RESISTANCE AND PROPULSION OF TRAWLERS

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SYNOPSIS.—*A statistical analysis of all resistance data for trawlers, obtained from model experiments conducted in No. 1 Tank, Ship Division, National Physical Laboratory, has been made. From an analysis of this type, a design method has been evolved, by means of which optimum resistance characteristics can be estimated for each trawler type, together with predictions of effective horse-power for any particular form.*

These e.h.p. calculations can be made by determining six parameters from the normal ship's lines plan, and to facilitate the computation of results a programme has been prepared for a digital computer (DEUCE), so that the N.P.L. can provide an estimated e.h.p./speed curve very quickly for a given set of parameters. In addition, design diagrams have been prepared for practical use in design offices.

From the propulsion aspect a series of propellers of 0·60 blade area ratio has been tested in open water over a wide range of slip, and forms part of the N.P.L. standard series. Some of these, together with additional propellers of the standard series type, have been tested in open water, under cavitating and non-cavitating conditions in the Lithgow water tunnel and behind a model of a bulbous-bow trawler.

From these three types of experiments, the most suitable propeller characteristics have been determined for free-running and trawling conditions. An analysis of existing N.P.L. propulsion data for trawlers has been made and propulsion factors for design and estimating purposes have been derived.

Introduction

FROM the point of view of achieving optimum resistance and propulsion characteristics, the design of a modern trawler presents several problems which are encountered individually in the design of some other classes of merchant ships, but which in the case of trawlers must be considered together. Trawlers are primarily required to operate at high speed-length ratios ($V/\sqrt{L}$ 1·0 to 1·20); the displacement, draughts and trim vary continually in service conditions; the stability requirements are usually quite critical, while they often have to work in adverse weather conditions in order to take full advantage of the rather limited time available for fishing operations.

The necessity of having to fish further afield from their home ports to make worthwhile catches has given further impetus to the trend of increasing size in these vessels, as well as to explore the possibilities of using new types of machinery installations in the power range from

1,000-2,000 s.h.p. In recent years, diesel and diesel-electric propulsion systems have made their appearance in greater numbers and, since a trawler propeller is required to operate efficiently over a wide range of slip, varying from that at trawling speeds of 4-5 knots up to perhaps 16 knots or more in the free-running condition, a more flexible propulsion system, such as the controllable pitch propeller has been adopted in some cases. With regard to the form of these vessels, the essential requirements are that they must be able to utilize the maximum power in the most efficient manner at the top speeds and have an easy motion in a seaway to enable work to proceed on deck during trawling operations. Various hazards encountered by trawlers, especially in Arctic regions, have refocussed the attention of ship designers on the question of adequate stability, Black ice, which can produce a dangerous unstable condition as it freezes on the masts, shrouds and rigging, the difficulty of storing the catch in a homogeneous manner, and the relatively high ratios of fuel capacity to total deadweight, necessitate that a sufficient magnitude and range of stability be provided in these designs. Unfortunately, these stability requirements sometimes conflict with those for minimum resistance and easy motion in a seaway.

In preparing this paper, the authors have endeavoured to record some aspects of trawler work at the N.P.L. with particular reference to the design of forms having optimum resistance and propulsion characteristics, bearing in mind the other requirements to which reference has already been made. A design method is presented by means of which the resistance characteristics can be predicted from the lines plan of a particular vessel, or alternatively the method may be applied to determine the optimum form parameters for any required operating conditions. This design method is based on a statistical analysis (of some hundred and thirty trawler forms which have been tested for resistance in No. 1 Tank, Ship Division, N.P.L.), using multi-curvilinear regression principles as outlined in Appendix I. Most of these forms are those of actual vessels which have been built over the last thirty years.

From the propulsion aspect, a series of propellers of 0·60 blade area ratio has been tested in open water over a wide range of slip. These propellers form part of the N.P.L. standard series. Some of these propellers, together with additional screws of this type, have been tested behind a modern deep-sea type trawler incorporating a bulbous bow, and their performance has been compared at both free-running and trawling conditions. Additional comparisons of performance have been made at reduced pressure conditions in the Lithgow water tunnel to determine the most useful pitch ratios, diameters and blade areas for free-running and trawling conditions. To assist in the estimation of propulsive efficiency, an analysis of the components of q.p.c. derived from existing N.P.L. model experiment data has been made. A typical calculation illustrating the design and estimating method (in current use at the Ship Division, N.P.L.) for the powering of these vessels is also presented.

Resistance

Resistance Criteria

When comparing the resistance of ships, it is particularly important to use a resistance coefficient which permits true comparisons to be made between vessels of different displacements. This matter has been discussed at great

length by Lackenby[1], and after careful consideration of all consistent systems, it was decided to use that first proposed by Telfer[2], namely, $C_R = \frac{R.L}{\Delta.V^2}$, plotted to a base of $V/\sqrt{L}$. This criterion enables the resistance of vessels of different displacement to be compared on the basis of resistance per ton of displacement at the same speed-length ratio. Also, the numerical values of C_R are of a convenient magnitude, namely 10-20, while the actual values of resistance per ton of displacement, at a particular speed-length ratio, are obtained by multiplying C_R by $(V/\sqrt{L})^2$, thus providing a convenient link with American practice of expressing the resistance of a ship in pounds per ton of displacement. From the point of view of conducting a statistical analysis of resistance data for a particular ship type, the $(C_R, V/\sqrt{L})$ presentation also has the advantage that the data may be sampled at constant values of Froude number, corresponding to well-defined crests and troughs in the resistance curves. All parameters used in the analysis presented in this paper can be calculated from the ship's lines and, provided these values are adhered to, the resistance performance of a new design can be predicted within known limits of accuracy.

Design Parameters

Six basic design parameters have been found in practice to be important in determining the resistance criterion C_R at particular values of $V/\sqrt{L}$.

namely, L/B, B/d, C_m, Cp, l.c.b. and $\frac{1}{2}\alpha^\circ_e$.

All of the six design parameters can be calculated at an early stage of the design. Before describing the statistical analysis, it should be noted that this particular combination of design parameters leads to certain physical changes in the form when any one is changed independently.

(1) Changes in L/B

Since the analysis is concerned with vessels of a standard length of 200ft., independent changes in L/B involve corresponding changes in B.

$$\text{Since } \frac{B}{d} = \text{constant}, \; B \propto d.$$

$$\text{Also } C_m = \frac{\text{Maximum area}}{B \times d} \propto \frac{\text{Maximum area}}{B^2} = \text{constant}$$

$$\text{Now } C_p = \text{constant, or } \frac{\text{Displacement}}{L \times \text{Maximum area}} = \text{constant}$$

so that Displacement $\propto B^2$ or $\propto d^2$.

Hence independent changes in L/B mean that the draught is varied in the same proportion as the beam to draught, and the displacement then varies as B^2 or d^2. In a similar manner, it can be demonstrated that the following specific changes in any one design parameter lead to the following physical interpretations.

(2) Changes in B/d mean that the draught is varied with beam constant, and the displacement is then proportional to the draught.

(3) Changes in C_m mean that the maximum section area is varied, with beam and draught constant, and the displacement is then proportional to the maximum area.

(4) Changes in C_p mean that the displacement is varied with all other parameters unaffected.

(5) Changes in l.c.b. position mean that the position of the centre of buoyancy varies longitudinally, the displacement and other parameters remaining constant.

(6) Changes in $\frac{1}{2}\alpha^\circ_e$ mean that the half angle of entrance varies, the displacement, l.c.b. and other parameters being constant.

[1] Numerals refer to list of References at the end of the paper.

Method of Analysis

The multi-curvilinear regression analysis is outlined in Appendix I where it can be seen from equation (7) that the individual design parameters have been included up to the second order, the cross-coupled terms therefore being included up to the fourth order.

The basic resistance data for some hundred and thirty trawler models have been examined at speed-length ratios of 0·80, 0·90, 1·00 and 1·10, all data being applicable to the condition for which flow over the models is fully turbulent. In cases where turbulence stimulators were not fitted to the model, estimated corrections to the measured resistances have been made based on model experiment data. These corrections seldom exceed 3 per cent of the total resistance, due to the relatively high speeds of these vessels and the fineness of the forms. The data were computed in C_R form and the basic design parameters evaluated in each case. The form of the regression equation having been decided, it is now possible to determine the coefficients in equation (7) by the theory of minimal variance already described. From the point of view of general application of results, it is desirable that there should be no highly significant correlation between the variables used in the analysis, and the data were therefore examined on this basis.

It was determined that no significant linear association exists between the variables, although it was thought desirable to obtain a few additional results in certain regions of the data. An additional nine models were therefore designed and resistance experiments conducted in No. 1 Tank. The determination of the regression coefficients was performed on the high-speed electronic computer (DEUCE) in the Mathematics Division, N.P.L.

Assessment of Completed Analysis

On completion of any statistical analysis of this type, the magnitude of the residuals provides the best indication that the regression equation fits the experiment data in a satisfactory manner. These residuals should be random in character with respect to each of the design parameters, and their magnitude is then largely determined by inherent inaccuracies in the experiment data coupled with any small but genuine effects of parameters not included in the analysis. After consideration of the practical requirements of the naval architect and the likely order of accuracy of the experiment data over a period of some thirty years, it was decided to aim for an overall accuracy in speed prediction of $\pm$ 1 per cent, which in the useful speed range of most trawlers built in this country amounts to approximately $\pm$ 1/10 knot. This permits a deviation in C_R of approximately $\pm$ 4 per cent in order that the speed calculated from the regression equation does not differ by more than 1/10 knot from that which would be obtained from the model experiments in a particular case.

The accuracy of prediction of C_R which has been obtained using equation (7) is within 3 per cent for 95 per cent of the data and within 5 per cent for 99 per cent of the data at speed-length ratios 0·80, 0·90 and 1·10, and falls to 35 per cent at the 5 per cent level at $V/\sqrt{L} = 1{\cdot}0$. The required limits of accuracy have therefore been met except at the unity speed-length ratio. Since, in this region, the rate of change of resistance with speed is normally quite high, it may be that experimental difficulties of measurement are genuinely responsible for the differences, although it is intended to explore this matter in further detail.

It should be noted that the variation in C_R of the measured resistance data used in the analysis exceeds 100 per cent at each speed-length ratio examined, and the fact that such large variations in resistance have been explained by the design parameters used in the regression equation may be regarded as very satisfactory.

On completion of the analysis, an additional fifteen models were tested for the fishing industry, and it was found that each of these results satisfied the regression equation to the required limits of accuracy.

In a similar manner, the e.h.p. values at other ship speeds can be calculated to deduce the e.h.p. speed curve for the ship (Table 1A of Appendix I.). Since the models chosen for this analysis are between 13 and 15ft. in length, it will be seen that due to the nearly constant ratio of model to ship lengths, predictions of resistance using alternative extrapolations can be made. Predictions of full-scale resistance have therefore been made using the new I.T.T.C. correlation line (Table 1B). In general, the predicted resistances for vessels of this type according to the I.T.T.C. correlation line will be found to be some 5-12 per cent below those given using the Froude coefficients.

Design Considerations

In addition to its use as a means of predicting ship resistance based on geometric properties of trawler forms, equation (7) can be minimized to determine optimum values of resistance within the ranges covered by the data. In many cases in practice, non-optimum conditions may have to be accepted due to other design considerations, and the penalties in resistance for these conditions can therefore be evaluated. To assist further in the evaluation of the regression equation (7), a programme has been prepared for DEUCE, by means of which the C_R — speed curve for any particular set of design parameters can be obtained very quickly By means of this programme, the equivalent resistance data of some forty model tests can be determined in a few hours, and the effect on resistance of systematic changes in the design parameters assessed (see Table 2).

The design diagrams may also be used to deduce near-optimum forms and the following conclusions drawn :—

(1) Changes in B/d.

Figs. 1-4 indicate the variation of resistance with C_p and B/d. For fixed values of C_p an increase in B/d generally results in an increase in resistance/ton of displacement. The exception to this general case is for $V/\sqrt{L} = 1 \cdot 10$ at which speed-length ratio a minimum resistance/ton has been obtained at approximately $B/d = 2 \cdot 25$ (Fig. 4). Figs. 47 and 48 have been prepared to show the B/d ratios for optimum resistance at $V/\sqrt{L} = 1 \cdot 10$ and $1 \cdot 00$.

(2) Changes in l.c.b. position.

Figs. 5-8 indicate the variation of resistance/ton of displacement with C_p and l.c.b. position. In general the optimum l.c.b. position moves further aft with increase in speed-length ratio. The penalties in resistance for l.c.b. positions between 0 and 2 per cent aft compared with those between 2 per cent and 6 per cent aft are particularly marked at the higher speed-length ratios, more so in the case of forms of high prismatic coefficient.

(3) Changes in $\frac{1}{2}\alpha^\circ_e$.

The effect on resistance/ton of changes in $\frac{1}{2}\alpha^\circ_e$ is dependent on the values of L/B and C_p, and can be seen by referring to Figs. 9-40. Particularly in the case of forms of low prismatic coefficient, there is a marked penalty in resistance for high values of $\frac{1}{2}\alpha^\circ_e$. With $\frac{1}{2}\alpha^\circ_e$ values in the region of 30 degrees for example, the total resistance is nearly doubled as compared with that of a vessel having a $\frac{1}{2}\alpha^\circ_e$ value of 5 degrees and otherwise identical form parameters. Approximately 10 per cent of the data is for bulbous bow trawlers, and it can be seen that the useful ranges of the parameters in which they are most effective are as follows :—

$V/\sqrt{L}$ $1 \cdot 0 - 1 \cdot 10$

$L/B > 5 \cdot 60$

$\frac{1}{2}\alpha^\circ_e$ $5 - 30$

$C_p < 0 \cdot 63$

The Prediction of Ship Resistance

In the case of a new design, it is required to find the variation of e.h.p. with ship speed. To facilitate computation of results, design diagrams based on equation (7) have been prepared which depend on the values of the six form parameters L/B, B/d, C_m, C_p, l.c.b. and $\frac{1}{2}\alpha^\circ_e$, the value of C_R being obtained at each speed-length ratio by adding the values obtained by interpolation in each diagram (Figs. 1-49), namely :—

$$C_{R(200')} = F_1 + F_2 + F'_3 + F_6. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

Where $F_1 = f(C_p, B/d) + K$ where K = constant

$F_2 = f(C_p,$ l.c.b.)

$F'_3 = f(C_p, \frac{1}{2}\alpha^\circ_e, L/B)$

and $F_6 = f(C_m)$

The design diagrams are applicable within the following limits :—

L/B (4·4 — 5·8) $\frac{B}{d}$ (2·0 — 2·6) C_m (0·81 — 0·91) C_p (0·6 — 0·7)

l.c.b. (0 — 6 per cent) aft $\frac{1}{2}\alpha^\circ_e$ (5 — 30.)

Considering the case where, for a new design, the form parameters are :—

$L/B = 5{\cdot}40$ $B/d = 2{\cdot}53$ $C_m = 0{\cdot}909$ $C_p = 0{\cdot}60$

l.c.b. = + 4·31 per cent aft $\frac{1}{2}\alpha^\circ_e = 15{\cdot}0$

we have at $V/\sqrt{L} = 1{\cdot}10$ $F_1 = + 17{\cdot}80$

$F_2 = - 1{\cdot}20$

$F'_3 = - 2{\cdot}50$

$F_6 = 0$

therefore $C_{R(200')} = 14{\cdot}10$

The C_R value for a ship 180ft. b.p. is therefore

$$C_{R(180')} = C_{R(200')} + \delta_1 \text{ where } \delta_1 = \frac{152{\cdot}5 \times \text{(s.f.c.)}}{\Delta^{\frac{1}{3}}_{(200')}}$$

and s.f.c. = Froude skin friction correction from 200ft. b.p. to 180ft. b.p.

$\Delta_{(200')}$ = Extreme displacement of 200ft. b.p. (35ft.^{3}/ton) vessel including stern.

In this case $\Delta_{(200')} = 1{,}710$ tons

s.f.c. = 0·012

Hence $\delta_1 = \frac{152{\cdot}5 \times 0{\cdot}012}{11{\cdot}97} = 0{\cdot}153$

Hence $C_{R(180')} = 14{\cdot}10 + 0{\cdot}153 = 14{\cdot}253$

and e.h.p. (Froude) = $\frac{C_{R_{(L)}} \times \Delta_{(L)} \times V^3}{325{\cdot}7 \times L} = \frac{14{\cdot}253 \times 1{,}250 \times (14{\cdot}76)^3}{325{\cdot}7 \times 180}$

therefore e.h.p. (Froude) = 975.

For prismatic coefficients in the region of 0·68, $V/\sqrt{L} = 1·10$, and L/B 5·6 — 5·8, the optimum value of $\frac{1}{2}\alpha^\circ_e$ is approximately 30 degrees. Similar optimum values of $\frac{1}{2}\alpha^\circ_e$ can be determined at other values of $V/\sqrt{L}$ and L/B by referring to Figs. 9-40.

(4) Changes in L/B.

The effect on resistance/ton of changes in L/B ratio depends on the values of C_p and $\frac{1}{2}\alpha^\circ_e$ at each speed-length ratio. Figs. 41-46 show these effects at $V/\sqrt{L} = 1·10$. For fixed values of $\frac{1}{2}\alpha^\circ_e$ the effect of these changes is more marked with the forms of high prismatic coefficient. For L/B ratios in the region of 5·6 — 5·8 there is a marked reduction in resistance, while maximum resistances usually occur in the range L/B 4·4 — 5·0.

(5) Changes in C_m.

Fig. 49A shows the effect on resistance/ton of changes in maximum area coefficient for each speed-length ratio. High values of C_m are generally beneficial in reducing resistance of these forms at constant speed-length ratio. Between $V/\sqrt{L}$ 0·8 — 1·0 these reductions in resistance are generally greater with increasing speed but at $V/\sqrt{L}$ = 1·10 they are unimportant.

(6) Changes in C_p.

The effect on resistance/ton of changes in C_p (displacement) is dependent on the magnitudes of B/d, l.c.b., $\frac{1}{2}\alpha^\circ_e$ and L/B and is therefore impossible to present in a single diagram, since the number of practical combinations of these four parameters is almost infinite. General trends may however be inferred by considering the three main trawler types and choosing representative parameters for each, namely:—

Class I. L/B 5·5 B/d 2·25 C_m 0·875 l.c.b. + 4 per cent $\frac{1}{2}\alpha^\circ_e$ 13·0
C_p varying

Class II L/B 5·0 B/d 2·50 C_m 0·875 l.c.b. + 4 per cent $\frac{1}{2}\alpha^\circ_e$ 19·5
C_p varying

Class III L/B 4·5 B/d 2·50 C_m 0·875 l.c.b. + 2 per cent $\frac{1}{2}\alpha^\circ_e$ 26·0
C_p *varying*

The effects on $C_{R(200')}$ of variations in C_p for these three trawler types are shown in Figs. 49B-51. For Class I, the optimum C_p is in the region of 0·60 for each speed-length ratio and penalties in resistance occur if this value is exceeded. For Class II, the intermediate type of trawler, a well-defined minimum C_p of 0·61-0·62, is revealed. Changes in C_p from this region result in higher values of resistance/ton of displacement. For Class III, the near-water trawlers, there is a clearly defined optimum relationship between C_p and $V/\sqrt{L}$ which is approximately linear and varies from 0·66 at $V/\sqrt{L} = 0·80$ and 0·63 at $V/\sqrt{L} = 1·10$.

It must be emphasized, therefore, that there is no unique value of C_p for optimum resistance/ton and it is essential to calculate the optimum prismatic coefficient in each particular case.

Propulsion

Particulars of Screws

(1) *Selection of Model Screws.* In determining the particulars of the model screws to be used, three aspects were considered.

(a) General types and dimensions of the ship screws
(b) Available model screws and existing model experiment data
(c) Alternative model experiment techniques.

After an assessment of the ship screw particulars summarized in Table 3, it was decided to relate the part of the work concerning the screws to the larger group of vessels (group C, of length greater than 160ft.). It was also decided to base this work on two sets of screws, one of moderate diameters and designed for high rates of rotation corresponding to high-speed diesel engines, the other of large diameters and designed for low rates of rotation corresponding to low-speed diesel or steam engines.

The probable dimensions of the ship screws were compared with those of the N.P.L. standard series summarized in Table 4, and it was found that, for the convenient model scale ratio of 1/12, six of the available standard series screws could be taken to represent two groups of 8·4-ft. diameter ship screws designed for high rates of rotation, one for free-running conditions, the other for trawling conditions. Moreover, the initial standard series open-water experiment results shown in Fig. 52 could be incorporated in this research. Having fixed the model scale, the geometric data for four additional model screws were chosen. These corresponded to two screws designed for high rate of rotation and for free-running conditions, one 9ft. in diameter and the other 9·5ft. in diameter, and two screws both 11·5ft. in diameter and designed for low rate of rotation, one for free-running conditions and the other for trawling conditions.

After checking the sizes of the additional model screws in relation to the capacity of the model experiment equipment (this procedure had, of course, previously been followed for the existing screws of the N.P.L. standard series), it was found that if desired all the screws could be tested in open water, in the Lithgow water tunnel, and behind a model of a bulbous bow trawler. Accordingly, the four additional model screws were made and subsequently tested using all three experiment techniques. Open-water and water-tunnel experiments were made for the six standard series screws and propulsion experiments were also made for two of these screws.

(2) *Screws PT1 to PT4.* The geometric details for these screws were chosen to correspond to those of a group of ship screws all designed for the same delivered horse-power and rate of rotation (d.h.p. = 1,455, $N = 250$ per minute), three (PT1 to 3) for free-running conditions at a ship speed of 14 knots and one (PT4) for trawling conditions at a ship speed of 4 knots. Particulars of screws PT1 to PT4 are given in Table 5, together with those of screws PT5 and 6.

The basic screw (PT1) was selected from the N. .L. standard series to represent a screw of about the optimum diameter. Screws PT2 and PT3 were designed using the Troost B series[3] data as a basis to represent screws of about 7 per cent and 13 per cent above the optimum diameter. In designing screw PT2, which was of N.P.L. standard series type, a pitch increase of 2 per cent was applied to make allowance for differences between the blade section shapes of the Troost B series and those of the N.P.L. standard series. The geometric data for screw PT3 were similar to those of the N.P.L. standard series, but the blade sections were designed to have low camber ratios (m/t values one half of those for the standard series). This was done to lessen the susceptibility to adverse performance at negative incidence associated with moderate camber-blade sections operating at advance coefficients greater than those corresponding to the optimum screw diameter. Typical blade-section performance values obtained using the calculation method due to Hill[4] are listed in Table 6. Geometric data for the basic screw of the N.P.L. standard series are shown in Fig. 53 and the blade section offsets for screw PT3 are given in Table 7.

Screw PT4 was selected from the N.P.L. standard series to represent a screw similar to PT1 but having a lower pitch ratio corresponding to the lower speed design condition.

(3) *Screws PT5 and PT6.* The geometric details for these screws were chosen to correspond to those of two ship screws, both designed for the same delivered horse-power as for screws PT1 to PT4 but at a lower rate of rotation (d.h.p. = 1,455, $N = 136$ per minute), PT5 for free-running conditions at a ship speed

of 14 knots, and PT6 for trawling conditions at a ship speed of 4 knots. Both screws of N.P.L. standard series type were designed using a procedure similar to that followed in designing screw PT2.

Model Screw Experiments

(1) *Open-water Experiments.* Open-water experiments were made for screws PT1 to PT6. Each screw was tested over a range of advance coefficient at a constant rate of rotation. The experiment results are given in Table 9 and in Fig. 54.

(2) *Water Tunnel Experiments.* Screws PT1 to PT6 and four selected screws of the N.P.L. standard series were tested in the slotted wall test section of the N.P.L. No. 1 (Lithgow) water tunnel. The four additional screws comprised two similar to PT1 but of lower blade-area ratios, and two similar to PT4 also of lower blade-area ratios. The ship screw design conditions and corresponding model screw operating conditions are listed in Table 8. The experiment results are given in Tables 10 to 12 and in Figs. 55 to 57.

Screws PT1 to PT6 were tested at atmospheric pressure conditions, each at a constant rate of rotation over a range of advance coefficient. Experiments at reduced pressure were made for screws PT1 to PT6 and the four additional standard series screws, each at two sets of conditions, one simulating the free-running design or operating condition and the other representing a trawling condition. The experiments simulating free-running were made for each screw at a constant rate of rotation and at the constant operating value of the advance coefficient over a range of cavitation number. The N.P.L. standard methods[5] were used in analysing these experiment results. For the trawling condition the tunnel impeller was stopped and each screw was run at a constant rate of rotation over a range of cavitation number. Under such conditions there was an axial velocity through the test section due to the model screw acting as an impeller, but no attempt was made to relate this velocity to an advance coefficient. Thus it was not possible to use the N.P.L. standard analysis methods since neither the resultant velocity cavitation number σ_R nor the screw efficiency could be evaluated ; instead, the results were analysed using a cavitation number σ_N, related to the rate of rotation only, together with a screw performance factor (k_T/k_Q) defined by,

$$\sigma_N = \frac{2(P-e)}{\rho(0{\cdot}7\pi nD)^2} \quad \text{and} \quad \frac{k_T}{k_Q} = \frac{TD}{Q}$$

(3) *Self-propulsion Experiments*

Screws PT1 to PT6 were tested behind a model of a bulbous bow trawler over a range of ship speed corresponding to 9·0 to 14·5 knots. Additional overload tests were conducted with each screw corresponding to trawling conditions at 4·0 knots. The ship propulsion estimates for free-running conditions using a ship correlation factor of 1·10 are given in Fig. 58. The r.p.m. for the ship include a 2 per cent allowance for scale effects. D.h.p. is defined as

$$\frac{\text{e.h.p.} \times 1{\cdot}10}{\text{q.p.c.}}$$

The estimates of pull, thrust and d.h.p. for trawling conditions at 4·0 knots are given in Fig. 59.

Comparisons of Model Screw Experiment Results

(1) *Performance Comparisons—Non-cavitating Conditions.* Three sets of corresponding comparisons based on open-water, water-tunnel and propulsion experiments are given in Table 13. Screws PT1 to 3, designed for and operating at free-running conditions, are compared at the design value of delivered horse-power and at the design value of either the speed of advance (open-water and water-tunnel experiments) or the ship speed (propulsion experiments). For screws PT1 to 3 and PT5, comparisons based on the propulsion experiments

are also made at the design value of delivered horse-power and at a constant value of ship-model correlation factor (s.c.f. = 1·10) corresponding to a trial condition. Screws PT4 and PT6, designed for trawling but operating at free-running conditions, are compared at the design value of the screw rate of rotation and at the constant ship-model correlation factor of 1·10. For screws PT1 to PT6 operating at trawling conditions, comparisons based on the open-water and propulsion experiments are made at the design value of torque and at the design value of either the speed of advance (open-water experiments) or the ship speed (propulsion experiments).

Significant aspects of these comparisons are as follows :—

(a) Screws PT1 to PT3 designed for the same free-running condition : effects of increased diameter and reduced blade-area ratio (PT1-2), and of increased diameter and reduced blade-section-camber ratio (PT2-3). An increase in diameter from $D = 8·4$ to $9·0$ and a reduction in blade-area ratio from $a_D = 0·6$ to $0·55$, while having no appreciable effect on screw efficiency as measured by open-water experiments, result in reduced screw efficiency as measured by water tunnel experiments ($3\frac{1}{2}$ per cent reduction) and as derived from propulsion experiments ($1\frac{1}{2}$ per cent reduction), and in reduced propulsive efficiency (5 per cent reduction) or loss in ship speed (1 per cent reduction) as measured by propulsion experiments, all at free running conditions. A further increase in diameter from $D = 9·0$ to $9·5$ and a reduction in blade-section-camber ratio (m/t for PT3 one half of that for PT2) have no appreciable effect on screw efficiency, but result in a further reduction in propulsive efficiency of about 3 per cent or a further loss in ship speed of $\frac{1}{2}$ per cent at free-running conditions. At trawling conditions screw PT2 operates more efficiently than PT1 (open-water tests ; 8 per cent increased thrust : propulsion tests ; $5\frac{1}{2}$ per cent increased thrust, $6\frac{1}{2}$ per cent increased pull). Screw PT3 also operates more efficiently than PT1, but the differences between screws PT3 and 1 are less than those between screws PT2 and 1 as measured by propulsion experiments (open-water tests ; $8\frac{1}{2}$ per cent increased thrust : propulsion tests $4\frac{1}{2}$ per cent increased thrust, 4 per cent increased pull).

(b) Screws PT1 and PT5 designed for free-running conditions and screws PT4 and PT6 designed for trawling conditions : comparisons betwe free-running and trawling operating conditions. The loss in free-running ship speed for the screws designed for trawling conditions is 15 per cent for screw PT4 and 17 per cent for screw PT6. The loss in thrust at the trawling conditions for the screws designed for free-running conditions is 24 per cent as measured by open-water experiments and 21 per cent as measured by propulsion experiments for screw PT1 ; it is 26 per cent (open-water and propulsion experiments) for screw PT5. Corresponding loss in pull is 22 per cent for screw PT1 and 30 per cent for screw PT5. Comparisons between free-running and trawling performance for intermediate pitch ratios between those for screws PT1-4 are shown in Fig. 60.

(2) *Screw Performance Comparisons—Cavitating Conditions.* The comparisons given in Table 14 express the relation between the model screw cavitation number at point of thrust breakdown σ_T and the model screw operating cavitation number σ_M, which had been derived by applying a ship model correlation factor of 0·8 to the ship screw operating cavitation number σ_S following the procedure given in Table 8. These cavitation numbers are linked by a thrust breakdown factor f_c or an overall thrust breakdown factor F_c defined by

$$f_c = \frac{\sigma_M}{\sigma_T} \qquad F_c = \frac{\sigma_S}{\sigma_T} = 1·25\, f_c$$

Significant aspects of these comparisons are as follows :—

(a) Screws PT1 to 3 designed for the same free-running conditions :

effects of increased diameter and reduced blade-area ratio (PT1-2), and of increased diameter and reduced blade-section-camber ratio (PT2-3). An increase in diameter from $D = 8{\cdot}4$ to $9{\cdot}0$ (PT1-2) and a reduction in blade-area ratio from $a_D = 0{\cdot}6$ to $0{\cdot}55$ results in a greater margin against thrust breakdown and a reduction in the extent of visible cavitation for both free-running and trawling conditions. A further increase in screw diameter from D = 9·0 to 9·5 (PT2-3) and a reduction in blade section camber ratio (m/t for PT3 one half of that for PT2) also results in improved performance, but the differences between screws PT2 and 3 are less appreciable than those between screws PT1 and 2.

(b) Screws PT1 and 5 designed for free-running conditions and screws PT4 and 6 designed for trawling conditions : comparisons between free-running and trawling operating conditions.

A screw designed for and operating at free-running conditions has a smaller margin against thrust breakdown and a greater extent of visible cavitation than a corresponding screw designed for trawling but operating at free-running conditions. This is to be expected, since both the engine power and ship speed are higher for the screw operating at its designed free-running condition. Moreover, a screw designed for and operating at trawling conditions has a smaller margin against thrust breakdown and a greater extent of visible cavitation than a corresponding screw designed for free-running but operating at trawling conditions. This is also to be expected ; although the two screws are compared at the same ship speed and absorb the same torque, both the thrust and the rate of rotation are higher for the screw operating at its designed trawling condition.

(c) Screws PT1 designed for free-running conditions and PT4 designed for trawling conditions: effects of reduced blade-area ratio. Reductions in the blade area ratio of screw PT1 from $a_D = 0{\cdot}6$ to $0{\cdot}5$ and to $0{\cdot}4$ result in reductions in the margin against thrust breakdown and increased extent of visible cavitation for both free-running and trawling conditions. The same reductions in the blade-area ratio of screw PT4 show similar effects on performance as for screw PT1. Relations between thrust breakdown factor and blade-area ratio for screws PT1 and 4 at free-running and trawling conditions are shown in Fig. 61.

For equivalent cavitating performance, as defined by equal margin against thrust breakdown and taking a thrust breakdown factor of 1·2 as the basis, screw PT1 designed for free-running conditions would require a blade area ratio of about 0·5 but screw PT4 designed for trawling conditions would require a blade area ratio greater than $a_D = 0{\cdot}6$.

Self-propulsion Experimental Data

Having estimated the effective horse-powers for a new trawler design as already described, it is then necessary to estimate the quasi-propulsive coefficients over a range of ship speed in order to predict the developed horse-power at the ship propeller. An analysis of propulsion data for trawlers, obtained from model experiments conducted at the Ship Division, N.P.L., over the last seven years, indicates that the formula

$$\text{q.p.c.} = 0{\cdot}77 - \frac{N\sqrt{L}}{18{,}000} \quad \text{where } N = \text{r.p.m. of ship propeller}, \; L = \text{l.b.p.}$$

gives a good first approximation for the quasi-propulsive coefficient provided the propeller diameter is reasonably close to the optimum. A more reliable estimate of q.p.c. will be obtained however, by calculating the efficiency of the

propeller in open water and multiplying by a suitable factor (f_p). This factor ($f_p = \eta_R \times \eta_H$) can be estimated from existing data. The following values of f_p have been derived from this analysis for near optimum diameter screws :—

Group	*l.b.p.*	$f_P = \eta_R \times \eta_H$
A	less than 120ft.	1·025
B	120-160ft.	1·015
C	greater than 160ft.	1·00
D	greater than 160ft. (BULBOUS BOW)	1·04

The results of the self-propulsion experiments with propellers PT1-PT3, designed for use with high-revving diesel machinery, indicate that the factor f_p reduces by 5 per cent for an increase of 7 per cent above the optimum diameter. The factor f_p is approximately 10 per cent less for propeller PT5 designed for low-revving steam machinery, as compared with that for propeller PT1 designed for high-revving diesel machinery, although both propellers have near-optimum diameters for their respective design conditions.

As far as the other components of propulsive efficiency are concerned at the usual operating speeds, the wake fraction does not vary appreciably for vessels in groups A, B, C or D, and a w_t value of 0·20 is usually sufficient for design purposes. For groups A, B and C, the average thrust-deduction fraction may be taken as 0·197 and for group *D* this value may be increased to 0·220. Under trawling conditions the thrust-deduction fraction generally reduces compared with free-running conditions, and an average design value may be taken as $t = 0{\cdot}15$.

Conclusions

Resistance

(1) By using the statistical method described in this paper, the e.h.p.-speed characteristics of trawler forms can be calculated from their lines plan with sufficient accuracy for practical purposes.

(2) Optimum form parameters can be determined for general or particular cases and penalties in resistance estimated for non-optimum conditions.

(3) The regression equation for C_R, based on the six form parameters used in this analysis, has explained variations of over 100 per cent in total resistance between the worst and best forms at each speed-length ratio examined.

(4) The analysis has confirmed the high importance of l.c.b. position in determining the resistance of trawler forms, and also the relative importance of the other form parameters.

(5) Finally, a cautious approach to the use of this type of analysis is recommended and more experience is necessary before it can be unconditionally recommended. There is no suggestion at this stage that the various expressions derived are the final word on the subject. They may have to be improved or modified in the light of new results. However, the method can be used for estimating purposes and to suggest modifications in the hull form of trawlers but, at the present time, these should be checked by model experiments. The method must not be used for values of parameters outside the range of those in the data, or estimates may be grossly in error.

Eventually, tank-testing may not be necessary except for designs which are clearly revolutionary in concept.

Propulsion

(6) An increase in screw diameter of about 7 per cent above the optimum free-running value and a reduction in blade-area ratio of about 10 per cent results in a loss in ship speed of about 1 per cent at free-running conditions, an increase in thrust of about 6 per cent at trawling conditions, and no adverse effects on cavitating performance at either free-running or trawling conditions.

A further increase in screw diameter and a reduction in blade-section camber ratios to one half of those for the standard series also results in a loss in free-running ship speed, but no significant improvement in trawling performance is obtained. Accordingly, such low-camber sections are not to be recommended for trawler screws.

(7) A screw designed for and operating at trawling conditions has a thrust about 20 per cent greater than that of a similar screw designed for the same delivered horse-power and rate of rotation at free-running conditions but operating at trawling conditions. However, there is a loss of about 15 per cent in free-running ship speed for the screw designed for trawling conditions.

(8) A screw designed for trawling conditions should have a larger blade-area ratio than a corresponding screw designed for the same delivered horse-power and rate of rotation but for free-running conditions. For equal margin against thrust breakdown the increase in blade-area ratio should be about 20 per cent.

(9) For a given ship speed, variations in screw diameter have no appreciable effect on the screw speed of advance since the variations in wake fraction are small. However, variations in screw diameter can have a significant effect on both screw efficiency and propulsive efficiency. A large diameter screw designed for free-running conditions at a low rate of rotation operates at a higher screw efficiency and at a higher propulsive efficiency than a moderate diameter screw designed for a high rate of rotation. However, the differences in screw efficiency are greater than those in propulsive efficiency. Typical values are—increase in screw diameter 37 per cent ; increase in screw efficiency about 12 per cent ; increase in propulsive efficiency about 3 per cent.

(10) The data given in this paper if used in conjunction with standard series design charts can be applied in designing trawler screws and in estimating their performance. Typical worked examples are given in Appendix II.

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NOMENCLATURE

L = Length between perpendiculars (ft.) = distance between the intersections of the trimmed waterline with the stem profile and the after side of the stern post.

)o(= Amidships = section 50 per cent L from the after perpendicular

B = Breadth moulded (ft.) = measured on the waterline at)o(

d = Mean moulded draught at)o(

C_m = Maximum area coefficient—evaluated to the trimmed waterline

C_p = Prismatic coefficient—based on the maximum section area and the moulded displacement, including stern (35ft.^{3}/ton)

l.c.b. = Position of the longitudinal centre of buoyancy of the underwater form, including stern, measured from)o(and expressed as a percentage of L (+ve aft)

$\frac{1}{2}\alpha^\circ_e$ = The half-angle of entrance, measured on the trimmed waterline forward

R = Ship resistance in pounds

V = Ship speed in knots

Δ = Extreme displacement, evaluated to the trimmed waterline, including stern (35ft.^{3}/ton)

C_R = $R.L/\Delta V^2$

L/B = Length-breadth ratio

B/d = Breadth-draft ratio

A_D = Developed blade area of screw (ft.^{2})

a_D = Developed blade area ratio of screw = $\frac{4A_D}{\pi D^2}$

D = Screw diameter (ft.)

d.h.p. = Delivered horse-power

e = Saturated vapour pressure (lb./ft.^{2})

F_c = Overall thrust breakdown factor = σ_s/σ_T

f_c = Thrust breakdown factor = σ_M/σ_T

f_p = Propulsive factor q.p.c./$\eta_o = \eta_R\,\eta_H$

I = Immersion to screw axis (ft.)

J = Advance coefficient = v_A/nD

J_o = Advance coefficient (tunnel experiments, corrected) = v_o/nD

J_T = Advance coefficient (tunnel experiments, uncorrected) = v_T/nD

k_Q = Torque coefficient = $Q/\rho n^2 D^5$

k_T = Thrust coefficient = $T/\rho n^2 D^4$

m = Maximum ordinate of blade section mean line

m/t = Blade section camber ratio

N = Screw rate of rotation (revolutions per minute)

n = Screw rate of rotation (revolutions per second)

P_F = Face pitch of screw (ft.)

P_T = Face pitch at blade tip (ft.)

P_u = Tow rope pull (tons)

$(P-e)$ = Static pressure at screw axis (lb./ft.^{2})

p_T = Tip pitch ratio = P_T/D

Q = Screw torque (lb. ft.)

q.p.c. = Propulsive efficiency or quasi-propulsive coefficient

T = Screw thrust in general (lb.). Screw thrust at trawling condition (tons)

t = Maximum cylindrical thickness of blade section

t = Thrust deduction fraction

t_A = Equivalent blade thickness at screw axis

V_A = Speed of advance of screw (knots)

v_A = Speed of advance of screw (ft./sec.)

v_T = Axial velocity in tunnel test section (ft./sec.)

v_o = Equivalent velocity in open water (ft./sec.)

v_R = Resultant velocity at the $x = 0{\cdot}7$ radius fraction (neglecting inflow) $= (v_A^2 + (0{\cdot}7\pi nD)^2)^{\frac{1}{2}}$

w_T = Wake fraction (Taylor)

η = Screw efficiency = $\dfrac{v_A\, T}{2\pi n Q}$

η_o = Screw efficiency (uniform flow in open water)

η_B = Screw efficiency (non-uniform flow behind a model hull)

η_R = Relative rotative factor = η_B/η_o

η_H = Hull factor = q.p.c./η_B = $\dfrac{1-t}{1-w_T}$

ρ = Mass density (lb. sec.^{2}/ft.^{4})

σ_R = Cavitation number (resultant velocity) = $\dfrac{2(P-e)}{\rho v_R^2}$

σ_N = Cavitation number (rotational velocity) = $\dfrac{2(P-e)}{\rho(0{\cdot}7\pi nD)^2}$

σ_S = Cavitation number (ship screw operating condition)

σ_M = Cavitation number (model screw operating condition)

σ_T = Cavitation number (model screw, point of thrust breakdown)

τ = Blade thickness ratio (axis) = t_A/D

APPENDIX I

The Regression Equation

In the simplest case, consider a set of observations $y_1\ y_2\ y_3 + \ldots\ldots y_n$, and $x_1\ x_2\ x_3 + \ldots\ldots x_n$, and it is supposed that we have to choose the unknown values in a regression equation of y, so that the residual variation is a minimum. In this simple case we assume that the regression equation of y is linear with x and of the form

$$y - y_o = \beta\,(x - x_o) + e \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

x_o and y_o are fixed values of x and y which normally vary, and it is required to find the best value of β such that the variance "e" is a minimum. In particular, choose $x_o = \bar{x}$ (the arithmetic mean of the observations).

Now since $\Sigma e^2 = \Sigma[(y - y_o) - \beta\,(x - \bar{x})]^2 = \text{minimal}$

therefore by differentiating with respect to β and y_o we have,

$$\Sigma[(y - y_o) - \beta\,(x - \bar{x})] = 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

and $$\Sigma[(y - y_o) - \beta\,(x - \bar{x})]\,(x - \bar{x}) = 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

and from equation (2) $\Sigma[(y - y_o) - \beta\,(x - \bar{x})] = 0$

therefore $\Sigma y - n y_o - 0 = 0$

therefore $$y_o = \frac{1}{n}\ \Sigma y = \bar{y} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

and from equation (3) $\Sigma[y - \bar{y}]\,(x - \bar{x}) = \beta\ \Sigma(x - \bar{x})^2$

therefore $$\beta = \frac{\Sigma(y - \bar{y})\,(x - \bar{x})}{\Sigma(x - \bar{x})^2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

In this way we see that by using the theory of minimal variance we can determine the best straight line through the observations. This passes through the point $(\bar{x}, \bar{y})$ and has a slope β such that the residual variation is a minimum. β can be found from equation (5).

By extending this argument to more complex regression equations, the coefficients of each parameter included in the equation can be determined, provided there is a larger number of observations than required coefficients. The number of observations required to solve a given number of coefficients is largely determined by the quality of the fit obtained by using the regression equation and comparing the results with those recorded in the experiments. If terms in x, higher than the first order, are included in the regression equation, combined with additional terms which are independent of x, the analysis is referred to as a multi-curvilinear regression analysis, and it is an analysis of this type which is presented in this paper.

Certain facts are known from experience of trawler design which assist in the formation of the regression equation.

(1) L.c.b. position is very important in determining ship resistance, the best position varying with prismatic coefficient C_p.

(2) Optimum values of half angle of entrance for minimum resistance vary with prismatic coefficient and $\frac{L}{B}$ ratio.

(3) Optimum values of $\frac{B}{d}$ for minimum resistance vary with prismatic coefficient.

(4) Optimum values of L/B for minimum resistance vary with prismatic coefficient.

These statements suggest that cross-coupling of terms is required in the regression equation for resistance of these vessels, namely, terms such as $(C_p.\text{l.c.b.})$, $(C_p.L/B)$, $(C_p.B/d)$, $(C_p.\frac{1}{2}\alpha^\circ_e)$, $(L/B.\frac{1}{2}\alpha^\circ_e)$.

In order to establish the relative importance of individual parameters, a regression equation of the form,

$$C_R = a_o + a_1.L/B + a_2.B/d + a_3.\ C_m + a_4.C_p + a_5.\ l.c.b. + a_6.\tfrac{1}{2}\alpha^\circ_e \quad \ldots\ldots(6)$$

was chosen, and the coefficients a_0 a_1 a_2 etc. determined by the theory of minimal variance. It was found that all parameters were significant, C_m being the least important. Evidence that cross-coupling of terms such as C_p.l.c.b. was required was verified by plotting the "residuals" from equation 6 against C_p.l.c.b. and a definite variation detected. The term "residual" used here, is defined as the difference between the observed and calculated values of C_R for any set of design parameters.

The final form of the regression equation for C_R, which includes the requirements already stated, is as follows :—

$$\begin{aligned} C_R = a_0 &+ a_1.\frac{B}{d} + a_2.\left(\frac{B}{d}\right)^2 + a_3.\ \text{l.c.b.} + a_4.\ \text{l.c.b.}^2 + a_5.\ Cp + a_6.\ C_p^2 \\ &+ a_7.\ L/B + a_8.\ (L/B)^2 + a_9.\ C_m + a_{10}.\ \tfrac{1}{2}\alpha^\circ_e + a_{11}.\ \tfrac{1}{2}\alpha^\circ_e{}^2 + a_{12}.\ C_p.\ \text{l.c.b.} \\ &+ a_{13}.\ Cp.\ \text{l.c.b.}^2 + a_{14}.\ Cp^2.\ \text{l.c.b.} + a_{15}.\ Cp^2.\ \text{l.c.b.}^2 + a_{16}.\ Cp.\ \tfrac{1}{2}\alpha^\circ_e \\ &+ a_{17}.\ Cp.\ \tfrac{1}{2}\alpha^\circ_e{}^3 + a_{18}.\ Cp^2.\ \tfrac{1}{2}\alpha^\circ_e + a_{19}.\ Cp^2.\ \tfrac{1}{2}\alpha^\circ_e{}^2 + a_{20}.\ Cp.\ L/B \\ &+ a_{21}.\ Cp.\ (L/B)^2 + a_{22}.\ C_p^2.\ L/B + a_{23}.\ C_p^2.\ (L/B)^2 + a_{24}.\ L/B.\ \tfrac{1}{2}\alpha^\circ_e \\ &+ a_{25}.\ L/B.\ \tfrac{1}{2}\alpha^\circ_e{}^2 + a_{26}.\ (L/B)^2.\ \tfrac{1}{2}\alpha^\circ_e + a_{27}.\ (L/B)^2.\ \tfrac{1}{2}\alpha^\circ_e{}^3 + a_{28}.\ \frac{B}{d}.\ C_p \\ &+ a_{29}.\ \left(\frac{B}{d}\right)^2.Cp \qquad \ldots\ldots(7) \end{aligned}$$

TABLE 1(A)—*Typical Calculation of e.h.p., (Froude) for a Trawler 97·5ft. b.p.*

Speed-length Ratio $V/\sqrt{L}$	0·80	0·90	1·00	1·10	*Remarks*
L	97·5	97·5	97·5	97·5	Length between perpendiculars (ft.)
V	7·90	8·89	9·88	10·85	Ship speed (knots)
$C_{R.(200')}$	8·141	8·544	10·406	19·433	Calculated from equation (7)
(L)	0·845	0·950	1·055	1·160	$(L) = 1{\cdot}055\ V/\sqrt{L}$
s.f.c.	0·0453	0·0444	0·0436	0·0428	Calculated from equation (12)
$\Delta_{(97\cdot5)}$	336	336	336	336	Extreme displacement of 97·5ft. b.p. ship (tons)
$\Delta^{\frac{1}{3}}_{(200')}$	14·27	14·27	14·27	14·27	$\Delta^{\frac{1}{3}}_{(200')} = \Delta^{\frac{1}{3}}_{(97\cdot5)} \times \frac{200}{97\cdot5}$
δ_1	0·485	0·475	0·467	0·458	Calculated from equation (11)
$C_{R(97\cdot5')}$	8·626	9·019	10·873	19·891	Calculated from equation (10)
e.h.p.$_{(L)}$	45·0	67·0	110·0	269·0	e.h.p. (Froude)—equation (9)

$$\text{e.h.p.}_{(L)} = \frac{C_{R(L)} \cdot \Delta_{(L)} \cdot V^3}{325{\cdot}7 \times L.} \qquad \ldots\ldots(9)$$

$$C_{R(L)} = C_{R(200')} + \delta_1 \qquad \ldots\ldots(10)$$

$$\delta_1 = \frac{(s.f.c.). \times 152{\cdot}5^{\frac{2}{3}}}{\Delta^{\frac{1}{3}}_{(200')}} \qquad \ldots\ldots(11)$$

$$(\text{s.f.c.}) = (S)\,(L)^{-0{\cdot}175}\left(0{\cdot}0196 + \frac{0{\cdot}29L}{10^4} - \frac{2{\cdot}77L^2}{10^6} + \frac{1{\cdot}22}{10^8} \cdot L^3\right) \qquad \ldots\ldots(12)$$

$$(S) = (6{\cdot}0)$$

$$\Delta(C)_1 = 0{\cdot}044\ (S)\,(L)^{-0{\cdot}175} \qquad \ldots\ldots(13)$$

$$\Delta(C)_2 = 2{\cdot}98\ (S)\left(\frac{1}{[\log_{10}(R_{n(14)})-2)]^2} - \frac{1}{[\log_{10}(R_{n(97\cdot5)})-2)]^2}\right) \qquad \ldots\ldots(14)$$

$$\Delta(C)_3 = 2{\cdot}98\ (S)\left(\frac{1}{[\log_{10}(R_{n(14)})-2)]^2} - \frac{1}{[\log_{10}(R_{n(200')})-2)]^2}\right) \qquad \ldots\ldots(15)$$

$$C'_{R\,(97\cdot5')} = C_{R(200')} + \delta_2 \qquad \ldots\ldots(16)$$

$$C'_{R\,(200')} = C_{R(200')} + \delta_3 \qquad \ldots\ldots(17)$$

TABLE 1(B)—*Typical Calculation of e.h.p. (I.T.T.C.) for a Trawler 97·5ft. b.p.*

Speed-length ratio $V/\sqrt{L}$	0·80	0·90	1·00	1·10	*Remarks*
L	97·5	97·5	97·5	97·5	Length between perpendiculars (ft.)
V	7·90	8·89	9·88	10·85	Ship speed (knots)
$V_{(97\cdot5')}$	13·34	15·02	16·69	18·33	Ship speed (ft./sec.)
$V_{(200')} = V_{97\cdot5} \times \sqrt{\frac{200}{97\cdot5}}$	19·09	21·49	23·88	26·23	200ft. ship speed (ft./sec.)
$V_{(14')} = V_{97\cdot5'} \times \sqrt{\frac{14}{97\cdot5}}$	5·05	5·69	6·32	6·94	14ft. model speed (ft./sec.)
$R_{n(97\cdot5')}$	$9\cdot883 \times 10^7$	$1\cdot113 \times 10^8$	$1\cdot237 \times 10^8$	$1\cdot358 \times 10^8$	Reynolds number 97·5ft. (ship) $= \frac{97\cdot5 \times V_{97\cdot5'}}{1\cdot316 \times 10^{-5}}$
$R_{n(200')}$	$2\cdot901 \times 10^8$	$3\cdot266 \times 10^8$	$3\cdot629 \times 10^8$	$3\cdot986 \times 10^8$	Reynolds number 200ft. (ship) $= \frac{200 \times V_{200'}}{1\cdot316 \times 10^{-5}}$
$R_{n(14')}$	$5\cdot75 \times 10^6$	$6\cdot48 \times 10^6$	$7\cdot200 \times 10^6$	$7\cdot905 \times 10^6$	Reynolds number 14ft. Model $= \frac{14 \times V_{(14')}}{1\cdot229 \times 10^{-5}}$
$\log_{10} R_{n(97\cdot5')}$	7·9949	8·0464	8·0923	8·1329	
$\log_{10} R_{n(200')}$	8·4625	8·5140	8·5598	8·6006	
$\log_{10} R_{n(14')}$	6·7597	6·8116	6·8573	6·8979	

(continued on page 375)

TABLE 1(B)—*Typical Calculation of e.h.p. (I.T.T.C.) for a Trawler 97·5ft. b.p.* (continued)

Speed-length ratio $V/\sqrt{L}$	0·80	0·90	1·00	1·10	*Remarks*
$\Delta(C)_1$	+0·272	+0·266	+0·262	+0·257	Froude correction to 14ft. model results. . Equation (13)
$\Delta(C)_2$	−0·291	−0·283	−0·276	−0·270	I.T.T.C. correction from 14ft. model to ship length ..... Equation (14)
$\Delta(C)_3$	−0·361	−0·352	−0·342	−0·336	I.T.T.C. correction from 14ft. model to 200ft. ship .....Equation (15)
$\Delta_{(97\cdot5)}$	336	336	336	336	Extreme displacement of 97·5ft. b.p. Ship (Tons)
$\Delta^{\frac{1}{3}}{}_{(200)}$	14·27	14·27	14·27	14·27	$\Delta^{\frac{1}{3}}{}_{(200)} = \Delta^{\frac{1}{3}}{}_{(97\cdot5)} \times \frac{200}{97\cdot5}$
δ_2	−0·203	−0·182	−0·150	−0·139	$\delta_2 = (\Delta(C)_1 + \Delta(C)_2) \times \frac{152\cdot5}{\Delta^{\frac{1}{3}}{}_{200'}}$
δ_3	−0·951	−0·919	−0·855	−0·845	$\delta_3 = (\Delta(C)_1 + \Delta(C)_3) \times \frac{152\cdot5}{\Delta^{\frac{1}{3}}{}_{200'}}$
$C_{R_{(200')}}$	8·141	8·544	10·406	19·433	$C_{R(200')}$ from Equation (7)
$C'_{R_{(97\cdot5')}}$	7·938	8·362	10·256	19·294	I.T.T.C. prediction for 97·5ft. Ship Equation (16)
E.h.p.	41·4	62·2	104·0	261·0	E.h.p. (I.T.T.C.) — Equation (9)
$C'_{R_{(200')}}$	7·190	7·625	9·551	18·588	I.T.T.C. Prediction for 200ft. Ship Equation (17)

TABLE 2—*Typical Results Performed on DEUCE Showing Effects on C_{R200} of Changes in Design Parameters*

Design parameters						$C_{R(200')}$			
						$V/\sqrt{L}$			
L/B	*B/d*	*Cm*	*Cp*	l.c.b.	$\frac{1}{2}e°$	0·80	0·90	1·00	1·10
5·5	2·25	0·875	0·60	+4%	13·0	9·09	9·52	10·89	12·51
5·5	2·25	0·875	0·62	+4%	13·0	9·19	9·88	12·23	13·51
5·5	2·25	0·875	0·64	+4%	13·0	9·18	10·16	13·60	15·31
5·5	2·25	0·875	0·66	+4%	13·0	9·09	10·38	14·99	17·90
5·5	2·25	0·875	0·68	+4%	13·0	8·90	10·51	16·41	21·30
5·5	2·25	0·875	0·70	+4%	13·0	8·62	10·58	17·86	25·50
5·5	2·25	0·875	0·64	+4%	5·0	9·16	10·62	14·40	16·77
5·5	2·25	0·875	0·64	+4%	7·5	9·06	10·33	13·99	16·06
5·5	2·25	0·875	0·64	+4%	10·0	9·05	10·18	13·73	15·58
5·5	2·25	0·875	0·64	+4%	12·5	9·15	10·15	13·61	15·33
5·5	2·25	0·875	0·64	+4%	15·0	9·35	10·26	13·63	15·30
5·5	2·25	0·875	0·64	+4%	17·5	9·66	10·49	13·80	15·51
5·5	2·25	0·875	0·64	+4%	20·0	10·06	10·84	14·11	15·94
5·5	2·25	0·875	0·64	+4%	22·5	10·57	11·33	14·56	16·60
5·5	2·25	0·875	0·64	+4%	25·0	11·19	11·94	15·16	17·49
5·5	2·25	0·875	0·64	+4%	27·5	11·90	12·68	15·91	18·60
5·5	2·25	0·875	0·64	+4%	30·0	12·72	13·55	16·80	19·95
5·5	2·25	0·875	0·64	0%	13·0	8·60	10·43	16·37	18·19
5·5	2·25	0·875	0·64	+1%	13·0	8·91	10·55	15·92	17·22
5·5	2·25	0·875	0·64	+2%	13·0	9·11	10·55	15·30	16·42
5·5	2·25	0·875	0·64	+3%	13·0	9·20	10·42	14·53	15·78
5·5	2·25	0·875	0·64	+4%	13·0	9·18	10·16	13·60	15·31
5·5	2·25	0·875	0·64	+5%	13·0	9·06	9·78	12·51	15·00
5·5	2·25	0·875	0·64	+6%	13·0	8·83	9·28	11·26	14·86
5·5	2·25	0·83	0·64	+4%	13·0	9·50	10·67	14·44	15·32
5·5	2·25	0·84	0·64	+4%	13·0	9·43	10·56	14·25	15·32
5·5	2·25	0·85	0·64	+4%	13·0	9·36	10·44	14·07	15·32
5·5	2·25	0·86	0·64	+4%	13·0	9·29	10·33	13·88	15·31
5·5	2·25	0·87	0·64	+4%	13·0	9·22	10·22	13·69	15·31
5·5	2·25	0·88	0·64	+4%	13·0	9·15	10·11	13·51	15·30
5·5	2·25	0·89	0·64	+4%	13·0	9·08	10·00	13·32	15·30
5·5	2·25	0·90	0·64	+4%	13·0	9·01	9·88	13·13	15·30
5·5	2·25	0·91	0·64	+4%	13·0	8·94	9·77	12·94	15·29
5·5	2·25	0·92	0·64	+4%	13·0	8·87	9·66	12·76	15·29
5·5	2·0	0·875	0·64	+4%	13·0	8·98	9·96	13·70	15·81
5·5	2·1	0·875	0·64	+4%	13·0	9·04	10·03	13·60	15·47
5·5	2·2	0·875	0·64	+4%	13·0	9·13	10·12	13·58	15·31
5·5	2·3	0·875	0·64	+4%	13·0	9·25	10·22	13·64	15·35
5·5	2·4	0·875	0·64	+4%	13·0	9·40	10·33	13·80	15·57
5·5	2·5	0·875	0·64	+4%	13·0	9·58	10·47	14·03	15·99
5·5	2·6	0·875	0·64	+4%	13·0	9·80	10·61	14·36	16·59

APPENDIX II

Estimate of Effective Horse-power and Design of Trawler Screws

Hull—Basic form of conventional design

$L/B = 5{\cdot}5$	B/d 2·25	C_m 0·875	C_p 0·64
	l.c.b. + 4·0 per cent aft	$\frac{1}{2}\alpha°_e$ 13·0	

$V/\sqrt{L}$	0·80	0·90	1·00	1·10
V (knots)	10·74	12·08	13·41	14·76
$C_{R_{(200)}}$	9·18	10·16	13·60	15·31
s.f.c.	0·0127	0·0125	0·0122	0·0120
δ_1	0·162	0·160	0·156	0·153
$C_{R_{(180)}}$	9·342	10·320	13·756	15·463
e.h.p. (Froude)	247	388	708	1060

Engine—diesel ; brake horse-power b.h.p. = 1,500, rate of rotation N_s = 250 revolutions per min.

Stern details—streamline rudder with fin. Shaft immersion I = 9ft.

Stipulations—number of blades, 4 ; blade sections of N.P.L. standard series type ; material, bronze.

Design conditions—screws PT7 and 8 : free running. d.h.p. = 1,455 (3 per cent. shaft losses) ; $N = 0{\cdot}98N_s = 245$ (2 per cent. scale effect). PT7 of optimum diameter. PT8 of diameter larger than optimum.

Screw PT9 : trawling. d.h.p. = 1,455 ; $N = N_s = 250$ (no scale effect correction) ; corresponding torque Q = 30,600 lb. ft. Trawling speed 4 knots. Screw diameter same as that of PT7.

Screw PT7 Propulsion factors $wT = 0{\cdot}20$, $\eta R = 1{\cdot}02$, $f_P = 1{\cdot}0$
Ship-model correlation factor = 1·10. $N = 245$

Estimate of free-running ship speed. Basic screw series : Troost B-4·55

V knots	V_A knots	Bp (1)	δo (2)	ηo (2)	Do ft. (3)	$q.p.c.$ (4)	$e.h.p._1$ (5)
13·0	10·4	26·7	200	0·585	8·50	0·585	775
13·5	10·8	24·3	191	0·600	8·43	0·600	790
14·0	11·2	22·2	183	0·610	8·35	0·610	805
14·5	11·6	20·3	175	0·620	8·28	0·620	820
15·0	12·0	18·7	167	0·630	8·21	0·630	835

Free-running ship speed = 13·7 knots (Fig. 62)
Optimum diameter D_o about 8·4ft.

Design calculations. Basic screw series : Troost B-4·55

V knots	V_A knots	D ft. (6)	Bp (1)	δ (7)	p'_T (2)	η_o (2)	p_T (8)
13·7	10·96	8·25	23·5	184	0·847	0·602	0·864
			Corrected for thickness			0·595	0·85

(1) $Bp = \dfrac{N}{1{\cdot}013 V_A^2} \sqrt{\dfrac{\eta_R \text{ d.h.p.}}{V_A}}$

(2) From Troost B series $Bp - \delta$ charts

(3) $D_o = \dfrac{V_A}{N} \delta_o$

(4) q.p.c. $= f_P \eta_o$

(5) $\text{e.h.p.}_1 = \dfrac{\text{d.h.p.}}{1{\cdot}10}$ q.p.c.

(6) $D = 0{\cdot}98\ D_o$ (reduction of 2 per cent below basic value to make allowance for subsequent increase in blade thickness : see Conclusion (d) of Ref. 6).

(7) $\delta = \dfrac{ND}{V_A}$

(8) Pitch correction for departure from Troost B to N.P.L. standard sections $p_T = 1{\cdot}02 p'_T$

From results of blade area estimates and blade strength calculations $a_D = 0{\cdot}55$, $\tau = 0{\cdot}053$.

Blade thickness corrections : reduce pitch by 1½ per cent, efficiency by 1 per cent (Fig. 63).

Screw PT8 propulsion factors $w_T = 0{\cdot}20$, $\eta_R = 1{\cdot}02$, $f_\beta = 0{\cdot}95$

Free-running ship speed about 13·5 knots, screw diameter $D = 8{\cdot}75$ft. blade area ratio $a_D = 0{\cdot}50$ (Basic screw PT7, V reduced about 1 per cent D increased about 7 per cent, a_D reduced about 10 per cent; see (Conclusion 6)

$B_P = 24{\cdot}3$, $\delta = 199$, $p'_T = 0{\cdot}737$, $p_T = 0{\cdot}752$, $\eta_o = 0{\cdot}605$

From results of strength calculations $\tau = 0{\cdot}055$

Blade thickness corrections: reduce pitch by 2 per cent, efficiency by 1½ per cent (Fig. 63).

$p_T = 0{\cdot}735$, $\eta_o = 0{\cdot}595$ (corrected for increased blade thickness)

Screw PT9 propulsion factors $w_T = 0{\cdot}20$, $\eta_R = 1{\cdot}0$, Pull $P_u = 0{\cdot}85_T$

Trawling speed $V = 4$ knots $v = 6{\cdot}76$ ft./sec. $v_A = 5{\cdot}4$ ft./sec.

$N = 250$ per min. $n = 4{\cdot}17$ per sec.

Screw diameter $D = 8{\cdot}25$ft.; blade-area ratio $a_D = 0{\cdot}65$

(Basic screw PT7, a_D increased about 20 per cent; see Conclusion 8)

Screw	ϕ	μ	p'_T	σ	p_T	T	P_u
	(9)	(10)	(11)	(11)	$1{\cdot}02p'_T$	(12)	$0{\cdot}85T$
B.4·55	1·03	6·56	0·625	1·49	—	—	—
B.4·70	1·03	6·56	0·635	1·48	—	—	—
$a_D = 0{\cdot}65$	1·03	6·56	0·632	1·483	0·645	15·4	13·1
		Corrected for thickness			0·64		

(9) $$\phi = v_A D \sqrt{\frac{\rho D}{\eta_R Q}}$$

(10) $$\mu = nD^2 \sqrt{\frac{\rho D}{\eta_R Q}}$$

(11) From Troost B series $\mu - \sigma$ charts

(12) Thrust (tons) $$T = \frac{Q\sigma}{357D}$$

From results of strength calculations $\tau = 0{\cdot}056$

Blade thickness corrections: reduce pitch by 1 per cent (based on the data given in Ref. 6).

Particulars of Screws PT7 to PT9

Screw	*Design condition*	*Diameter (ft.)*	*Blade-area ratio*	*Pitch ratio*	*Thickness ratio*	*Rake angle (degrees)*
		D	a_D	p_T	τ	
PT7	Free running	8·25	0·55	0·850	0·053	10
PT8	Free running	8·75	0·50	0·735	0·055	10
PT9	Trawling	8·25	0·65	0·640	0·056	10

TABLE 3—*Summary of Ship Screw Particulars*

Group	*L.b.p.*	*No. of screws*	*Rate of rotation*	*Screw diameter*	*Blade-area ratio*	*Pitch ratio*
	ft.		N per min.	D ft.	a_D	p
A	less than 120	7	160—250	6·3— 7·8	0·40—0·46	0·67—1·05
B	120—160	8 3	200—270 125—135	7·2— 8·0 9·8—10·5	0·48—0·60 0·48—0·53	0·65—0·95 0·97—1·02
C	greater than 160	8 14	225—260 125—175	7·1— 9·2 10·2—12·8	0·53—0·67 0·40—0·55	0·72—0·87 0·75—1·05

Note : The above screws are all of four-blade type.

TABLE 4—*N.P.L. Standard Screw Series—Summary of Geometric Data*

Item	*Series A (Pitch ratio)*	*Series B (Rake angle)*	*Series C (Area ratio)*
Diameter (in.) ..	8·4	8·4	8·4
Blade number ..	4	4	4
Pitch ratio	0·5 to 1·2	0·7, 1·0	0·5 to 1·2
Area ratio	0·5	0·5	0·4, 0·6
Rake angle (degrees)	10	5, 12·5, 15	10
Boss-diameter ratio..	0·167	0·167	0·167
Thickness ratio ..	0·045	0·045	0·045

TABLE 5—*Particulars of Screws PT1 to PT6*

Screw		*PT1*	*PT2*	*PT3*	*PT4*	*PT5*	*PT6*
Design condition		Free running	Free running	Free running	Trawling	Free running	Trawling
Rate of rotation (revs. per min.)	N	250	250	250	250	136	136
Blade number		4	4	4	4	4	4
Screw diameter (ship ft., model in.)	D	8·4	9·0	9·5	8·4	11·5	11·5
Blade area ratio	a_D	0·60	0·55	0·55	0·60	0·50	0·50
Pitch ratio (standard sections)	p_T	0·85	0·725	0·64	0·60	1·05	0·725
Pitch ratio (low camber sections)	p_T	—	—	0·67	—	—	—
Blade thickness ratio (at axis)		0·045	0·045	0·045	0·045	0·045	0·045
Rake angle (degrees)		10	10	10	10	7	7
Screw diameter/optimum diameter	D/D_o	1·0	1·07	1·13	—	1·0	—

Notes : Screws PT1, 2, 4, 5 and 6 are of N.P.L. standard series type. Screw PT3 has low camber-blade sections (Table 7) ; other details as N.P.L. standard series (Fig. 53).

The optimum diameter D_o is that derived from the Troost B.4.55 series B_p——δ chart.

TABLE 6—*Screw PT1 to PT3—Blade Section Performance Values*
(x = 0·7 radius fraction)

Screws		*PT1*	*PT2*		*PT3*	
Diameter	*D*	8·4	9·0		9·5	
Blade-section-camber ratio	$\frac{m}{t}$	0·42	0·42		0·42	0·21
Pitch ratio	*p*	0·85	0·725		0·64	0·67
Speed coefficient (corresponding to optimum diameter)	δ_o	182	222		276	—
Advance coefficient (corresponding to optimum diameter)	*J*	0·56	0·46	—	0·37	— —
Advance coefficient (operating value)	*J*	0·56	—	0·52	—	0·49 0·49
Lift coefficient	C_L	0·20	0·19	0·16	0·18	0·12 0·12
Angle of incidence (degrees) ..	α	1·5	1·3	0·8	1·3	0·2 1·0

TABLE 7—*Screw PT3—Blade Section Offsets*

Cylindrical Section Offsets from Pitch Line

RAD x		*From max t to T.E.*					*MAX* t	*% Distance from max. thickness to L.E.*									y_1	y_2	*RAD* x
		T.E.	80	60	40	20		20	40	60	70	80	85	90	95	*L.E.*			
0·95	Back	0·374	0·576	0·775	0·907	0·977	1·000	0·980	0·919	0·814	0·742	0·655	0·603	0·541	0·465	0·374		0·293	0·95
	Face	0·212	0·159	0·076	0·027	0·006	—	0·004	0·014	0·037	0·056	0·081	0·099	0·124	0·163	0·212			
0·90	Back	0·362	0·569	0·770	0·904	0·978	1·000	0·979	0·917	0·810	0·737	0·648	0·595	0·532	0·453	0·362		0·281	0·90
	Face	0·200	0·151	0·072	0·026	0·004	—	0·003	0·013	0·032	0·050	0·072	0·089	0·117	0·152	0·200			
0·80	Back	0·351	0·563	0·767	0·902	0·977	1·000	0·979	0·915	0·806	0·732	0·642	0·587	0·522	0·443	0·351		0·270	0·80
	Face	0·189	0·143	0·067	0·024	0·005	—	0·002	0·011	0·028	0·043	0·065	0·080	0·104	0·148	0·189			
0·70	Back	0·369	0·573	0·773	0·905	0·977	1·000	0·979	0·917	0·812	0·739	0·651	0·600	0·537	0·459	0·369		0·288	0·70
	Face	0·207	0·155	0·074	0·027	0·005	—	0·003	0·015	0·034	0·052	0·076	0·095	0·120	0·158	0·207			
0·60	Back	0·405	0·597	0·786	0·911	0·979	1·000	0·981	0·923	0·825	0·757	0·675	0·625	0·566	0·491	0·405		0·324	0·60
	Face	0·243	0·172	0·087	0·027	0·007	—	0·004	0·020	0·047	0·070	0·094	0·120	0·148	0·190	0·243			
0·50	Back	0·439	0·619	0·798	0·916	0·980	1·000	0·983	0·928	0·837	0·774	0·696	0·650	0·594	0·522			0·384	0·358	0·50
	Face	0·277	0·200	0·099	0·038	0·008	—	0·006	0·025	0·060	0·086	0·116	0·145	0·176	0·221				
0·40	Back	0·468	0·637	0·809	0·921	0·982	1·000	0·984	0·933	0·849	0·789	0·715	0·671	0·617	0·548			0·403	0·387	0·40
	Face	0·306	0·218	0·109	0·043	0·009	—	0·007	0·031	0·071	0·100	0·140	0·166	0·200	0·248				
0·30	Back	0·495	0·655	0·819	0·925	0·983	1·000	0·985	0·938	0·859	0·802	0·733	0·690	0·639	0·573			0·423	0·414	0·30
	Face	0·333	0·235	0·119	0·047	0·010	—	0·008	0·035	0·080	0·114	0·157	0·186	0·221	0·272				
0·20	Back	0·519	0·670	0·828	0·929	0·983	1·000	0·986	0·942	0·867	0·814	0·748	0·708	0·659	0·595			0·440	0·438	0·20
	Face	0·357	0·251	0·128	0·051	0·012	—	0·009	0·039	0·088	0·126	0·173	0·203	0·241	0·293				

0,585

TABLE 8—*Ship Screw Design Conditions and Nominal Model Screw Operating Conditions*

Ship screw design conditions							
Screw		PT1	PT2	PT3	PT4	PT5	PT6
Delivered horse-power	*d.h.p.*	1,455	1,455	1,455	1,455	1,455	1,455
Rate of rotation (revs. per min.)	N_s	250	250	250	250	136	136
Rate of rotation (free running : reduced 2 per cent. for scale effect) (trawling : no correction)	N	245	245	245	250	133	136
Speed of ship (knots)	V	14·0	14·0	14·0	4·0	14·0	4·0
Speed of advance of screw (knots) (assumed wake fraction $W_T=0{\cdot}18$)	V_A	11·5	11·5	11·5	3·3	11·5	3·3
Nominal model-screw operating conditions							
Screw		PT1	PT2	PT3	PT4	PT5	PT6
Free-Running	Corresponding speed of ship V	14·0	14·0	14·0	11·5	14·0	11·2
	Advance coefficient J	0·56	0·52	0·49	0·46	0·76	0·61
	Cavitation number (ship screw) σ_{RS}	0·43	0·37	0·33	0·45	0·77	0·78
	Cavitation number (model screw, $0{\cdot}8\sigma_{RS}$) σ_{RM}	0·34	0·29	0·26	0·36	0·61	0·62
Trawling	Corresponding speed of ship V	4·0	4·0	4·0	4·0	4·0	4·0
	Corresponding rate of rotation of ship screw N	190	190	190	260	97	136
	Advance coefficient J	0·21	0·20	0·19	0·15	0·30	0·21
	Cavitation number (ship screw) σ_{NS}	0·79	0·69	0·64	0·41	1·59	0·78
	Cavitation number (model screw, $0{\cdot}8\ \sigma_{NS}$) σ_{NM}	0·63	0·55	0·51	0·33	1·27	0·63

TABLE 9—*Open-Water Experiment Results—Screws PT1 to PT6*

SCREW PT1

$n = 10$ per sec.

J	k_T	k_Q
0	0·362	0·0435
0·064	0·346	0·0415
0·138	0·322	0·0394
0·210	0·300	0·0369
0·284	0·271	0·0343
0·351	0·246	0·0317
0·435	0·215	0·0287
0·508	0·183	0·0253
0·573	0·150	0·0217
0·641	0·119	0·0179
0·717	0·083	0·0139
0·786	0·050	0·0105
0·862	0·011	0·0061
0·892	−0·005	0·0044

SCREW PT2

$n = 10$ per sec.

J	k_T	k_Q
0	0·295	0·0310
0·062	0·278	0·0296
0·131	0·258	0·0281
0·198	0·239	0·0266
0·265	0·216	0·0245
0·333	0·192	0·0224
0·401	0·164	0·0196
0·471	0·135	0·0169
0·536	0·099	0·0137
0·605	0·073	0·0111
0·675	0·041	0·0082
0·742	0·009	0·0051
0·767	−0·004	0·0039

SCREW PT3

$n = 10$ per sec.

J	k_T	k_Q
0	0·252	0·0249
0·060	0·238	0·0236
0·123	0·220	0·0222
0·188	0·200	0·0207
0·252	0·180	0·0191
0·317	0·156	0·0171
0·386	0·131	0·0149
0·448	0·107	0·0123
0·511	0·077	0·0097
0·580	0·046	0·0070
0·641	0·017	0·0042
0·699	−0·011	0·0018

SCREW PT4

$n = 10$ per sec.

J	k_T	k_Q
0	0·238	0·0223
0·063	0·227	0·0215
0·136	0·211	0·0198
0·200	0·182	0·0184
0·280	0·159	0·0164
0·353	0·132	0·0145
0·427	0·097	0·0119
0·500	0·065	0·0095
0·566	0·034	0·0072
0·640	0	0·0043

SCREW PT5

$n = 7$ per sec.

J	k_T	k_Q
0	0·442	0·0639
0·078	0·425	0·0616
0·154	0·401	0·0588
0·234	0·380	0·0559
0·317	0·353	0·0526
0·396	0·323	0·0491
0·475	0·292	0·0449
0·553	0·262	0·0413
0·636	0·228	0·0373
0·720	0·195	0·0331
0·800	0·161	0·0283
0·877	0·121	0·0227
0·962	0·080	0·0174
1·032	0·039	0·0114
1·109	0·002	0·0065
1·141	−0·015	0·0033

SCREW PT6

$n = 7$ per sec.

J	k_T	k_Q
0	0·295	0·0308
0·071	0·278	0·0294
0·154	0·257	0·0278
0·230	0·233	0·0256
0·312	0·205	0·0235
0·390	0·177	0·0212
0·478	0·140	0·0176
0·552	0·108	0·0145
0·638	0·072	0·0113
0·718	0·033	0·0073
0·800	−0·011	0·0029

TABLE 10—*Water-Tunnel Experiment Results—Screws PT1 to PT6—Atmospheric Pressure Conditions*

SCREW PT1

n = 20 per sec.

J_T	k_T	k_Q
0·269	0·282	0·0357
0·273	0·283	0·0359
0·318	0·264	0·0340
0·353	0·250	0·0326
0·394	0·232	0·0310
0·441	0·213	0·0289
0·496	0·190	0·0266
0·569	0·158	0·0299
0·616	0·137	0·0209
0·622	0·134	0·0203
0·673	0·111	0·0176
0·722	0·086	0·0149
0·772	0·062	0·0118
0·816	0·038	0·0094
0·852	0·018	0·0066
0·861	0·015	0·00[illegible]
0·892	0	0·004[illegible]
0·902	−0·014	0·0029

SCREW PT2

n = 20 per sec.

J_T	k_T	k_Q
0·258	0·225	0·0254
0·271	0·218	0·0251
0·287	0·211	0·0245
0·313	0·203	0·0240
0·337	0·193	0·0229
0·366	0·183	0·0224
0·396	0·171	0·0211
0·430	0·157	0·0203
0·454	0·146	0·0191
0·486	0·134	0·0181
0·504	0·126	0·0171
0·552	0·107	0·0152
0·586	0·093	0·0140
0·624	0·075	0·0121
0·661	0·056	0·0105
0·690	0·042	0·0088
0·720	0·027	0·0072
0·747	0·011	0·0056
0·772	−0·002	0·0042

SCREW PT3

n = 20 per sec.

J_T	k_T	k_Q
0·251	0·183	0·0194
0·267	0·176	0·0190
0·286	0·169	0·0184
0·317	0·159	0·0177
0·357	0·143	0·0163
0·395	0·128	0·0151
0·445	0·108	0·0135
0·494	0·088	0·0116
0·516	0·079	0·0105
0·545	0·065	0·0094
0·572	0·054	0·0082
0·602	0·039	0·00[illegible]
0·633	0·023	0·00[illegible]3
0·654	0·011	0·0041
0·689	−0·006	0·0024
0·710	−0·020	0·0011

SCREW PT4

n = 20 per sec.

J_T	k_T	k_Q
0·217	0·179	0·0190
0·244	0·172	0·0185
0·274	0·163	0·0177
0·305	0·151	0·0170
0·341	0·136	0·0160
0·385	0·120	0·0144
0·405	0·112	0·0138
0·433	0·103	0·0129
0·490	0·076	0·0110
0·532	0·059	0·0093
0·567	0·040	0·0078
0·589	0·028	0·0070
0·614	0·016	0·0057
0·630	0·006	0·0051
0·654	−0·006	0·0036

SCREW PT5

n = 15 per sec.

J_T	k_T	k_Q
0·428	0·318	0·0[illegible]6
0·441	0·311	0·0[illegible]5
0·461	0·304	0·0466
0·497	0·289	0·0449
0·530	0·276	0·0432
0·561	0·264	0·0418
0·593	0·252	0·0404
0·639	0·231	0·0380
0·682	0·211	0·0355
0·722	0·195	0·0336
0·782	0·167	0·0299
0·834	0·146	0·0268
0·879	0·124	0·0241
0·919	0·104	0·0211
0·956	0·088	0·0190
1·005	0·062	0·0150
1·033	0·049	0·0129
1·059	0·032	0·0103
1·107	0·006	0·0062
1·141	−0·018	0·0024

SCREW PT6

n = 15 per sec.

J_T	k_T	k_Q
0·328	0·200	0·0233
0·355	0·190	0·0224
0·366	0·186	0·0223
0·400	0·174	0·0212
0·446	0·156	0·0198
0·475	0·145	0·0186
0·496	0·137	0·0179
0·520	0·127	0·0169
0·555	0·113	0·0156
0·580	0·102	0·0145
0·609	0·090	0·0132
0·627	0·081	0·0123
0·654	0·069	0·0111
0·682	0·060	0·0102
0·685	0·054	0·0095
0·699	0·047	0·0086
0·739	0·031	0·0069
0·752	0·019	0·0057
0·777	0·006	0·0041
0·783	−0·003	0·0032

TABLE 11—*Water-Tunnel Experiment Results—Screws PT1 to PT6*
Reduced Pressure Conditions—Free Running

SCREW PT1

$J_o = 0{\cdot}56$ $n = 20$ per sec.

σ_R	k_T	k_Q
0·160	0·133	0·0205
0·181	0·141	0·0213
0·206	0·147	0·0221
0·230	0·152	0·0266
0·261	0·155	0·0230
0·287	0·156	0·0231
0·312	0·157	0·0232
0·339	0·159	0·0235
0·360	0·159	0·0233
0·383	0·158	0·0233
0·413	0·157	0·0234
0·438	0·157	0·0233
0·466	0·157	0·0232
0·519	0·156	0·0232
0·687	0·156	0·0230
0·705	0·155	0·0230
2·244	0·155	0·0230

SCREW PT2

$J_o = 0{\cdot}52$ $n = 20$ per sec.

σ_R	k_T	k_Q
0·114	0·083	0·0131
0·124	0·085	0·0137
0·140	0·094	0·0147
0·165	0·105	0·0156
0·184	0·114	0·0163
0·188	0·114	0·0163
0·209	0·115	0·0165
0·227	0·115	0·0164
0·246	0·114	0·0164
0·252	0·114	0·0164
0·277	0·116	0·0165
0·319	0·114	0·0165
0·423	0·116	0·0167
0·542	0·116	0·0165
0·704	0·115	0·0165
0·852	0·116	0·0165
0·969	0·115	0·0164
1·180	0·114	0·0164
1·428	0·116	0·0165
1·886	0·115	0·0164

SCREW PT3

$J_o = 0{\cdot}49$ $n = 20$ per sec.

σ_R	k_T	k_Q
0·093	0·049	0·0079
0·100	0·053	0·0083
0·126	0·065	0·0091
0·146	0·075	0·0107
0·166	0·083	0·0112
0·179	0·085	0·0115
0·196	0·086	0·0115
0·208	0·085	0·0115
0·226	0·085	0·0115
0·245	0·085	0·0114
0·288	0·085	0·0115
0·329	0·085	0·0114
0·368	0·084	0·0114
0·408	0·084	0·0113
0·460	0·085	0·0115
0·542	0·085	0·0114
0·657	0·085	0·0115
1·774	0·085	0·0115

SCREW PT4

$J_o = 0{\cdot}46$ $n = 20$ per sec.

σ_R	k_T	k_Q
0·156	0·083	0·0114
0·167	0·083	0·0114
0·177	0·083	0·0114
0·184	0·085	0·0115
0·198	0·083	0·0116
0·211	0·084	0·0116
0·232	0·084	0·0116
0·266	0·085	0·0116
0·329	0·084	0·0116
0·487	0·085	0·0116
0·800	0·086	0·0117
1·051	0·085	0·0116
1·525	0·085	0·0116
2·278	0·084	0·0116

TABLE 11—*Water-Tunnel Experiment Results—Screws PT1 to PT6*
Reduced Pressure Conditions—Free Running—continued

SCREW PT5

$J_o = 0{\cdot}76$ $n = 15$ per sec.

σ_R	k_T	k_Q
0·151	0·108	0·0214
0·173	0·118	0·0234
0·190	0·128	0·0247
0·213	0·140	0·0265
0·236	0·151	0·0280
0·248	0·156	0·0286
0·261	0·159	0·0292
0·284	0·163	0·0297
0·307	0·166	0·0300
0·330	0·168	0·0304
0·351	0·168	0·0304
0·400	0·168	0·0304
0·441	0·168	0·0301
0·481	0·169	0·0302
0·660	0·168	0·0302
1·130	0·168	0·0301
1·540	0·167	0·0301
2·022	0·168	0·0301

SCREW PT6

$J_o = 0{\cdot}61$ $n = 15$ per sec.

σ_R	k_T	k_Q
0·153	0·062	0·0111
0·163	0·067	0·0115
0·178	0·072	0·0120
0·198	0·078	0·0124
0·204	0·081	0·0126
0·220	0·082	0·0127
0·237	0·082	0·0126
0·245	0·082	0·0125
0·249	0·081	0·0126
0·269	0·081	0·0124
0·293	0·083	0·0126
0·320	0·081	0·0125
0·339	0·081	0·0124
0·394	0·081	0·0125
0·439	0·081	0·0124
0·484	0·081	0·0124
0·599	0·082	0·0125
0·795	0·082	0·0125
1·172	0·082	0·0126
2·108	0·081	0·0123

TABLE 12—*Water-Tunnel Experiment Results—Screws PT1 to PT6*
Reduced Pressure Conditions—Trawling

SCREW PT1

$n = 16$ per sec.

σ_N	k_T	k_Q
0·258	0·240	0·0321
0·286	0·249	0·0331
0·312	0·257	0·0343
0·346	0·267	0·0354
0·383	0·275	0·0366
0·419	0·282	0·0371
0·450	0·287	0·0372
0·483	0·290	0·0372
0·522	0·290	0·0368
0·564	0·290	0·0366
0·649	0·291	0·0365
0·692	0·290	0·0366
0·735	0·290	0·0363
0·775	0·288	0·0363
0·862	0·288	0·0363
1·030	0·287	0·0359
1·388	0·285	0·0360
3·808	0·284	0·0359

SCREW PT2

$n = 16$ per sec.

σ_N	k_T	k_Q
0·219	0·188	0·0225
0·279	0·203	0·0246
0·319	0·212	0·0257
0·354	0·219	0·0258
0·394	0·224	0·0263
0·436	0·224	0·0265
0·476	0·228	0·0264
0·514	0·225	0·0266
0·579	0·224	0·0262
0·615	0·226	0·0261
0·646	0·224	0·0259
0·710	0·224	0·0262
0·776	0·223	0·0259
0·892	0·222	0·0260
1·085	0·223	0·0256
1·475	0·221	0·0254
1·840	0·221	0·0257
3·218	0·221	0·0257

TABLE 12—*Water-Tunnel Experiment Results—Screws PT1 to PT6 Reduced Pressure Conditions—Trawling*—continued

SCREW PT3

n = 16 per sec.

σ_N	k_T	k_Q
0·206	0·154	0·0176
0·238	0·164	0·0186
0·269	0·173	0·0193
0·303	0·180	0·0199
0·333	0·186	0·0202
0·363	0·191	0·0204
0·398	0·191	0·0204
0·435	0·190	0·0202
0·464	0·190	0·0200
0·497	0·191	0·0200
0·533	0·188	0·0198
0·591	0·188	0·0198
0·666	0·187	0·0197
0·730	0·187	0·0196
0·797	0·186	0·0195
0·924	0·186	0·0196
1·778	0·186	0·0195
2·942	0·186	0·0195

SCREW PT4

n = 20 per sec.

σ_N	k_T	k_Q
0·174	0·156	0·0164
0·206	0·164	0·0176
9·232	0·170	0·0183
0·256	0·174	0·0188
0·282	0·177	0·0191
0·289	0·178	0·0190
0·304	0·181	0·0193
0·324	0·182	0·0193
0·364	0·183	0·0193
0·391	0·183	0·0193
0·430	0·185	0·0193
0·490	0·183	0·0192
0·601	0·183	0·0191
0·774	0·183	0·0191
1·136	0·182	0·0189
1·581	0·182	0·0190
1·806	0·184	0·0191
2·388	0·182	0·0190

SCREW PT5

n = 12 per sec.

σ_N	k_T	k_Q
0·295	0·241	0·0409
0·345	0·261	0·0438
0·408	0·280	0·0463
0·471	0·295	0·0488
0·500	0·304	0·0497
0·529	0·307	0·0500
0·555	0·312	0·0506
0·578	0·316	0·0510
0·621	0·317	0·0511
0·673	0·321	0·0509
0·736	0·322	0·0509
0·822	0·321	0·0509
0·862	0·321	0·0498
0·978	0·320	0·0498
1·141	0·319	0·0493
1·455	0·318	0·0492
2·031	0·316	0·0498
3·548	0·316	0·0485

SCREW PT6

n = 15 per sec.

σ_N	k_T	k_Q
0·173	0·151	0·0191
0·187	0·155	0·0191
0·221	0·166	0·0203
0·256	0·176	0·0217
0·303	0·186	0·0229
0·330	0·192	0·0234
0·352	0·195	0·0239
0·376	0·199	0·0240
0·400	0·200	0·0242
0·426	0·201	0·0241
0·445	0·201	0·0241
0·479	0·201	0·0240
0·516	0·202	0·0238
0·560	0·201	0·0236
0·716	0·201	0·0236
0·917	0·201	0·0236
1·434	0·201	0·0235
2·299	0·200	0·0234

TABLE 13—*Comparisons of Model Screw Experiment Results—Non-cavitating Conditions*

Free-running Conditions

Comparisons at constant power (d.h.p. = 1455)					Comparisons at constant ship-model correlation factor (s.c.f. = 1·10)		
		Experiment Technique			Propulsion experiment results		
Screw		Open water $V_A = 11{\cdot}5$	Water tunnel $V_A = 11{\cdot}5$	Propulsion $V = 14$	Screw		d.h.p. = 1455
Basic screw PT1	Basic N	253	251	247	Basic screw PT1	Basic V	14·5
PT2	% Above	1·5	0	1·5	PT2	% Above	−1·0
PT3	Basic N	2·5	2·5	1·5	PT3	Basic V	−1·5
Basic screw PT1	Basic η	0·625	0·610	0·640	Basic screw		$N = 250$
PT2	% Above	0·5	−3·5	−1·5	PT1	Basic V	14·5
PT3	Basic η	0	−3·5	−2·0	PT4	% Above Basic V	−15·0
Basic screw PT1	Basic q.p.c.	—	—	0·680	Basic screw	Basic V	$N = 136$
							14·7
PT2	% Above	—	—	−5·0	PT5		−17·0
PT3	Basic q.p.c.	—	—	−8·0	PT6	% Above Basic V	

TABLE 13—*Comparisons of Model Screw Experiment Results—Non-cavitating Conditions* (continued)

Trawling Conditions					
Comparisons of thrust T and overall P_U at constant torque (PT1—4, Q = 30,600 : PT5—6, Q = 36,200)					
Screw		Open-water experiments	Propulsion experiments		Propulsion experiments
		$V_A = 3{\cdot}3$	$V = 4{\cdot}0$		$V = 4{\cdot}0$
Basic screw PT1	Basic T	12·8	13·0	Basic P_U	11·2
PT2	% Above	8·0	5·5	% Above	6·5
PT3	Basic T	8·5	4·5	Basic P_U	4·0
Basic screw PT4	Basic T	16·8	16·5	Basic P_U	14·4
PT1	% Above Basic T	−24	−21	% Above Basic P_U	−22
Basic screw PT6	Basic T	19·9	20·0	Basic P_U	17·5
PT5	% Above Basic T	−26	−26	% Above Basic P_U	−30

TABLE 14—*Comparisons of Model Screw Experiment Results—Cavitating Conditions*

Screw	*Diameter*	*Blade-area ratio*	*Pitch ratio*	*Free running*			*Trawling*		
				Cavitation Number		*Thrust breakdown factor* σ_{RM}/σ_{RT}	*Cavitation Number*		*Thrust breakdown factor* σ_{NM}/σ_{NT}
				Model screw operating	*Point of thrust breakdown*		*Model screw operating*	*Point of thrust breakdown*	
	D	a_D	p_T	σ_{RM}	σ_{RT}	f_c	σ_{NM}	σ_{NT}	f_c
PT1	8·4	0·60	0·850	0·34	0·24	1·41	0·63	0·41	1·53
PT1 reduced a_D	8·4	0·50	0·850	0·34	0·29	1·17	0·63	0·50	1·25
	8·4	0·40	0·850	0·34	0·34	1·00	0·63	0·56	1·12
PT2	9·0	0·55	0·725	0·29	0·20	1·47	0·55	0·35	1·57
PT3	9·5	0·55	0·670	0·26	0·17	1·50	0·51	0·32	1·61
PT4	8·4	0·60	0·600	0·36	0·21	1·71	0·33	0·30	1·10
PT4 reduced a_D	8·4	0·50	0·600	0·36	0·23	1·57	0·33	0·35	0·95
	8·4	0·40	0·600	0·36	0·28	1·27	0·33	0·47	0·71
PT5	11·5	0·50	1·050	0·61	0·31	1·97	1·27	0·57	2·23
PT6	11·5	0·50	0·725	0·62	0·20	3·05	0·63	0·37	1·70

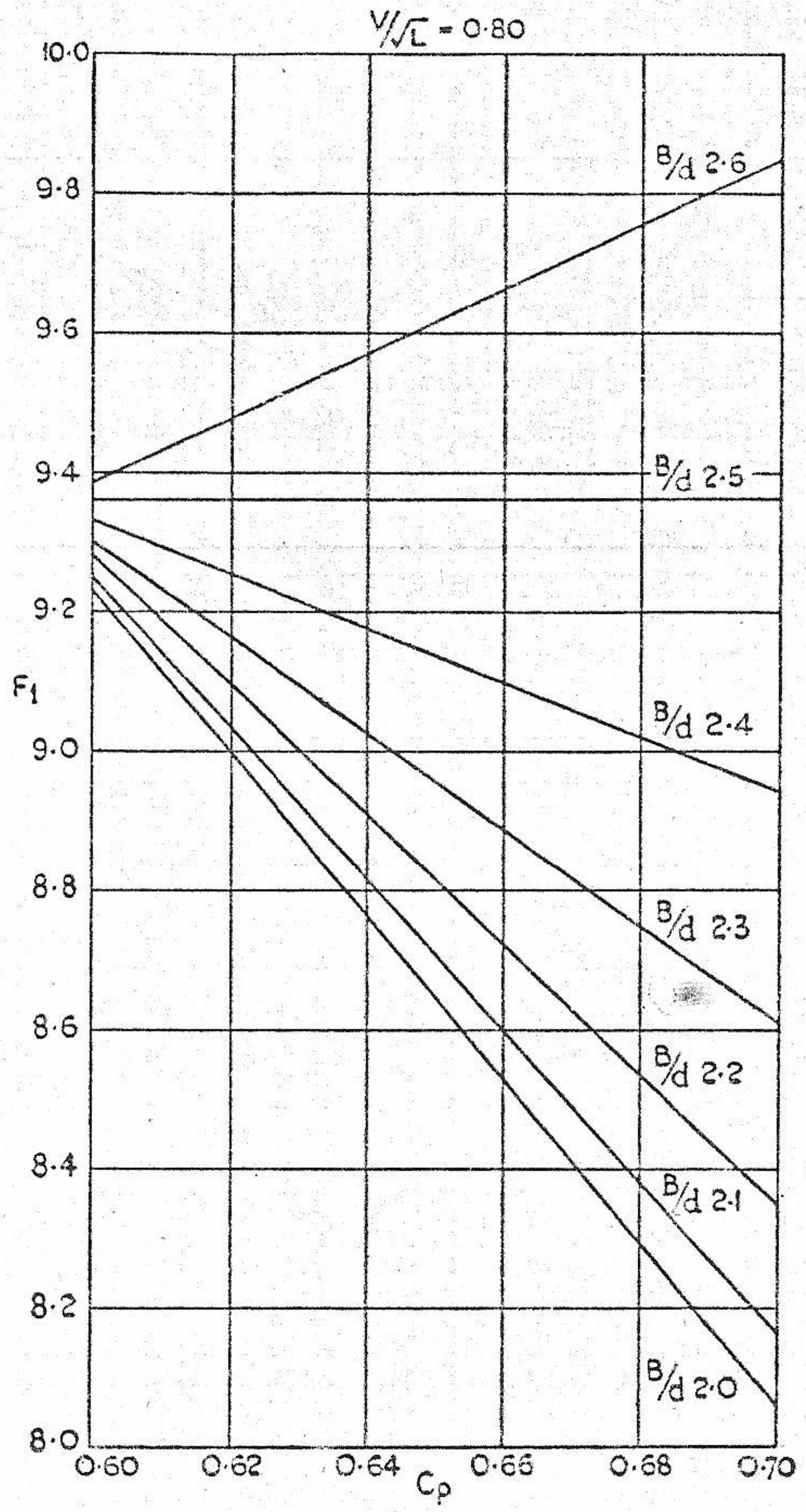

V/√L = 0·80
10·0
9·8
9·6
9·4
9·2
9·0
8·8
8·6
8·4
8·2
8·0
F1
B/d 2·6
B/d 2·5
B/d 2·4
B/d 2·3
B/d 2·2
B/d 2·1
B/d 2·0
0·60
0·62
0·64
0·66
0·68
0·70
Cp

Fig. 1

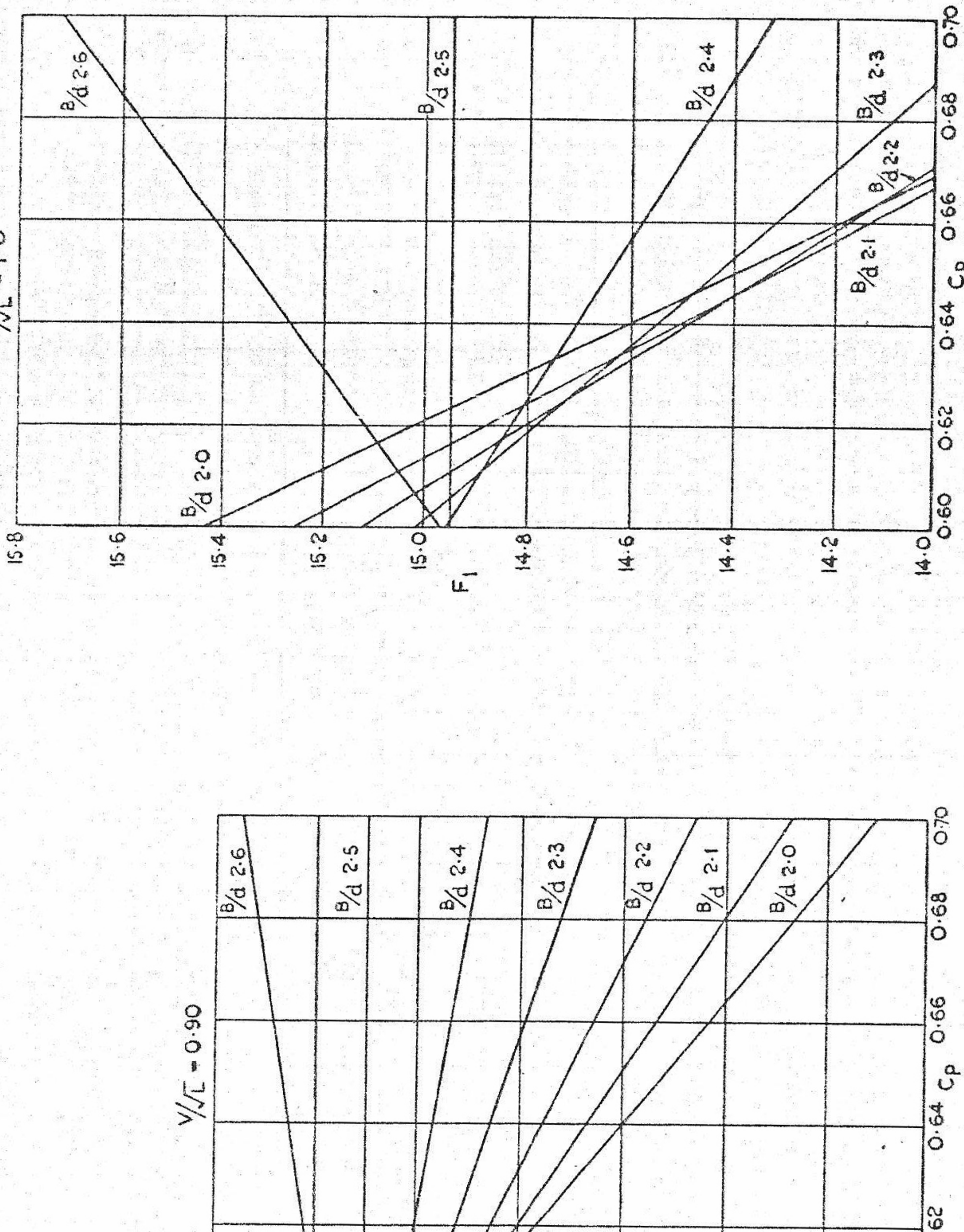

V/√L = 1·0
B/d 2·6
B/d 2·5
B/d 2·4
B/d 2·3
B/d 2·2
B/d 2·1
B/d 2·0
15·8
15·6
15·4
15·2
15·0
14·8
14·6
14·4
14·2
14·0
F1
0·60
0·62
0·64
0·66
0·68
0·70
Cp

Fig. 1

V/√L = 0·90
B/d 2·6
B/d 2·5
B/d 2·4
B/d 2·3
B/d 2·2
B/d 2·1
B/d 2·0
10·8
10·6
10·4
10·2
10·0
9·8
9·6
9·4
F1
0·60
0·62
0·64
0·66
0·68
0·70
Cp

Fig. 2

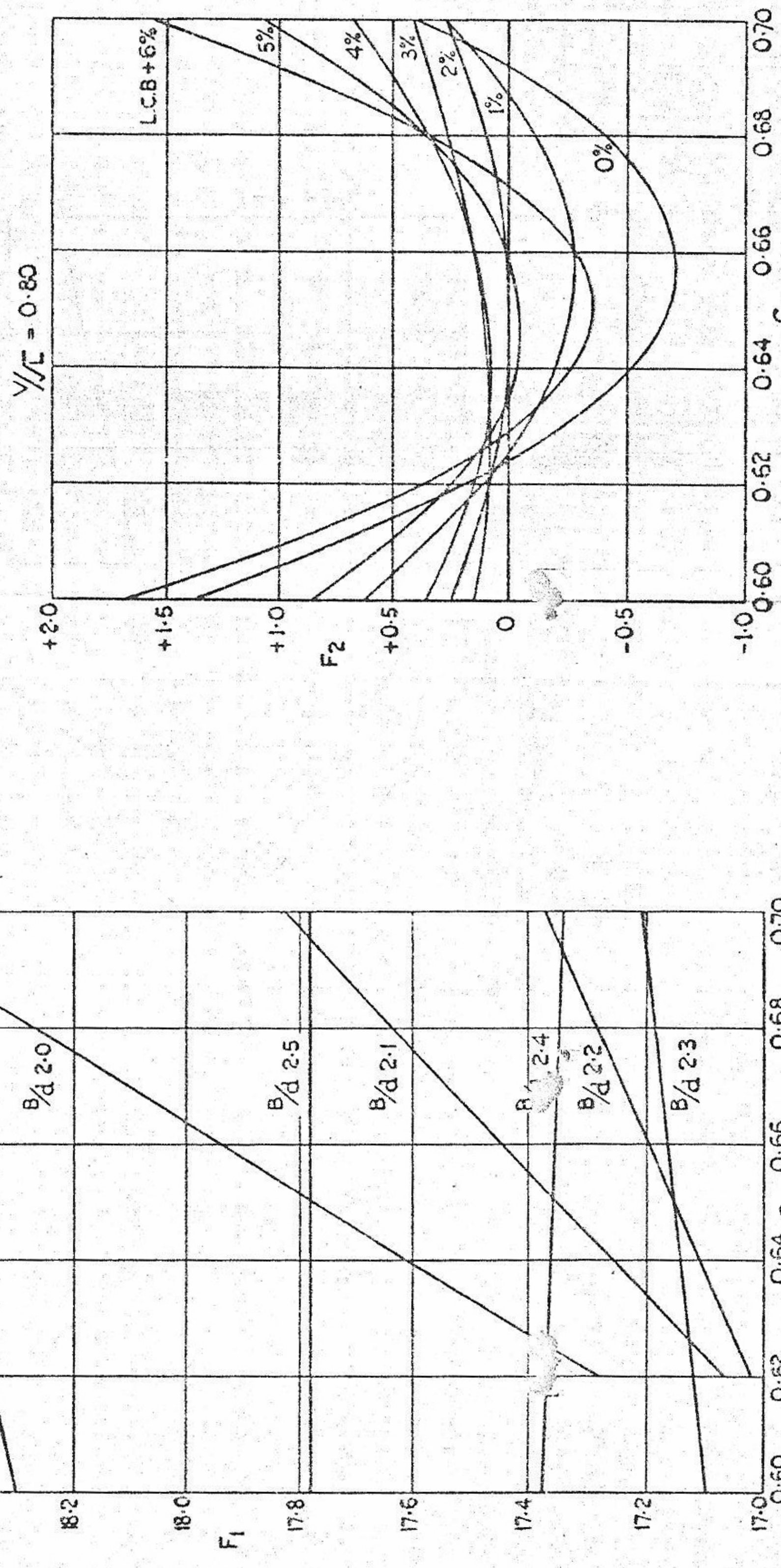

L.C.B + 6%
5%
4%
3%
2%
1%
0%
V/√L = 0·80
+2·0
+1·5
+1·0
+0·5
0
-0·5
-1·0
F2
0·60
0·62
0·64
0·66
0·68
0·70
Cp

Fig. 5

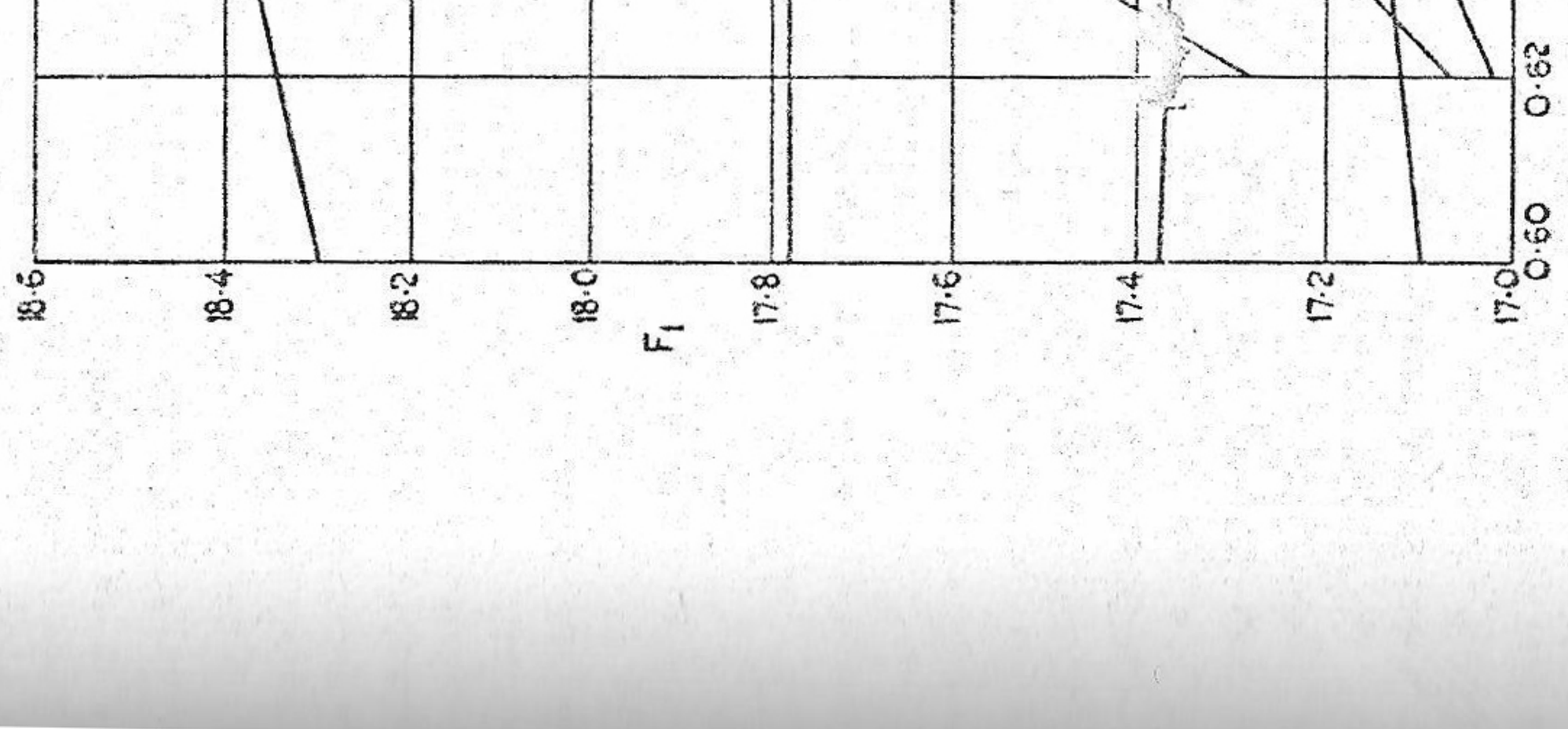

V/√L = 1·10
B/d 2·6
B/d 2·0
B/d 2·5
B/d 2·1
B/d 2·4
B/d 2·2
B/d 2·3
18·6
18·4
18·2
18·0
17·8
17·6
17·4
17·2
17·0
F1
0·60
0·62
0·64
0·66
0·68
0·70
Cp

Fig. 4

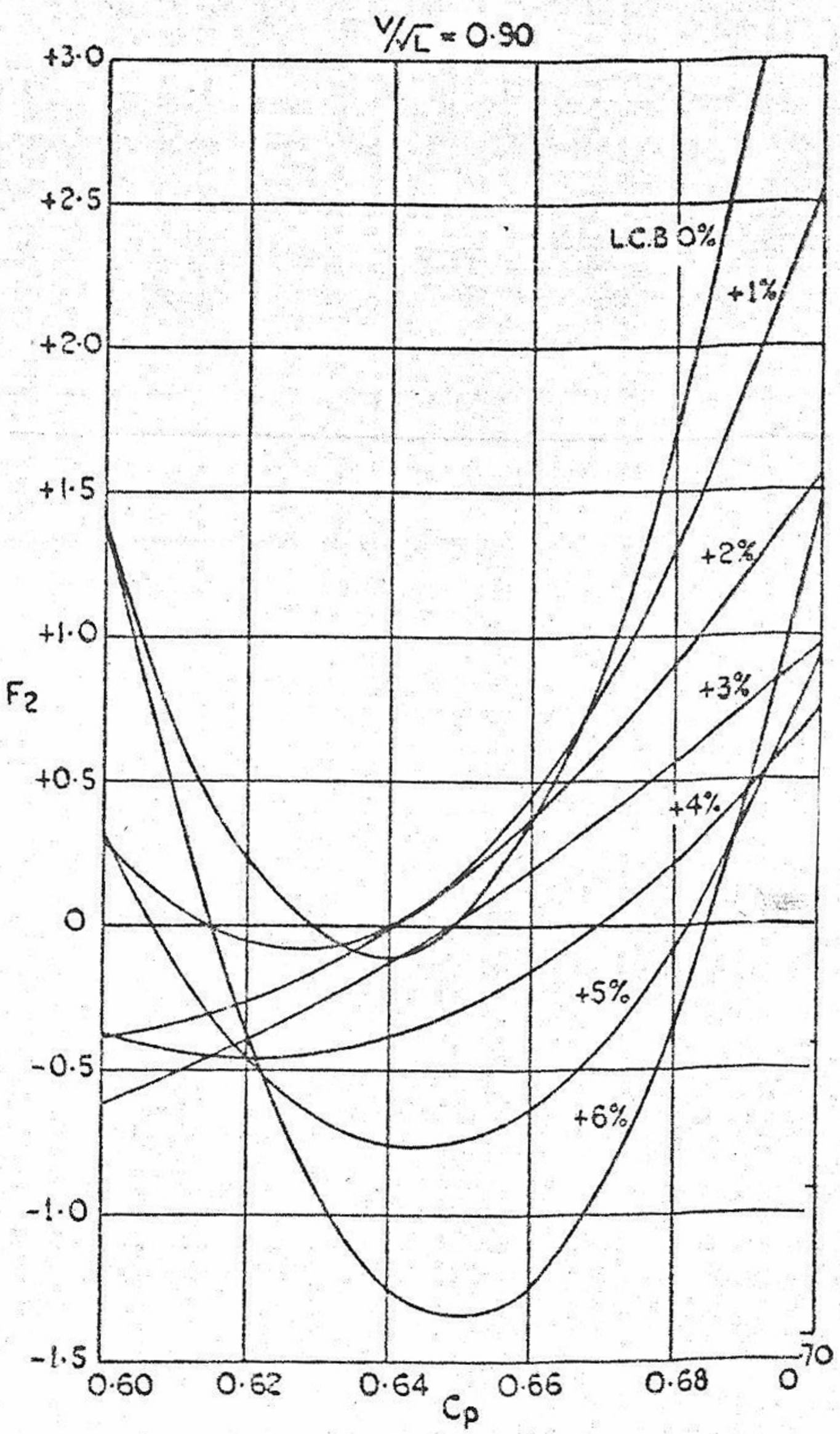

V/√L = 0·90
+3·0
+2·5
+2·0
+1·5
+1·0
+0·5
0
-0.5
-1·0
-1·5
F2
L.C.B 0%
+1%
+2%
+3%
+4%
+5%
+6%
0·60
0·62
0·64
0·66
0·68
70
Cp

Fig. 6

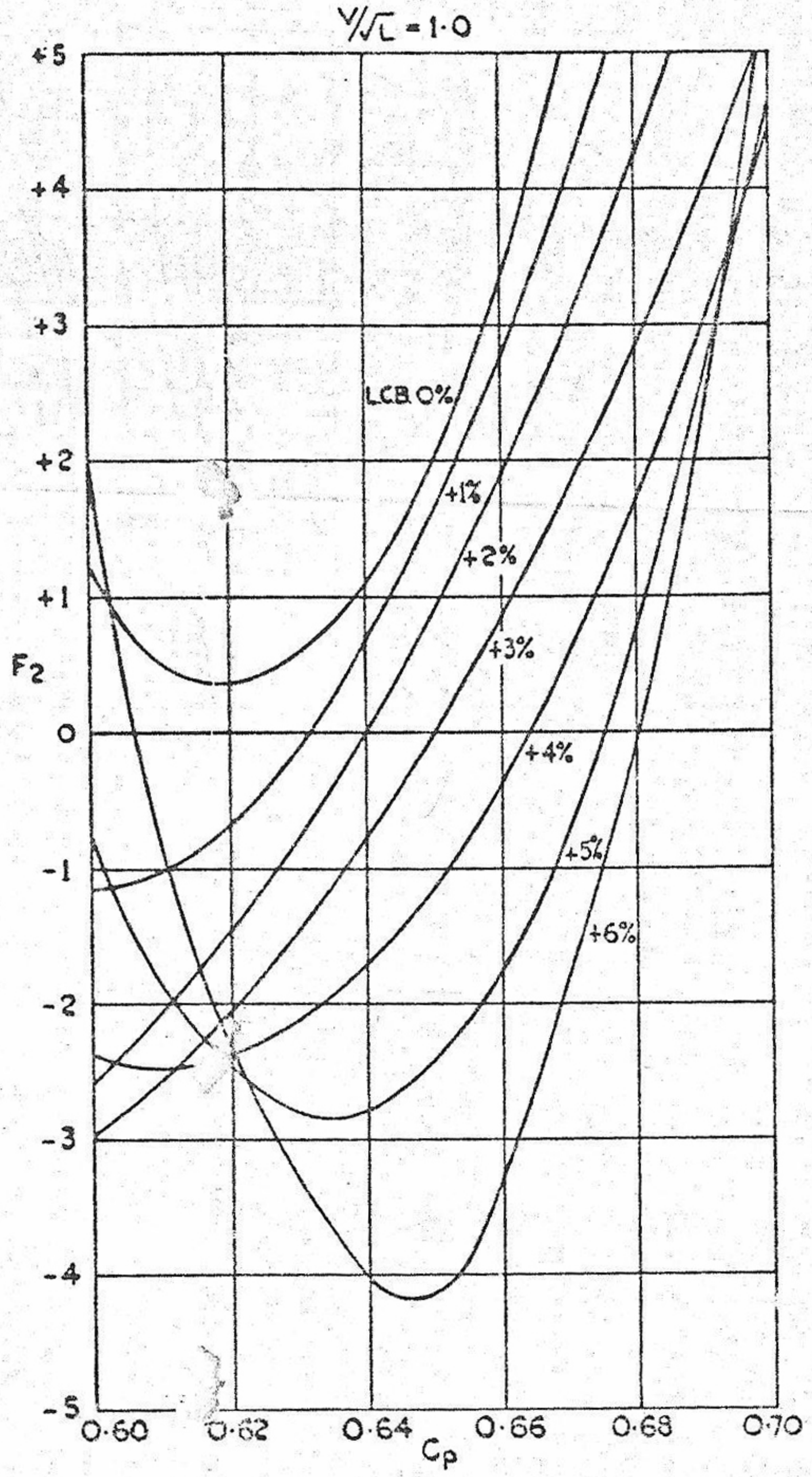


Fig. 7

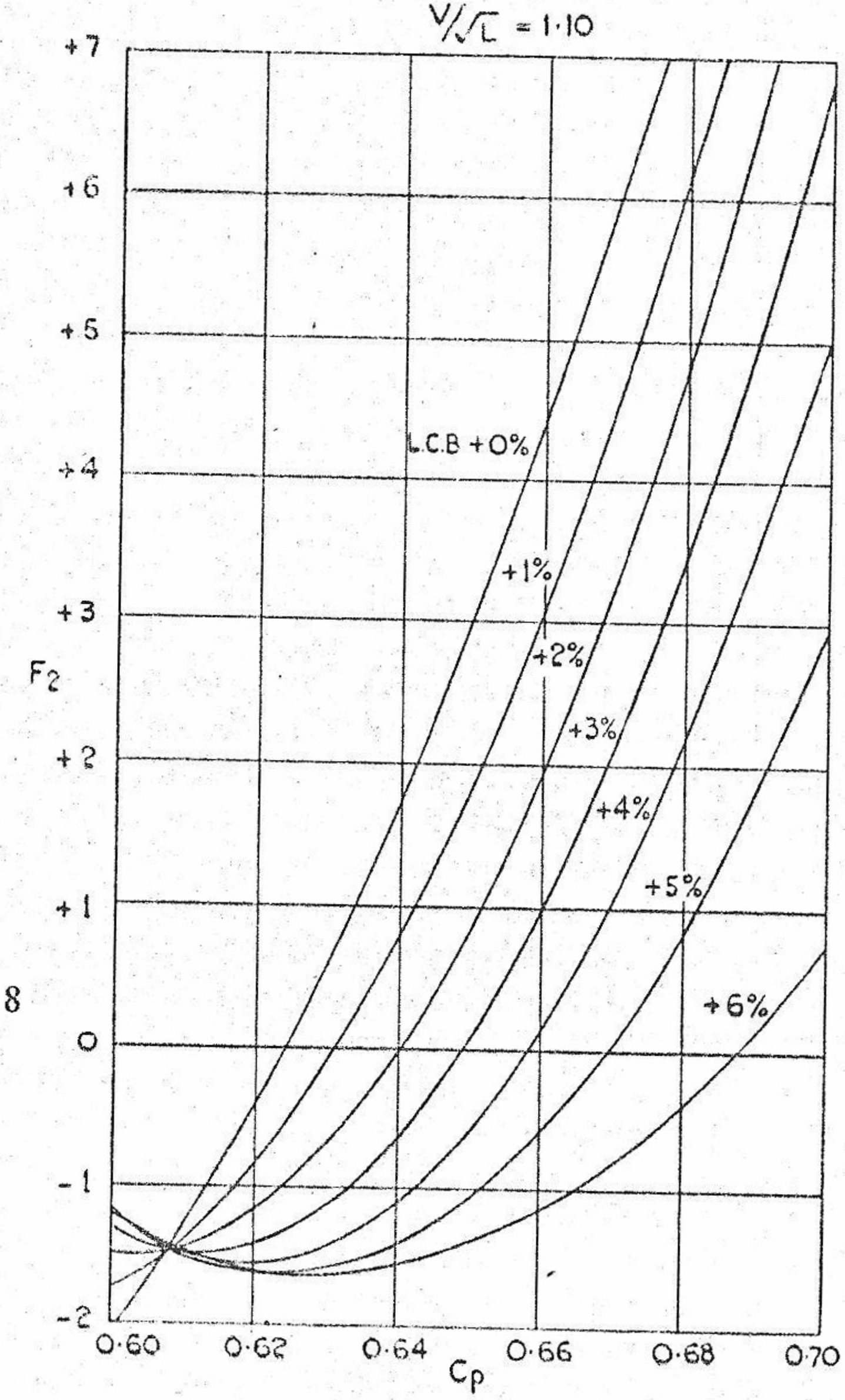

V/√L = 1·10
+7
+6
+5
+4
+3
+2
+1
0
-1
-2
F2
L.C.B +0%
+1%
+2%
+3%
+4%
+5%
+6%
0·60
0·62
0·64
0·66
0·68
0·70
Cp

Fig. 8

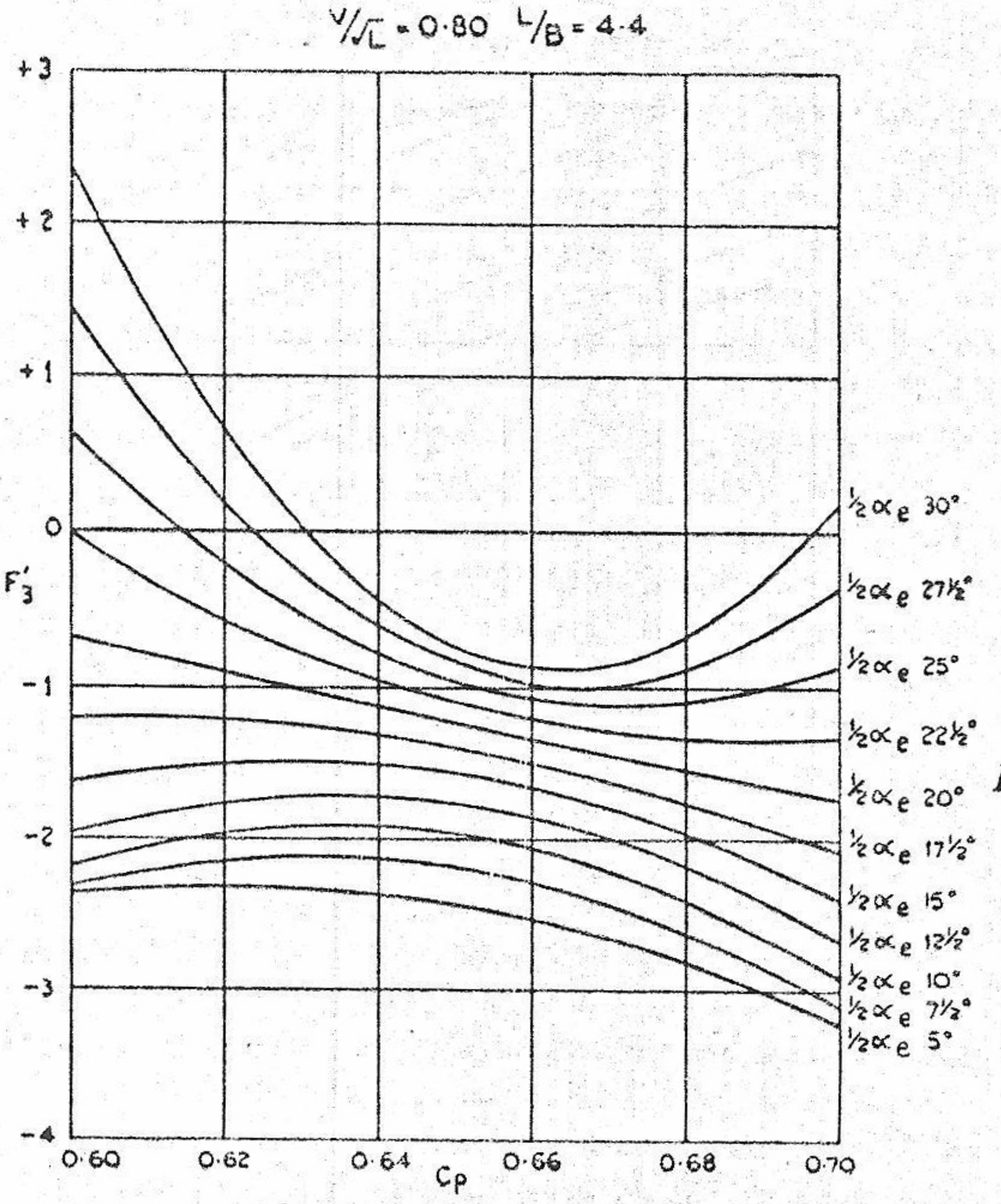

V/√L = 0·80 L/B = 4·4
+3
+2
+1
0
-1
-2
-3
-4
F'3
½αe 30°
½αe 27½°
½αe 25°
½αe 22½°
½αe 20°
½αe 17½°
½αe 15°
½αe 12½°
½αe 10°
½αe 7½°
½αe 5°
0·60
0·62
0·64
0·66
0·68
0·70
Cp

Fig. 9

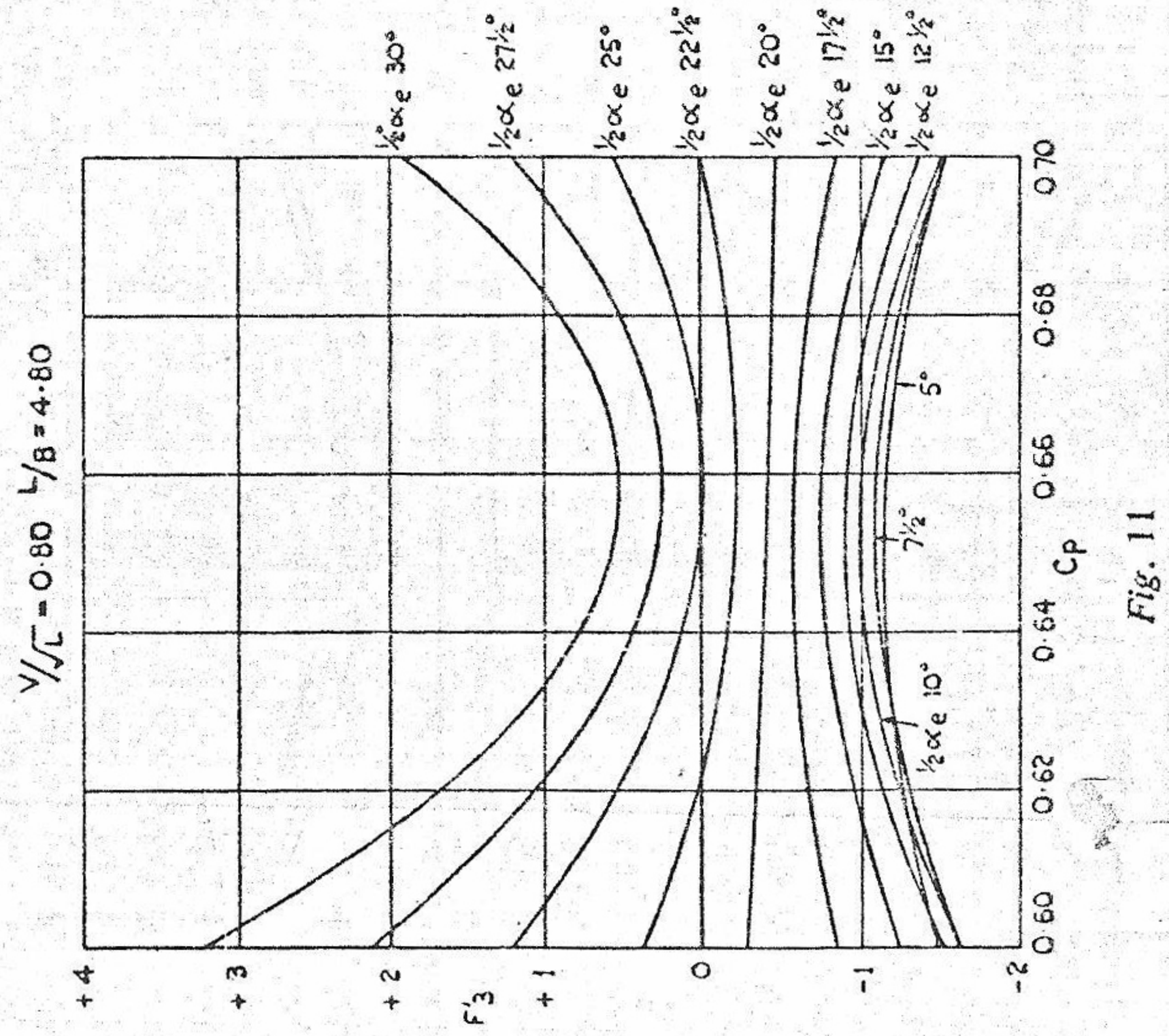

V/√L = 0·80 L/B = 4·80
½α e 30°
½α e 27½°
½α e 25°
½α e 22½°
½α e 20°
½α e 17½°
½α e 15°
½α e 12½°
5°
7½°
½α e 10°
+4
+3
+2
+1
0
-1
-2
F'3
0·70
0·68
0·66
0·64
0·62
0·60
Cp

Fig. 11

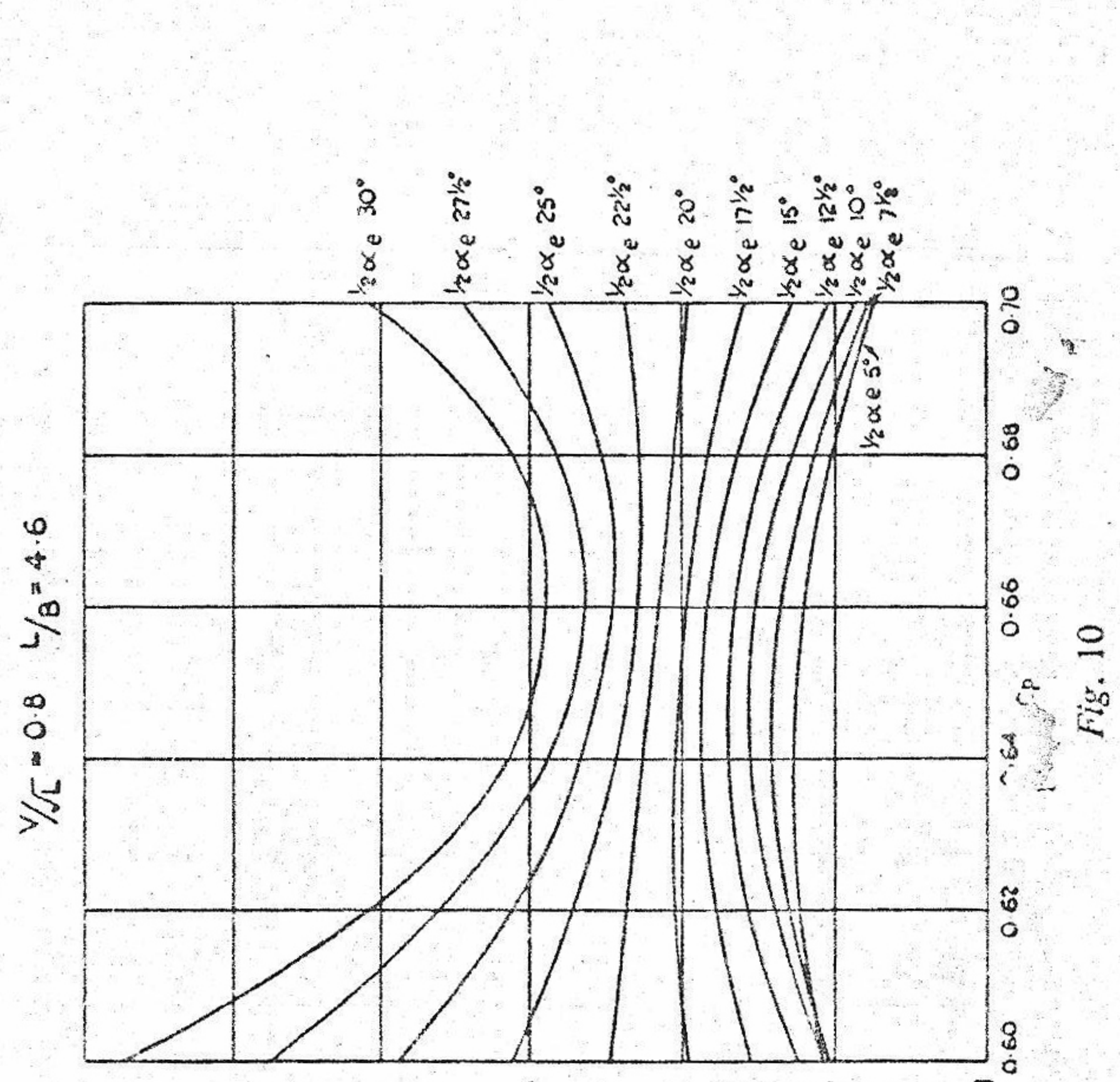

V/√L = 0·8 L/B = 4·6
½α e 30°
½α e 27½°
½α e 25°
½α e 22½°
½α e 20°
½α e 17½°
½α e 15°
½α e 12½°
½α e 10°
½α e 7½°
½α e 5°
+3
+2
+1
0
-1
-2
-3
F'3
0·70
0·68
0·66
0·64
0·62
0·60
Cp

Fig. 10

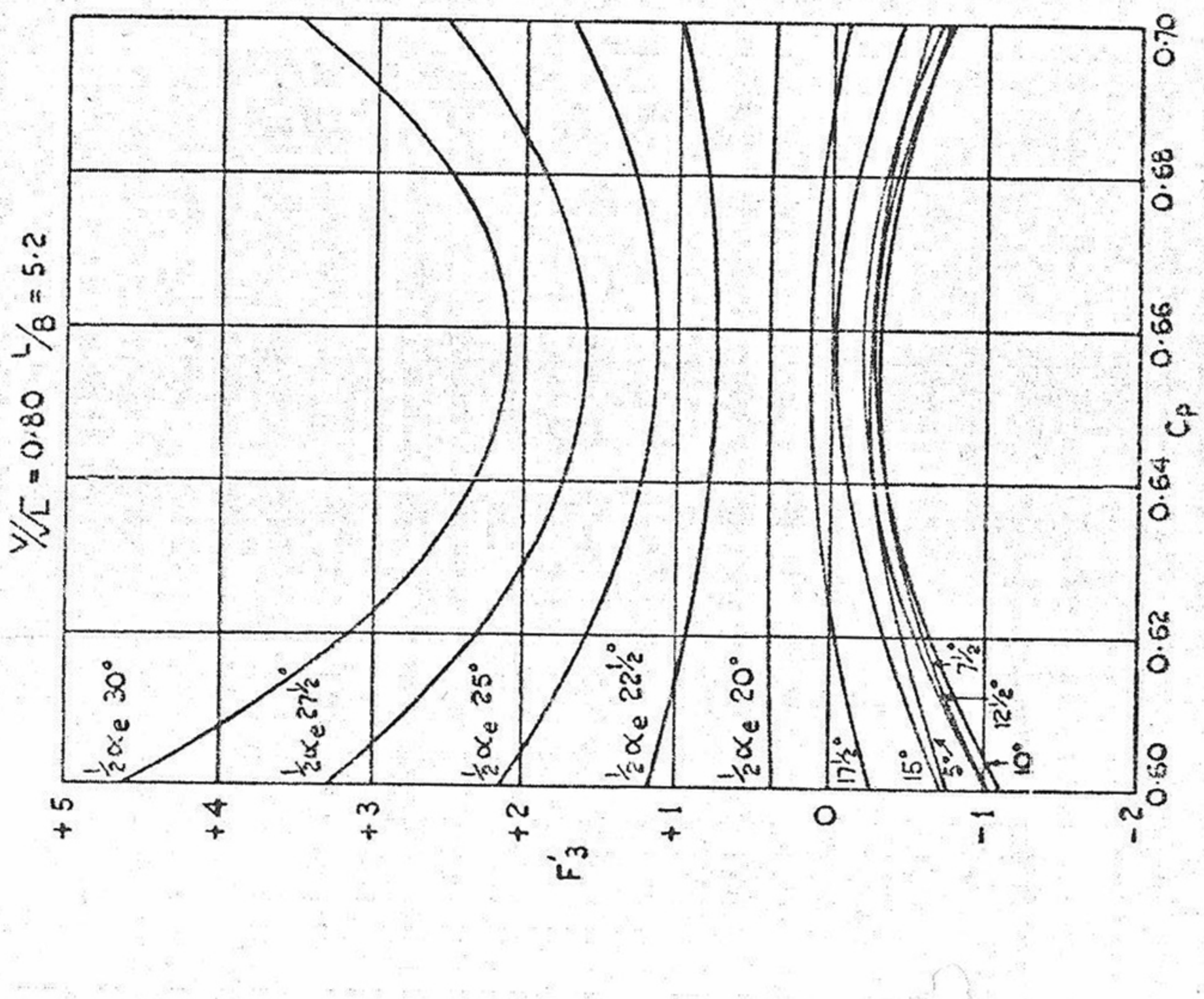

L/B = 5·2
V/√L = 0·80
½αe 30°
½αe 27½°
½αe 25°
½αe 22½°
½αe 20°
17½°
15°
12½°
10°
7½°
5°
F'3
+5
+4
+3
+2
+1
0
-1
-2
0·70
0·68
0·66
0·64
0·62
0·60
CP

Fig. 13

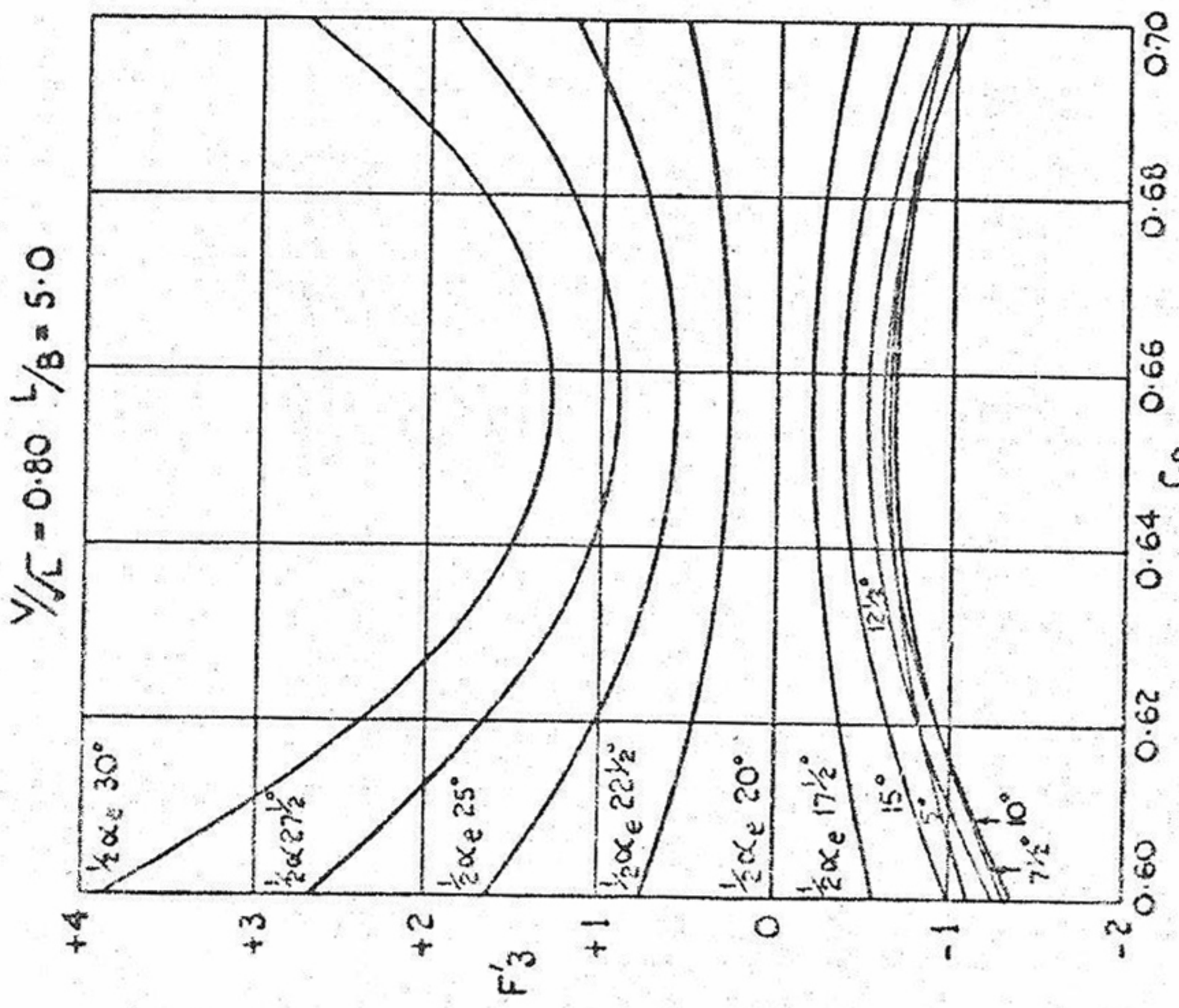

L/B = 5·0
V/√L = 0·80
½αe 30°
½αe 27½°
½αe 25°
½αe 22½°
½αe 20°
½αe 17½°
15°
12½°
10°
7½°
5°
F'3
+4
+3
+2
+1
0
-1
-2
0·70
0·68
0·66
0·64
0·62
0·60
CP

Fig. 12

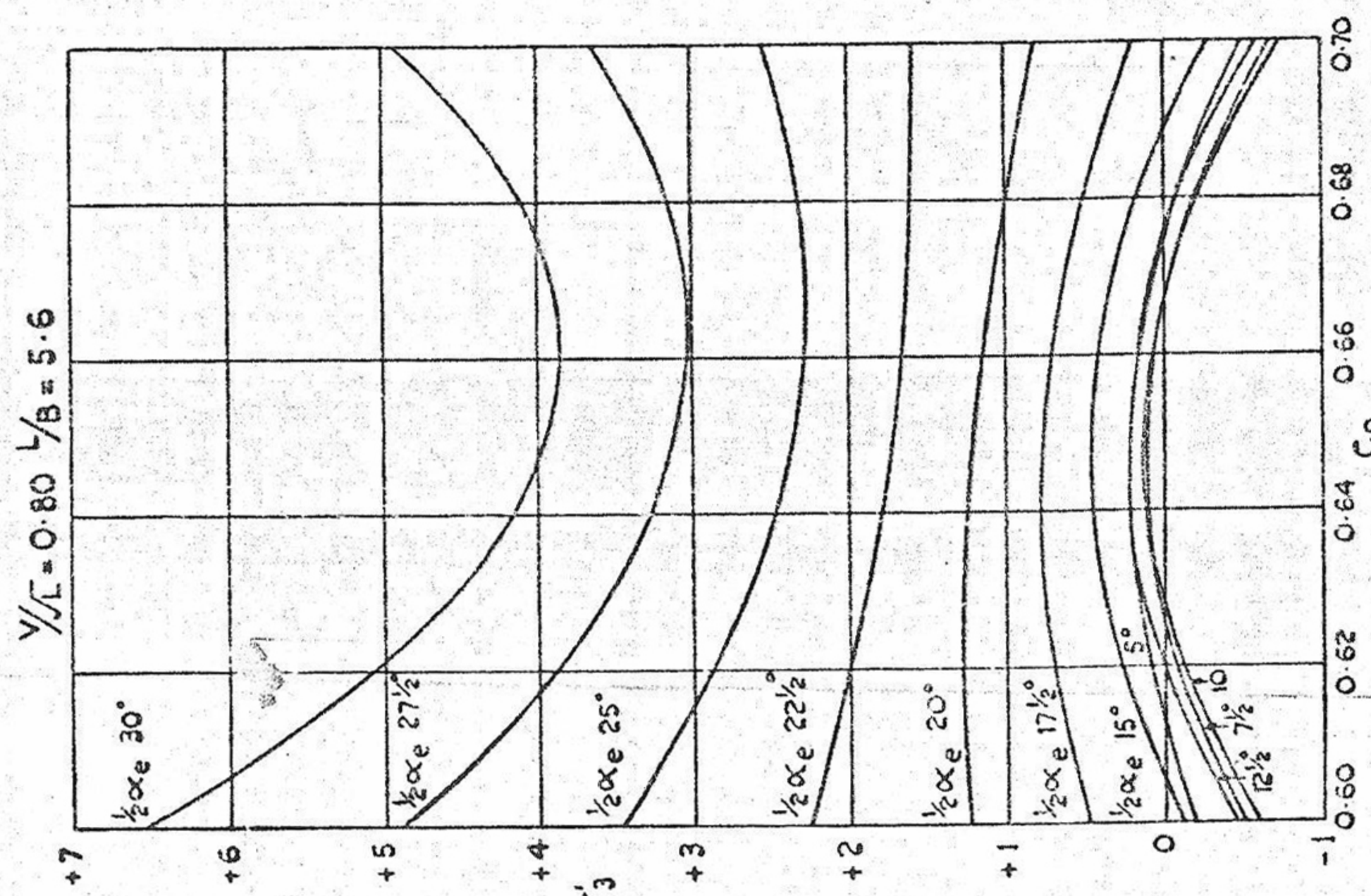

V/√L = 0·80 L/B = 5·6
½αe 30°
½αe 27½°
½αe 25°
½αe 22½°
½αe 20°
½αe 17½°
½αe 15°
12½°
10°
7½°
5°
F'3
+7
+6
+5
+4
+3
+2
+1
0
-1
0·60
0·62
0·64
0·66
0·68
0·70
Cp

Fig. 15

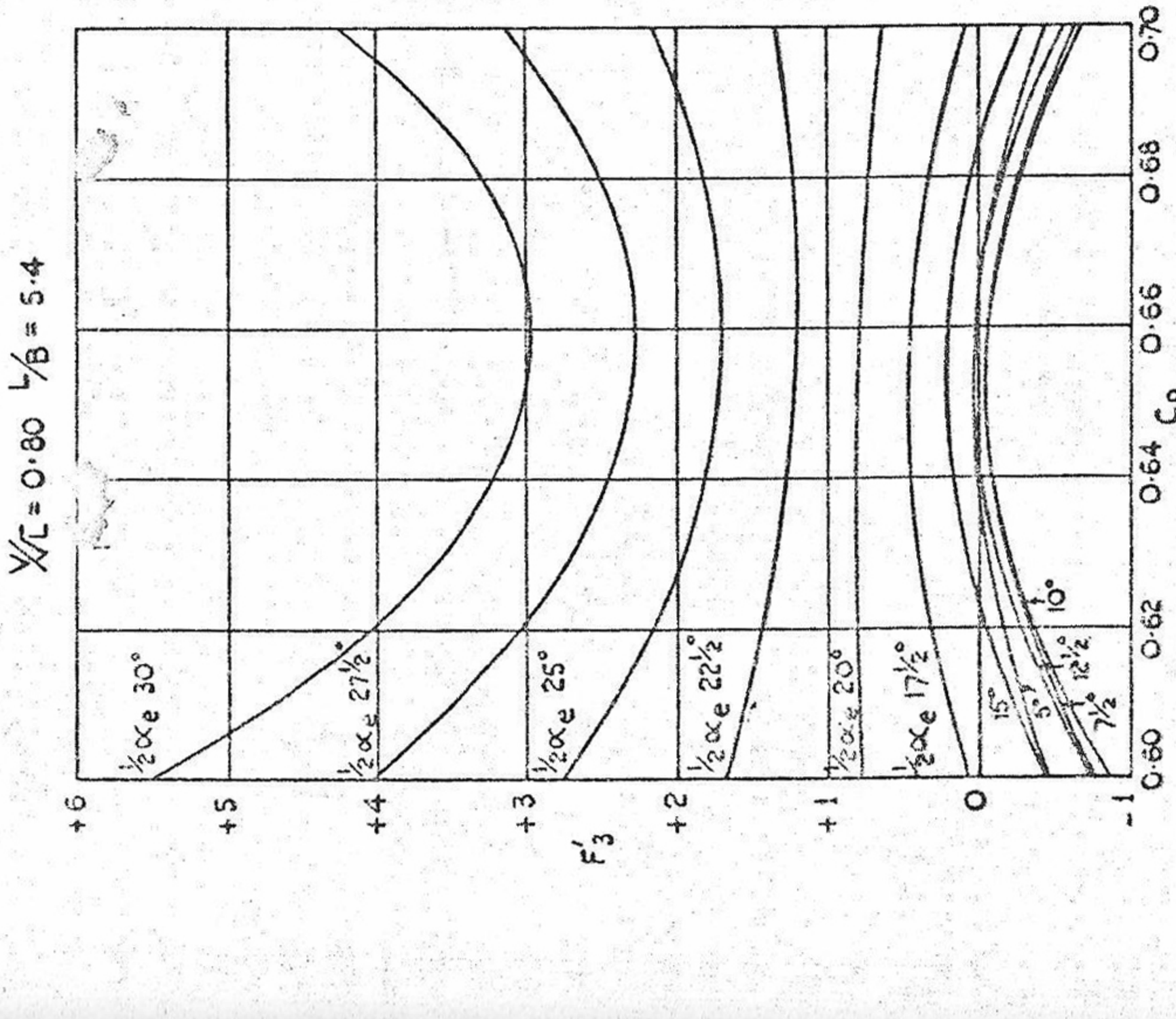

V/√L = 0·80 L/B = 5·4
½αe 30°
½αe 27½°
½αe 25°
½αe 22½°
½αe 20°
½αe 17½°
15°
12½°
10°
7½°
5°
F'3
+6
+5
+4
+3
+2
+1
0
-1
0·60
0·62
0·64
0·66
0·68
0·70
Cp

Fig. 14

V/√L = 0·90 L/B = 4·4
½α e 5°
7½°
10°
½α e 30°
½α e 27½°
½α e 25°
22½°
20°
17½°
15°
12½°
+4
+3
+2
+1
0
-1
-2
-3
F'3
0·70
0·68
0·66
0·64
0·62
0·60
Cp

Fig. 17

V/√L = 0·80 L/B = 5·8
½α e 30°
½α e 27½°
½α e 25°
½α e 22½°
½α e 20°
½α e 17½°
½α e 15°
5°
12½°
7½° 10°
+8
+7
+6
+5
+4
+3
+2
+1
0
-1
F'3
0·70
0·68
0·66
0·64
0·62
0·60
Cp

Fig. 16

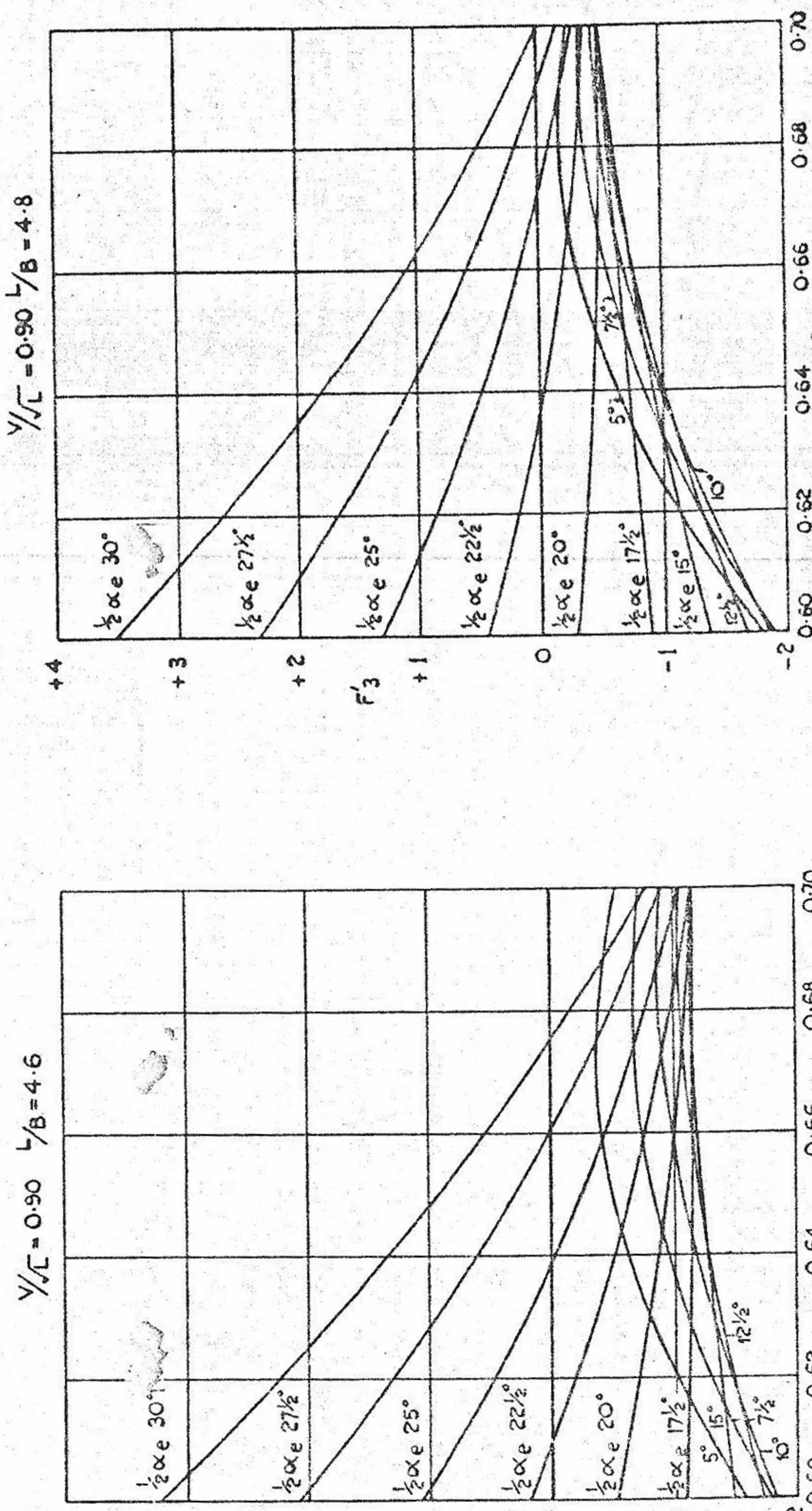

V/√L = 0·90 L/B = 4·8
½ α e 30°
½ α e 27½°
½ α e 25°
½ α e 22½°
½ α e 20°
½ α e 17½°
½ α e 15°
12½°
10°
7½°
5°
0·60
0·62
0·64
0·66
0·68
0·70
Cp
+4
+3
+2
+1
0
−1
−2
F'3

Fig. 19

V/√L = 0·90 L/B = 4·6
½ α e 30°
½ α e 27½°
½ α e 25°
½ α e 22½°
½ α e 20°
½ α e 17½°
5°
15°
12½°
10°
7½°
0·60
0·62
0·64
0·66
0·68
0·70
Cp
+4
+3
+2
+1
0
−1
−2
F'3

Fig. 18

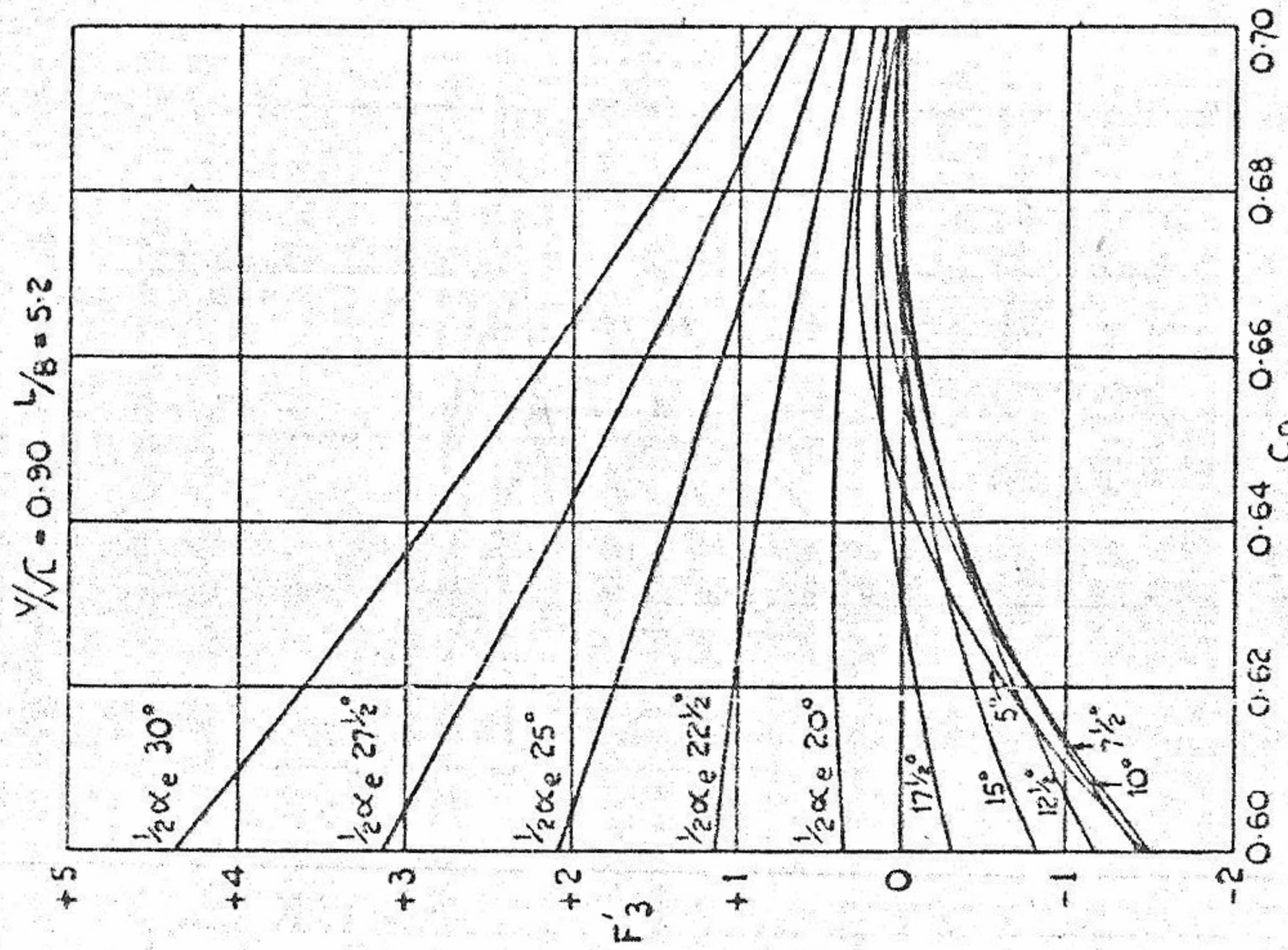

V/√L = 0·90 L/B = 5·2
½αe 30°
½αe 27½°
½αe 25°
½αe 22½°
½αe 20°
17½°
15°
12½°
10°
7½°
5°
+5
+4
+3
+2
+1
0
-1
-2
F'3
0·60
0·62
0·64
0·66
0·68
0·70
Cp

Fig. 21

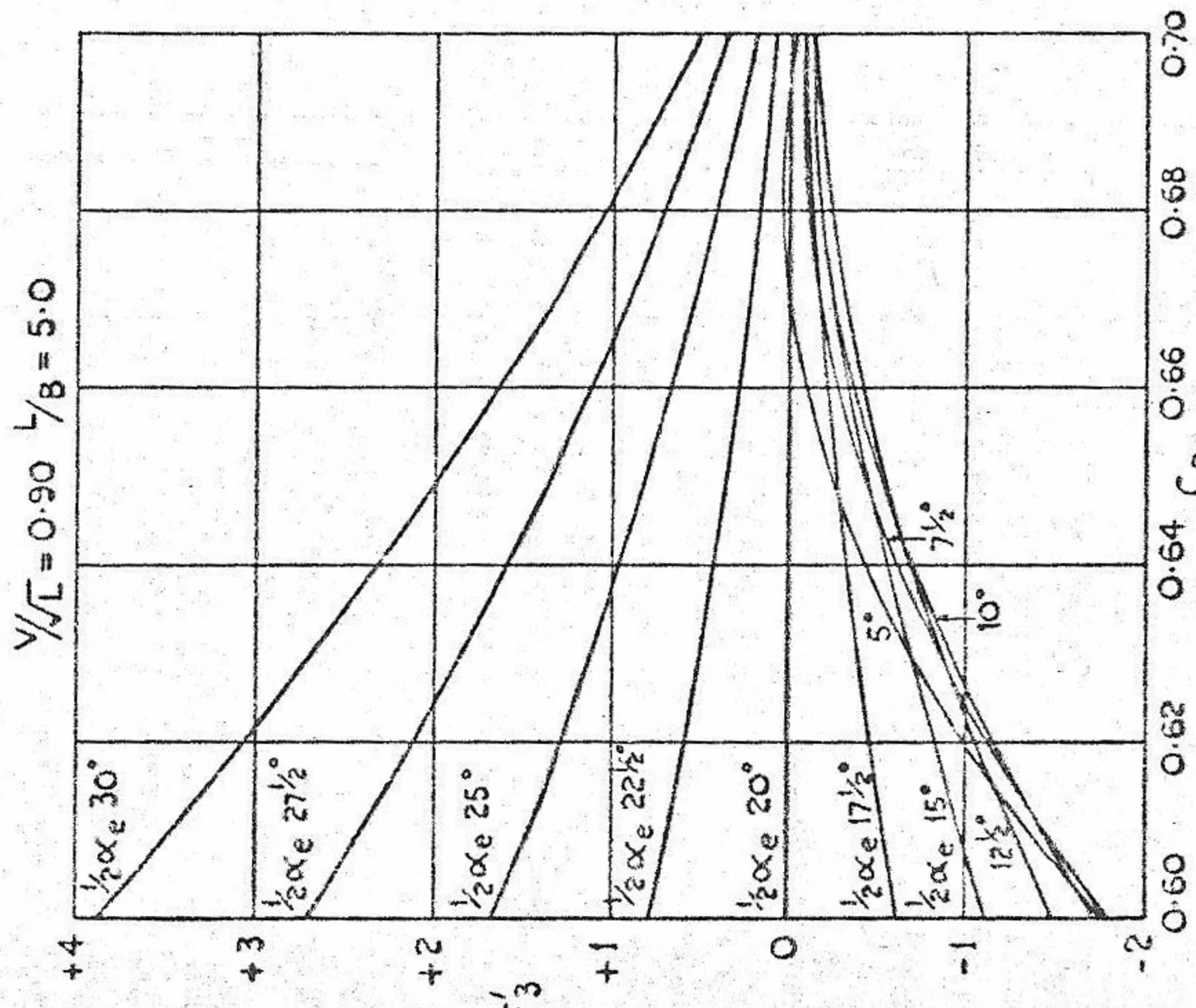

V/√L = 0·90 L/B = 5·0
½αe 30°
½αe 27½°
½αe 25°
½αe 22½°
½αe 20°
½αe 17½°
½αe 15°
½αe 12½°
5°
7½°
10°
+4
+3
+2
+1
0
-1
-2
F'3
0·60
0·62
0·64
0·66
0·68
0·70
Cp

Fig. 20

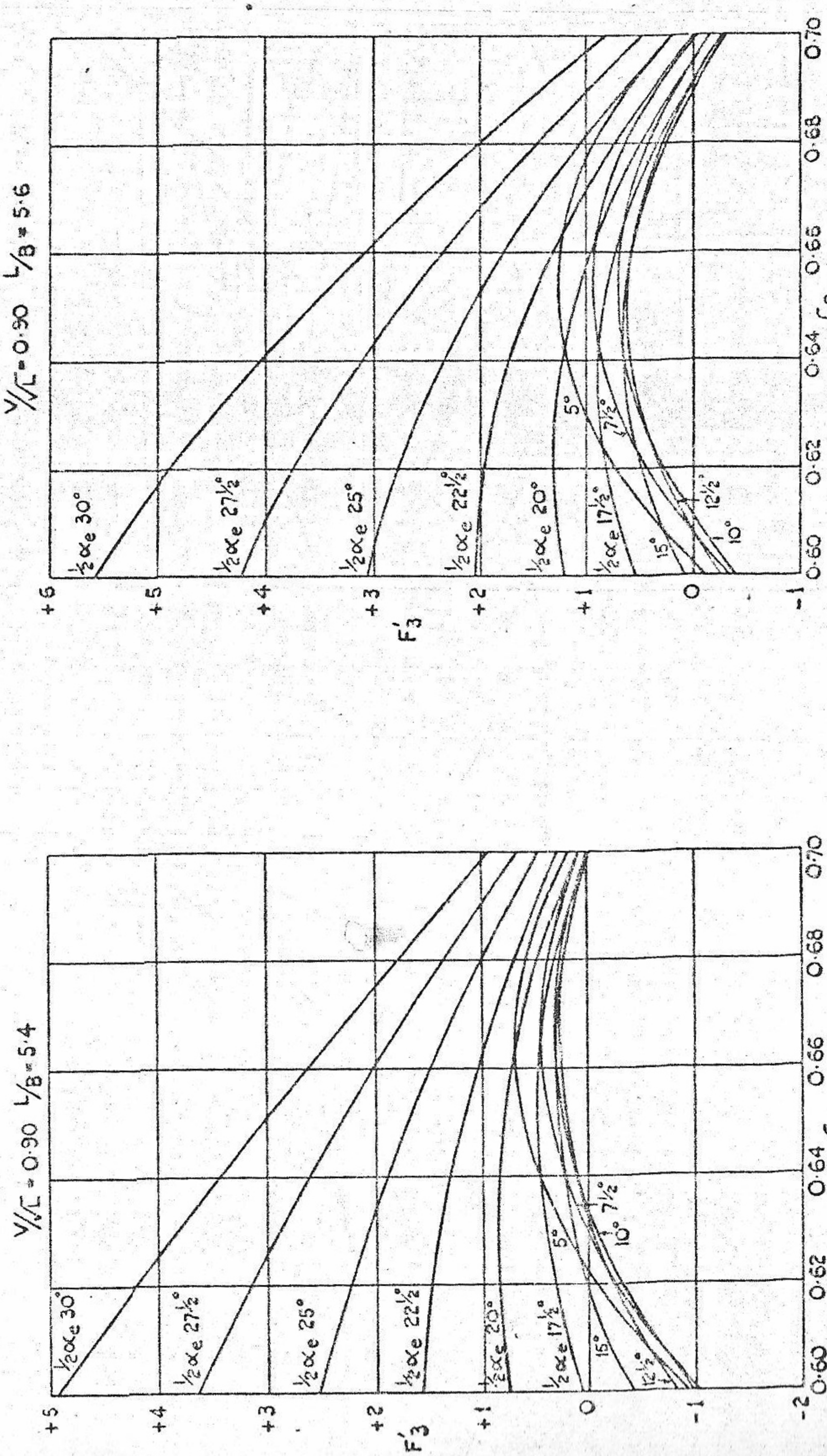

V/√L = 0·90 L/B = 5·6
½αe 30°
½αe 27½°
½αe 25°
½αe 22½°
½αe 20°
½αe 17½°
15°
12½°
10°
7½°
5°
F'3
+6
+5
+4
+3
+2
+1
0
-1
0·60
0·62
0·64
0·65
0·66
0·68
0·70
Cp

Fig. 23

V/√L = 0·90 L/B = 5·4
½αe 30°
½αe 27½°
½αe 25°
½αe 22½°
½αe 20°
½αe 17½°
15°
12½°
10°
7½°
5°
F'3
+5
+4
+3
+2
+1
0
-1
-2
0·60
0·62
0·64
0·66
0·68
0·70
Cp

Fig. 22

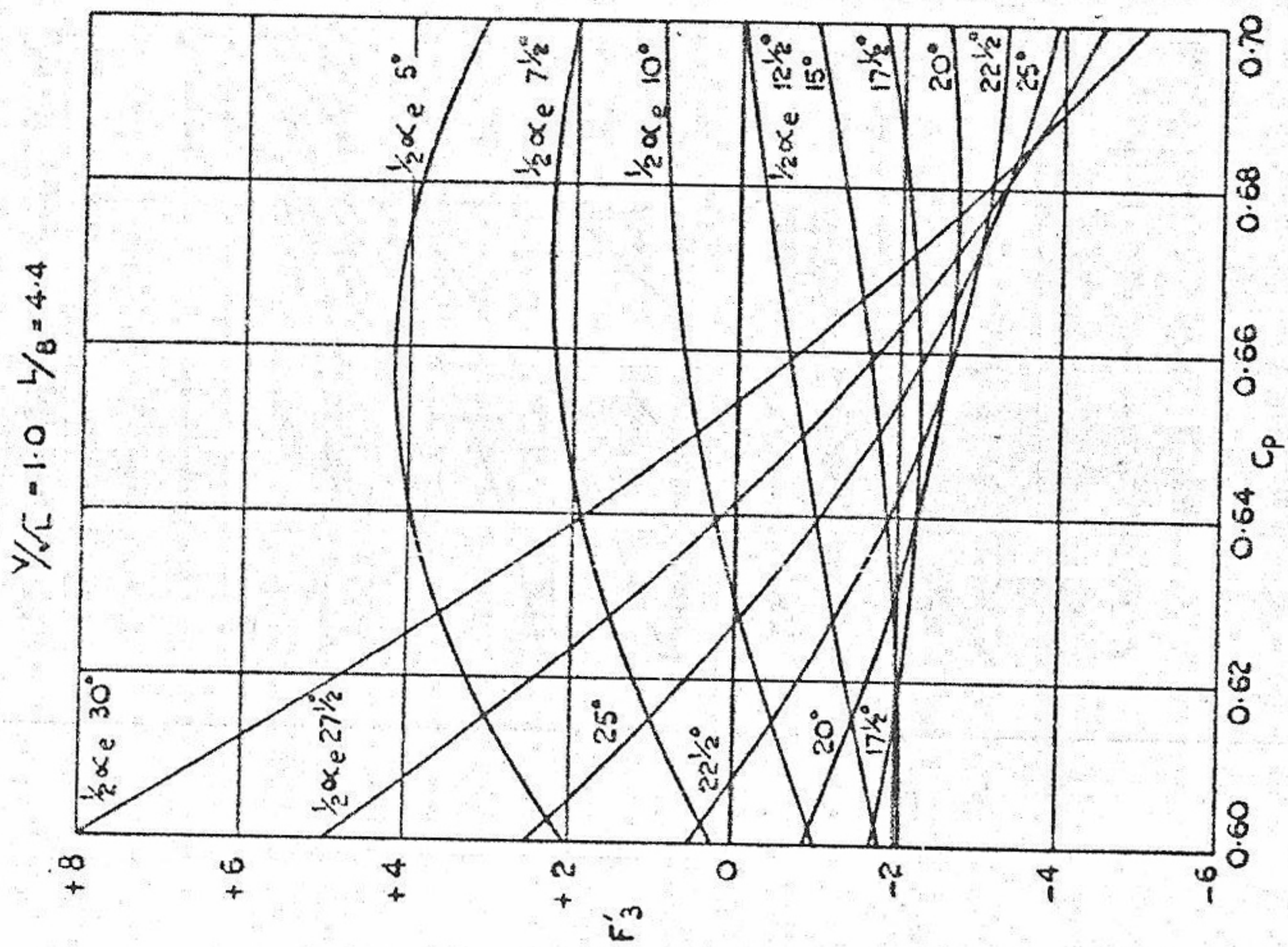

V/√L = 1·0 L/B = 4·4
½αe 5°
½αe 7½°
½αe 10°
½αe 12½°
15°
17½°
20°
22½°
25°
½αe 30°
½αe 27½°
25°
22½°
20°
17½°
+8
+6
+4
+2
0
-2
-4
-6
F'3
0·70
0·68
0·66
0·64
0·62
0·60
CP

Fig. 25

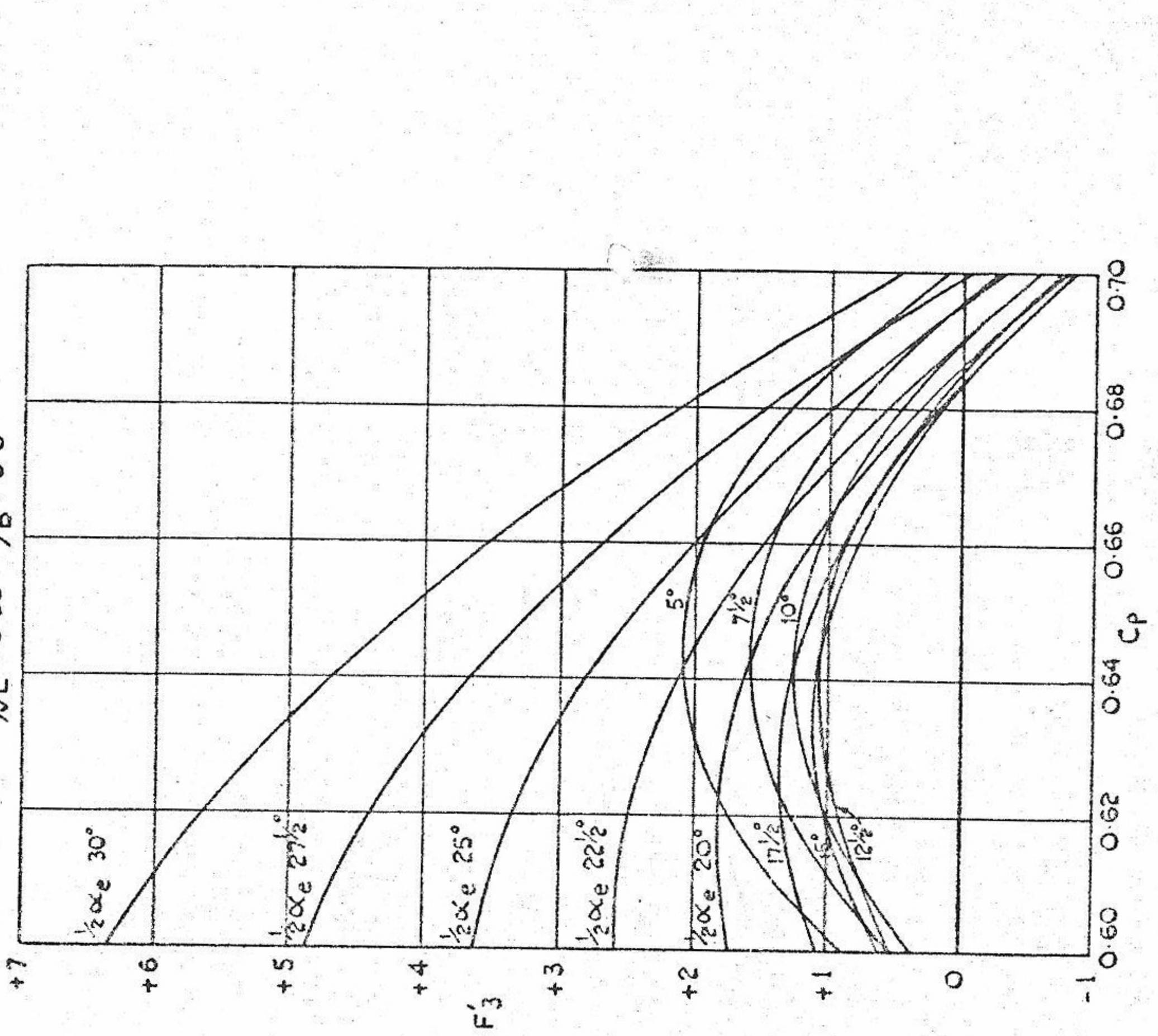

V/√L = 0·90 L/B = 5·8
5°
7½°
10°
½αe 30°
½αe 27½°
½αe 25°
½αe 22½°
½αe 20°
17½°
15°
12½°
+7
+6
+5
+4
+3
+2
+1
0
-1
F'3
0·70
0·68
0·66
0·64
0·62
0·60
CP

Fig. 24

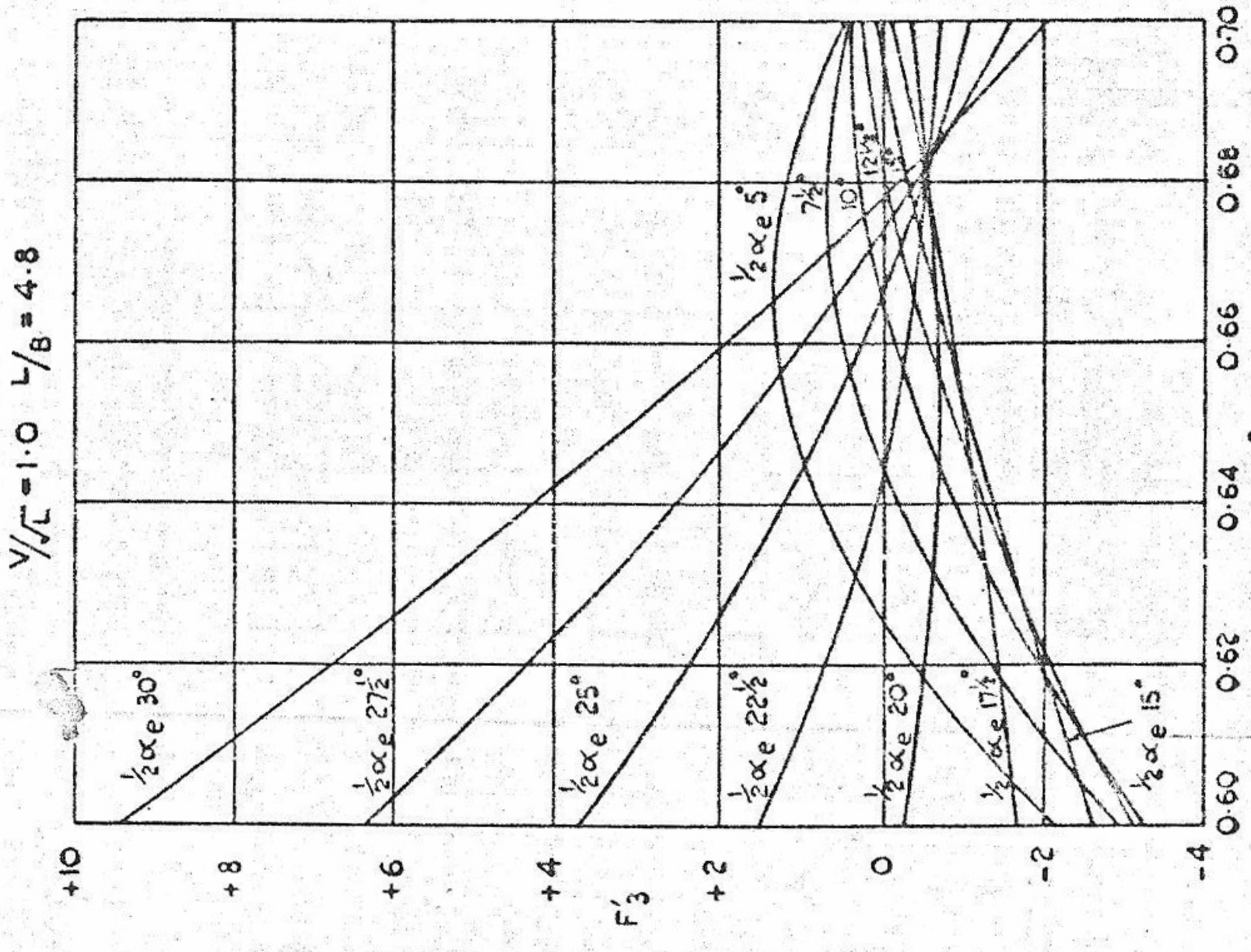

V/√L = 1·0 L/B = 4·8
½αe 5°
7½°
10°
12½°
15°
17½°
20°
22½°
½αe 30°
½αe 27½°
½αe 25°
½αe 22½°
½αe 20°
½αe 17½°
½αe 15°
+10
+8
+6
+4
+2
0
-2
-4
F'3
0·60
0·62
0·64
0·66
0·68
0·70
CP

Fig. 27

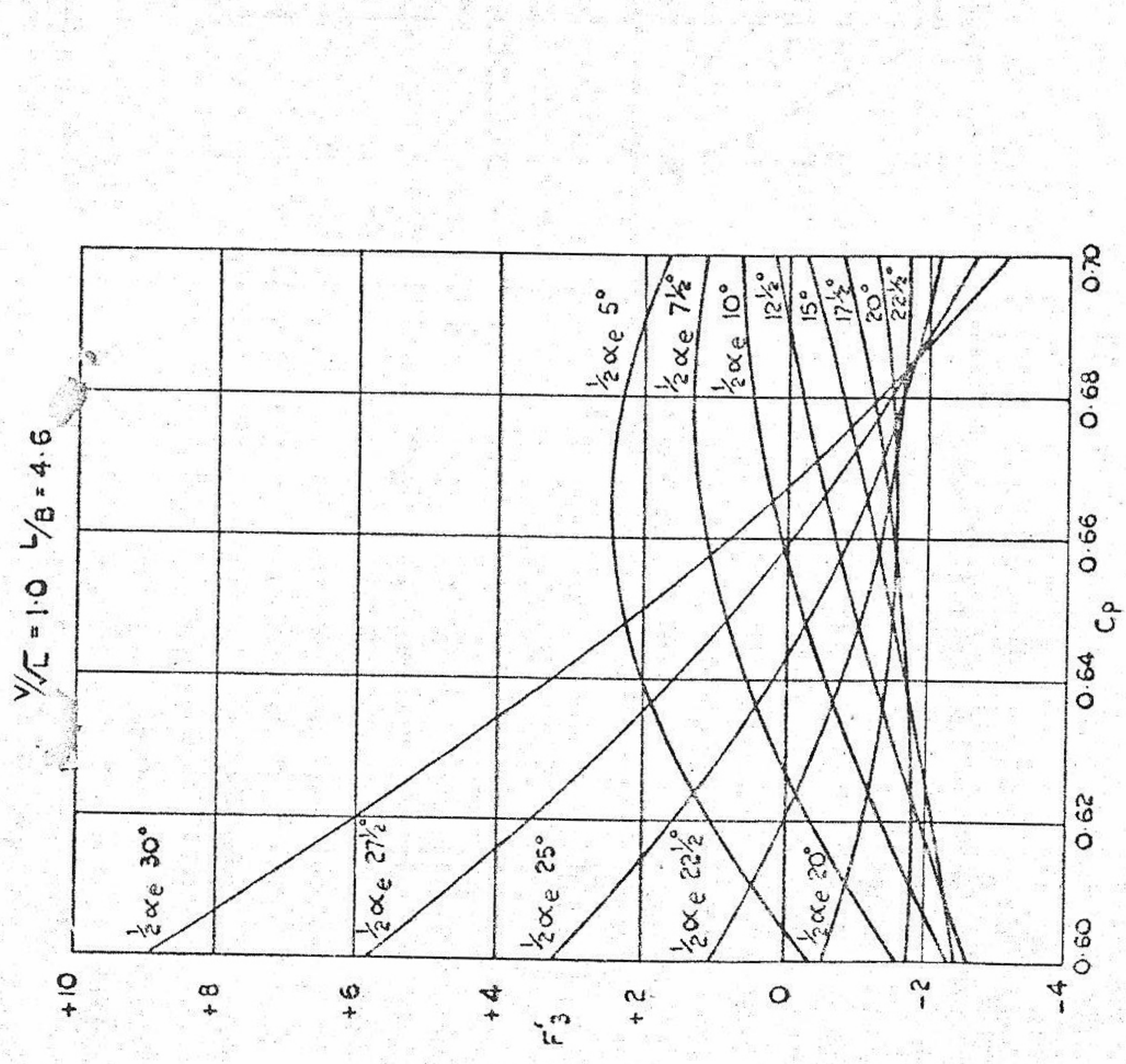

V/√L = 1·0 L/B = 4·6
½αe 5°
7½°
10°
12½°
15°
17½°
20°
22½°
½αe 30°
½αe 27½°
½αe 25°
½αe 22½°
½αe 20°
+10
+8
+6
+4
+2
0
-2
-4
F'3
0·60
0·62
0·64
0·66
0·68
0·70
CP

Fig. 26

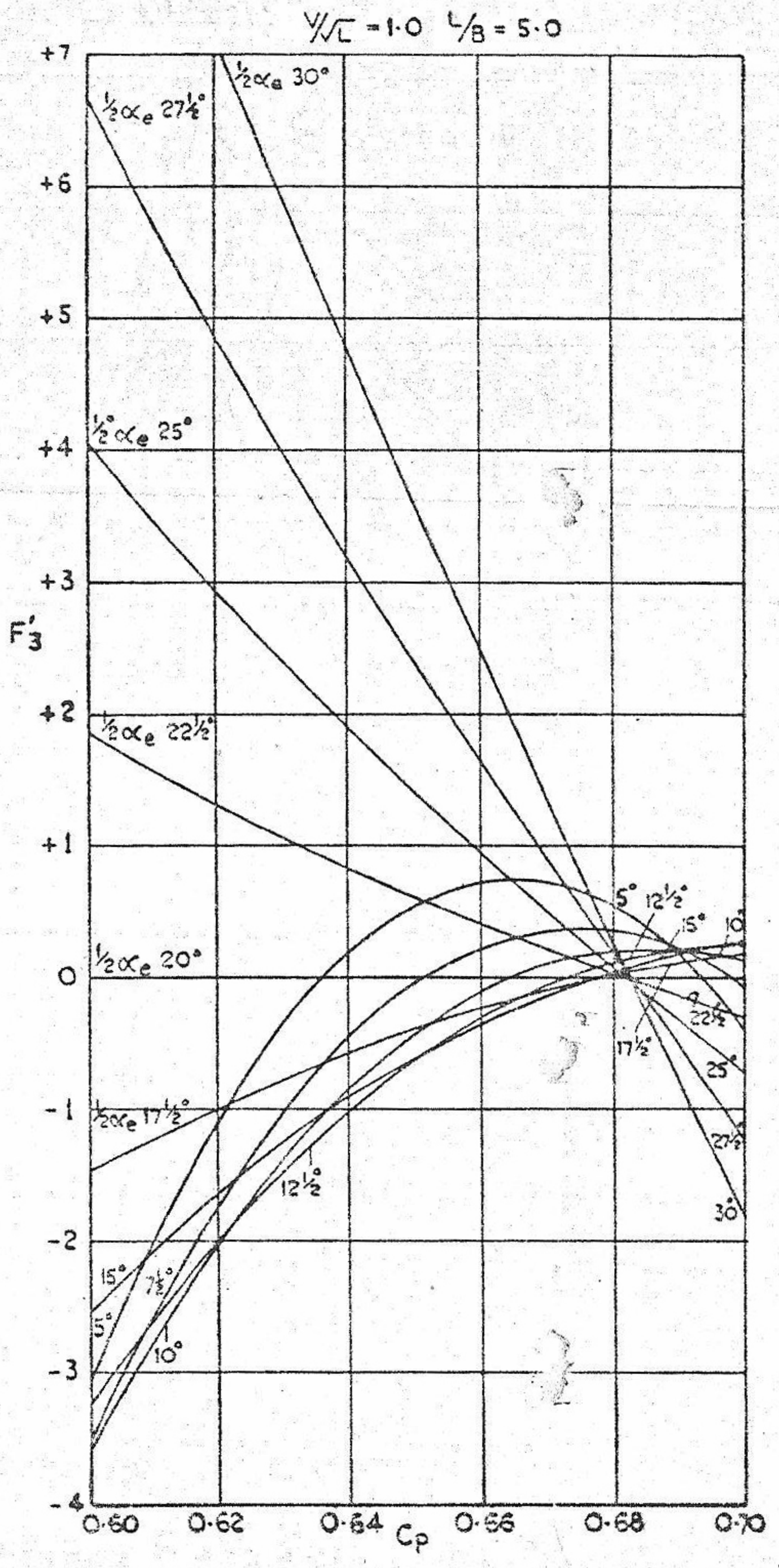

V/√L = 1·0 L/B = 5·0
+7
+6
+5
+4
+3
+2
+1
0
-1
-2
-3
-4
F'3
Cp
0·60
0·62
0·64
0·66
0·68
0·70
½αe 30°
½αe 27½°
½αe 25°
½αe 22½°
½αe 20°
½αe 17½°
5°
7½°
10°
12½°
15°
17½°
20°
22½°
25°
27½°
30°

Fig. 28

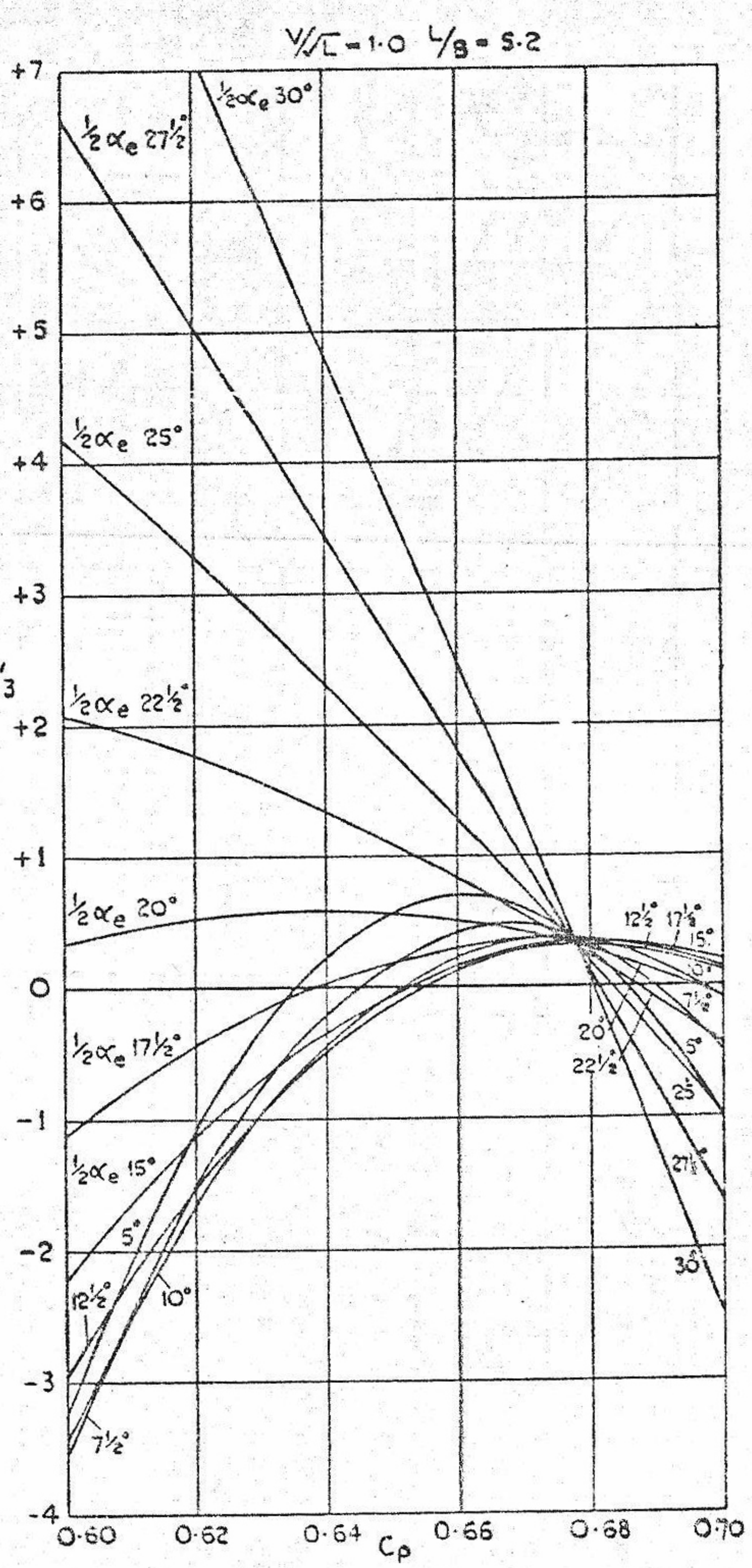

V/√L = 1·0 L/B = 5·2
+7
+6
+5
+4
+3
+2
+1
0
-1
-2
-3
-4
F'3
½αe 30°
½αe 27½°
½αe 25°
½αe 22½°
½αe 20°
½αe 17½°
½αe 15°
12½°
17½°
15°
10°
7½°
20°
22½°
5°
25°
27½°
30°
0·60
0·62
0·64
0·66
0·68
0·70
Cp

Fig. 29

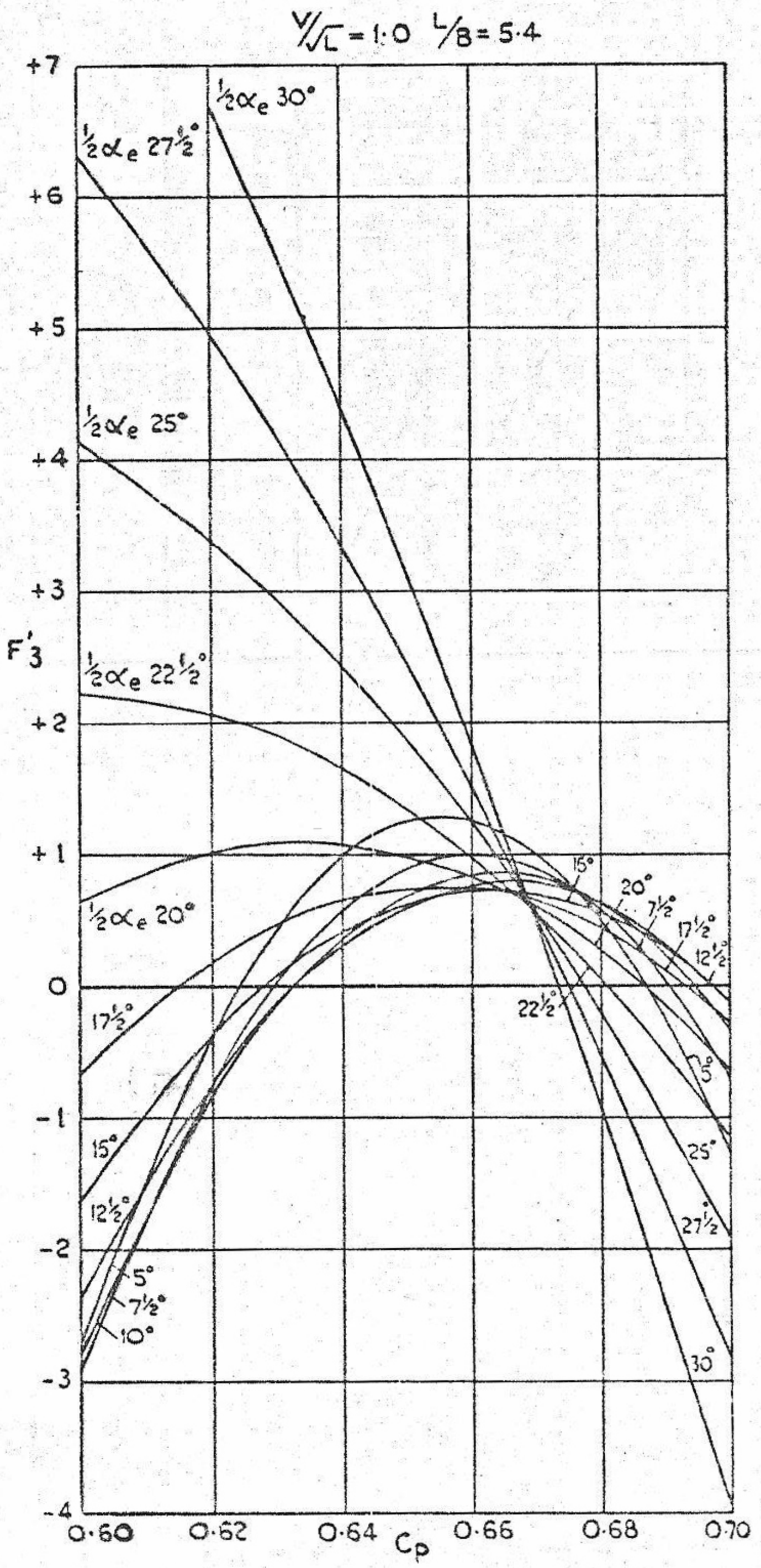

V/√L = 1·0 L/B = 5·4
+7
+6
+5
+4
+3
+2
+1
0
-1
-2
-3
-4
F'3
½αe 27½°
½αe 30°
½αe 25°
½αe 22½°
½αe 20°
17½°
15°
12½°
10°
7½°
5°
20°
25°
27½°
30°
22½°
0·60
0·62
0·64
0·66
0·68
0·70
Cp

Fig. 30

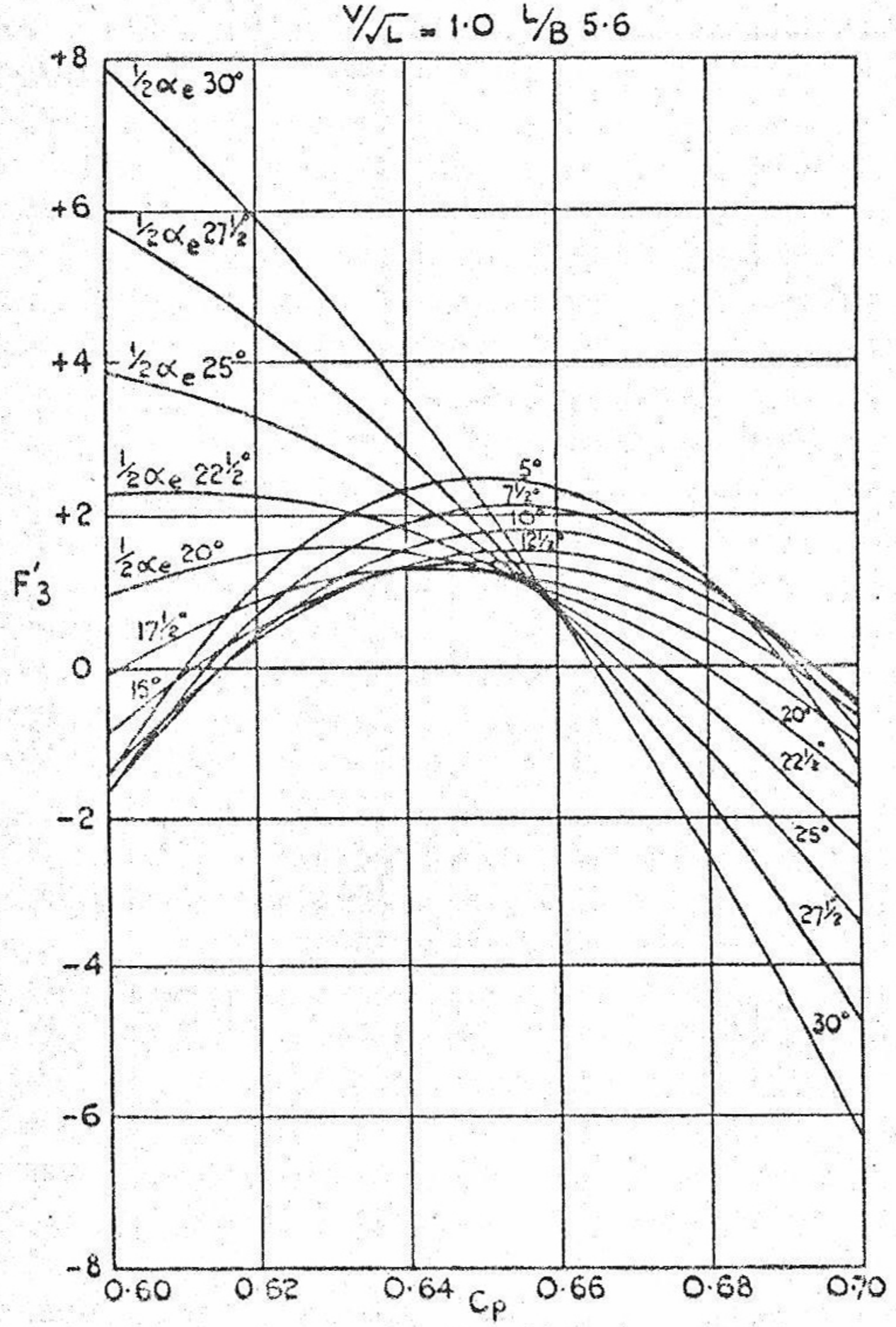

V/√L = 1·0 L/B 5·6
+8
+6
+4
+2
0
-2
-4
-6
-8
F'3
½αe 30°
½αe 27½°
½αe 25°
½αe 22½°
½αe 20°
17½°
15°
5°
7½°
10°
12½°
20°
22½°
25°
27½°
30°
0·60
0·62
0·64
0·66
0·68
0·70
Cp

Fig. 31

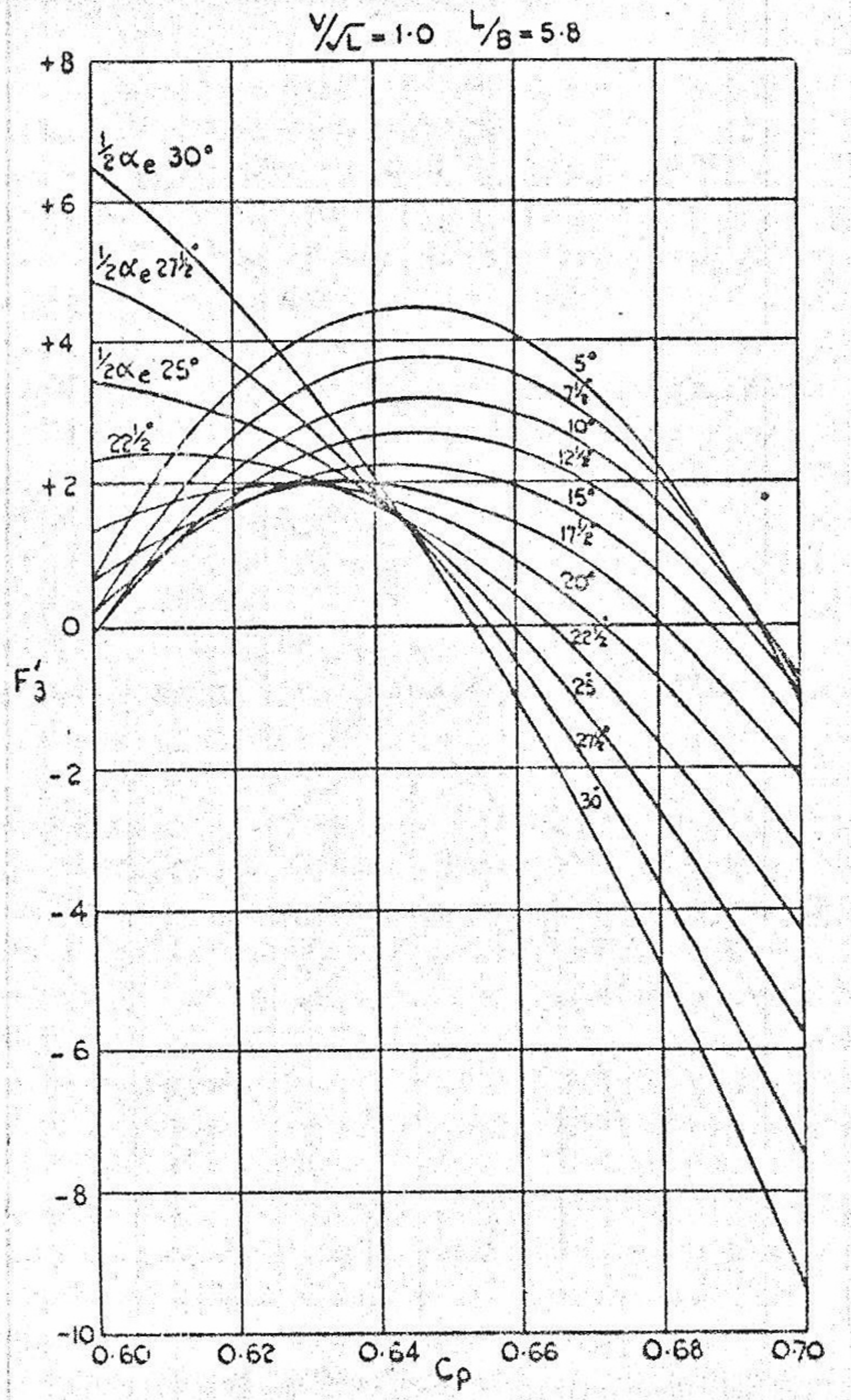

V/√L = 1·0 L/B = 5·8
+8
+6
+4
+2
0
-2
-4
-6
-8
-10
F'3
½αe 30°
½αe 27½°
½αe 25°
22½°
5°
7½°
10°
12½°
15°
17½°
20°
22½°
25°
27½°
30°
0·60
0·62
0·64
0·66
0·68
0·70
Cp

Fig. 32

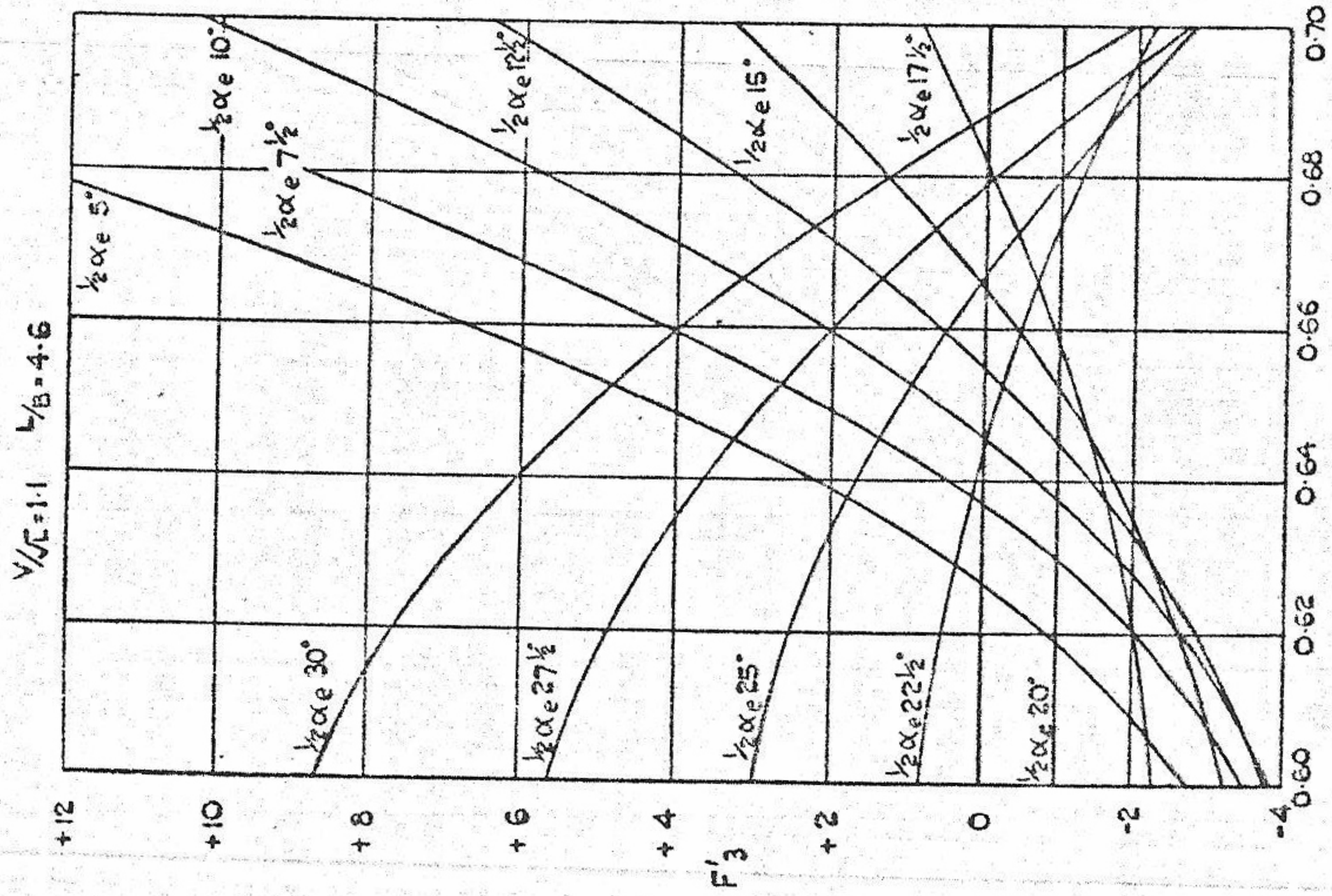

V/√L=1·1 L/B=4·6
½αe 5°
½αe 7½°
½αe 10°
½αe 12½°
½αe 15°
½αe 17½°
½αe 20°
½αe 22½°
½αe 25°
½αe 27½°
½αe 30°
+12
+10
+8
+6
+4
+2
0
-2
-4
F'3
0·60
0·62
0·64
0·66
0·68
0·70
CP

Fig. 34

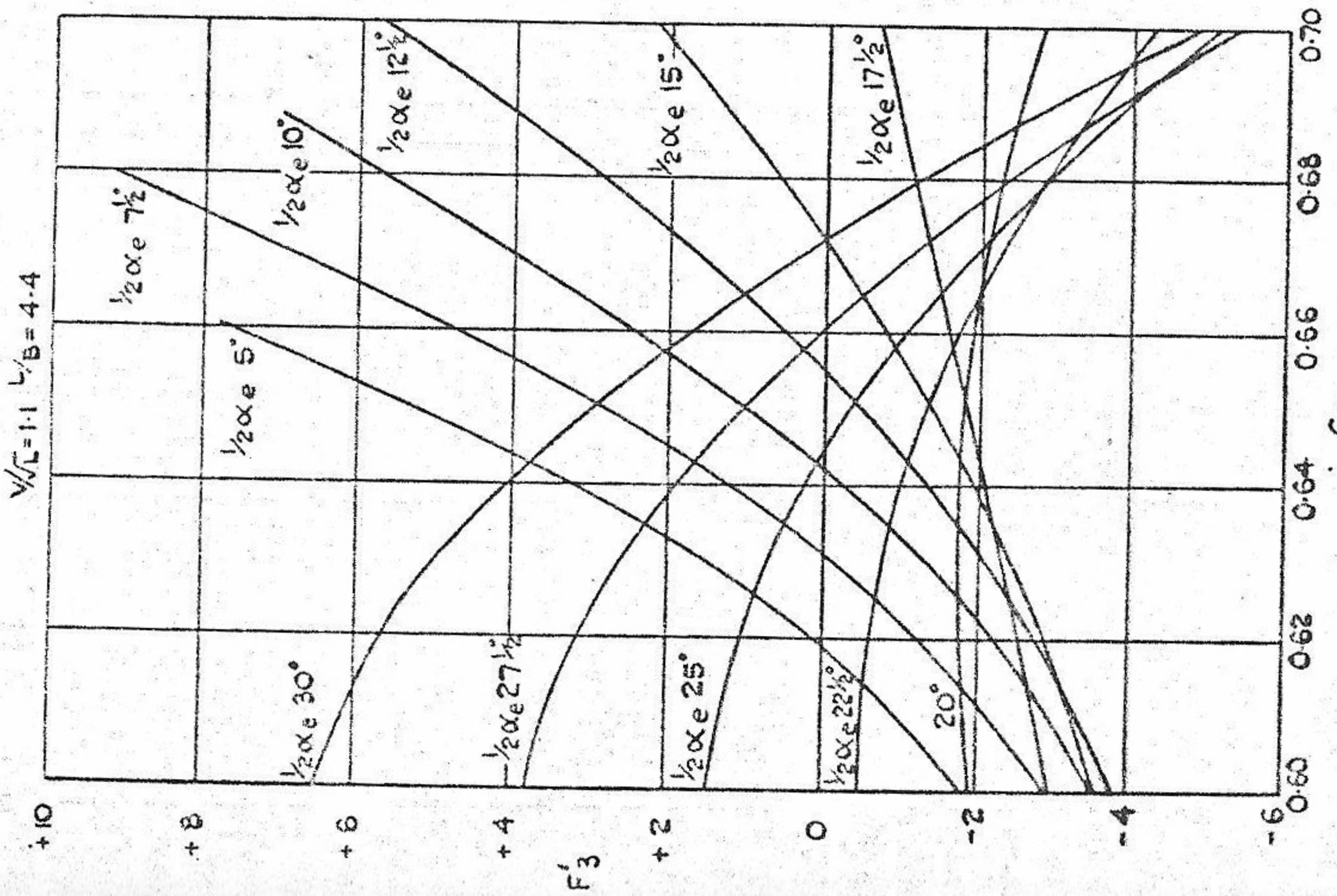

V/√L=1·1 L/B=4·4
½αe 5°
½αe 7½°
½αe 10°
½αe 12½°
½αe 15°
½αe 17½°
½αe 20°
½αe 22½°
½αe 25°
½αe 27½°
½αe 30°
+10
+8
+6
+4
+2
0
-2
-4
-6
F'3
0·60
0·62
0·64
0·66
0·68
0·70
CP

Fig. 33

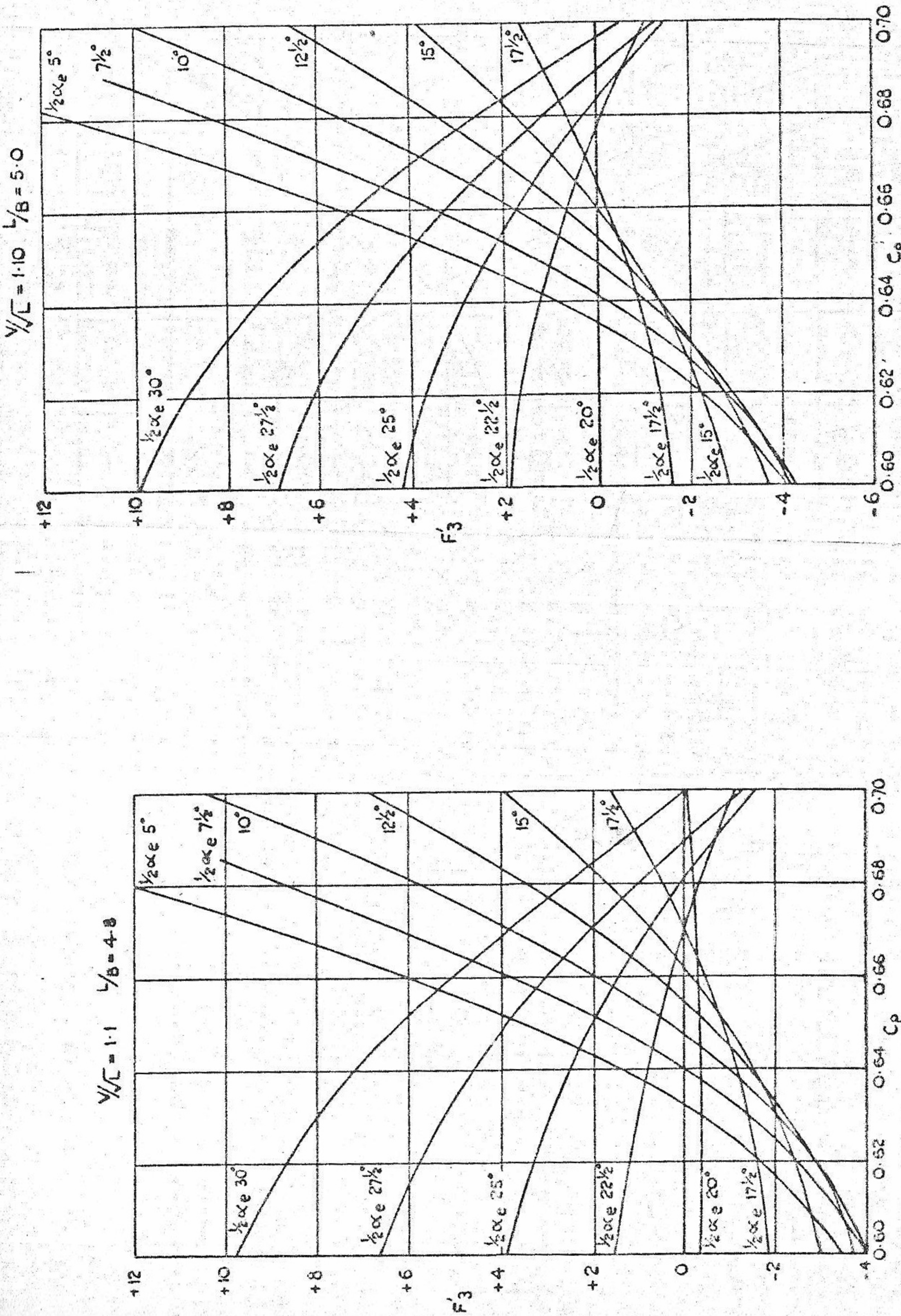

V/√L = 1·10 L/B = 5·0
½α_e 5°
7½°
10°
12½°
15°
17½°
½α_e 30°
½α_e 27½°
½α_e 25°
½α_e 22½°
½α_e 20°
½α_e 17½°
½α_e 15°
+12
+10
+8
+6
+4
+2
0
-2
-4
-6
F'3
0·60
0·62
0·64
0·66
0·68
0·70
C_P

Fig. 36

V/√L = 1·1 L/B = 4·8
½α_e 5°
½α_e 7½°
10°
12½°
15°
17½°
½α_e 30°
½α_e 27½°
½α_e 25°
½α_e 22½°
½α_e 20°
½α_e 17½°
+12
+10
+8
+6
+4
+2
0
-2
-4
F'3
0·60
0·62
0·64
0·66
0·68
0·70
C_P

Fig. 35

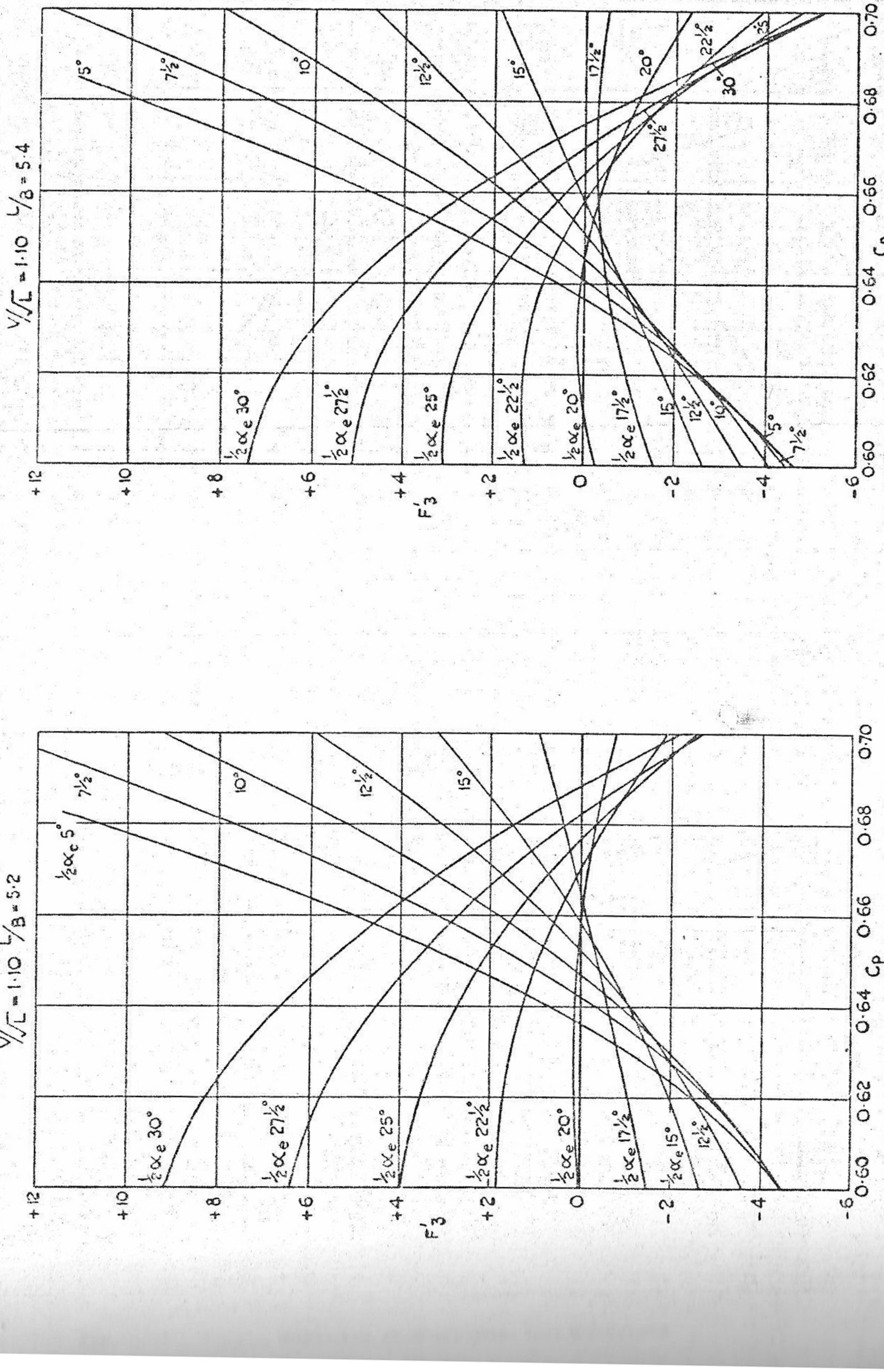

V/√L = 1·10 L/B = 5·4
15°
7½°
10°
12½°
15°
17½°
20°
22½°
25
30°
27½°
½αe 30°
½αe 27½°
½αe 25°
½αe 22½°
½αe 20°
½αe 17½°
15°
12½°
10°
5°
7½°
+12
+10
+8
+6
+4
+2
0
-2
-4
-6
F'3
0·60
0·62
0·64
0·66
0·68
0·70
Cp

Fig. 38

V/√L = 1·10 L/B = 5·2
½αc 5°
7½°
10°
12½°
15°
½αe 30°
½αe 27½°
½αe 25°
½αe 22½°
½αe 20°
½αe 17½°
½αe 15°
12½°
+12
+10
+8
+6
+4
+2
0
-2
-4
-6
F'3
0·60
0·62
0·64
0·66
0·68
0·70
Cp

Fig. 37

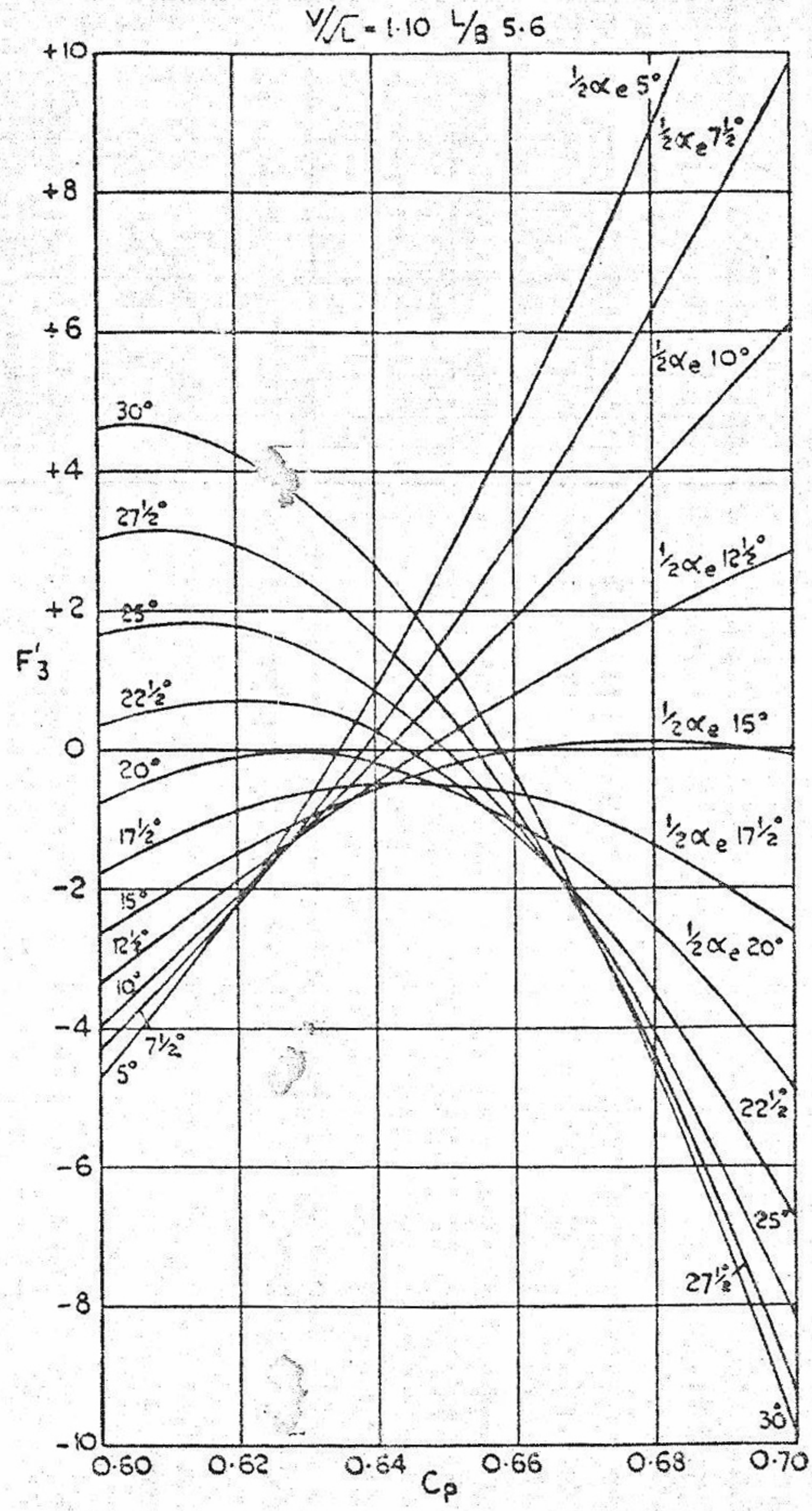

V/√L = 1·10 L/B 5·6
+10
+8
+6
+4
+2
0
-2
-4
-6
-8
-10
F'3
0·60
0·62
0·64
0·66
0·68
0·70
Cp
½α e 5°
½α e 7½°
½α e 10°
½α e 12½°
½α e 15°
½α e 17½°
½α e 20°
½α e 22½°
½α e 25°
½α e 27½°
½α e 30°
30°
27½°
25°
22½°
20°
17½°
15°
12½°
10°
7½°
5°

Fig. 39

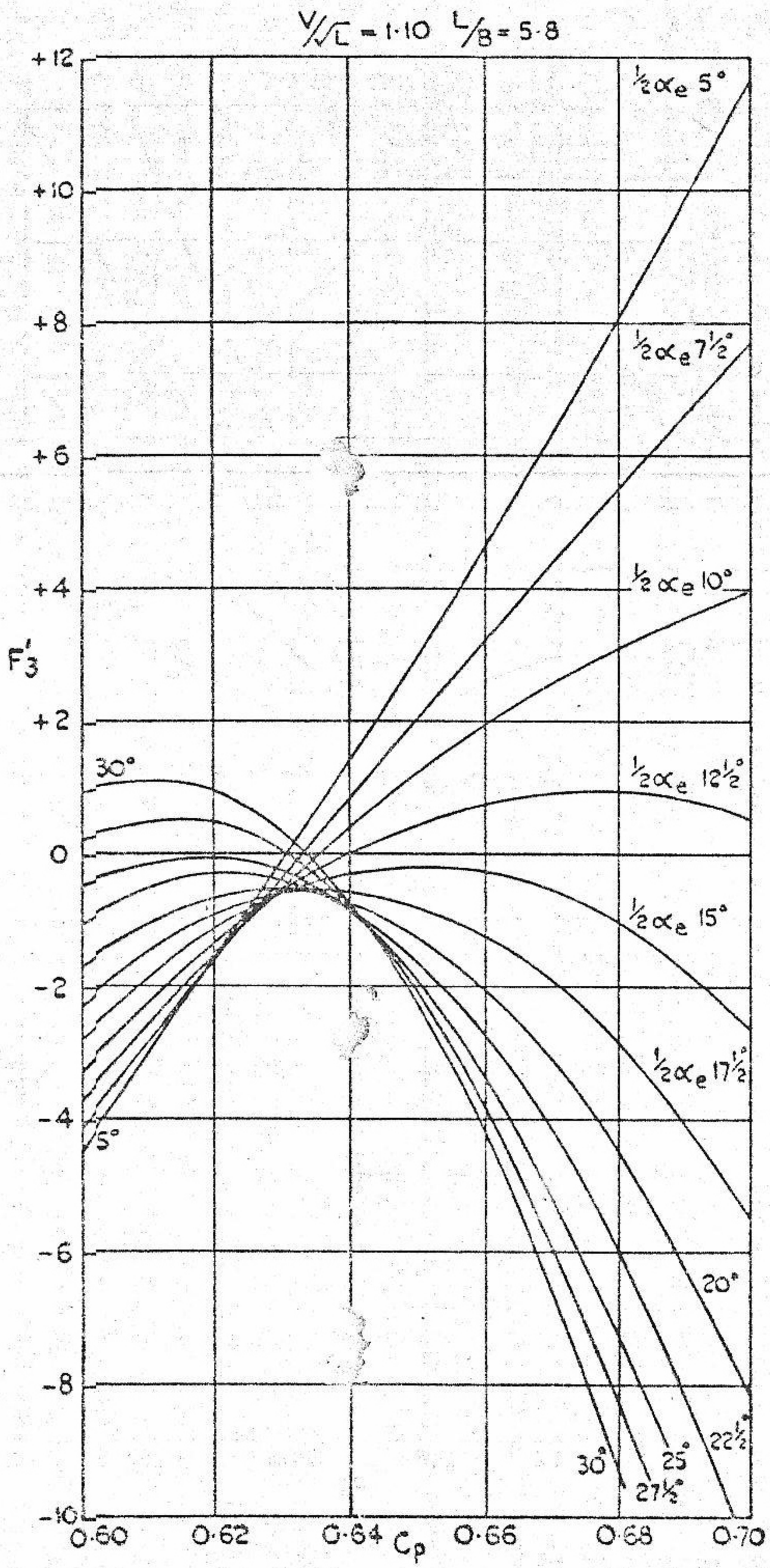

V/√L = 1·10 L/B = 5·8
+12
+10
+8
+6
+4
+2
0
-2
-4
-6
-8
-10
F'3
½αe 5°
½αe 7½°
½αe 10°
½αe 12½°
½αe 15°
½αe 17½°
20°
22½°
25°
27½°
30°
30°
5°
0·60
0·62
0·64
0·66
0·68
0·70
Cp

Fig. 40

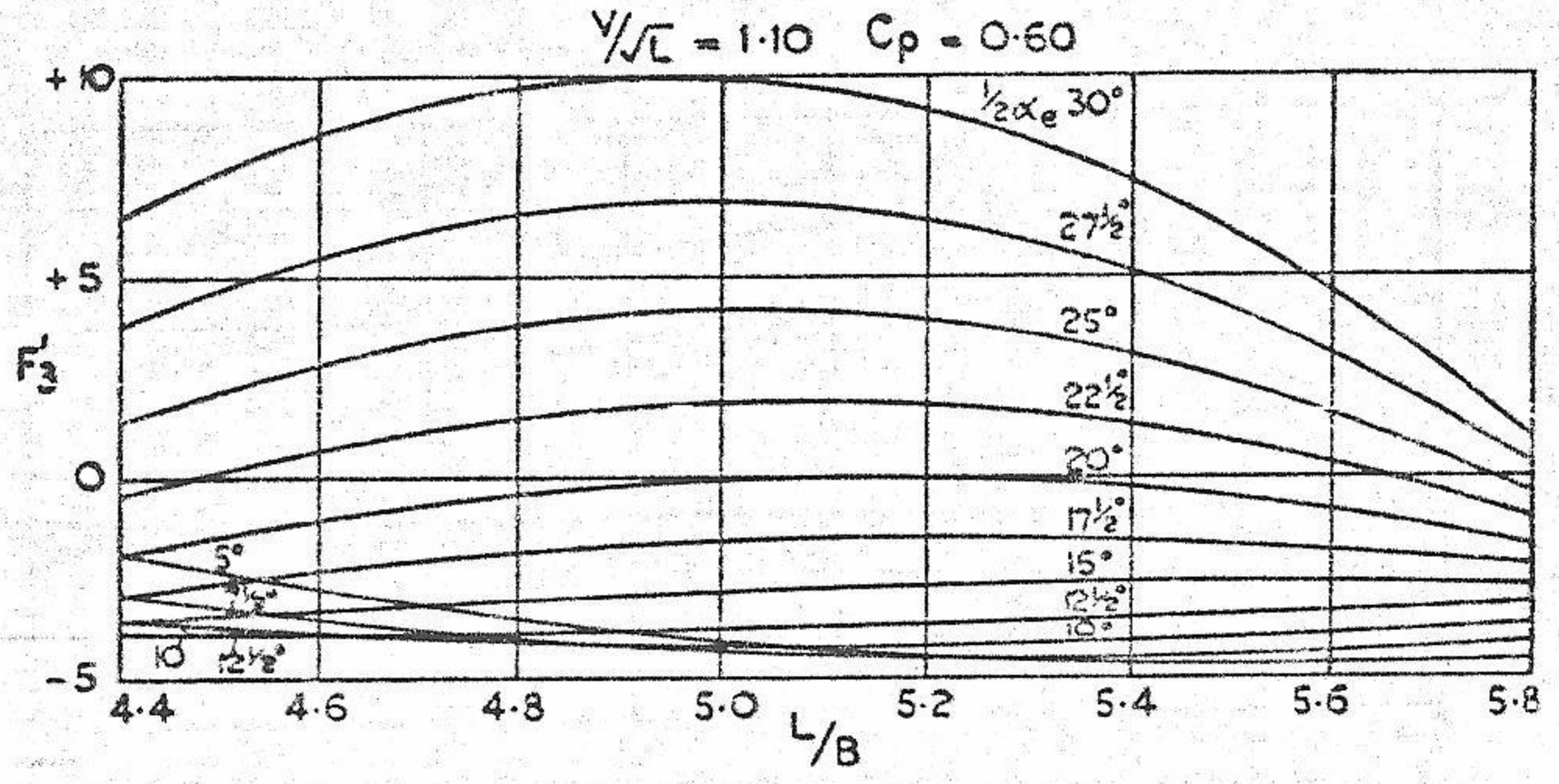

V/√L = 1·10 Cp = 0·60
+10
+5
0
-5
F'3
½αe 30°
27½°
25°
22½°
20°
17½°
15°
12½°
10°
5°
7½°
4·4
4·6
4·8
5·0
5·2
5·4
5·6
5·8
L/B

Fig. 41

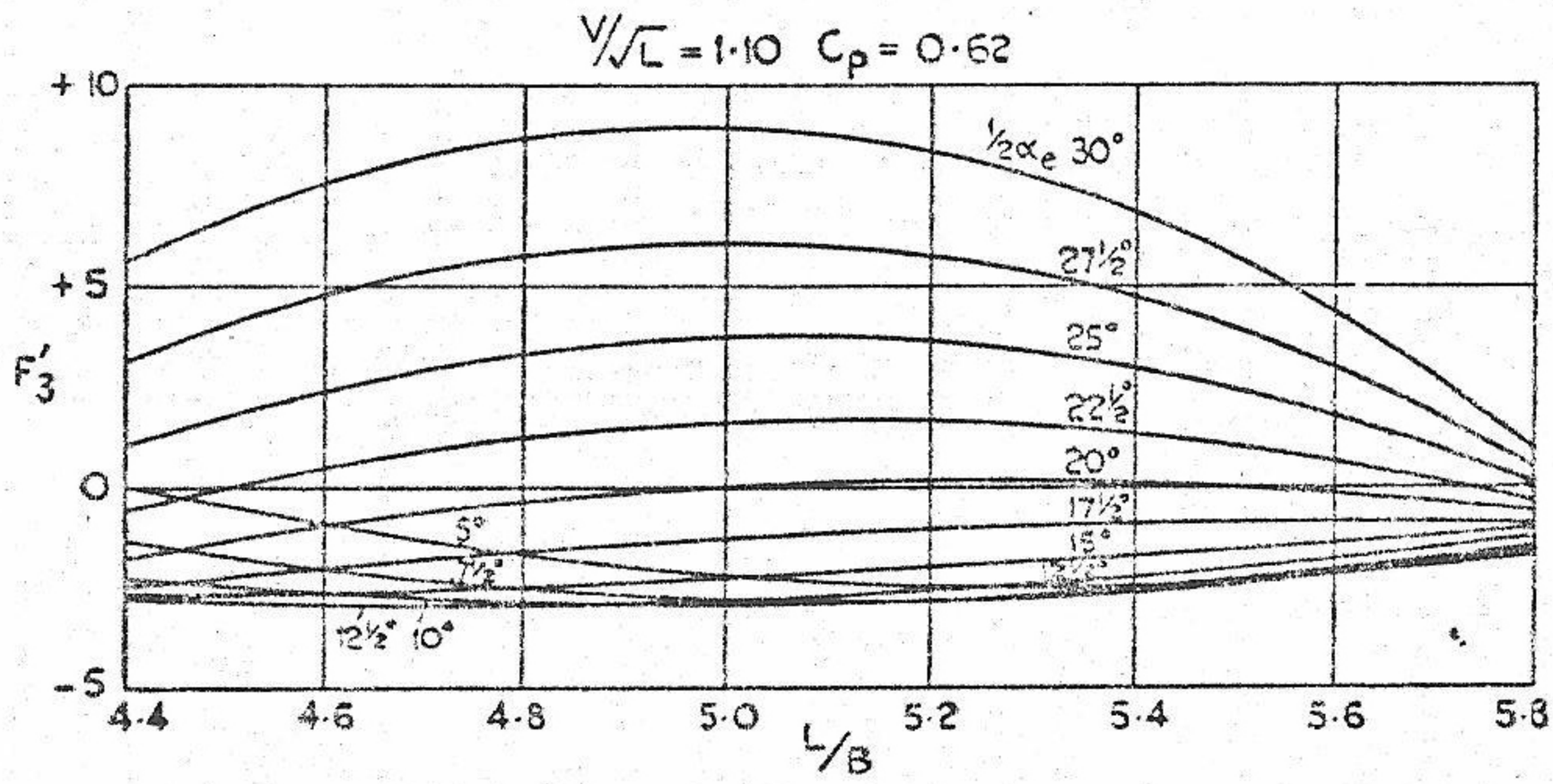

V/√L = 1·10 Cp = 0·62
+10
+5
0
-5
F'3
½αe 30°
27½°
25°
22½°
20°
17½°
15°
12½°
10°
5°
7½°
4·4
4·6
4·8
5·0
5·2
5·4
5·6
5·8
L/B

Fig. 42

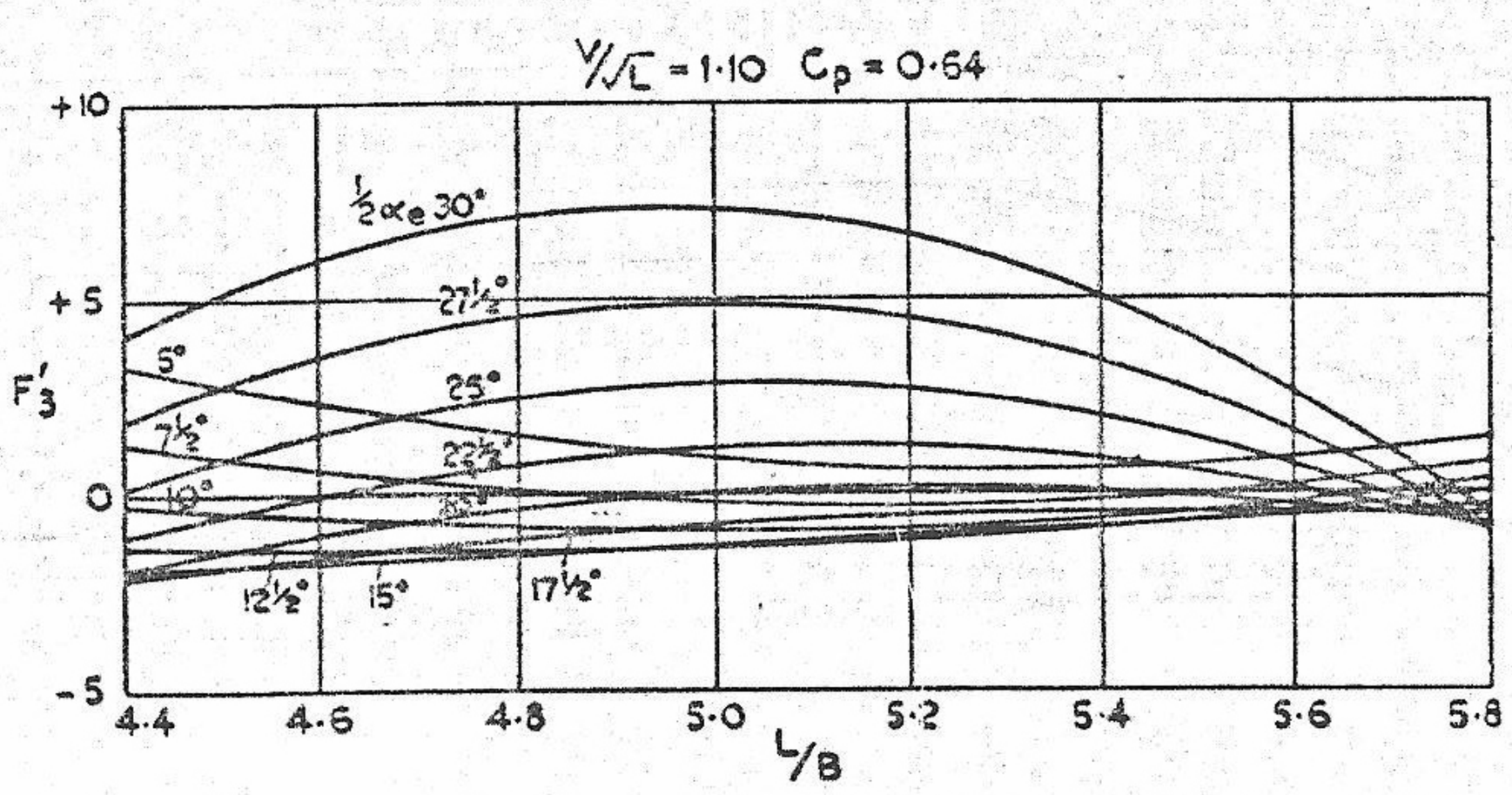

V/√L = 1·10 Cp = 0·64
+10
+5
0
-5
F'3
½αe 30°
27½°
25°
22½°
20°
17½°
15°
12½°
7½°
5°
4·4
4·6
4·8
5·0
5·2
5·4
5·6
5·8
L/B

Fig. 43

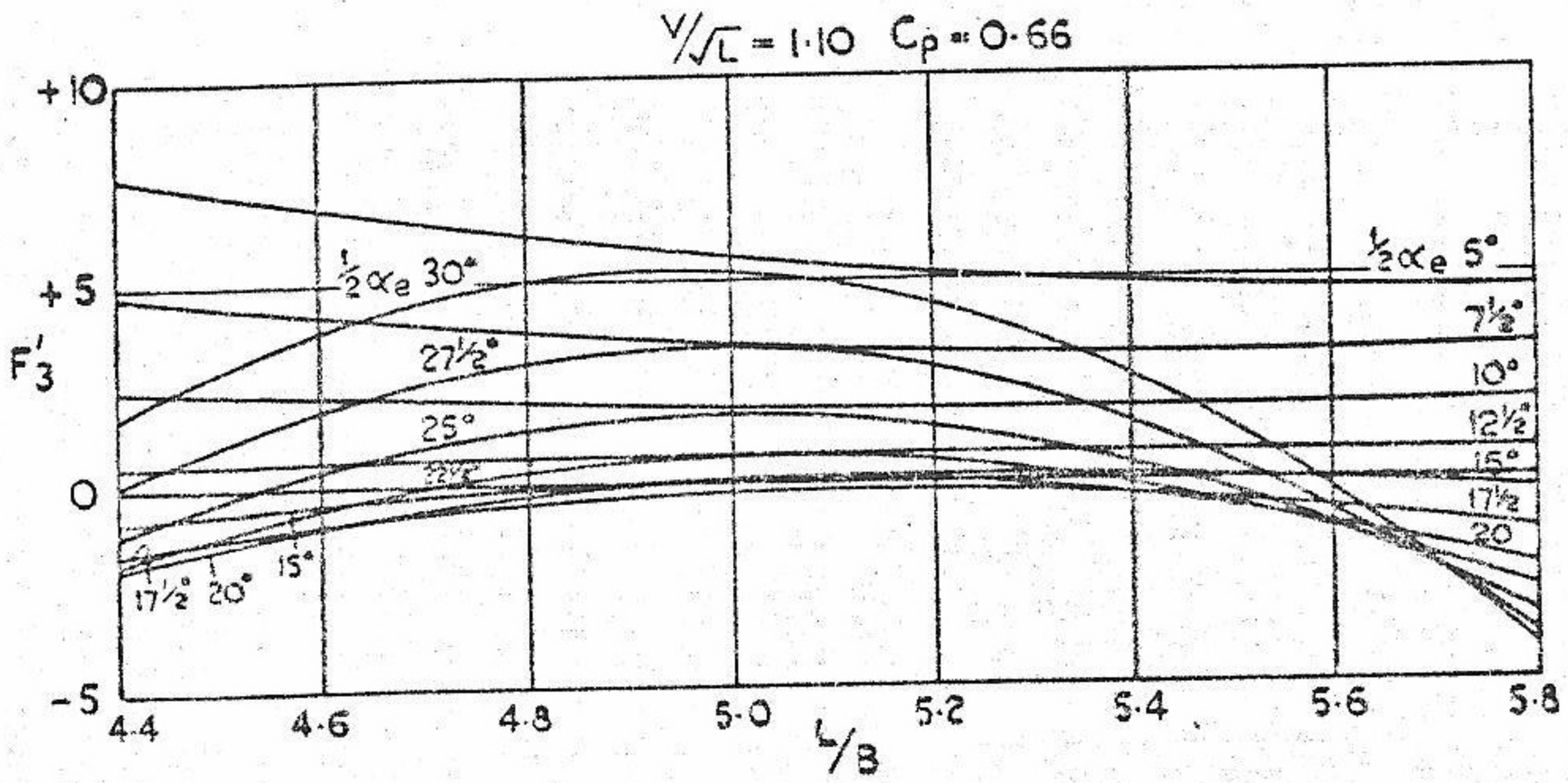

V/√L = 1·10 Cp = 0·66
+10
+5
0
-5
F'3
½αe 30°
27½°
25°
22½°
17½°
20°
15°
½αe 5°
7½°
10°
12½°
15°
17½
20
4·4
4·6
4·8
5·0
5·2
5·4
5·6
5·8
L/B

Fig. 44

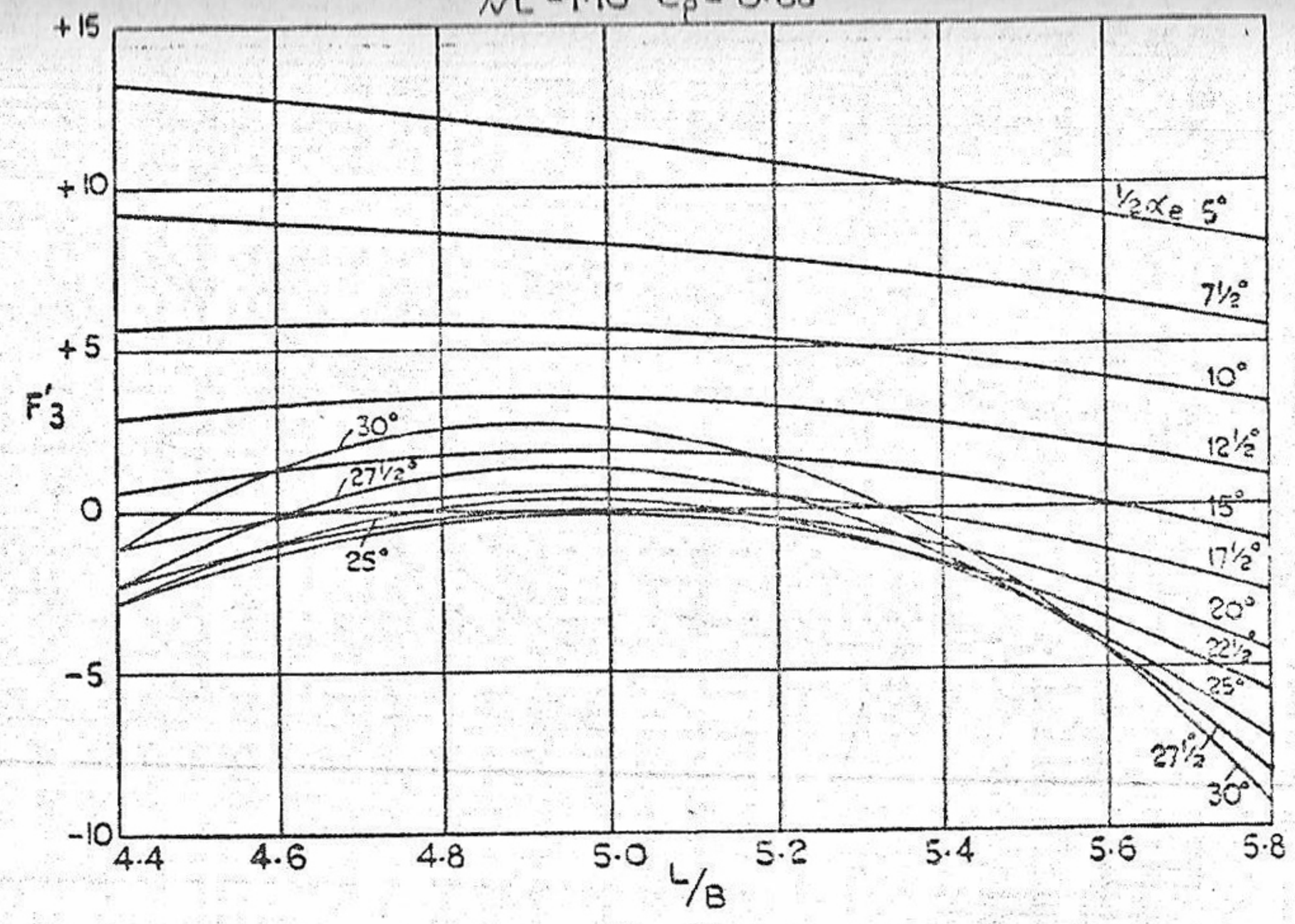

V/√L = 1·10 Cp = 0·68
+15
+10
+5
0
-5
-10
F'3
½αe 5°
7½°
10°
12½°
15°
17½°
20°
22½°
25°
27½°
30°
4·4
4·6
4·8
5·0
5·2
5·4
5·6
5·8
L/B

Fig. 45

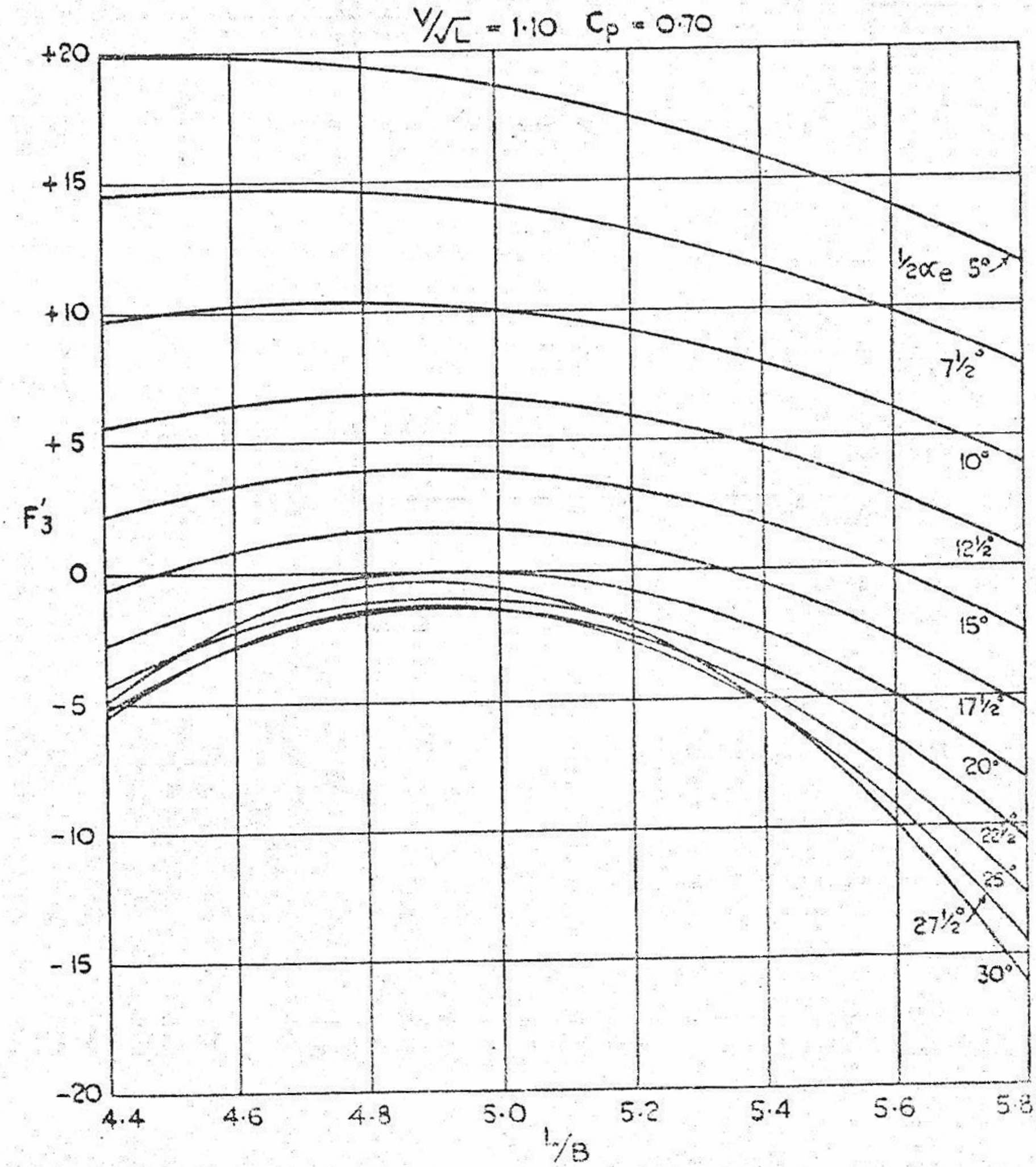

V/√L = 1·10 Cp = 0·70
+20
+15
+10
+5
0
-5
-10
-15
-20
F'3
½αe 5°
7½°
10°
12½°
15°
17½°
20°
22½°
25°
27½°
30°
4·4
4·6
4·8
5·0
5·2
5·4
5·6
5·8
L/B

Fig. 46

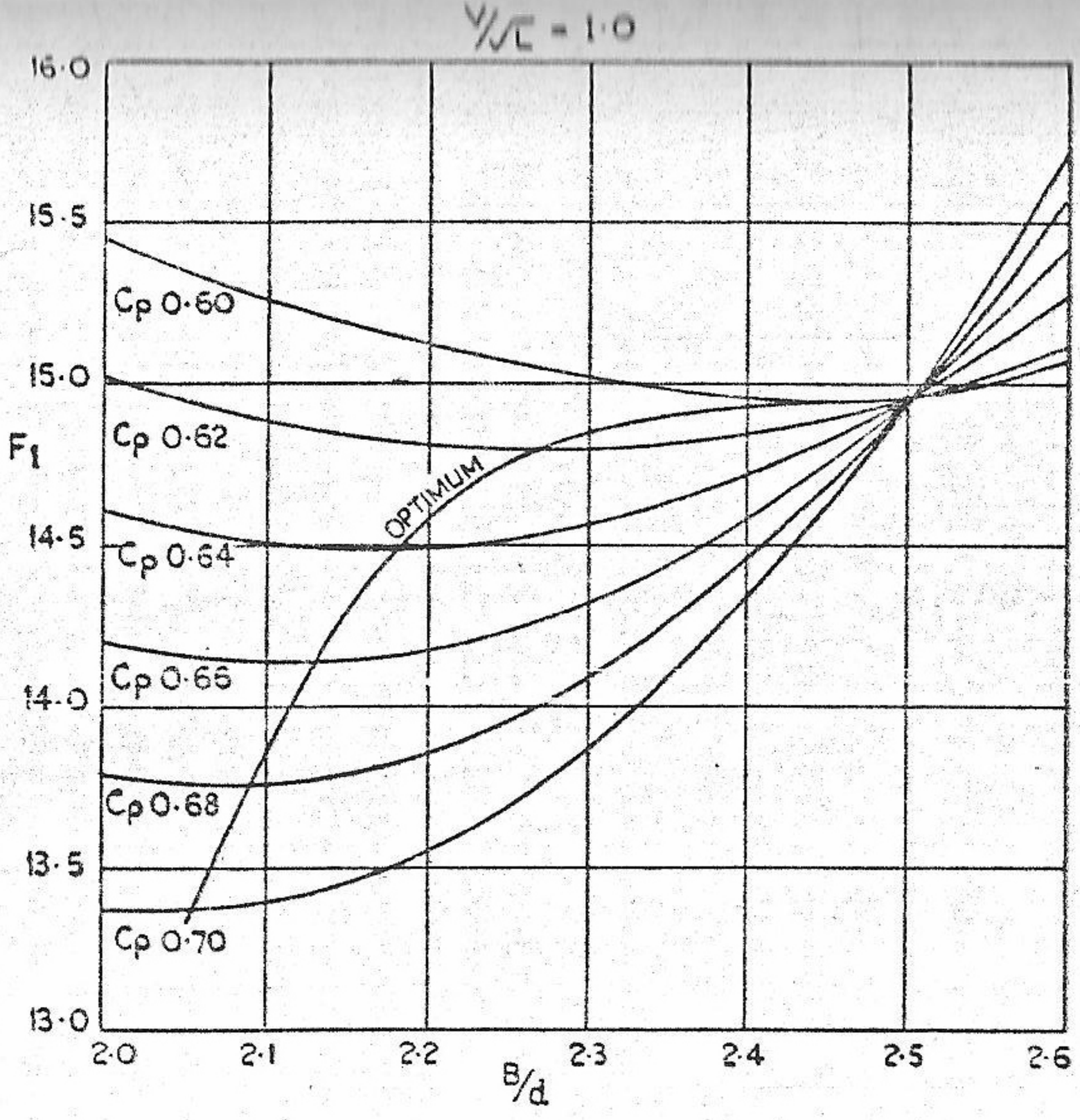

V/√L = 1·0
16·0
15·5
15·0
14·5
14·0
13·5
13·0
Ft
Cp 0·60
Cp 0·62
Cp 0·64
Cp 0·66
Cp 0·68
Cp 0·70
OPTIMUM
2·0
2·1
2·2
2·3
2·4
2·5
2·6
B/d

Fig. 47

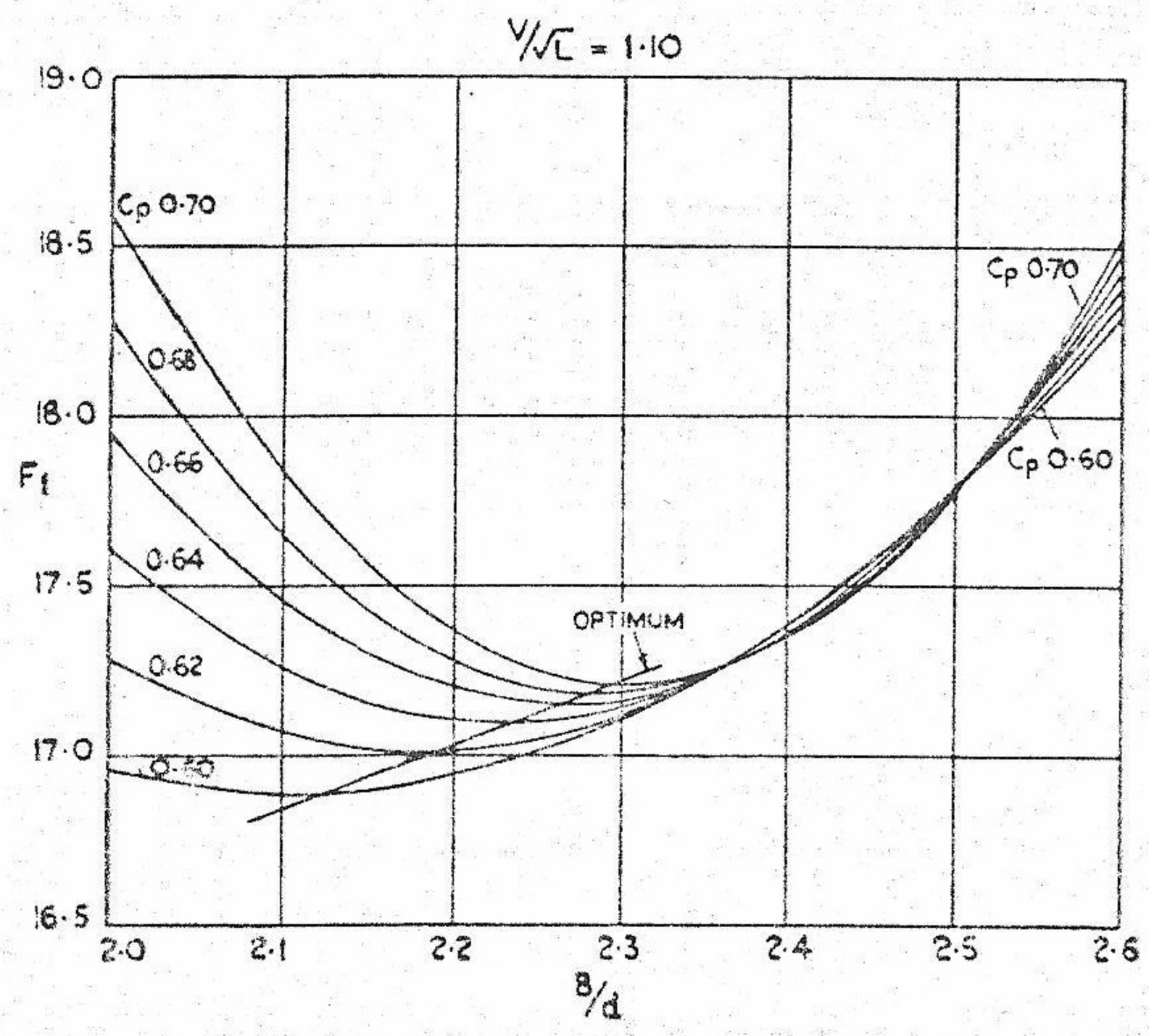

V/√L = 1·10
19·0
18·5
18·0
17·5
17·0
16·5
Ft
Cp 0·70
0·68
0·66
0·64
0·62
0·60
Cp 0·70
Cp 0·60
OPTIMUM
2·0
2·1
2·2
2·3
2·4
2·5
2·6
B/d

Fig. 48

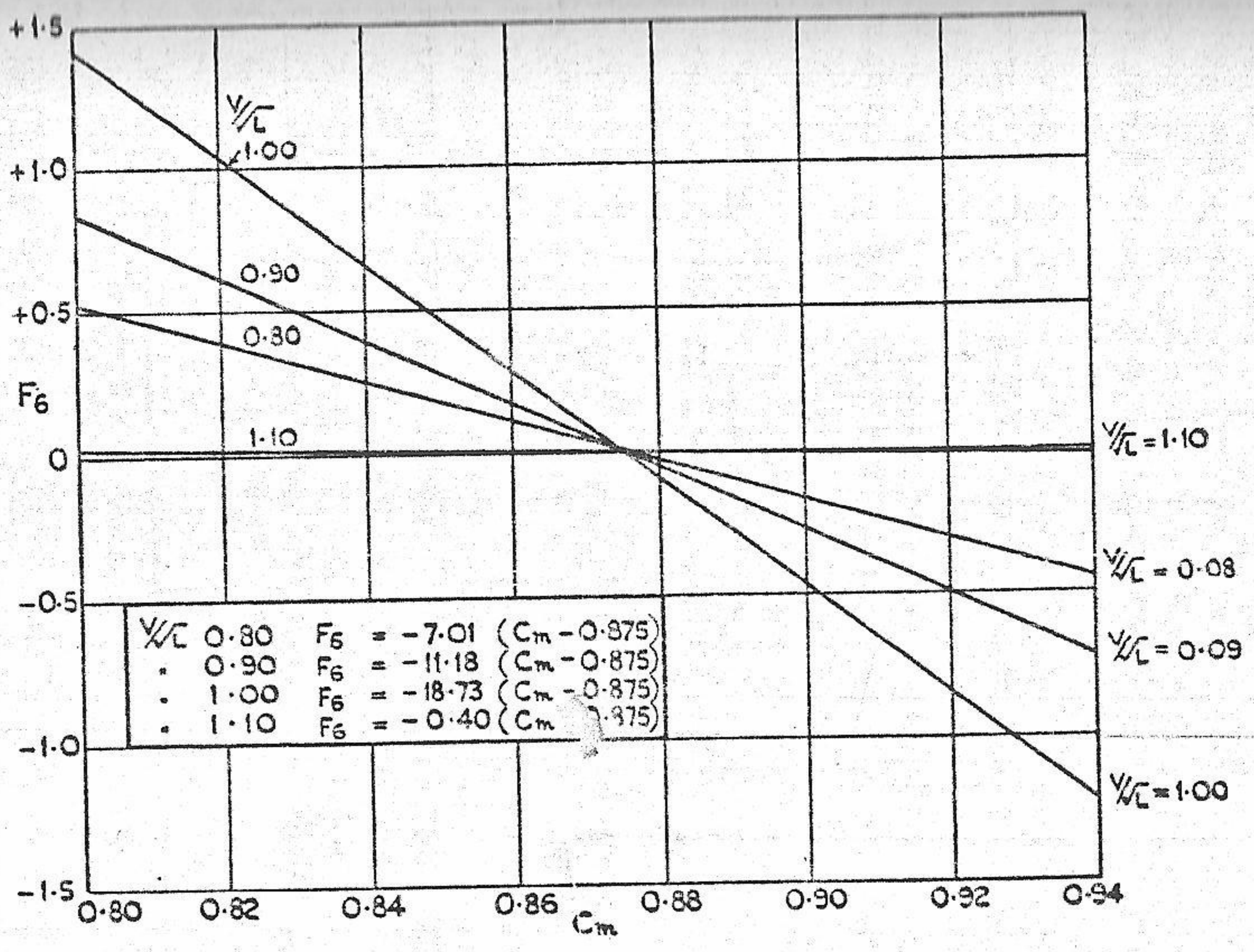
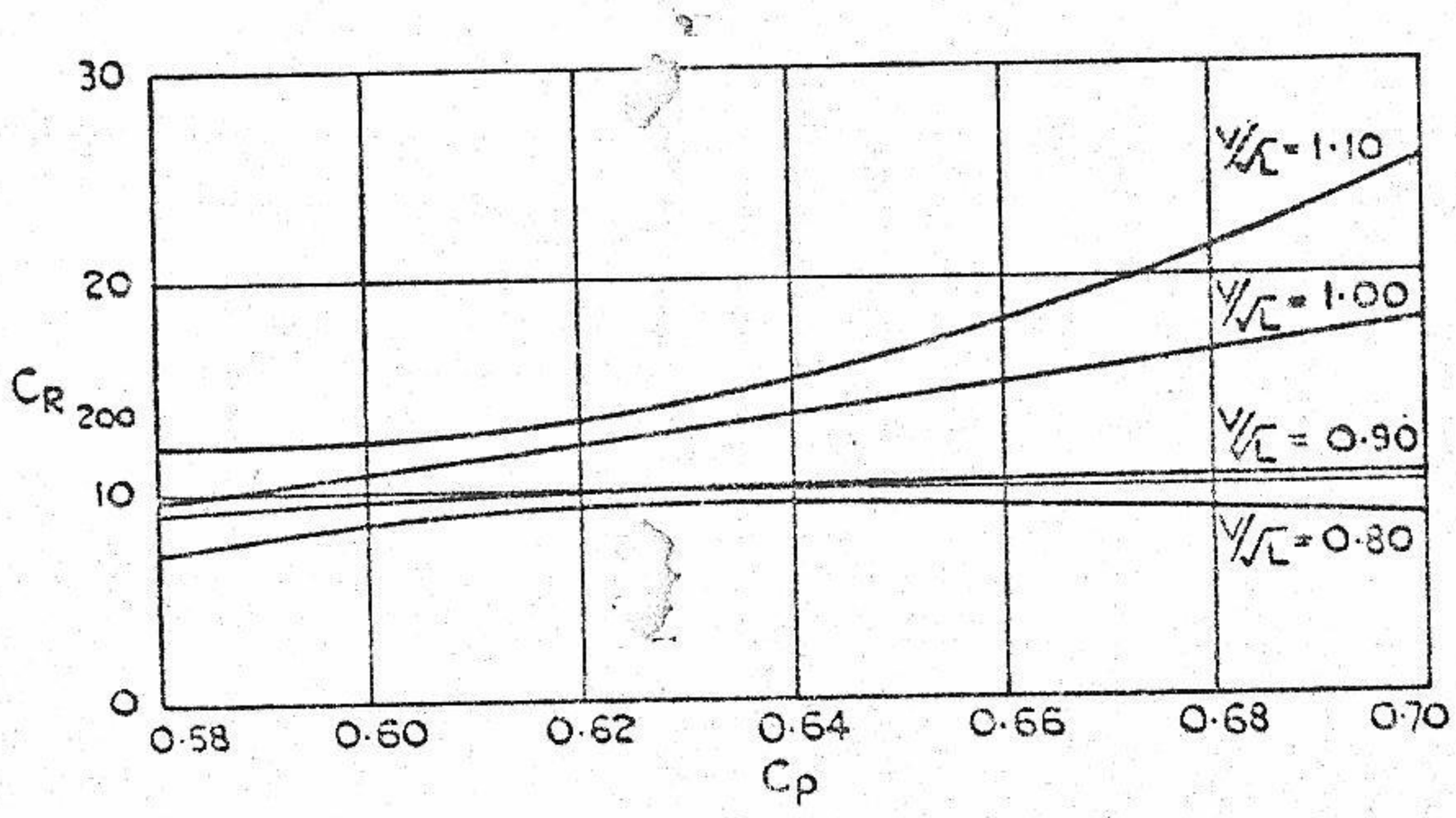


Fig. 49(a)—*Change in* C_R *due to* C_m

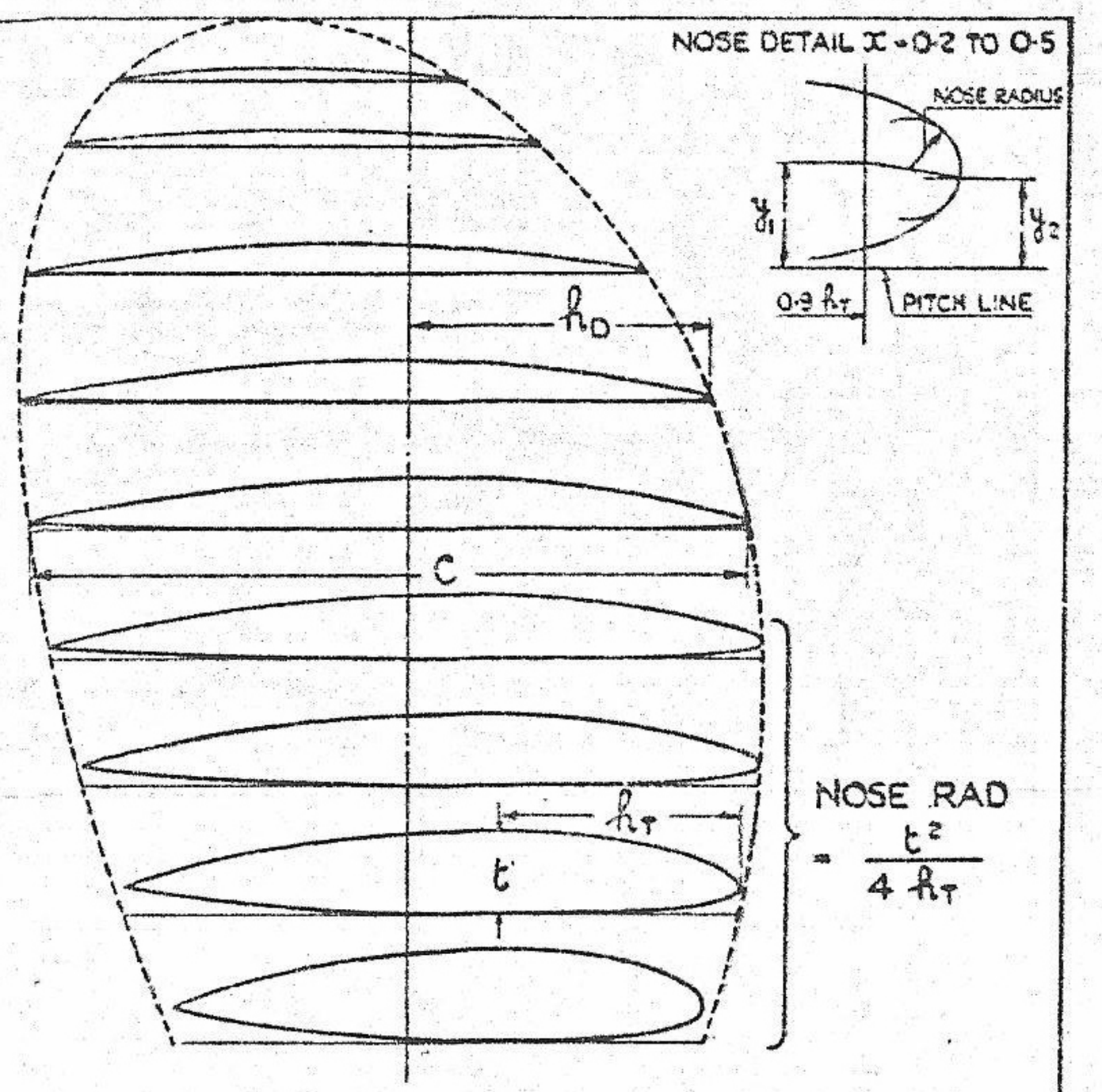


Case I

Design Parameters | L/B 5·5, B/d 2·25, C_m 0·875, l.c.b. + 4 %, $\frac{1}{2}\alpha°_e$ 13·0

Fig. 49(b)

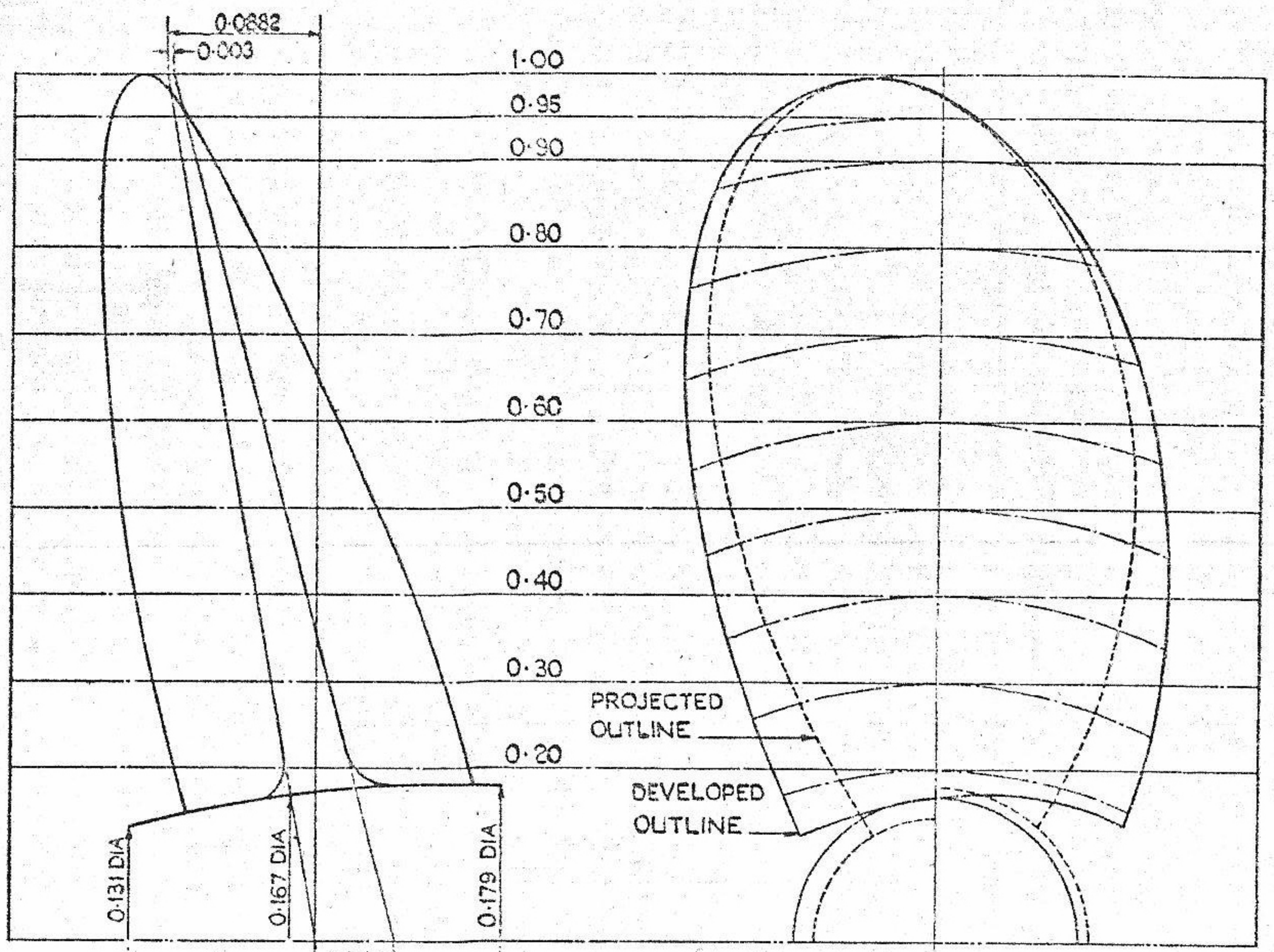
x	P/D	C/D	h_D/D	t/D	h_T/C
1·0	1·00	0	-·053	·0030	0·500
0·95	1·00	0·135	0·020	·0051	0·500
0·90	1·00	0·184	0·051	·0072	0·500
0·80	1·00	0·241	0·092	·0114	0·500
0·70	1·00	0·269	0·118	·0156	0·493
0·60	1·00	0·279	0·132	·0198	0·475
0·50	0·99	0·276	0·137	·0240	0·450
0·40	0·95	0·263	0·136	·0282	0·420
0·30	0·90	0·241	0·129	·0324	0·387
0·20	0·85	0·208	0·116	·0366	0·350



CYLINDRICAL SECTION OFFSETS FROM PITCH LINE

RAD x		FROM MAX t TO T.E					MAX	% DISTANCE FROM MAX. THICKNESS TO LE									y_1	y_2	RAD x
		T.E.	80	60	40	20	t	20	40	60	70	80	85	90	95	L.E			
0·95	BACK	0·163	0·464	0·699	0·866	0·967	1·000	0·967	0·866	0·699	0·590	0·464	0·395	0·322	0·245	0·163		0·082	0·95
	FACE	0	----	----	----	----	0	----	----	----	----	----	----	----	----	0			
0·90	BACK	0·116	0·434	0·682	0·859	0·965	1·000	0·965	0·859	0·682	0·567	0·434	0·361	0·284	0·202	0·116		0·058	0·90
	FACE	0	----	----	----	----	0	----	----	----	----	----	----	----	----	0			
0·80	BACK	0·073	0·407	0·669	0·852	0·963	1·000	0·963	0·852	0·669	0·546	0·407	0·330	0·249	0·163	0·073		0·037	0·80
	FACE	0	----	----	----	----	0	----	----	----	----	----	----	----	----	0			
0·70	BACK	0·102	0·436	0·687	0·859	0·965	1·000	0·968	0·866	0·698	0·590	0·465	0·390	0·305	0·210	0·102		0·076	0·70
	FACE	0·048	0·013	0	----	----	0	----	----	----	----	0	0·002	0·004	0·012	0·048			
0·60	BACK	0·171	0·477	0·712	0·875	0·970	1·000	0·975	0·881	0·737	0·647	0·530	0·465	0·386	0·238	0·171		0·151	0·60
	FACE	0·129	0·056	0·016	0	----	0	----	----	0	0·003	0·012	0·020	0·034	0·058	0·129			
0·50	BACK	0·233	0·521	0·742	0·892	0·975	1·000	0·978	0·900	0·774	0·692	0·591	0·531	0·463	0·377		0·270	0·218	0·50
	FACE	0·199	0·100	0·045	0·013	0·003	0	0	0·004	0·012	0·021	0·037	0·049	0·068	0·101				
0·40	BACK	0·288	0·565	0·769	0·903	0·977	1·000	0·979	0·915	0·804	0·732	0·637	0·582	0·523	0·444		0·307	0·274	0·40
	FACE	0·259	0·139	0·068	0·025	0·005	0	0·003	0·012	0·030	0·045	0·067	0·084	0·108	0·146				
0·30	BACK	0·338	0·598	0·787	0·911	0·979	1·000	0·981	0·924	0·826	0·759	0·676	0·626	0·563	0·497		0·343	0·325	0·30
	FACE	0·312	0·178	0·087	0·033	0·007	0	0·005	0·020	0·048	0·070	0·100	0·121	0·149	0·192				
0·20	BACK	0·386	0·630	0·805	0·919	0·981	1·000	0·983	0·932	0·844	0·783	0·708	0·662	0·603	0·538		0·380	0·375	0·20
	FACE	0·364	0·210	0·105	0·041	0·009	0	0·007	0·029	0·066	0·094	0·132	0·157	0·190	0·237				

Fig. 53(a)—N.P.L. Standard Screw Series—Geometric Data for Basic Screw—0·5 Blade Area Ratio, 4 Blades, 1·0 Pitch Ratio



ALL DIMENSIONS ARE FOR A SCREW OF UNITY DIAMETER.

BASIC SCREW. N.P.L. STANDARD SERIES SHEET 2.

Nº OF BLADES.	4	BOSS-DIAMETER RATIO	0·167
BLADE AREA RATIO.	0·5	THICKNESS-DIAM: RATIO (AXIS)	0·045
PITCH RATIO (TIP).	1·0	" " " (ROOT)	0·038
PITCH RATIO (MEAN).	0·984	RAKE ANGLE.	10°

Fig. 53(b)—*N.P.L. Standard Screw Series—Geometric Data for Basic Screw*

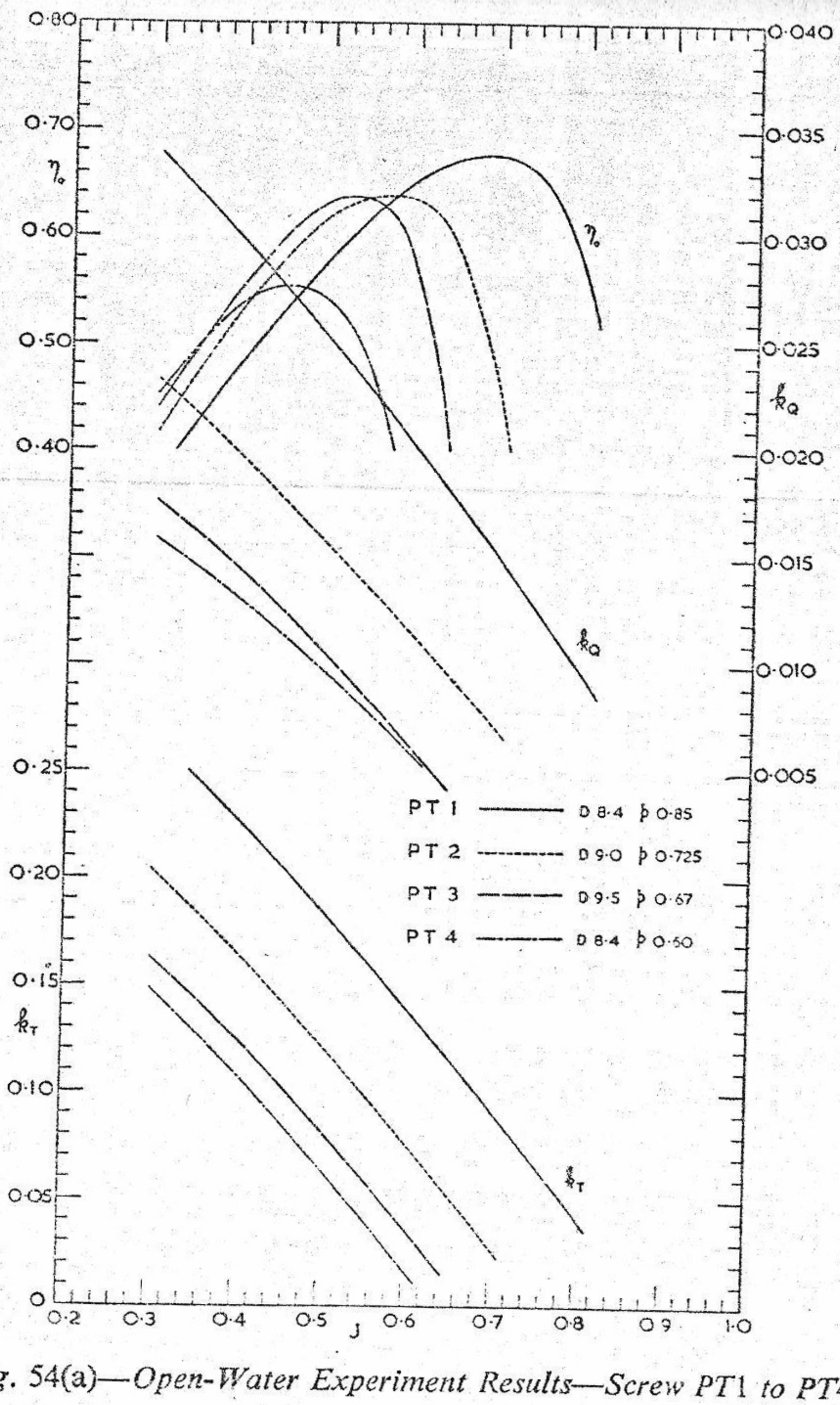


Fig. 54(a)—*Open-Water Experiment Results—Screw PT*1 *to PT*4

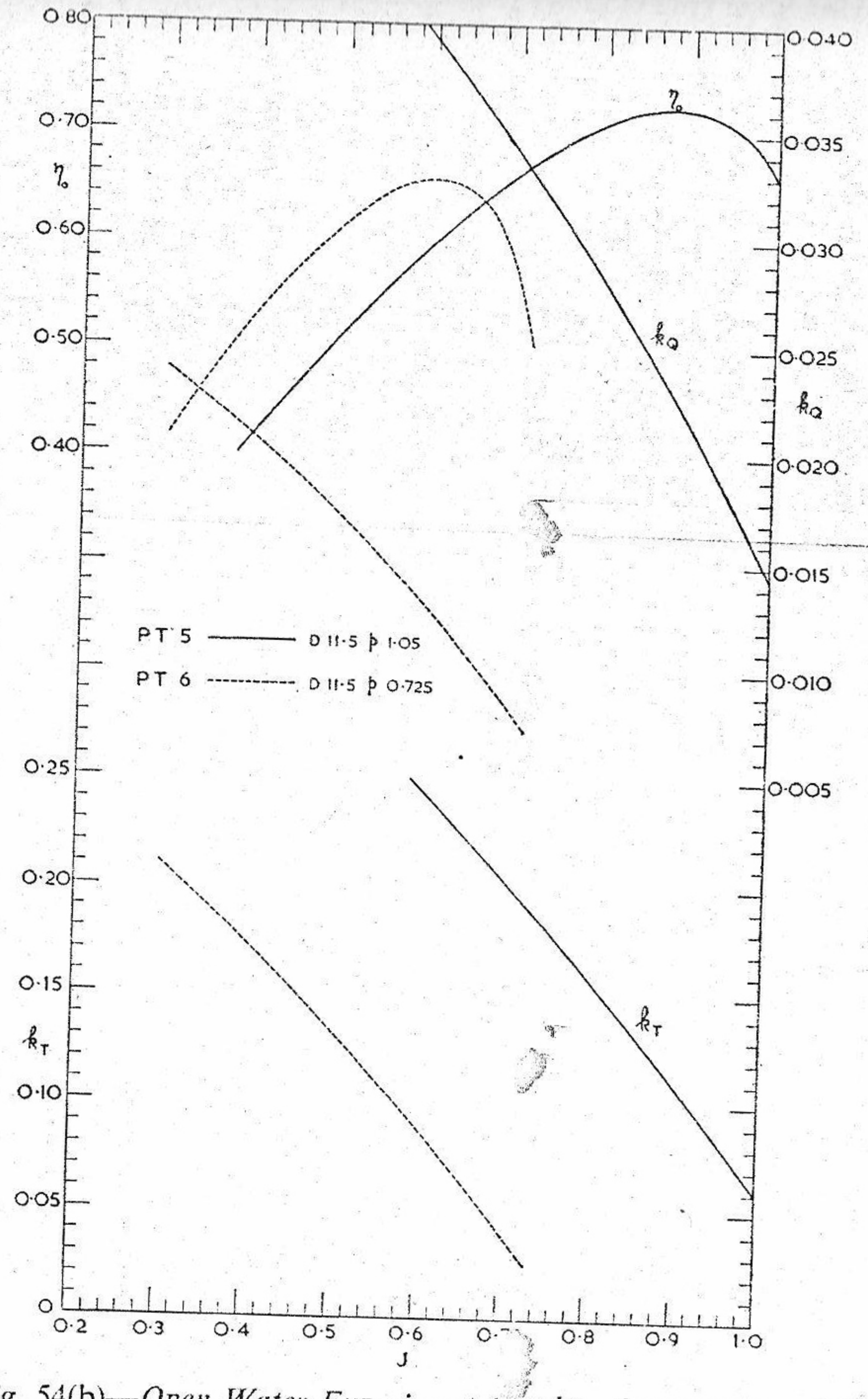


Fig. 54(b)—*Open-Water Experiment Results—Screw PT5 and 6*

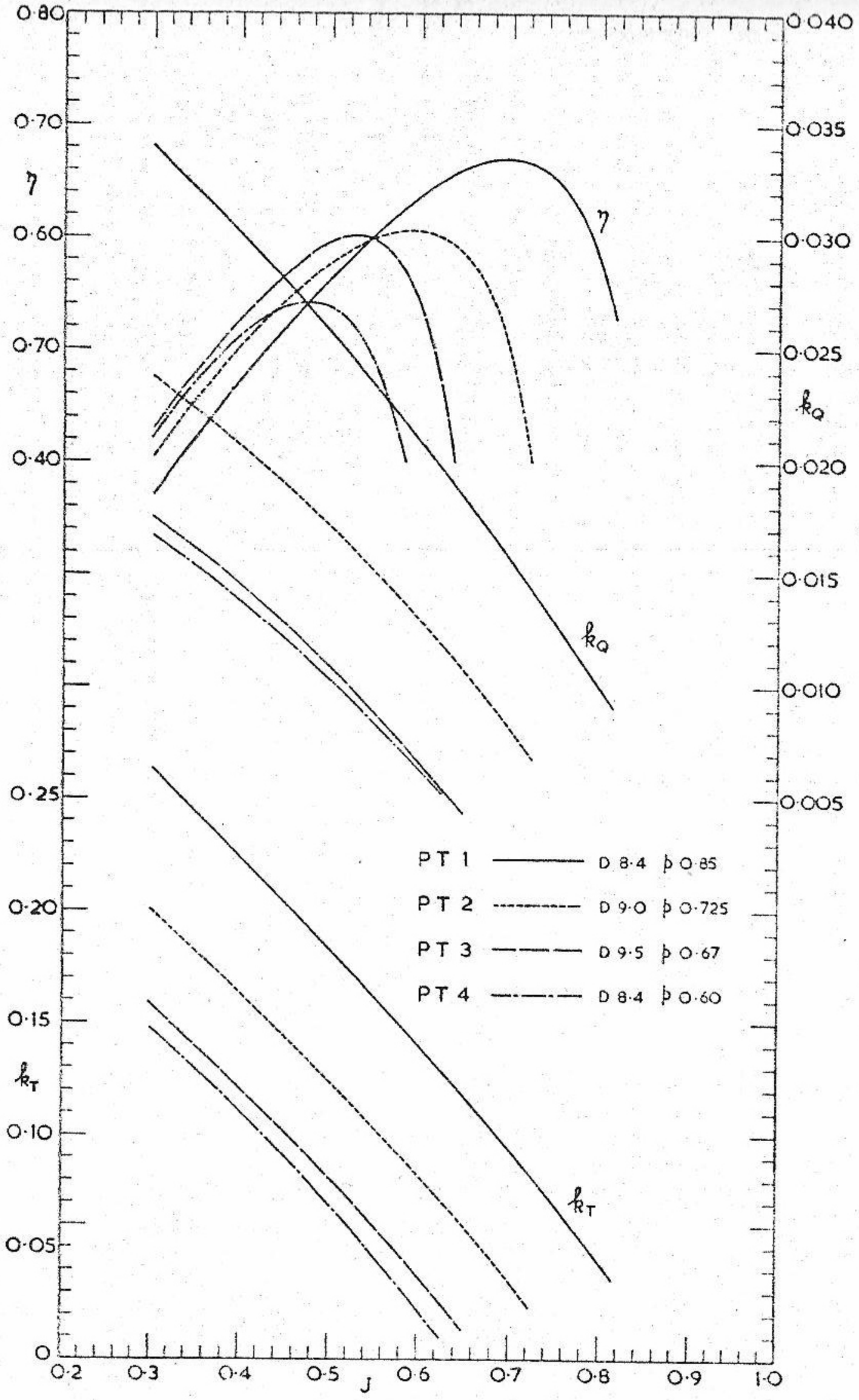


Fig. 55(a)—Water-Tunnel Experiment Results—Screws PT1 to PT4 Atmospheric Pressure Conditions

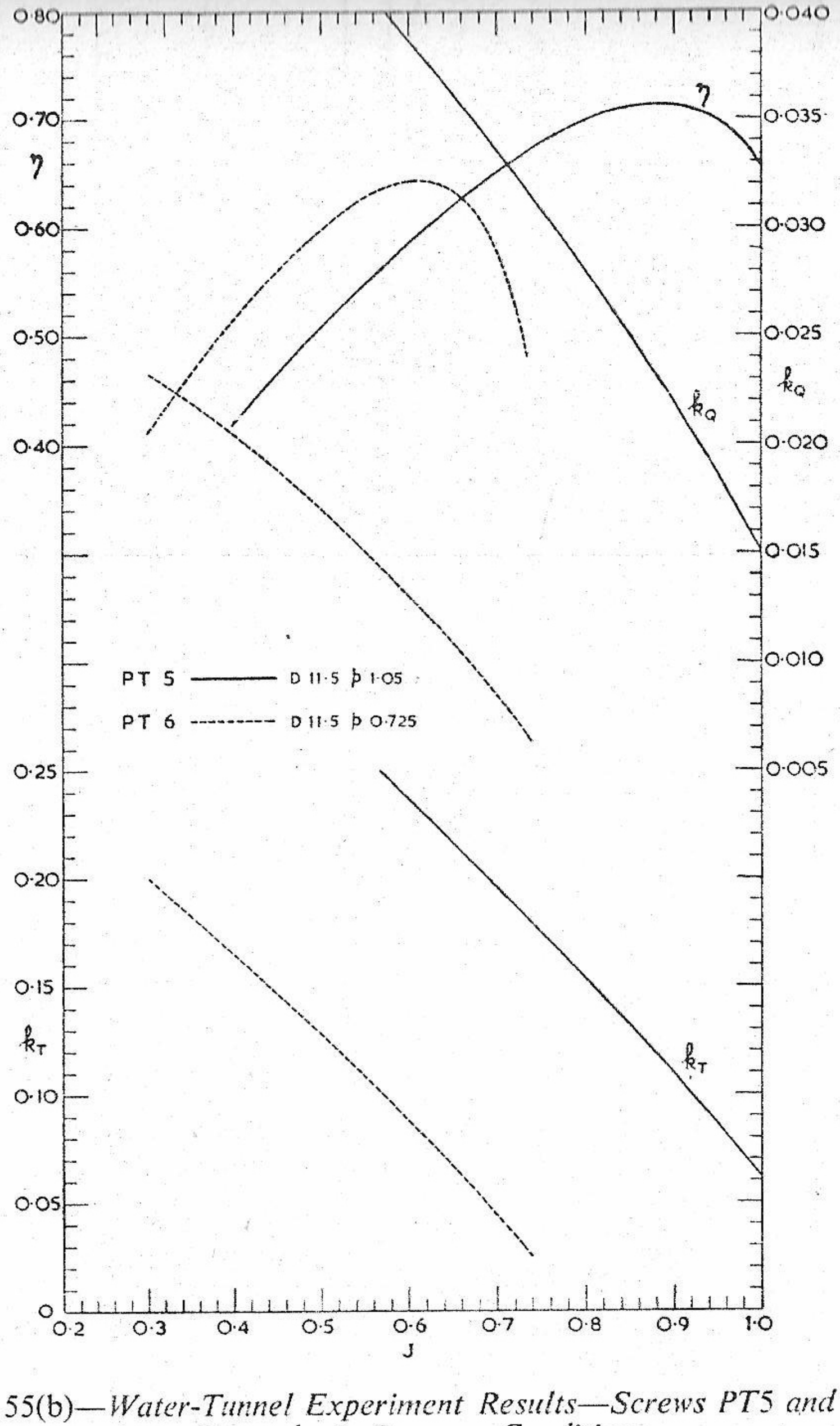
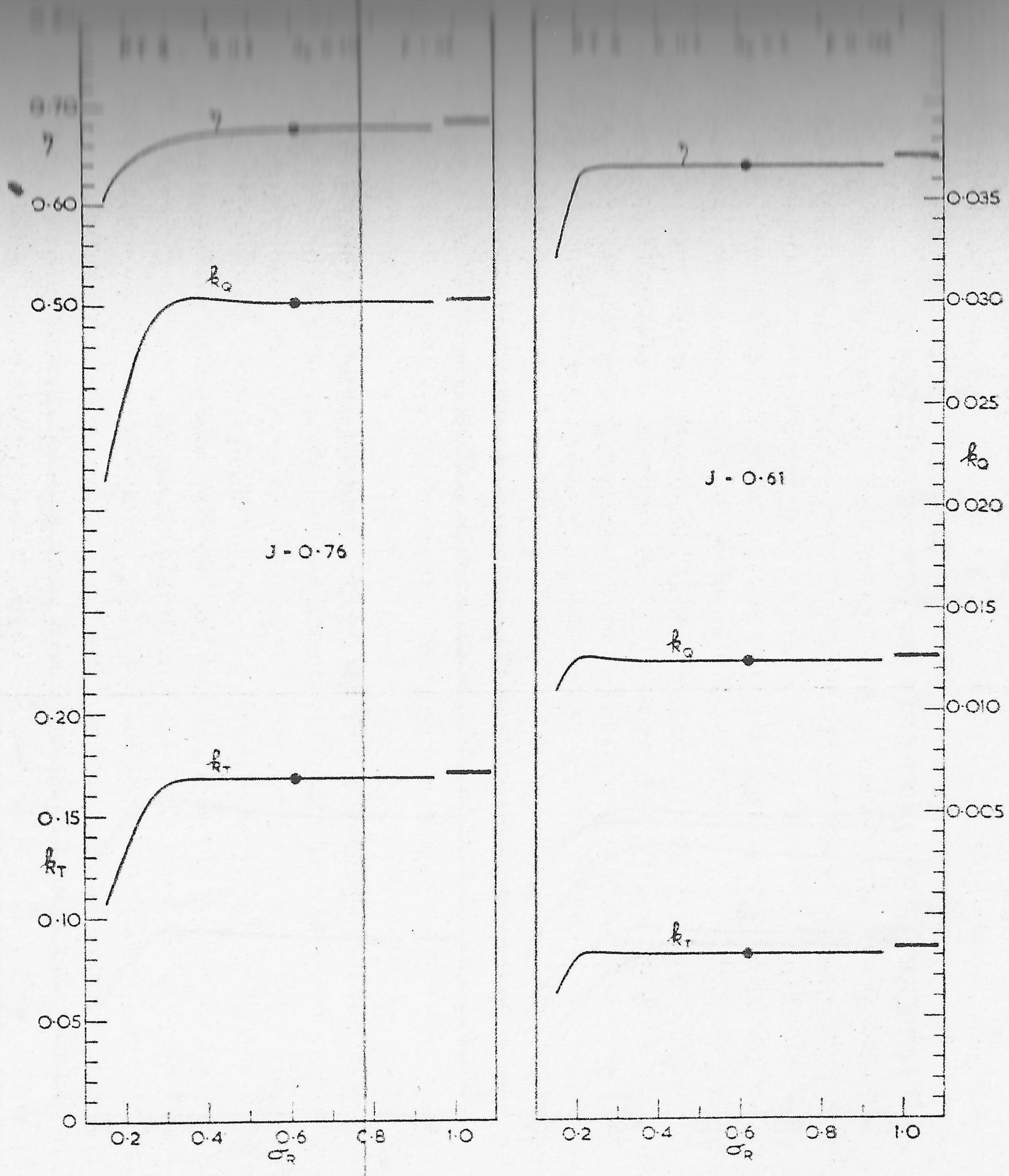
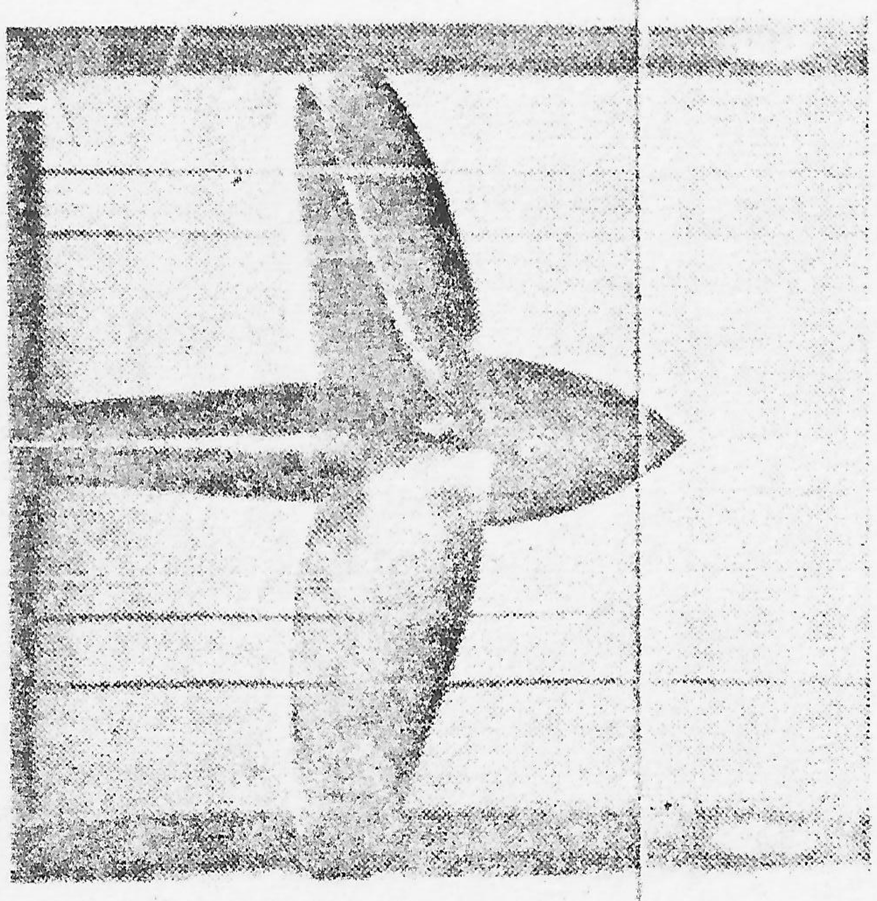
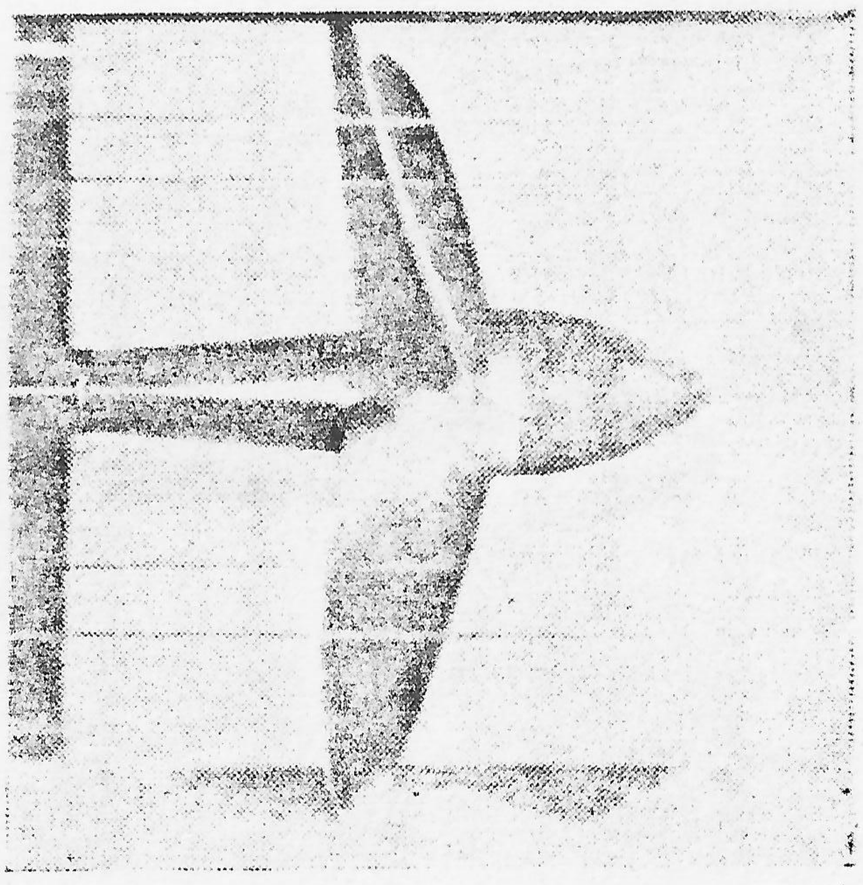


Fig. 55(b)—*Water-Tunnel Experiment Results—Screws PT5 and* 6—*Atmospheric Pressure Conditions*



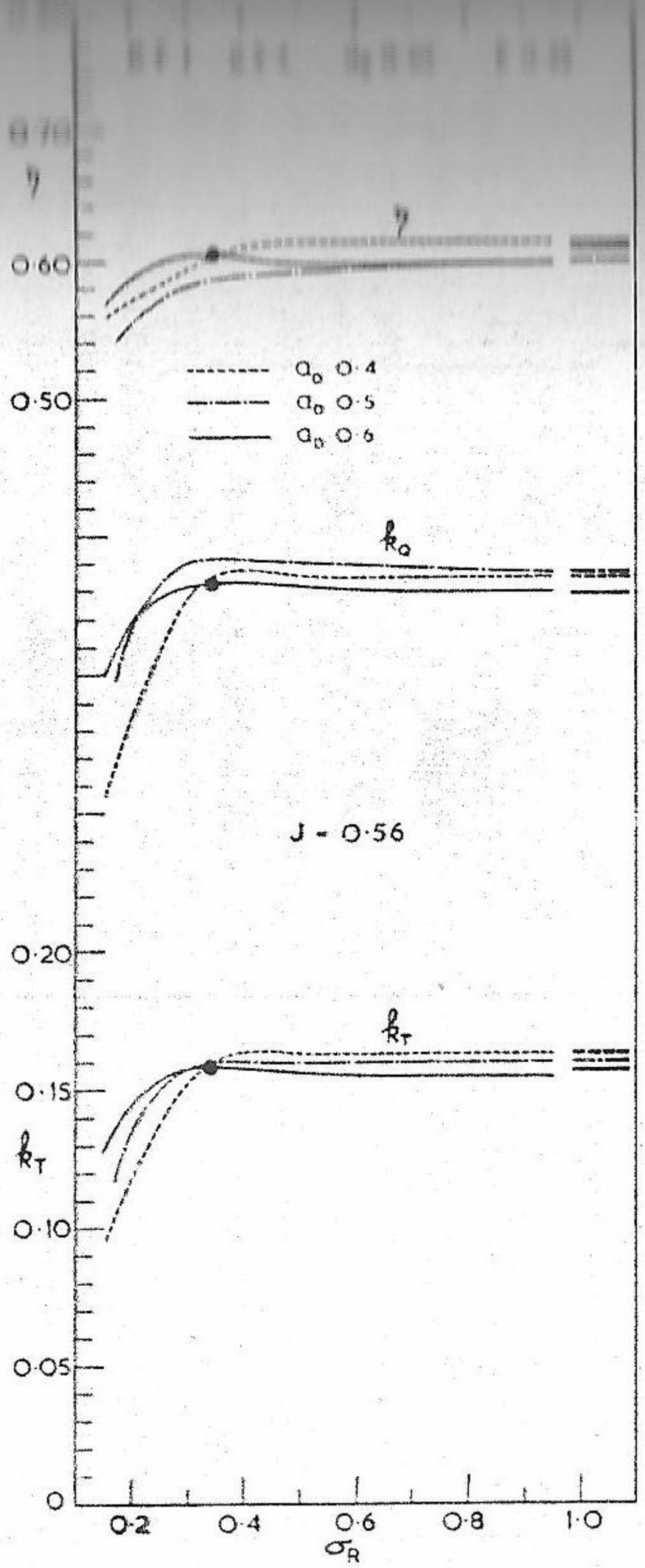


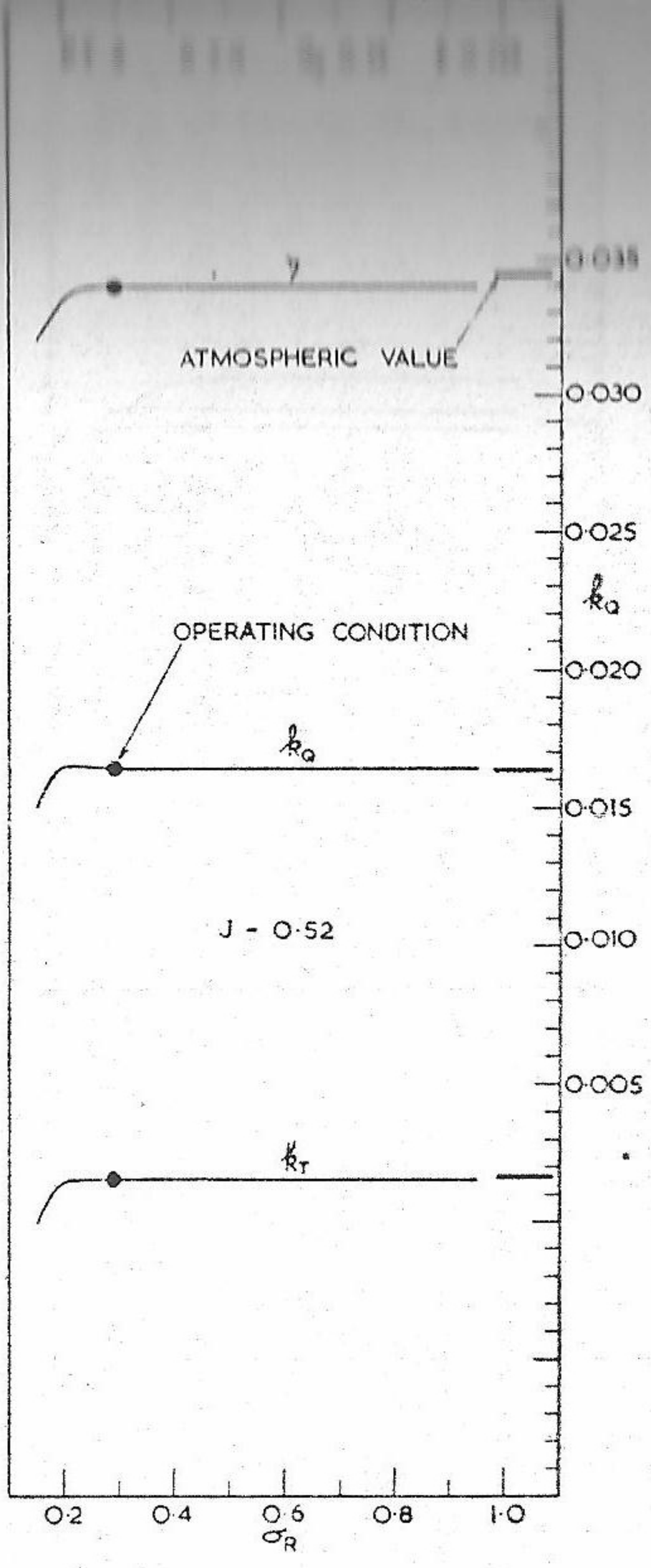
PT5 σ 0·61

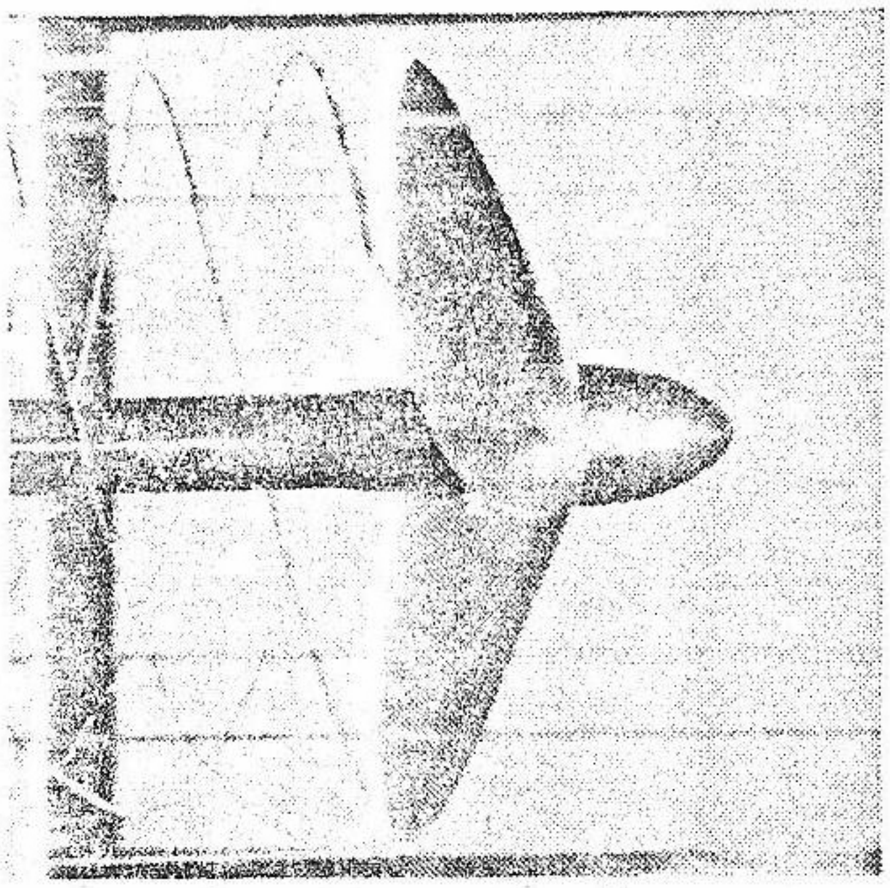


PT6 σ_R 0·62

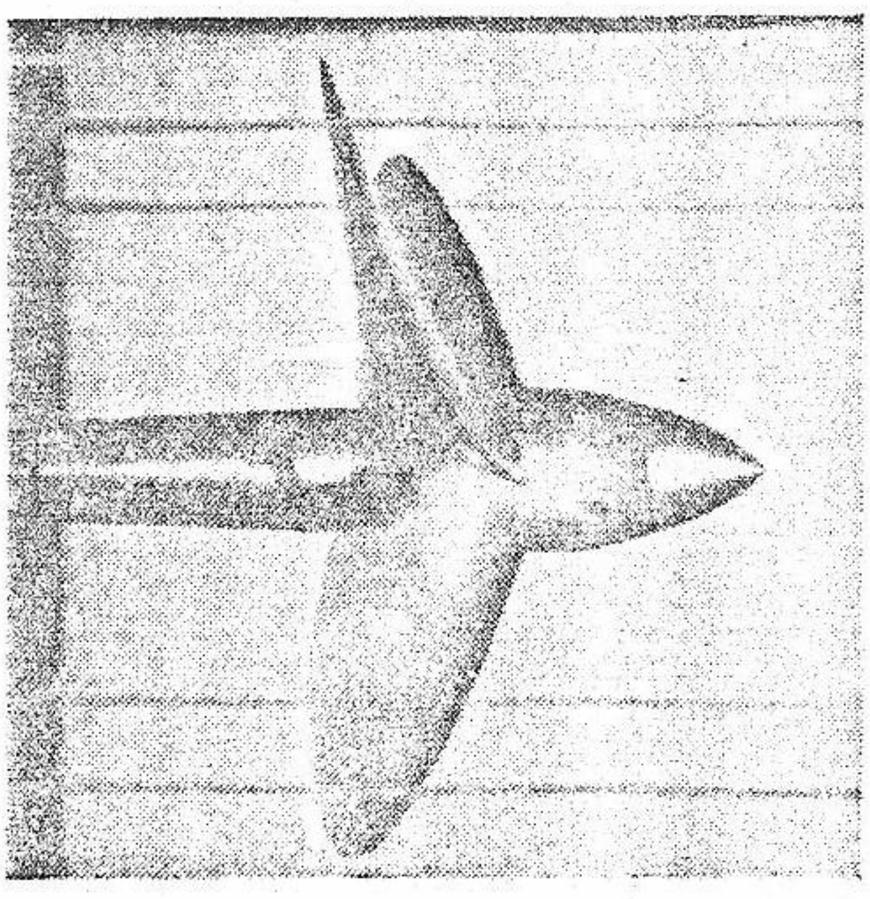
Fig. 56(c)—Water-Tunnel Experiment Results—Screws PT5 and 6—Reduced Pressure Conditions—Free-Running





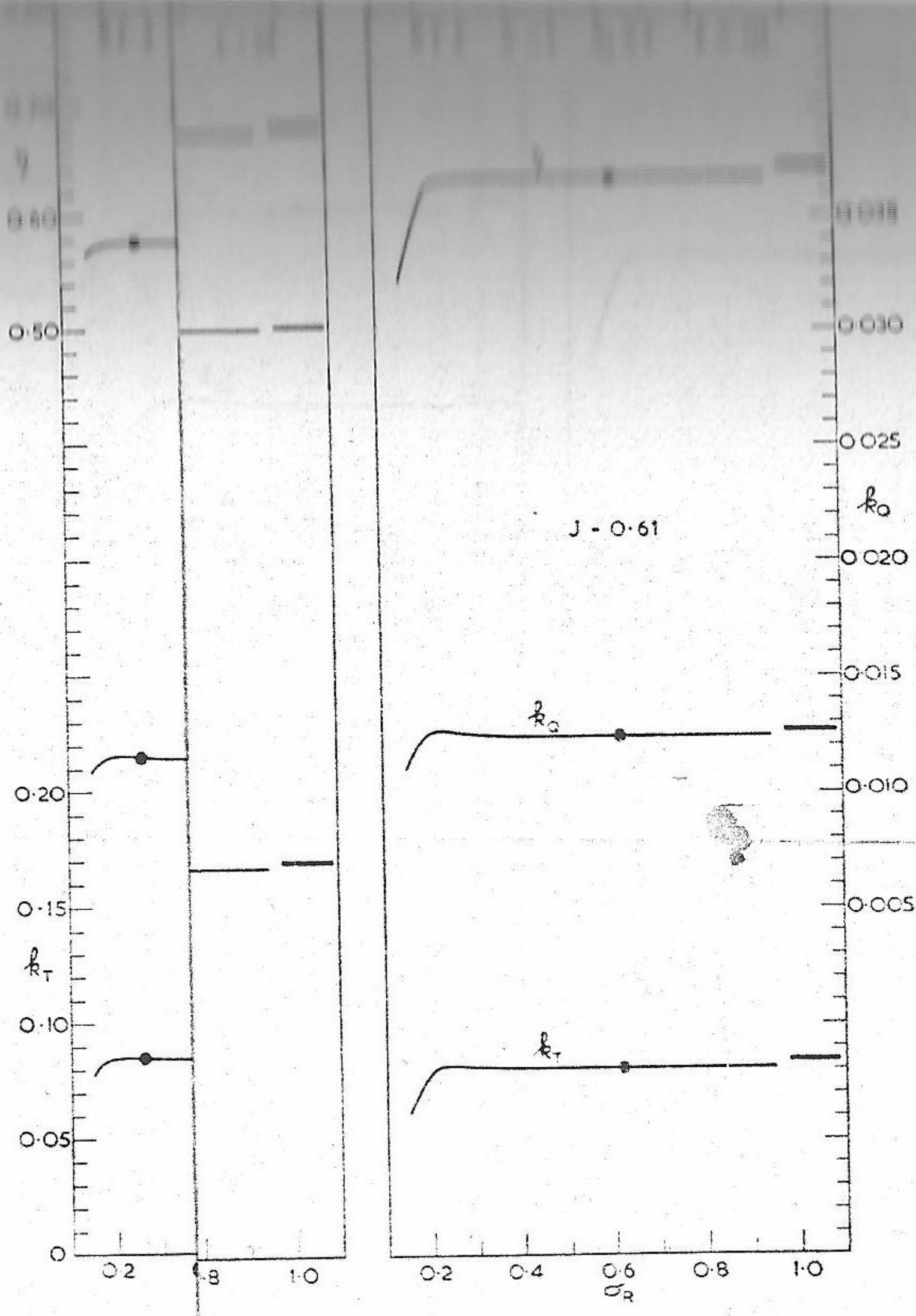


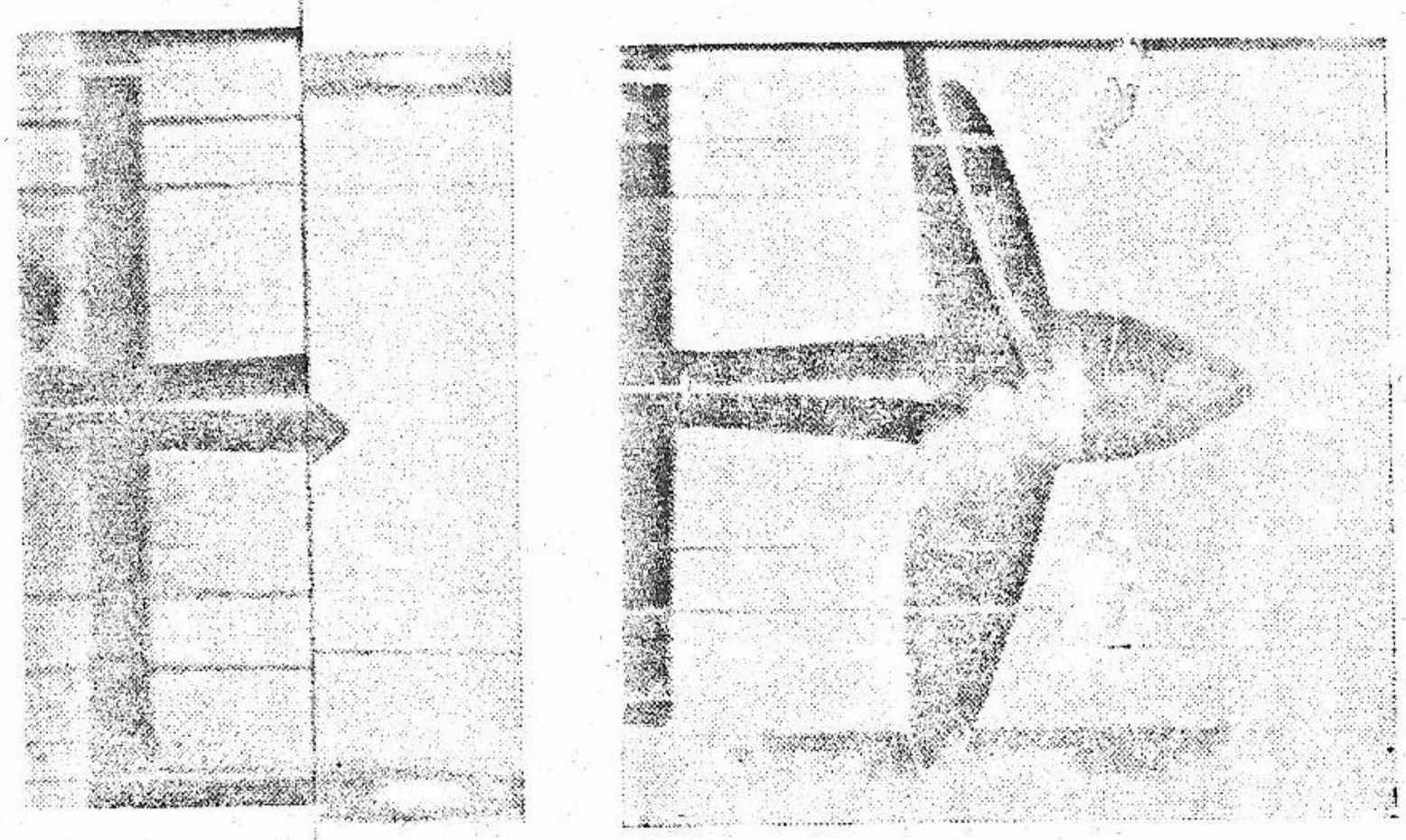
PT1 σ_R 0·34



PT2 σ_R 0·29

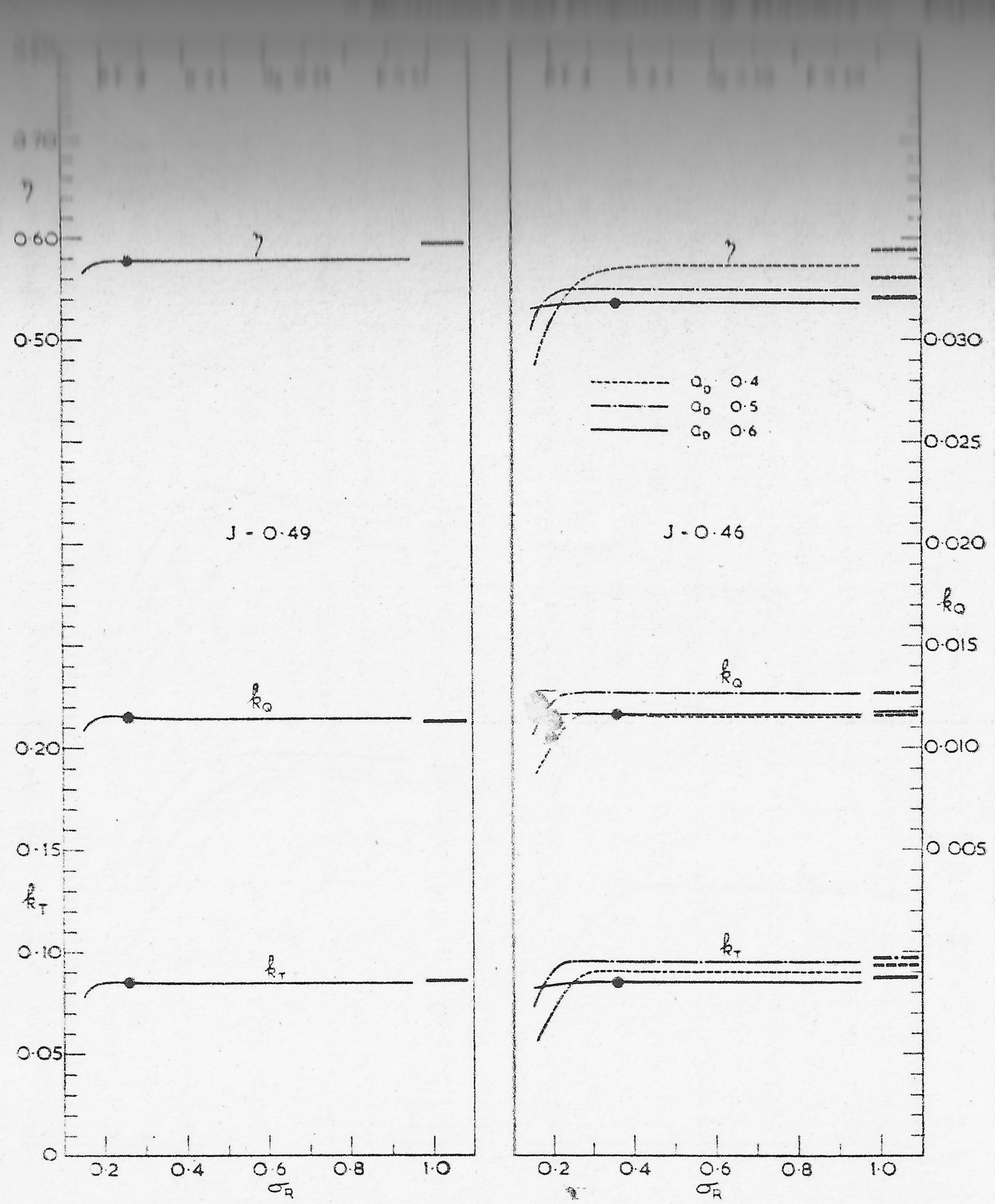
Fig. 56(a)—Water-Tunnel Experiment Results—Screws PT1 and 2—Reduced Pressure Conditions—Free-Running

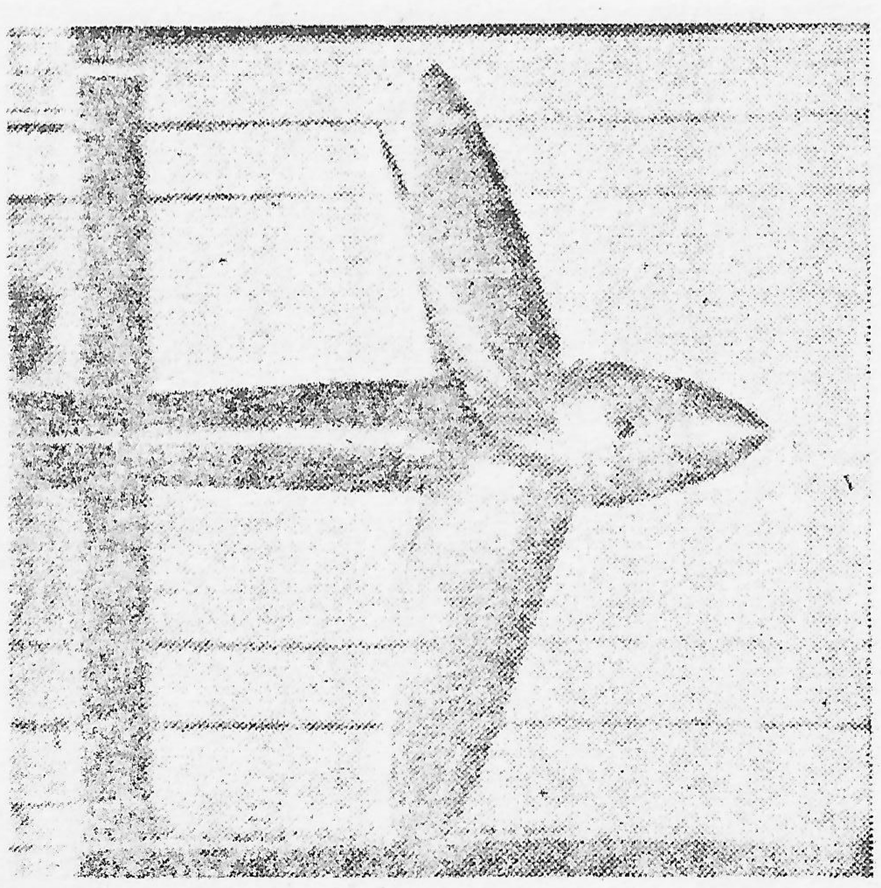


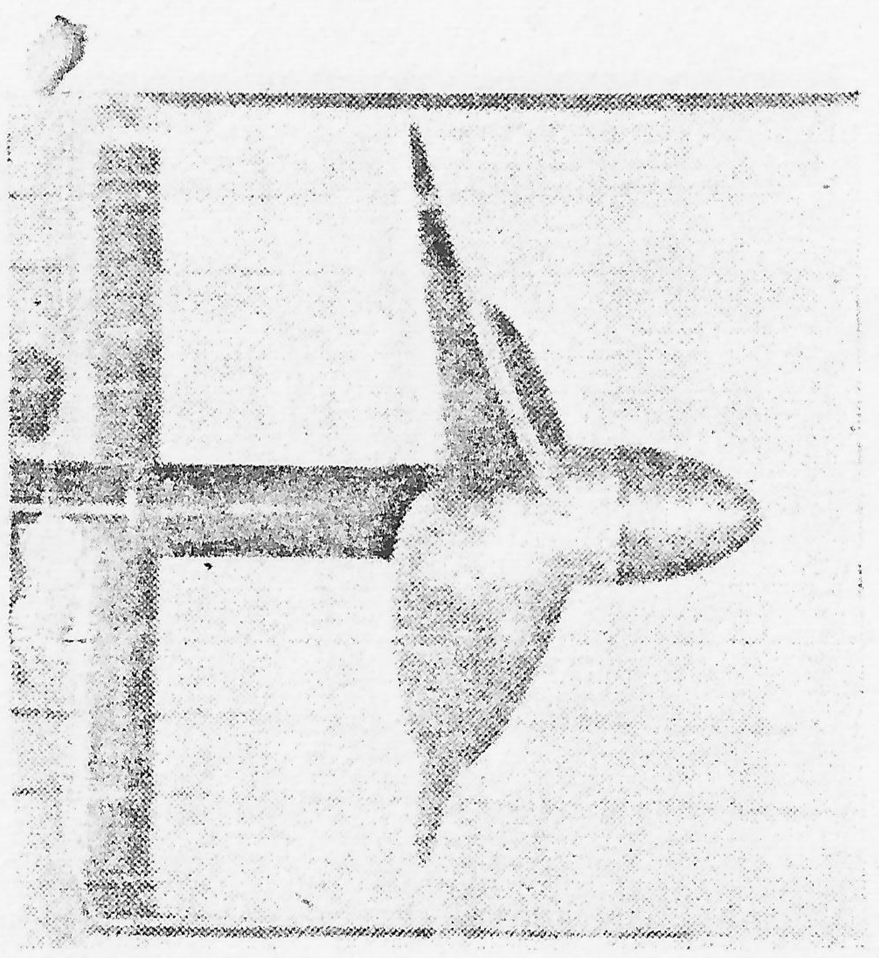


PT3 σ 0·61 PT6 σ_R 0·62

Fig. 56(b)—*el Experiment Results—Screws PT5 and 6—*
ressure Conditions—Free-Running

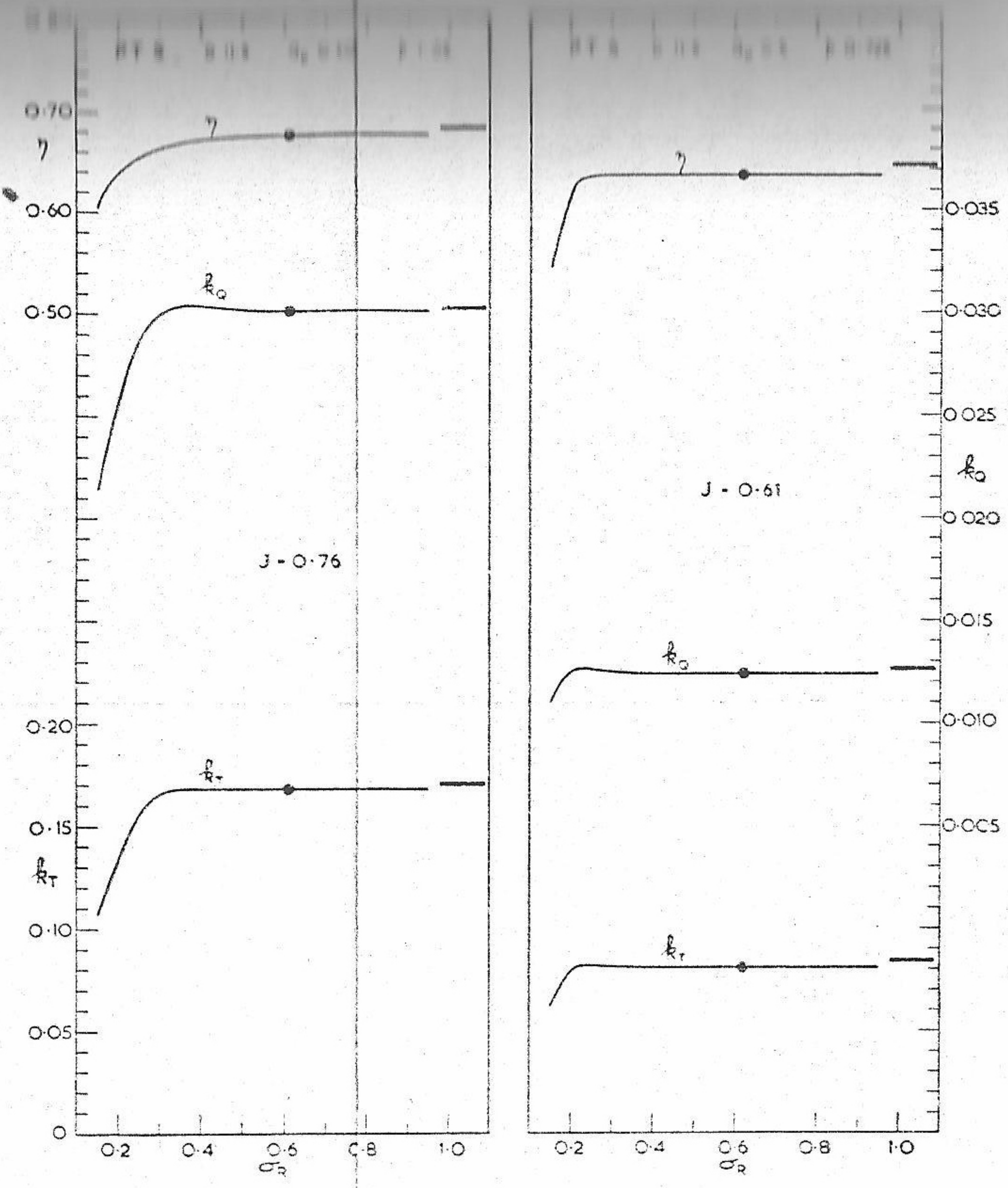


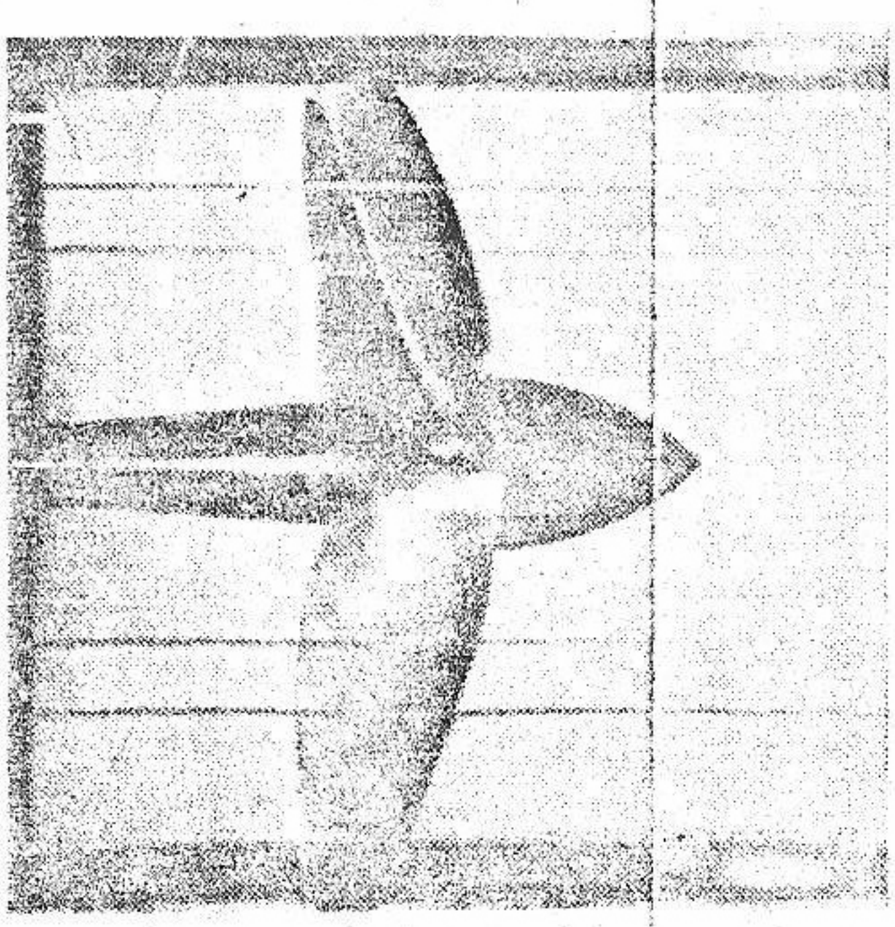


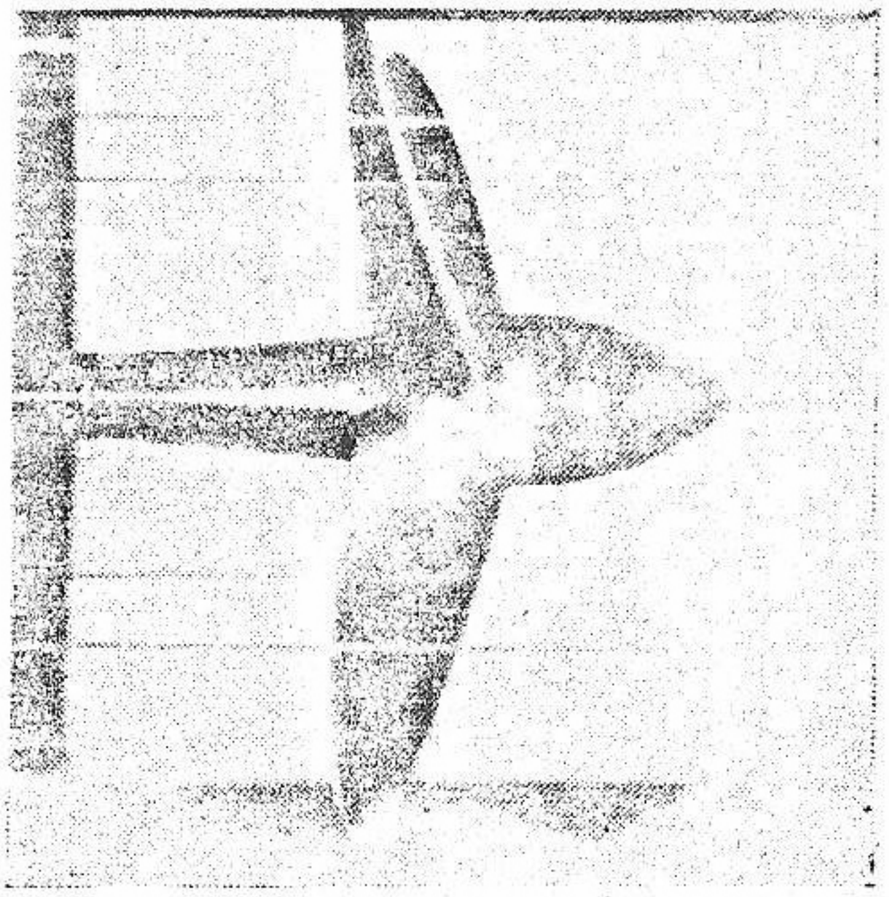


PT3 σ_R 0·26 PT4 σ_R 0·36

Fig. 56(b)—Water-Tunnel Experiment Results—Screws PT3 and 4—Reduced Pressure Conditions—Free-Running

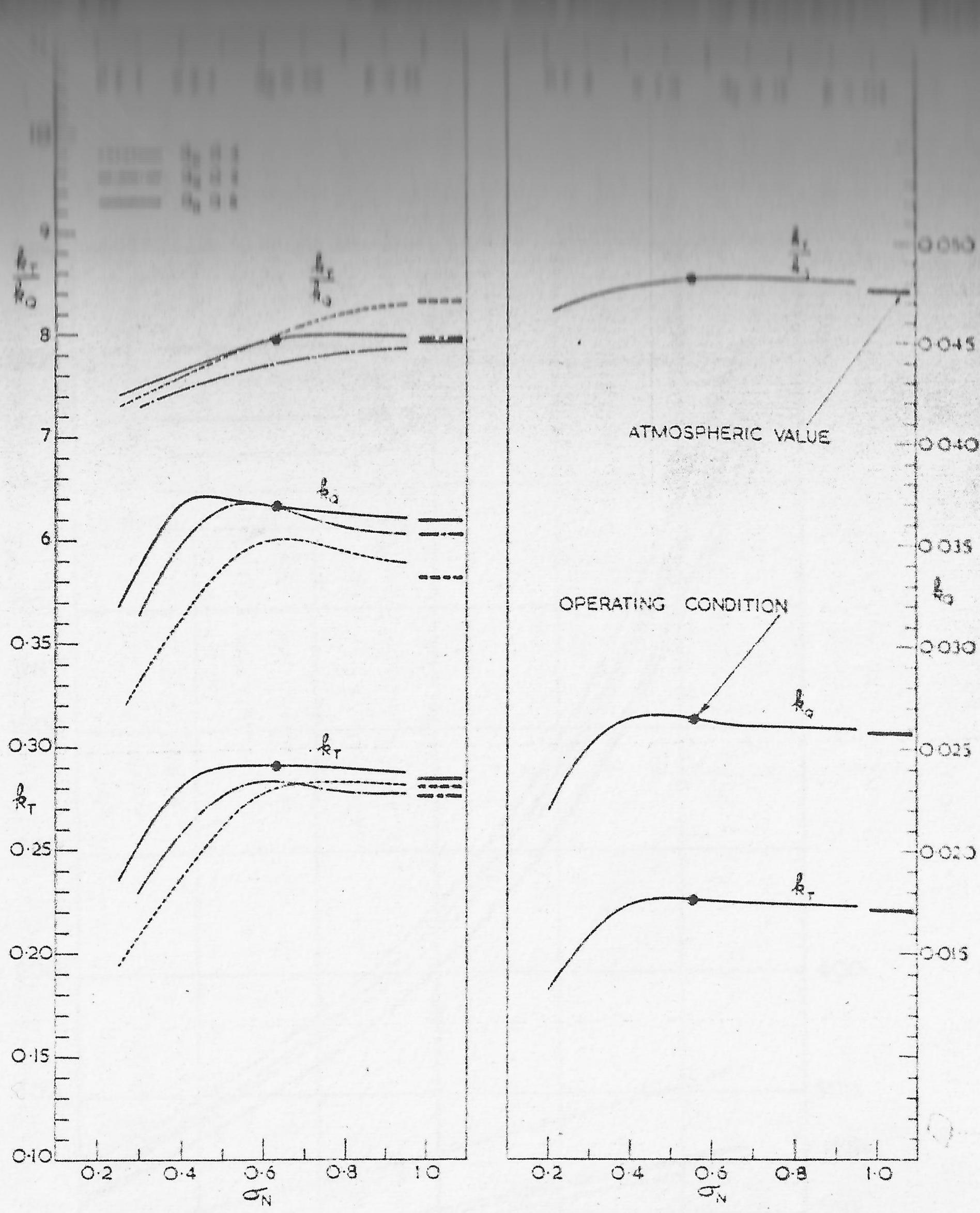


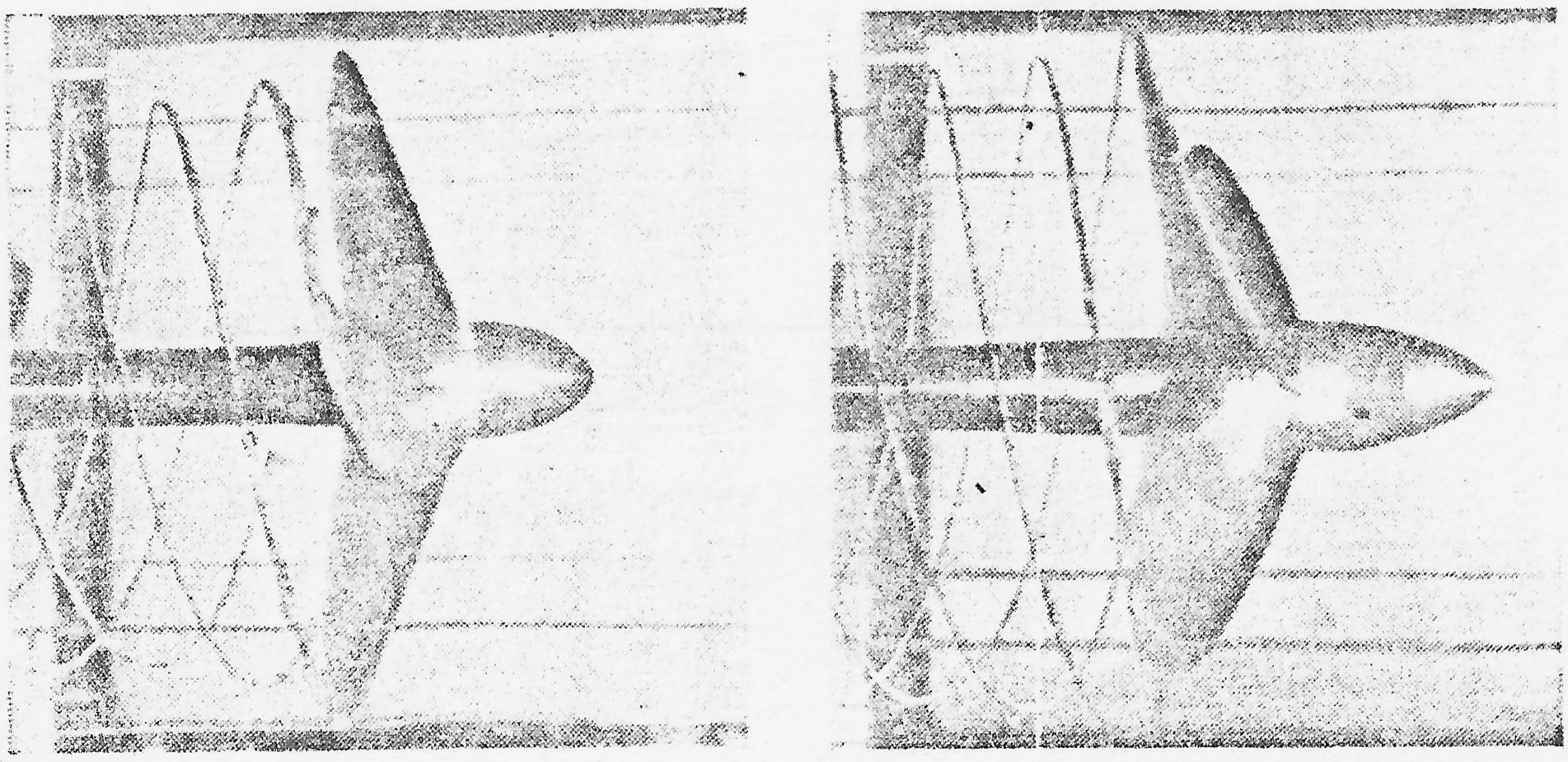




PT5 σ 0·61 PT6 σ_R 0·62

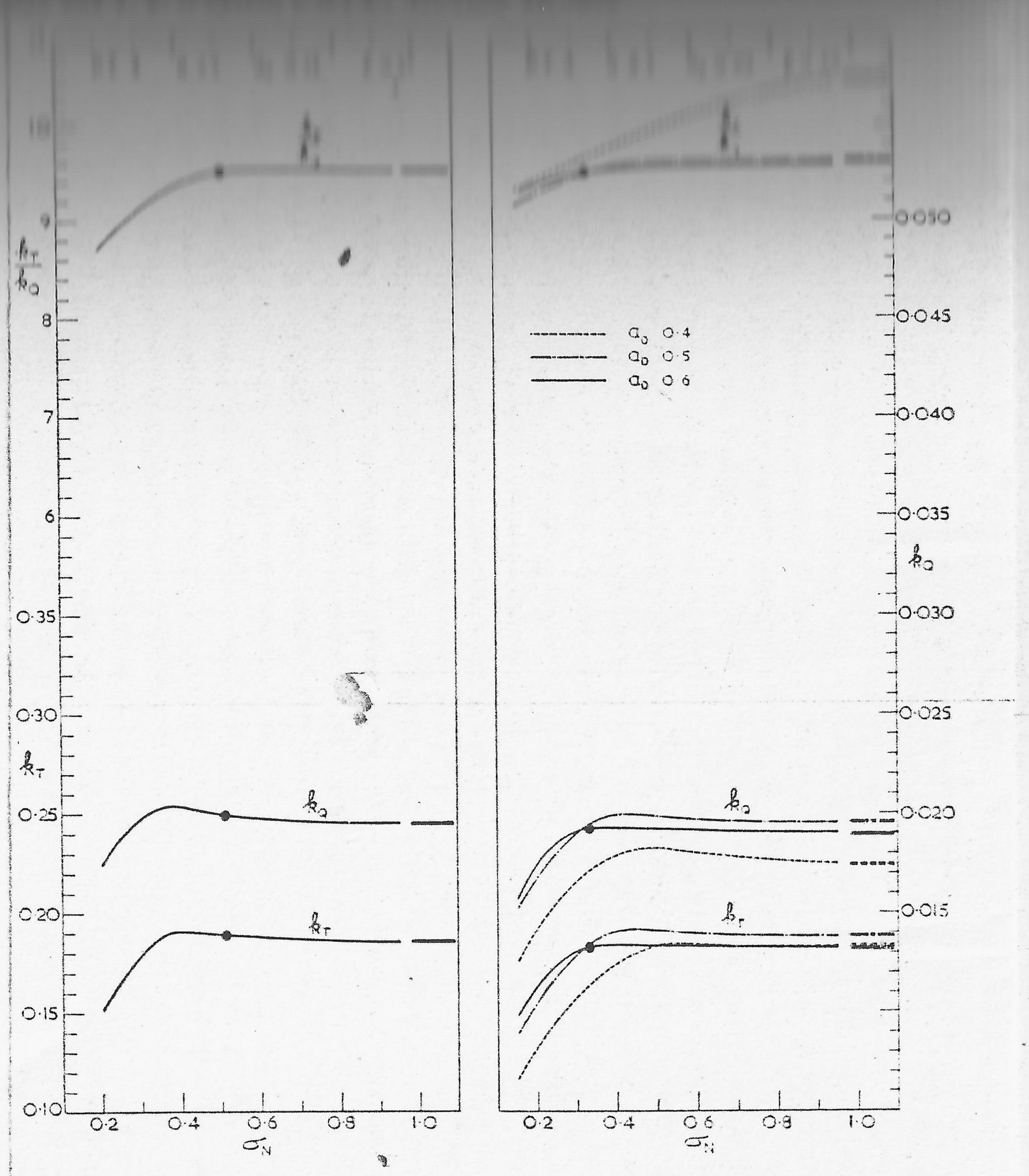
Fig. 56(c)—*Water-Tunnel Experiment Results—Screws PT5 and 6—Reduced Pressure Conditions—Free-Running*

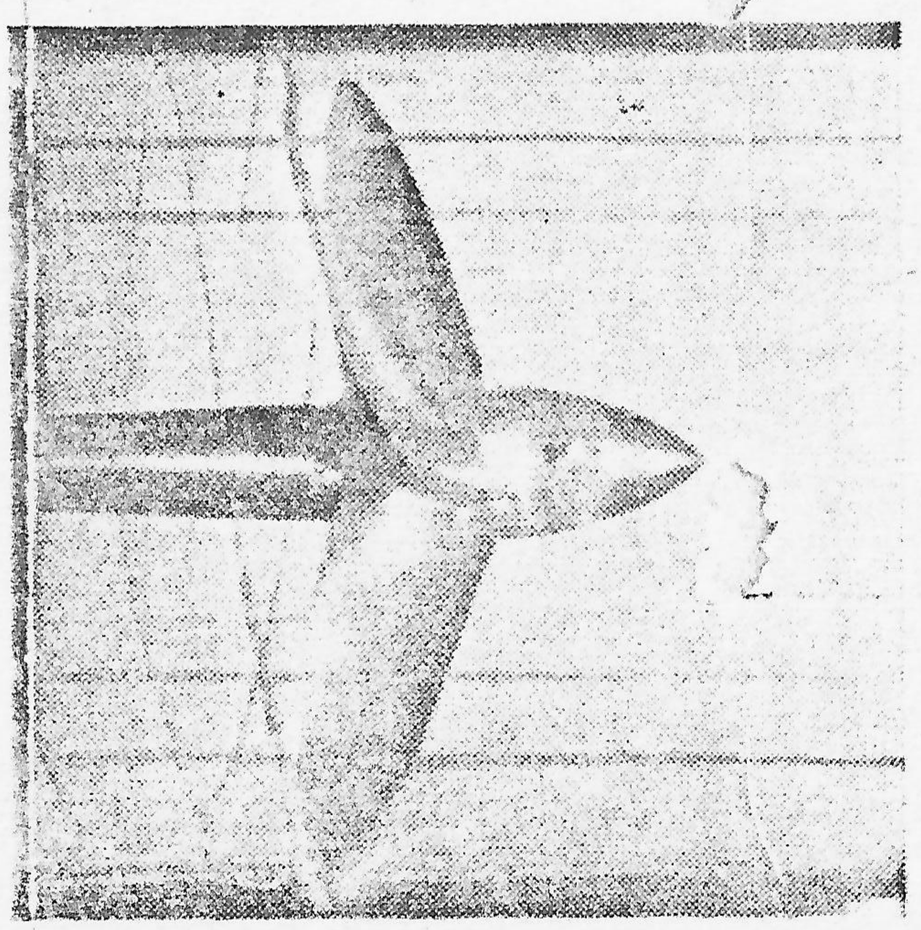




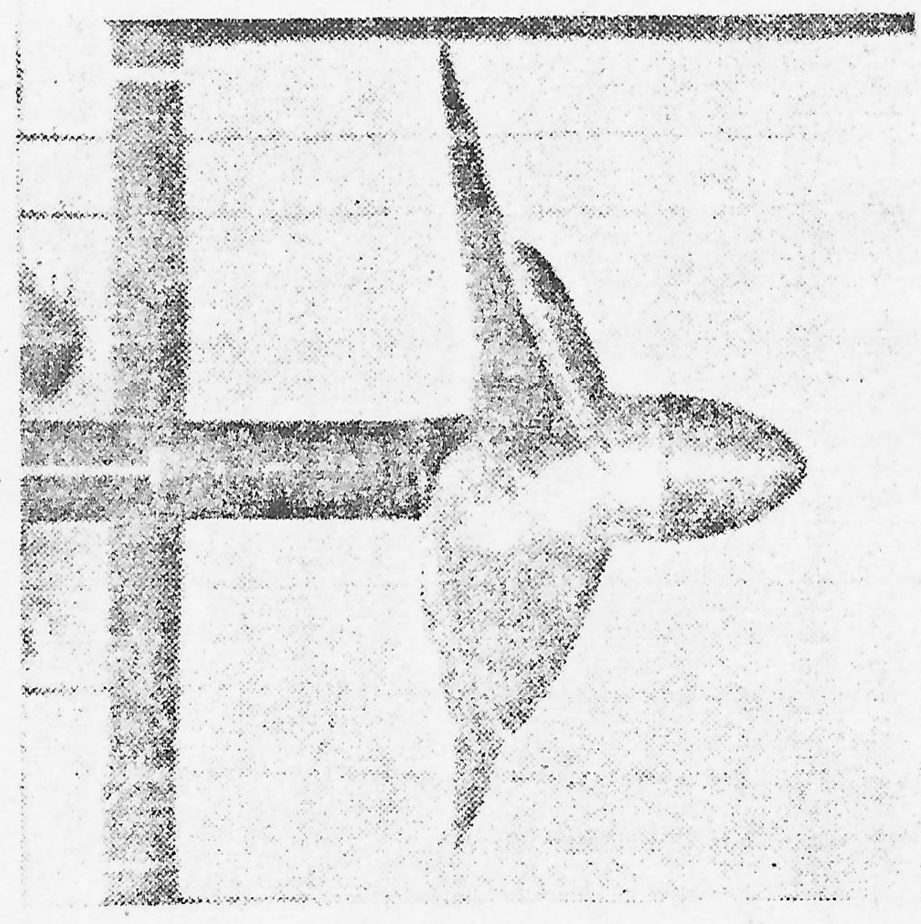
PT1 σ_N 0·63 PT2 σ_N 0·55

Fig. 57(a)—Water-Tunnel Experiment Results—Screws PT1 and 2—Reduced Pressure Conditions—Trawling





PT3 σ_N 0·51



PT4 σ_N 0·33

Fig. 57(b)—Water-Tunnel Experiment Results—Screws PT3 and 4—Reduced Pressure Conditions—Trawling

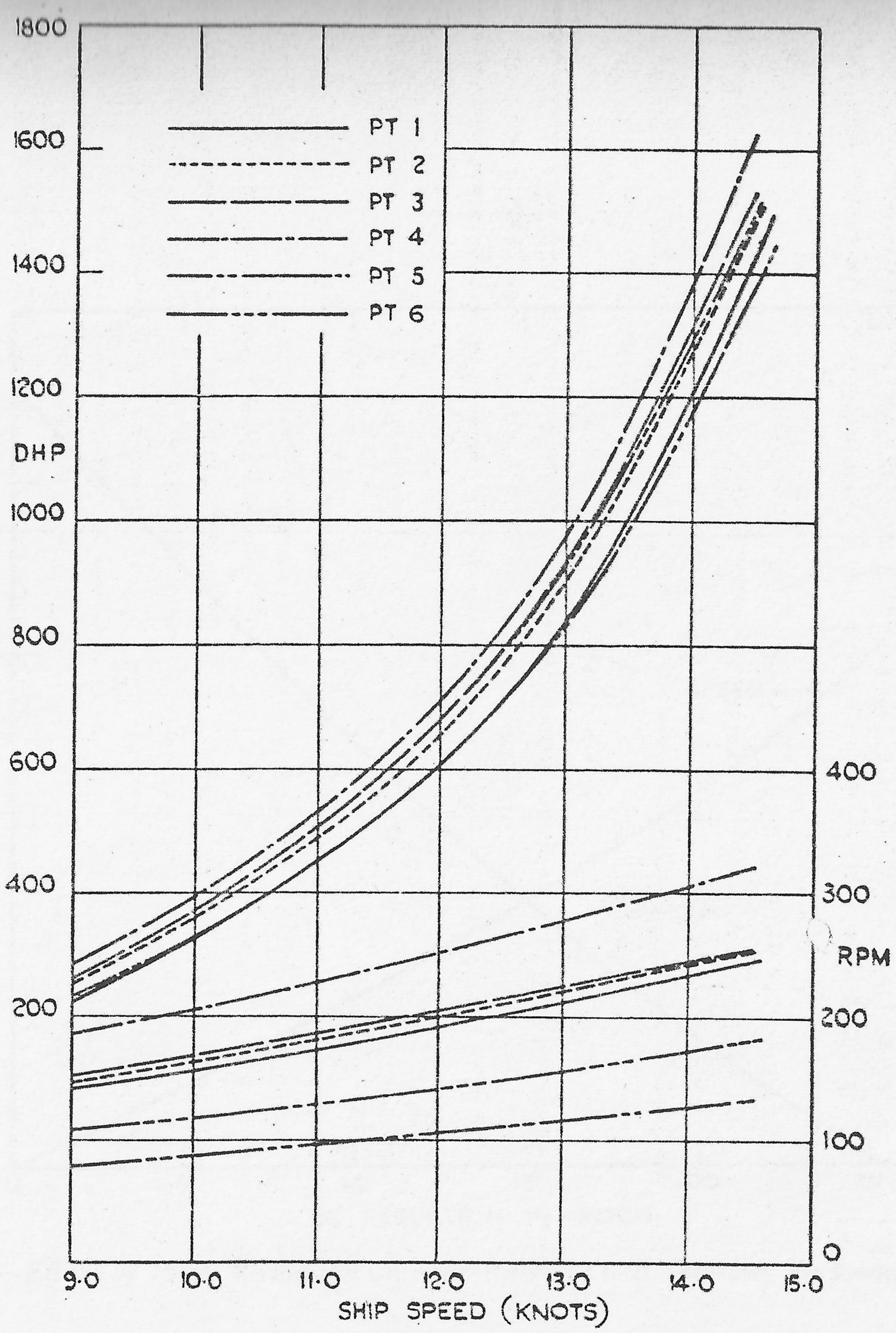


Fig. 58—Ship Propulsion Estimates for Free-Running Conditions—Screws PT1 to PT6—Model Hull 3977

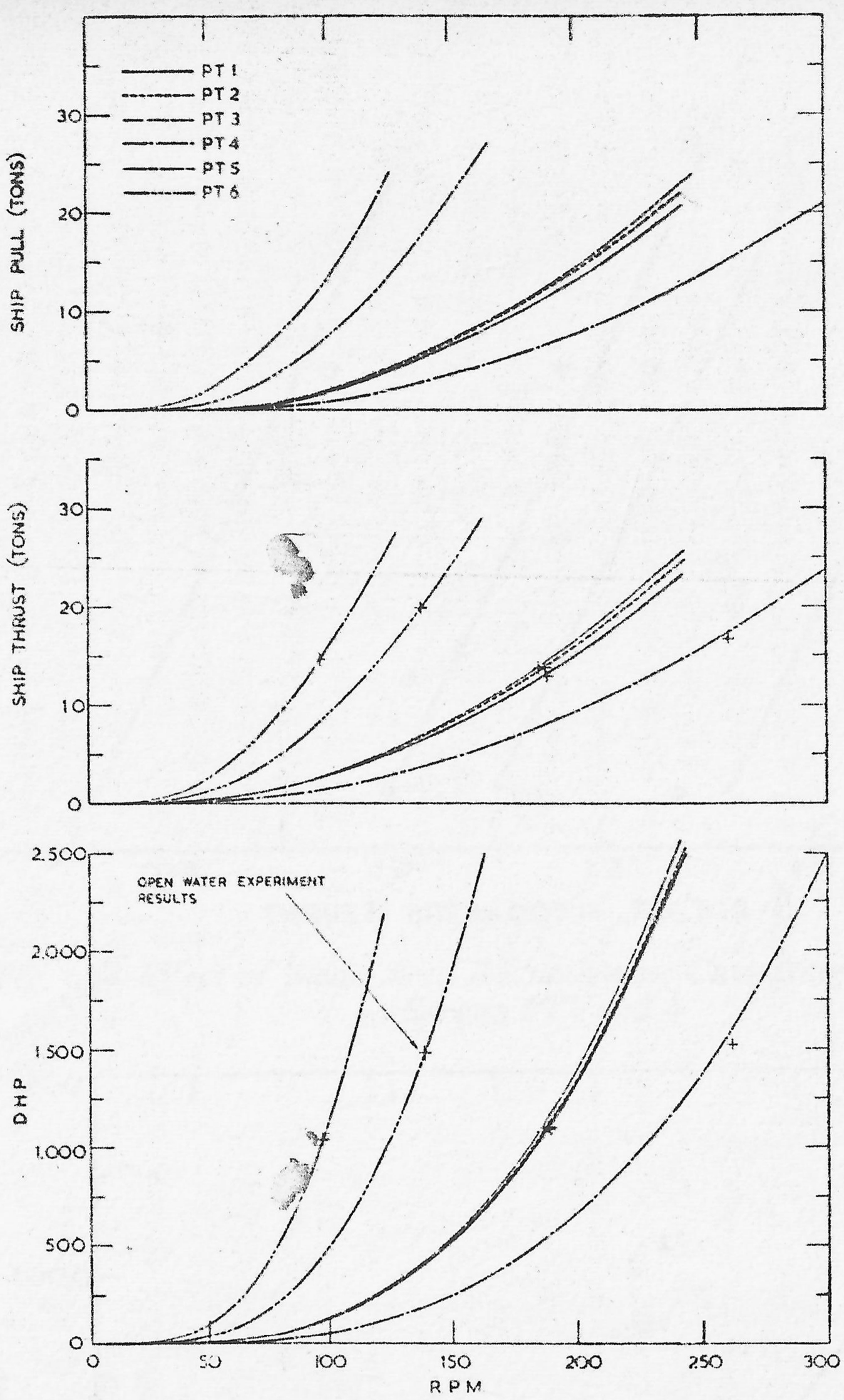


Fig. 59—Estimates of Pull, Thrust and D.H.P. for Trawling Conditions—Screws PT1 to PT6—Model Hull 3977

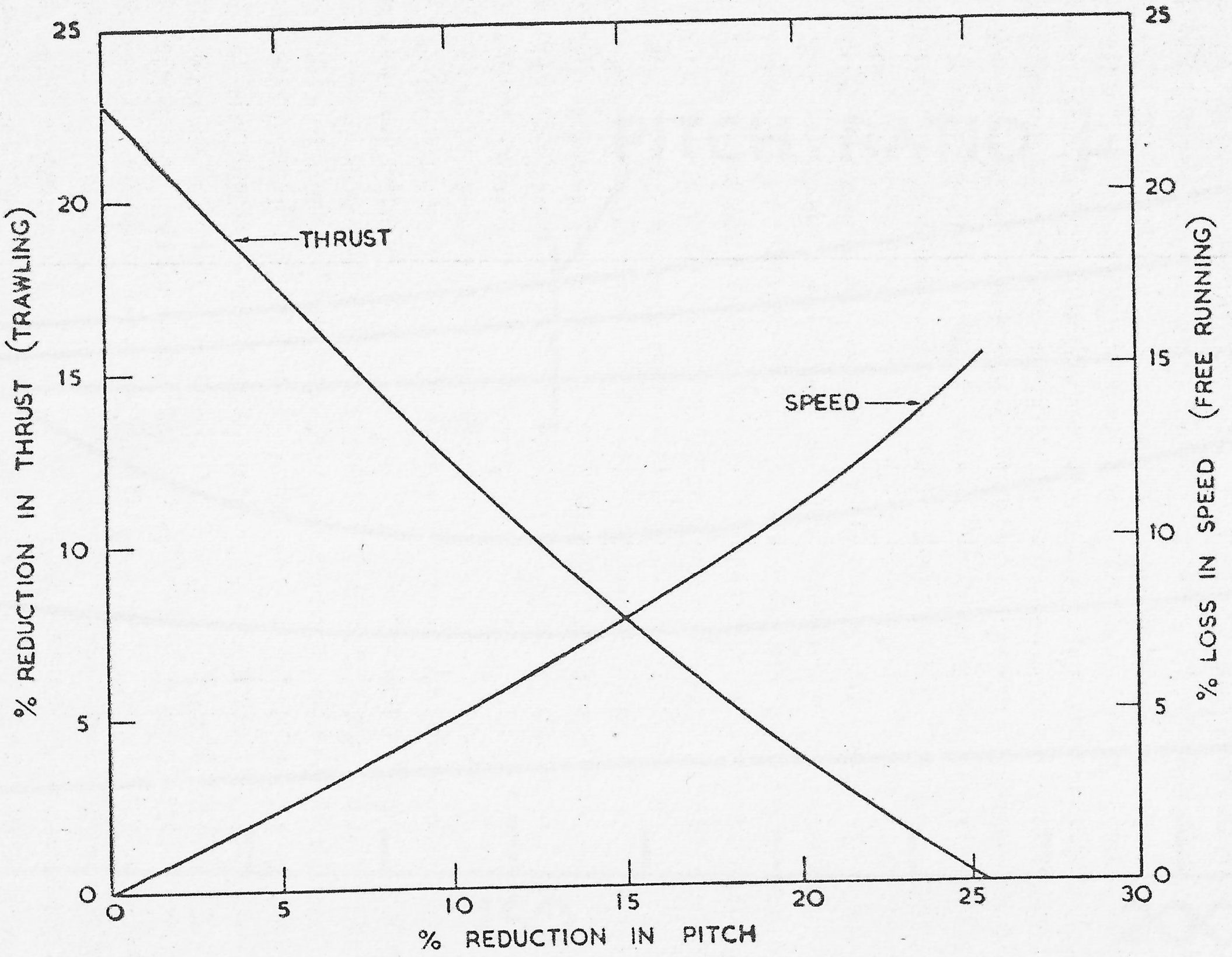


Fig. 60—Effect of Pitch Reduction on Free-Running and Trawling Performance—Screw PT1

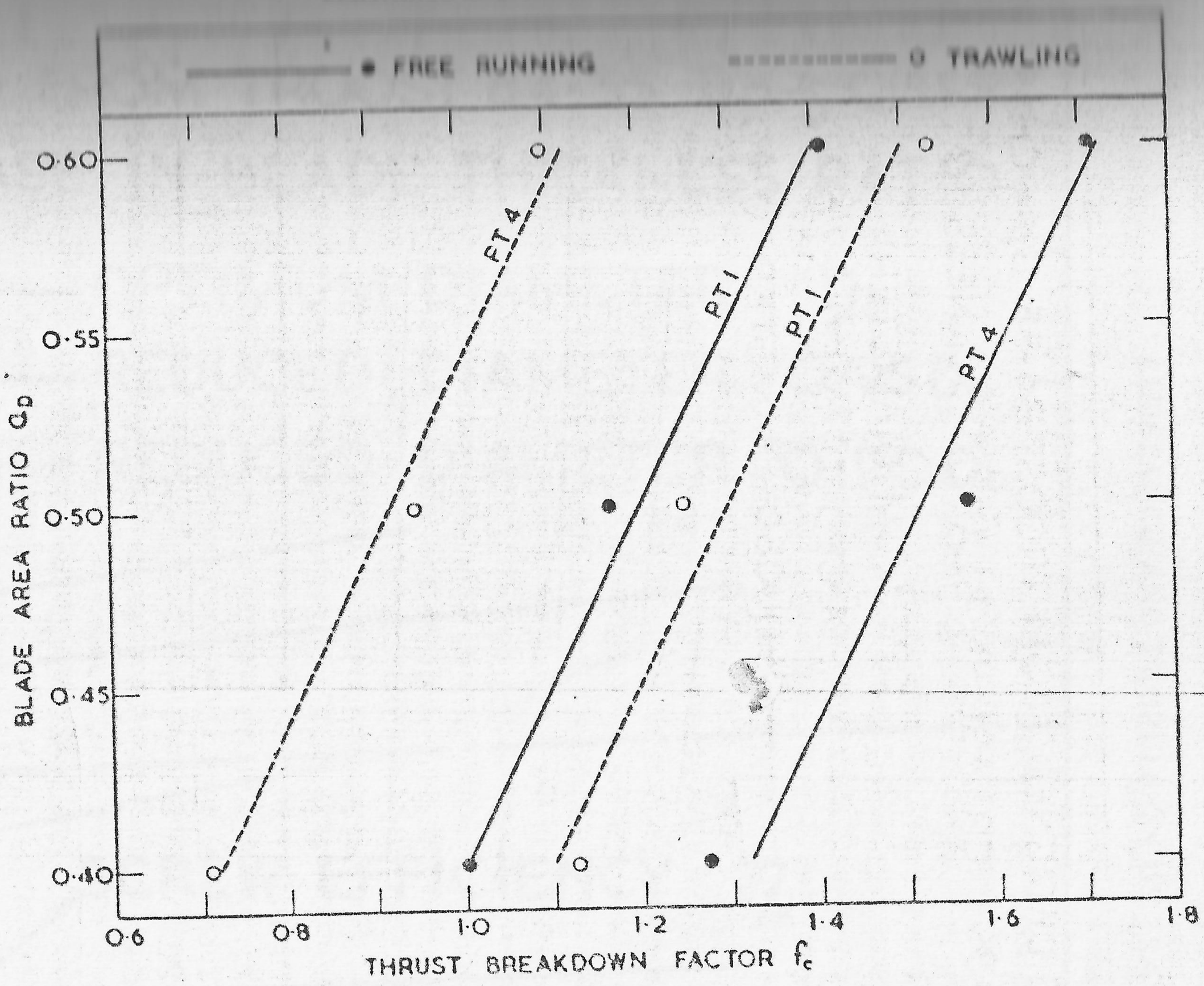


Fig. 61—Effect of Blade-Area Reduction on Cavitating Performance—Screws PT1 and 4

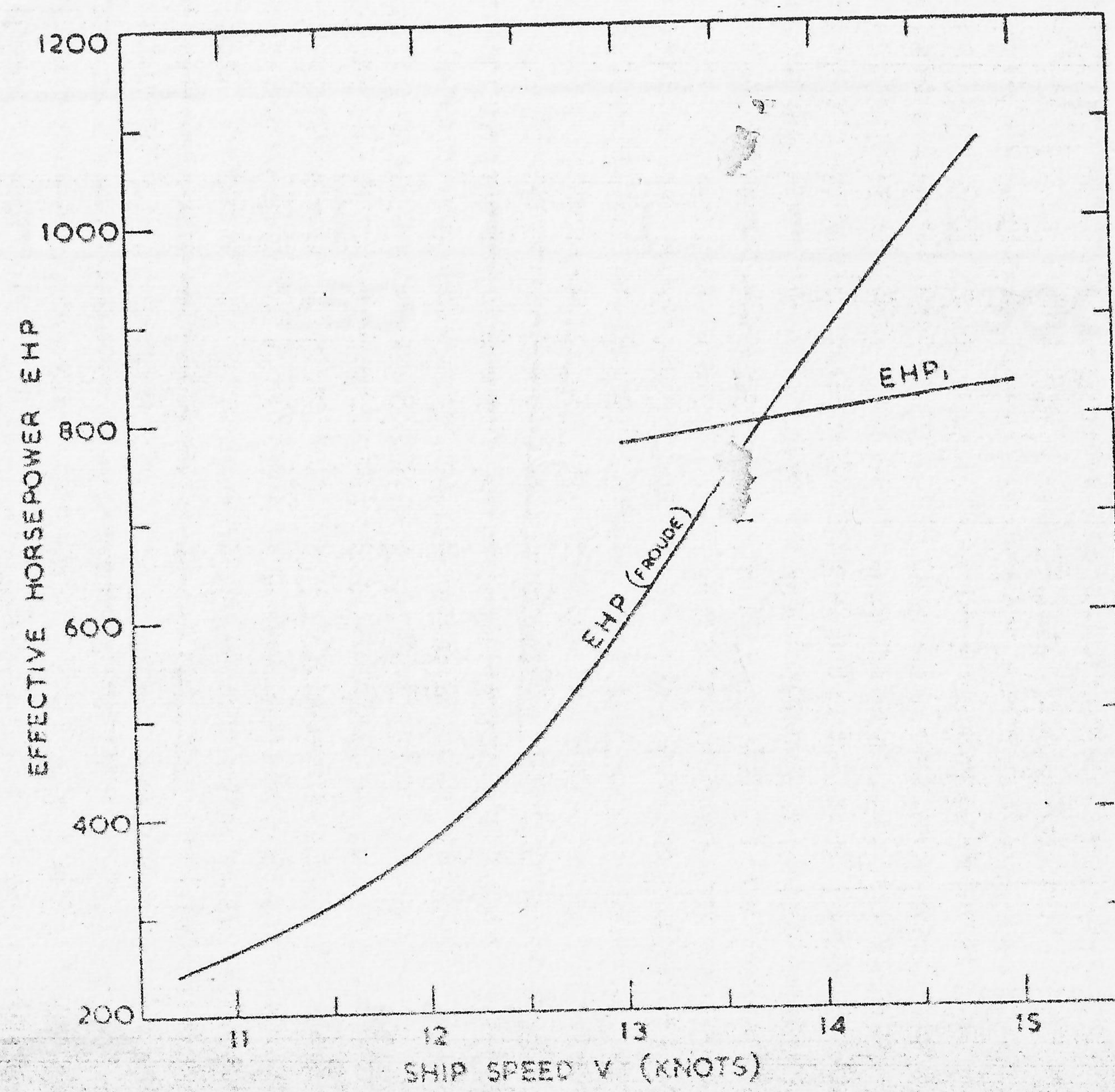


Fig. 62—Estimation of Effective Horse-Power and Free-Running Ship Speed

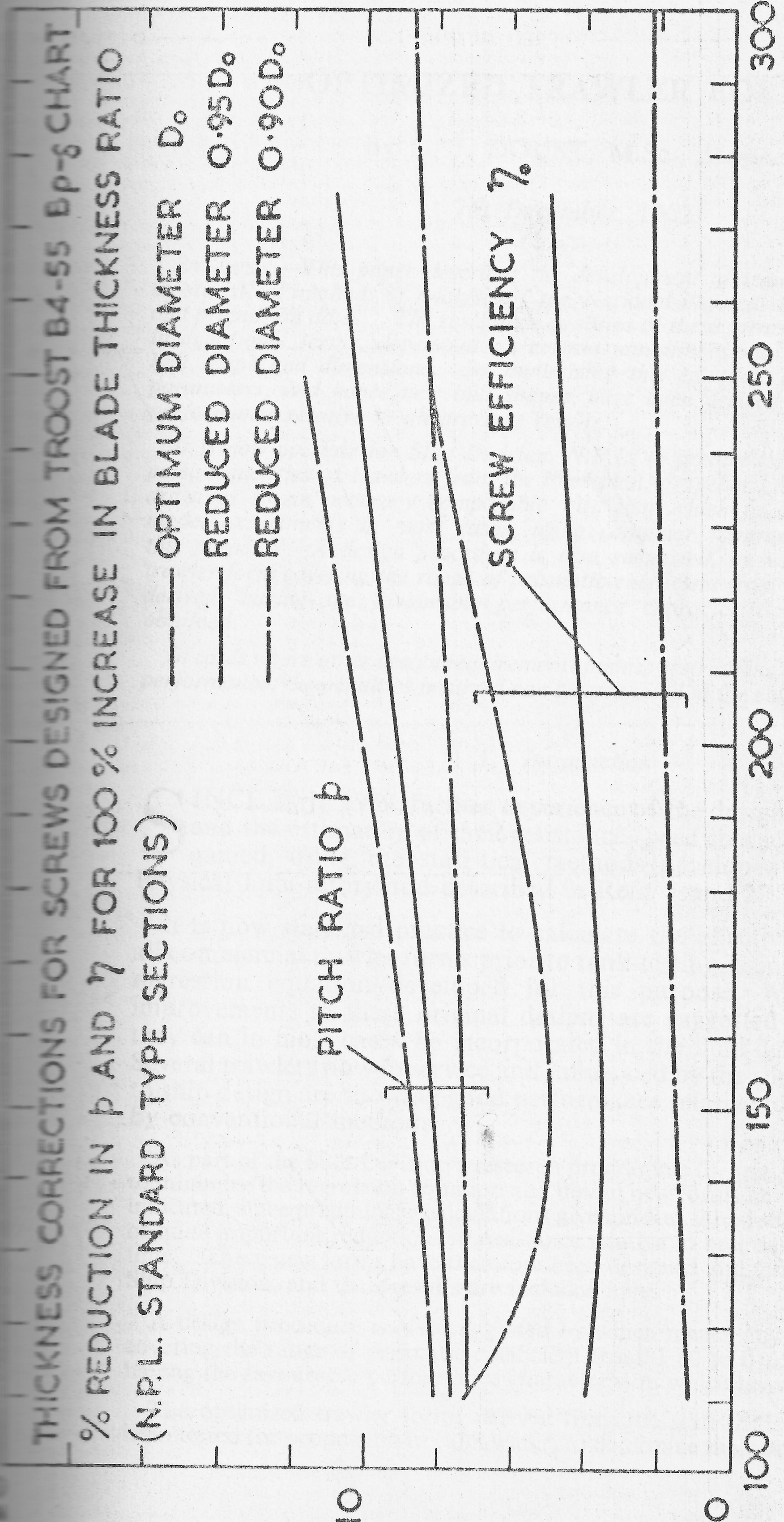


Fig. 63—Blade Thickness Correction Chart