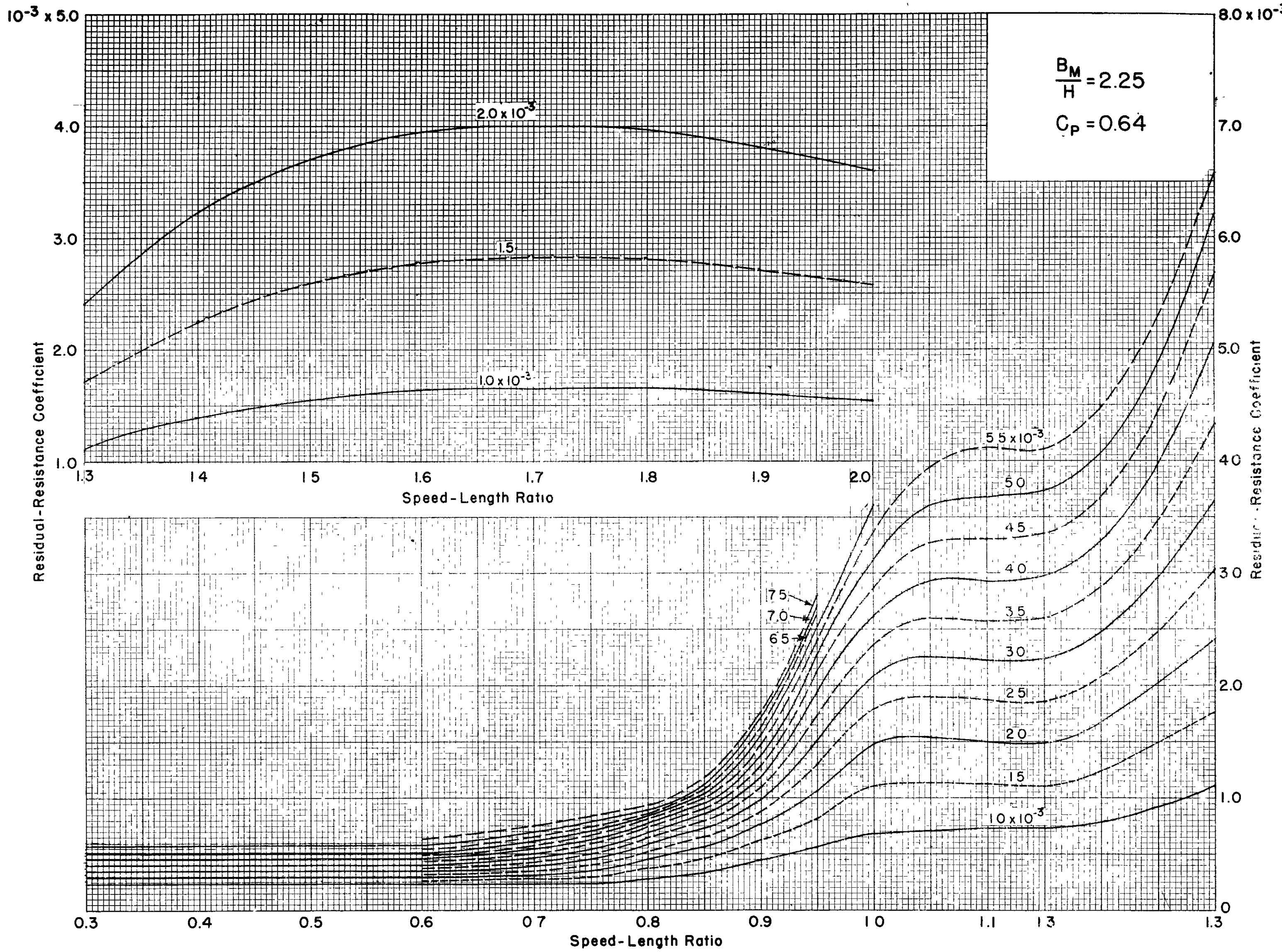


Figure 10 - Contours of Prismatic Coefficient, $B_M/H = 2.25$, Speed-Length Ratio = 1.0



$\frac{B_M}{H} = 2.25$
$C_P = 0.64$
$10^{-3} \times 5.0$
4.0
3.0
2.0
1.0
8.0×10^{-3}
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
2.0×10^{-3}
1.5
1.0×10^{-3}
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
Speed-Length Ratio
5.5×10^{-3}
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0×10^{-3}
7.5
7.0
6.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.3
Speed-Length Ratio
Residual-Resistance Coefficient
Residual-Resistance Coefficient

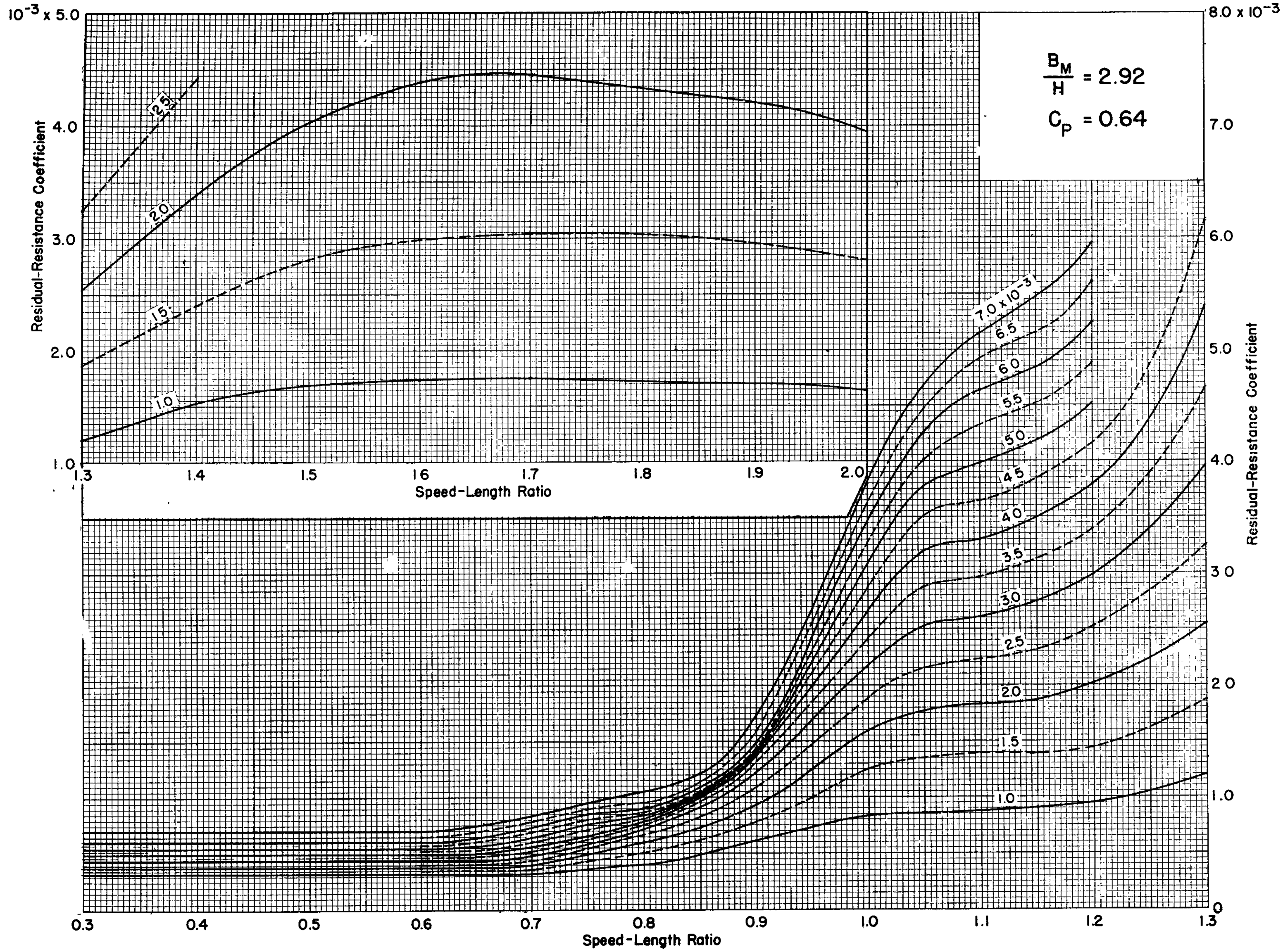


Figure 12 - Contours of Volumetric Coefficient, $B_M/H = 2.92$, $C_P = 0.64$

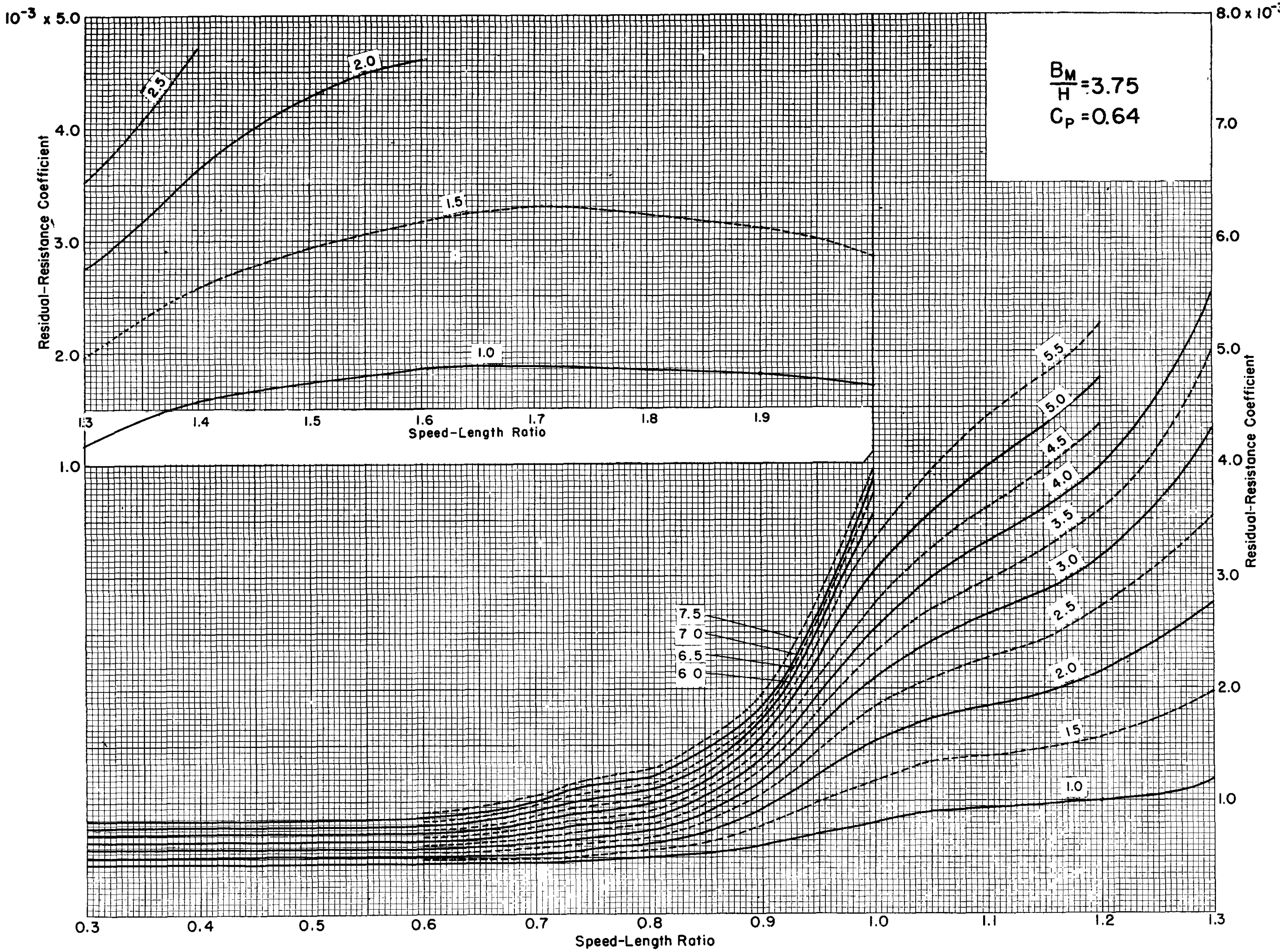


Figure 13 - Contours of Volumetric Coefficient, $B_M/H = 3.75$, $C_P = 0.64$

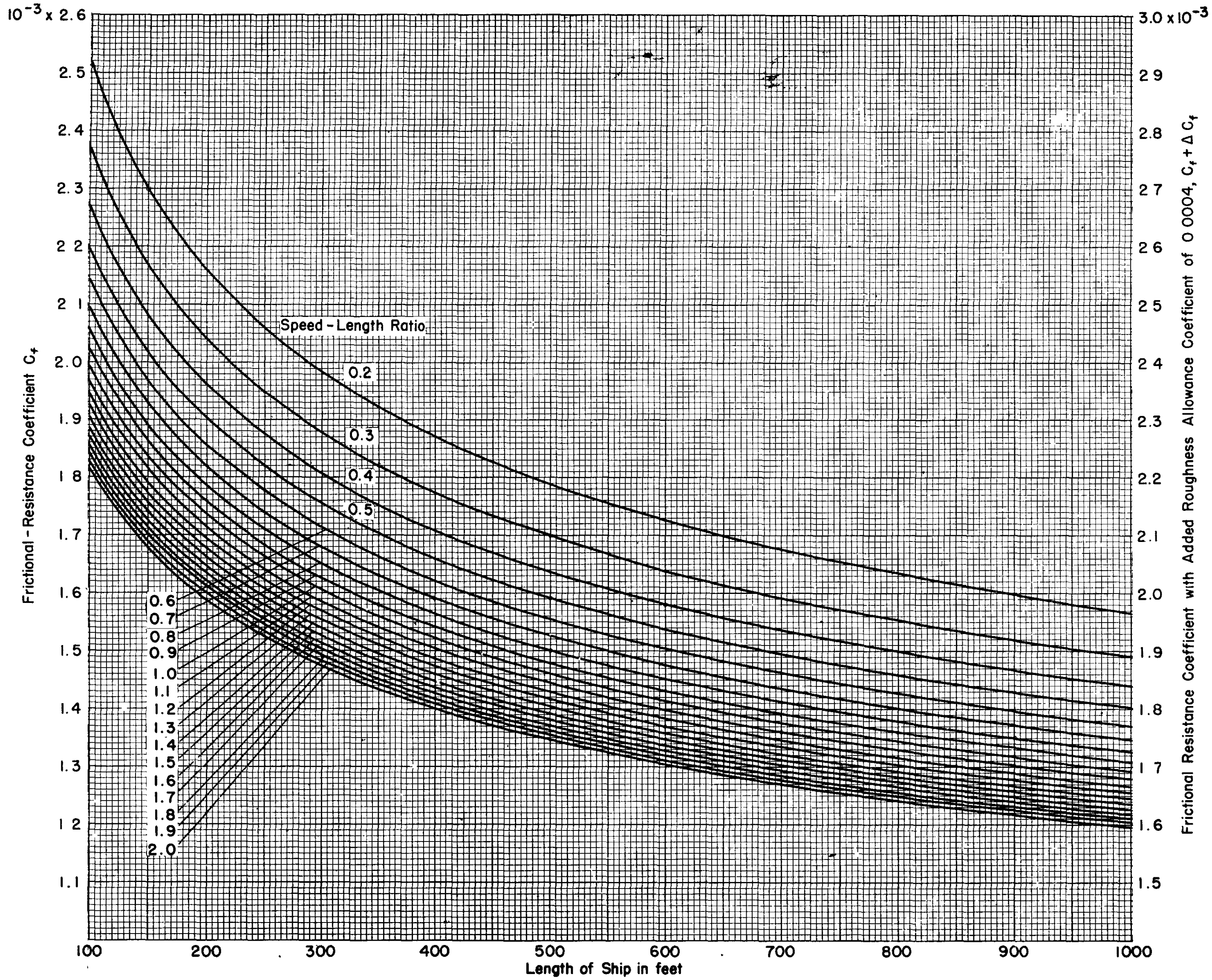


Figure 14 - Schoenherr Frictional-Resistance Coefficients for Vessels Operating in Salt Water at a Temperature of 59° F.

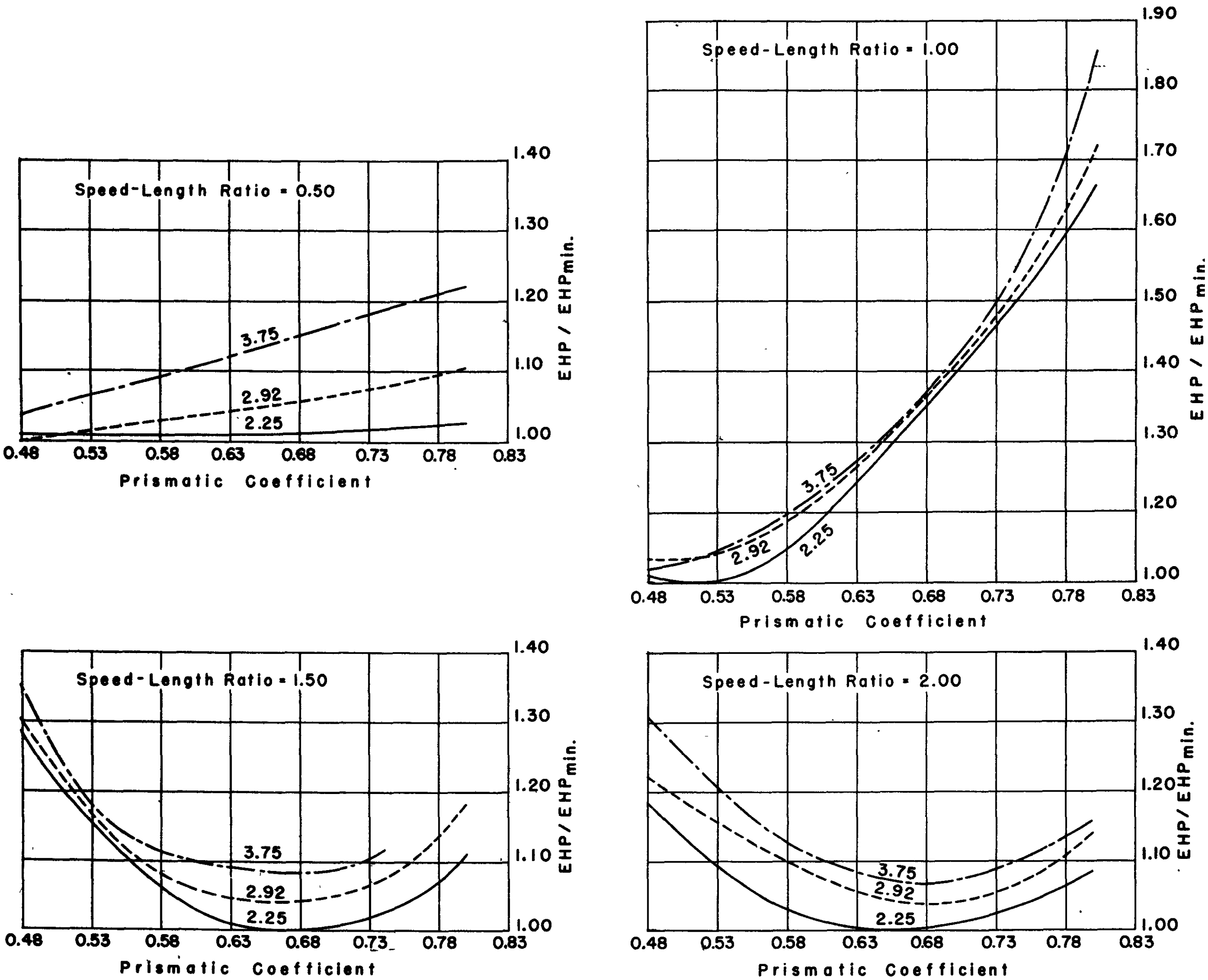


Figure 15 - The Variation in Effective Horsepower of Standard Series Vessels with Change in Prismatic Coefficient

The effective horsepowers pertain to a 400-foot ship operating in salt water at a temperature of 59° F. and are expressed as ratios to the minimum.

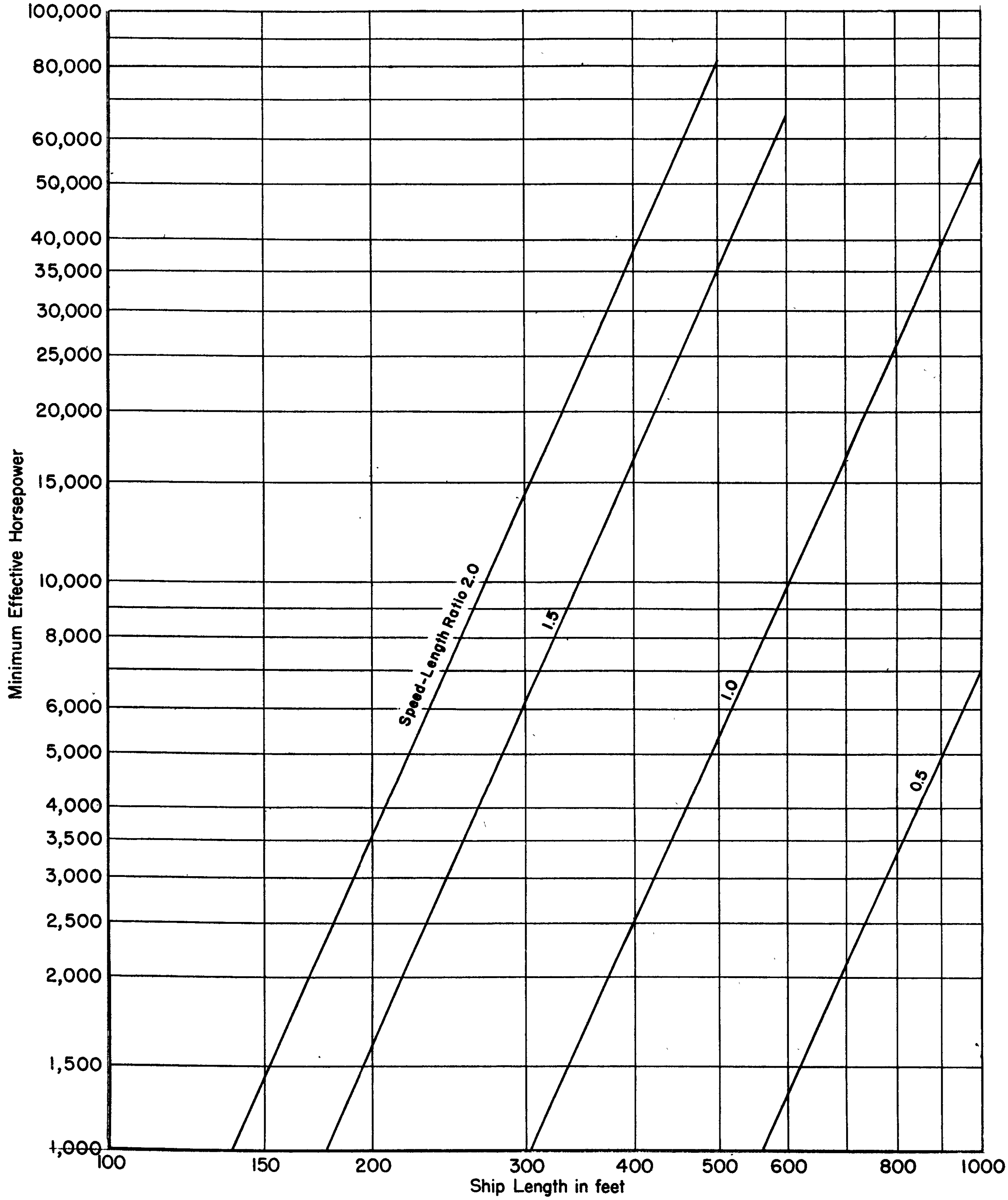
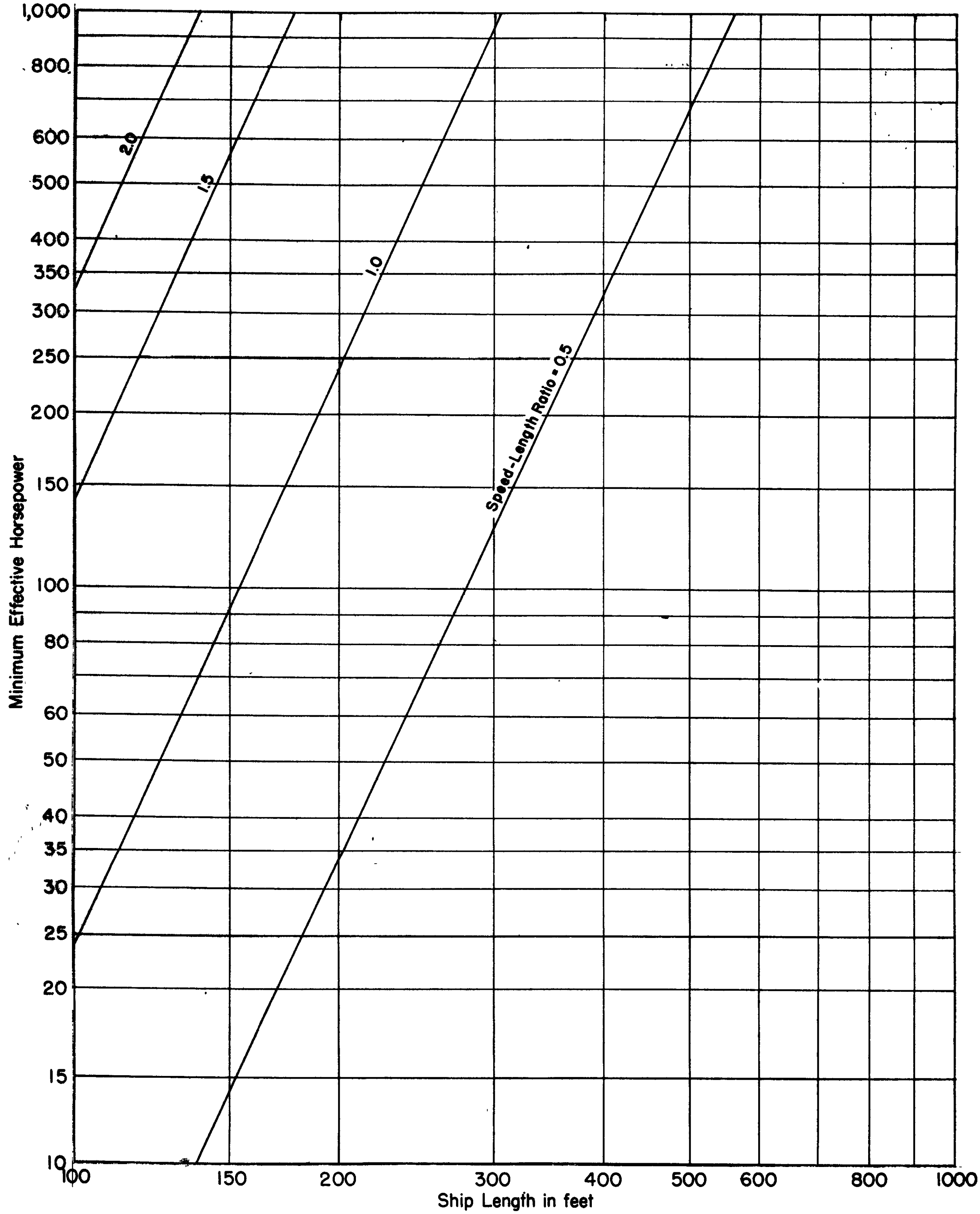


Figure 16 - The Minimum Effective Horsepowers of Standard Series Vessels of Various Lengths with a Volumetric Coefficient Equal to 1.5 x 10^{-3}



1,000
800
600
500
400
350
300
250
200
150
100
80
60
50
40
35
30
25
20
15
10
Minimum Effective Horsepower
2.0
1.5
1.0
Speed-Length Ratio = 0.5
100
150
200
300
400
500
600
800
1000
Ship Length in feet

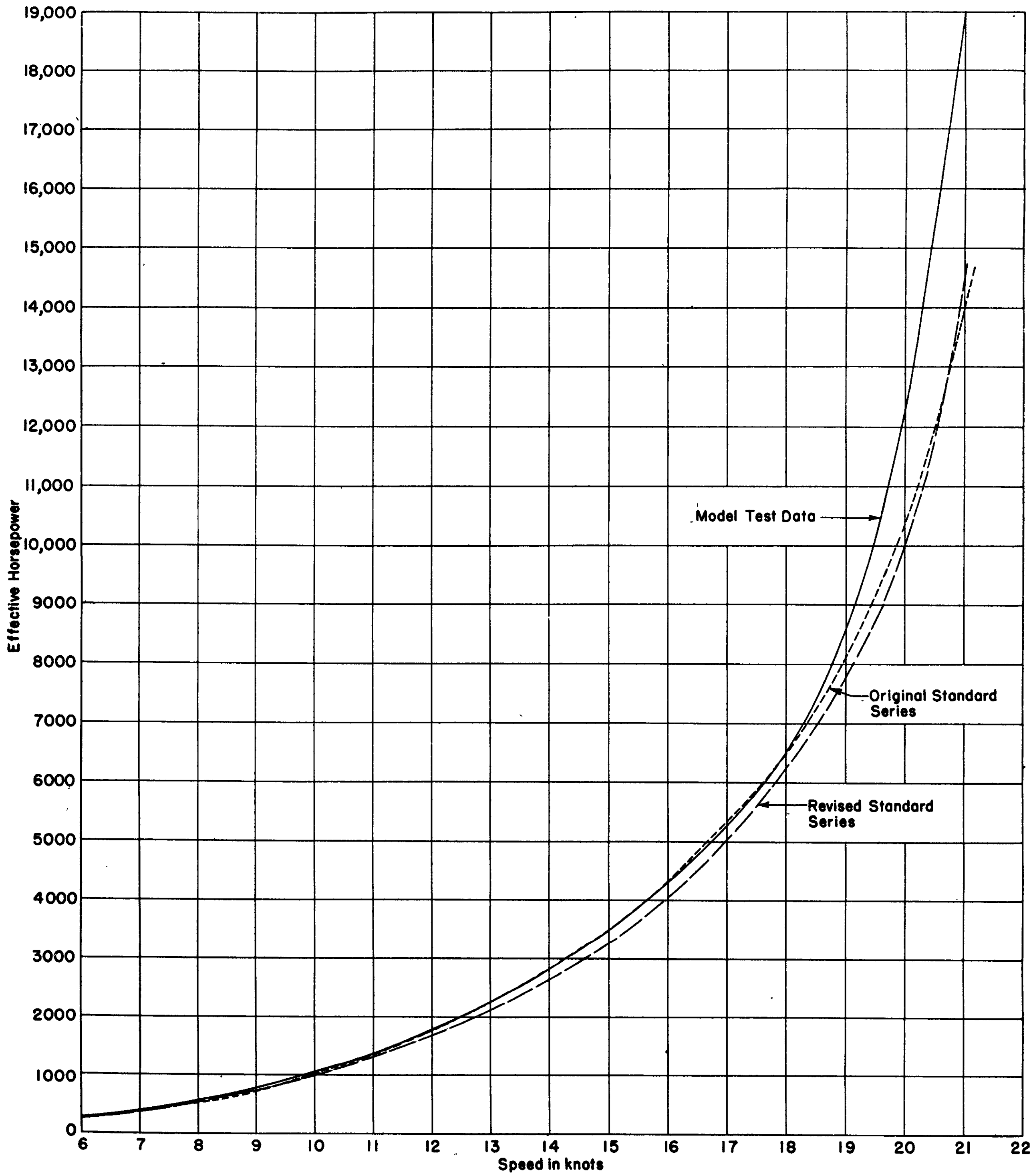


Figure 17 - The Effective Horsepower of a 495-Foot Cargo Vessel

The effective horsepowers are calculated separately from model test data, the Revised Standard Series, and the Original Standard Series.

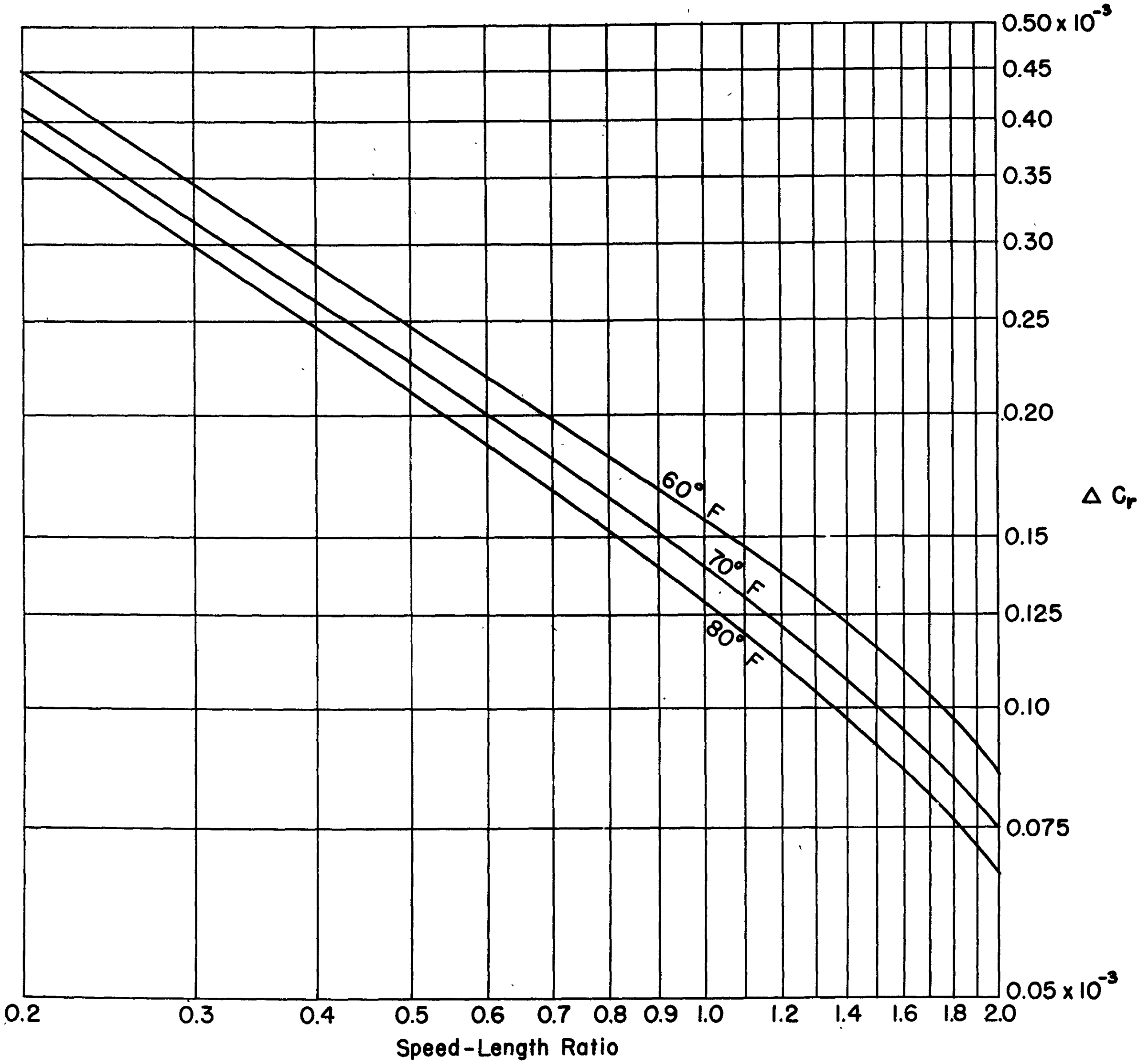


Figure 18 - Residual-Resistance Coefficient Corrections

These values are added to the residual-resistance coefficients of the Revised Standard Series to convert from C_r based on the use of the Schoenherr Formula to C_r based on the use of Gebers Formula.