THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
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DEVELOPMENT OF HIGH-SPEED FULL-FORM HULL

(Second Report)

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PREFACE

The following chart and pictures of models which were tested under the program descirbed in this report are included here to assist the reader, at the outset in developing a clear idea of what types of bulbous bow forms have been investigated, and what magnitudes of resistance reduction have been achieved.

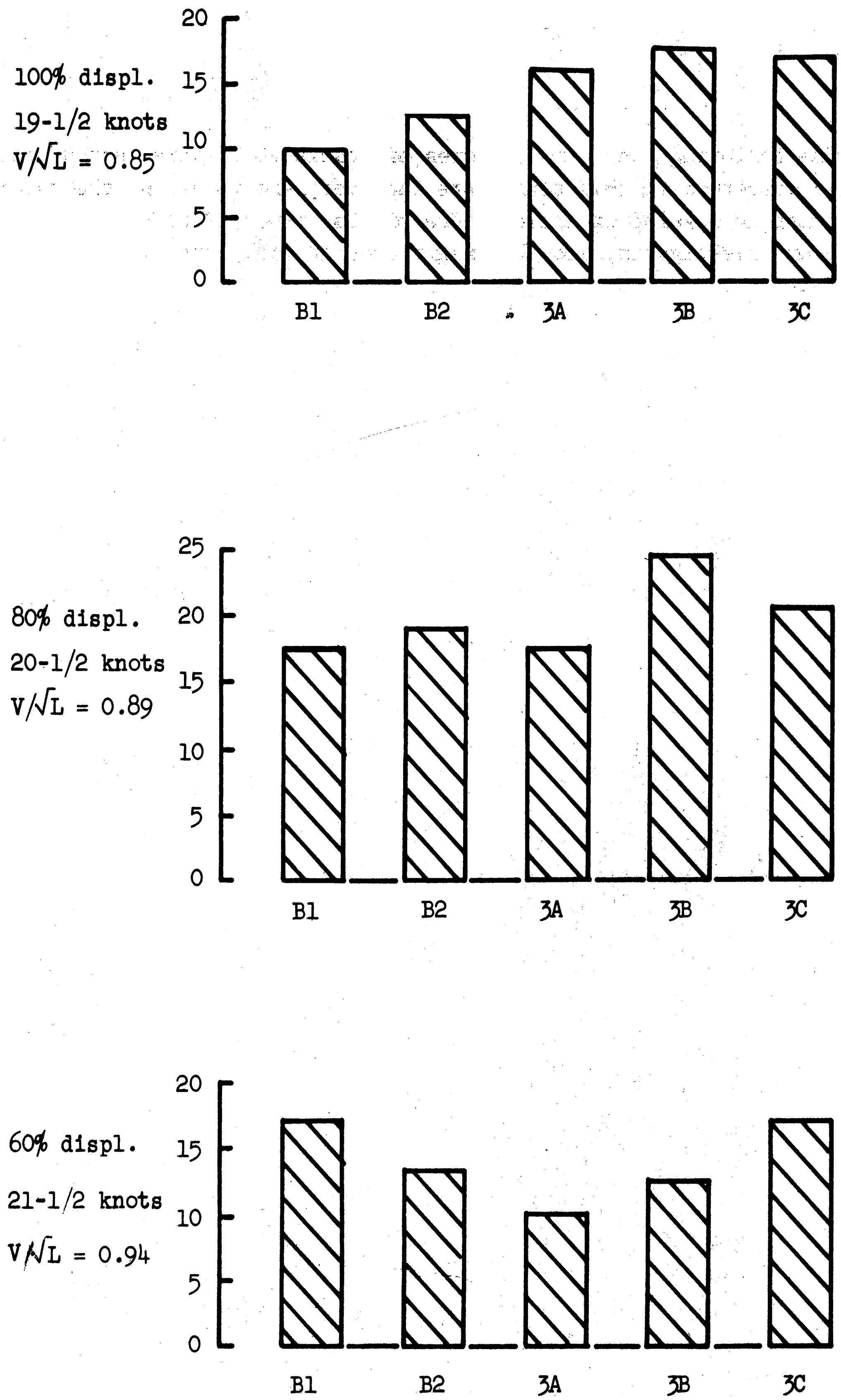
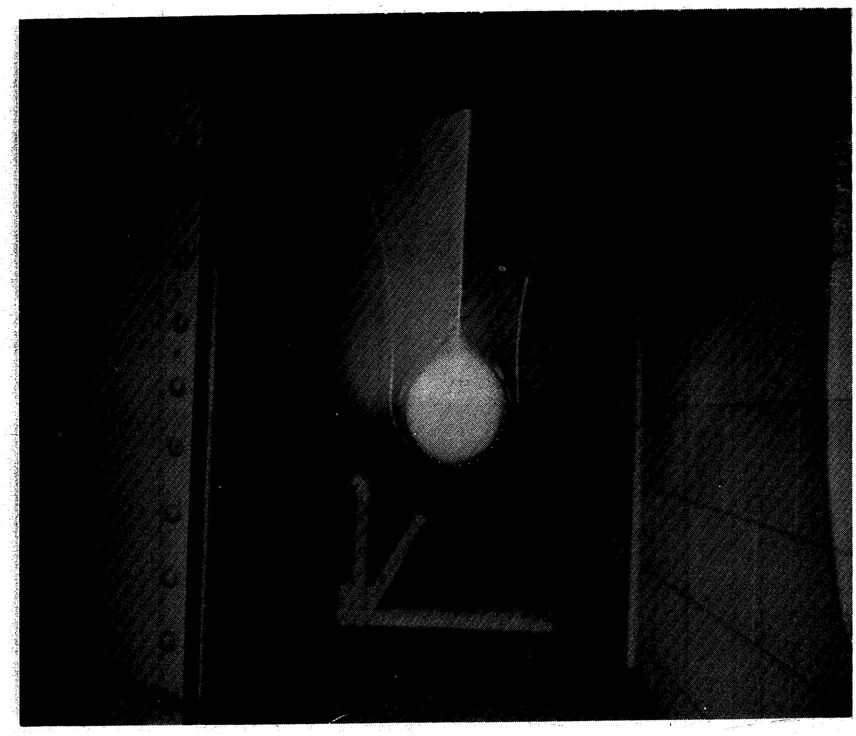


Fig. i. Percent decrease of EHP due to addition of bulbs.



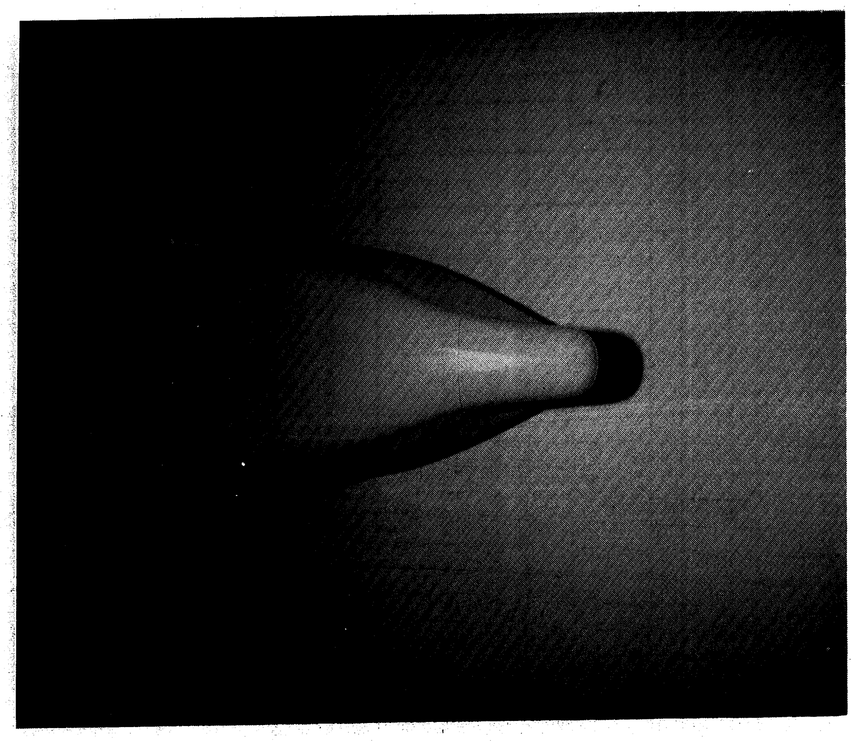


Fig. ii. Bulbous bow B1.

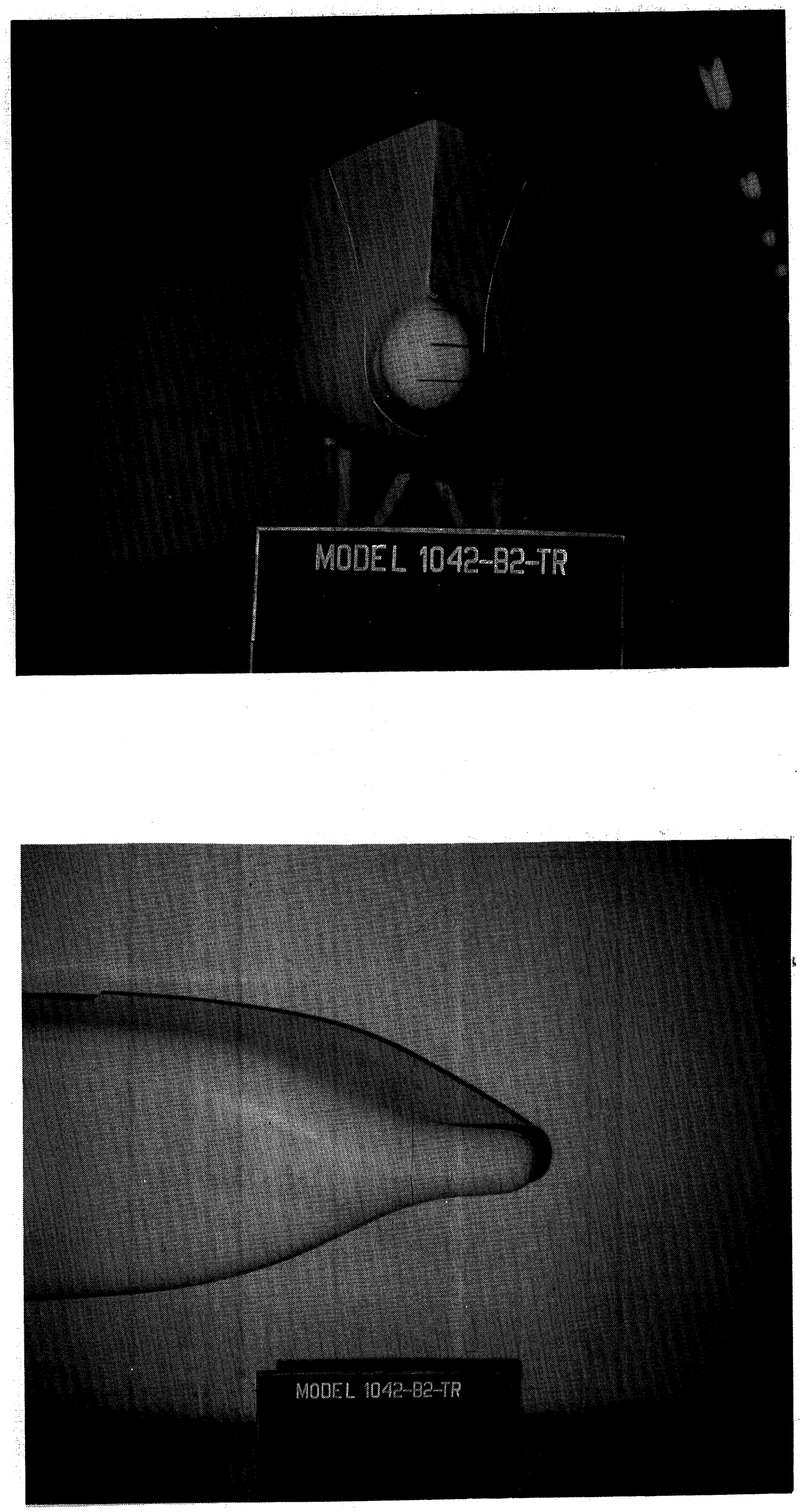
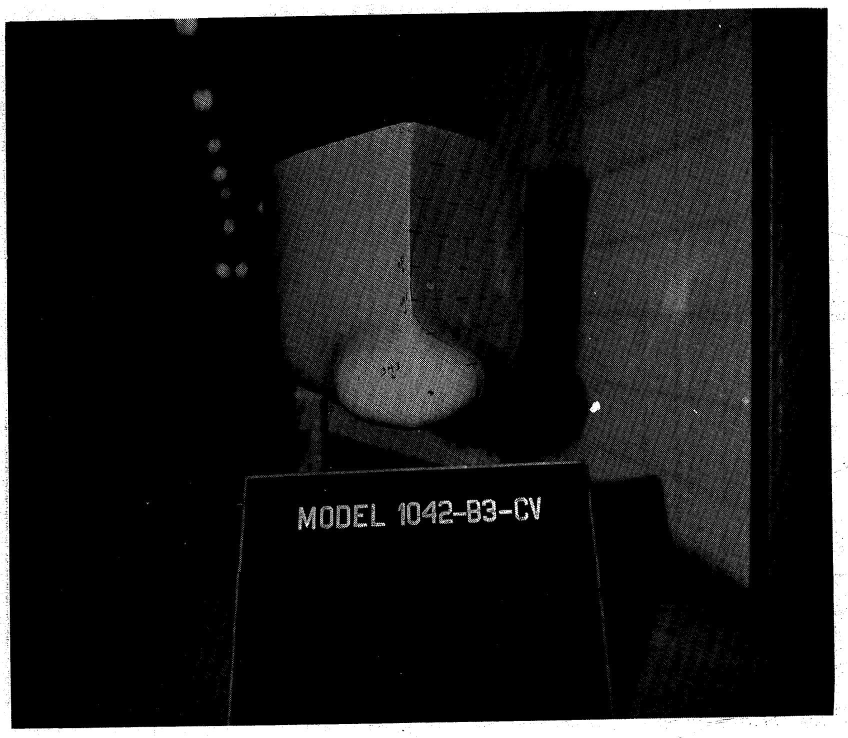


Fig. iii. Bulbous bow B2.



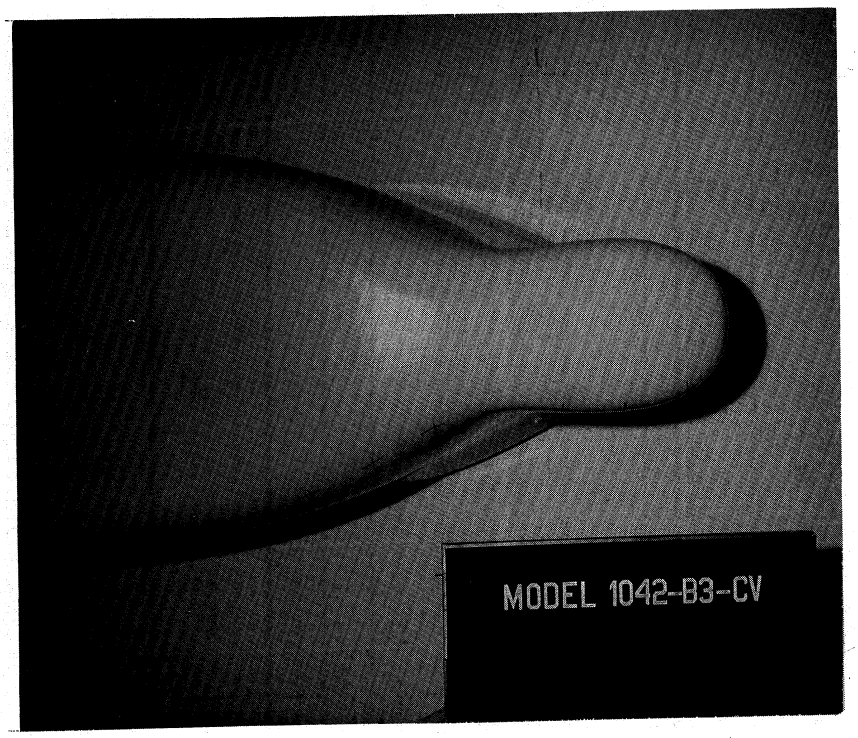


Fig. iv. Bulbous bow 3A.

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INTRODUCTION

The purpose of the research reported herein is the continued development of a high-speed full-form hull configuration for the U.S. Maritime Administration, and constitutes the second report on that development. The first report,[1] issued under this same cover in February 1966, deals with several alternative stern configurations and one bulbous bow configuration, in addition to the conventional (bulb-less) bow. This report concerns the continued development by means of four additional bulbous bow configurations. The work has been supported entirely by the Maritime Administration, and was initiated upon its request in September, 1964.

The course of this work has been to develop an understanding based on experimental work, of the potential benefits of bulbous bows, and to demonstrate the possible benefits in several displacement conditions.

In order to make the report comprehensive, summaries of the tests are first presented, enabling the reader to readily see the benefits of each of the bulbs. Details of the developments are then given, with the hope that the reader may gain insight into the design of bulbous bows. Some of the material presented in the first report is included here for completeness. That report should be consulted if additional information is needed.

The resistance tests were carried on at The University of Michigan Ship Hydrodynamics Laboratory on model number 1042, having a 14'-0" LBP, between June 1965 and May 1967. This model has a block coefficient of 0.75 and is the parent form for a series of models ranging in block coefficients from 0.75 to 0.55. A separate report entitled "Series-1042," dealing with that family of hull configurations is published separately. The model having a block coefficient of 0.75 will henceforth be referred to as model 75-CV when it is fitted with a conventional (bulb-less) bow, 75-B2 when fitted with the second bulbous bow, and similarly named when fitted with other bulbs.

As noted in the first report, three stern configurations for the same model were subjected to resistance tests. Of those three (transom, conventional, and modified Hogner-type), it was found that the transom stern configuration offered the least resistance in the 100% and 80% displacement conditions. Where a comparison was possible, it was found that, in the 100% displacement condition, the model had the same resistance as an equivalent Series-60 Ship. At the request of the Maritime Administration, however, all tests reported herein were conducted on the model fitted with the conventional stern configuration.

The lines of the conventional fore-body are given in Figure 1; those of the conventional after-body are given in Figures 2 and 3; and the section area curve is given in Figure 4.

The principal characteristics of the full scale ship used as a basis for comparison are given in the following table.

LBP	530'-0"
LWL	530'-0"
Beam	83'-9"
Draft	30'-0"
Displ. (mld, L.T.)	28400
Block Coeff.	.747
Prismatic Coeff. (total)	.762
Prismatic Coeff. (entrance)	.747
Prismatic Coeff. (run)	.644
Midship Coeff.	.980
LCB/LBP (fwd)	1.73%
L_X/LBP	.215
L_E/LBP	.400
L_R/LBP	.385
$\Delta/(L/100)^3$	191
Length/Beam	6.33
Beam/Draft	2.79
1/2 Angle of Entrance	25°
Wetted Surface (sq ft)	60,310

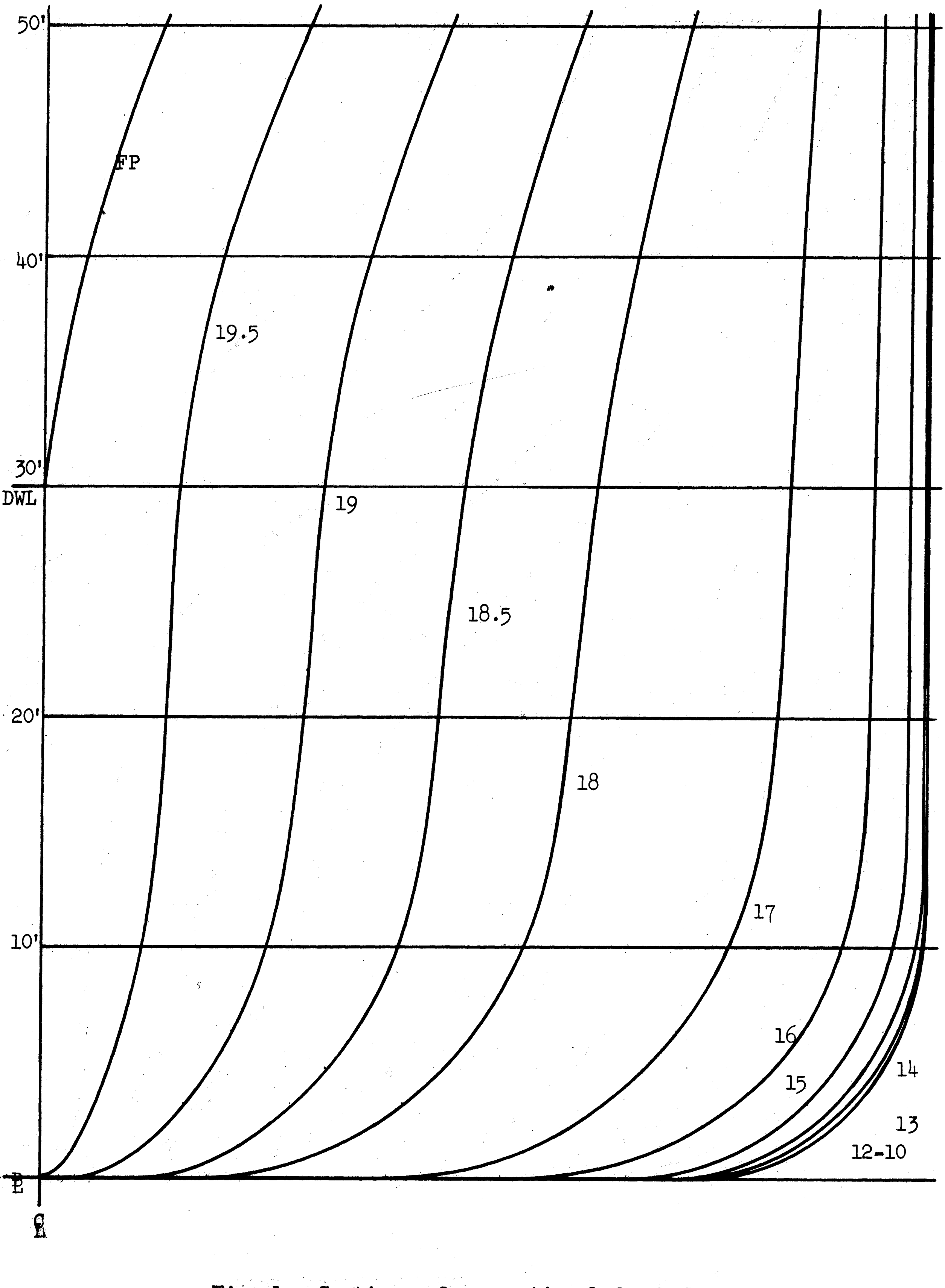

Fig. 1. Sections of conventional forebody.

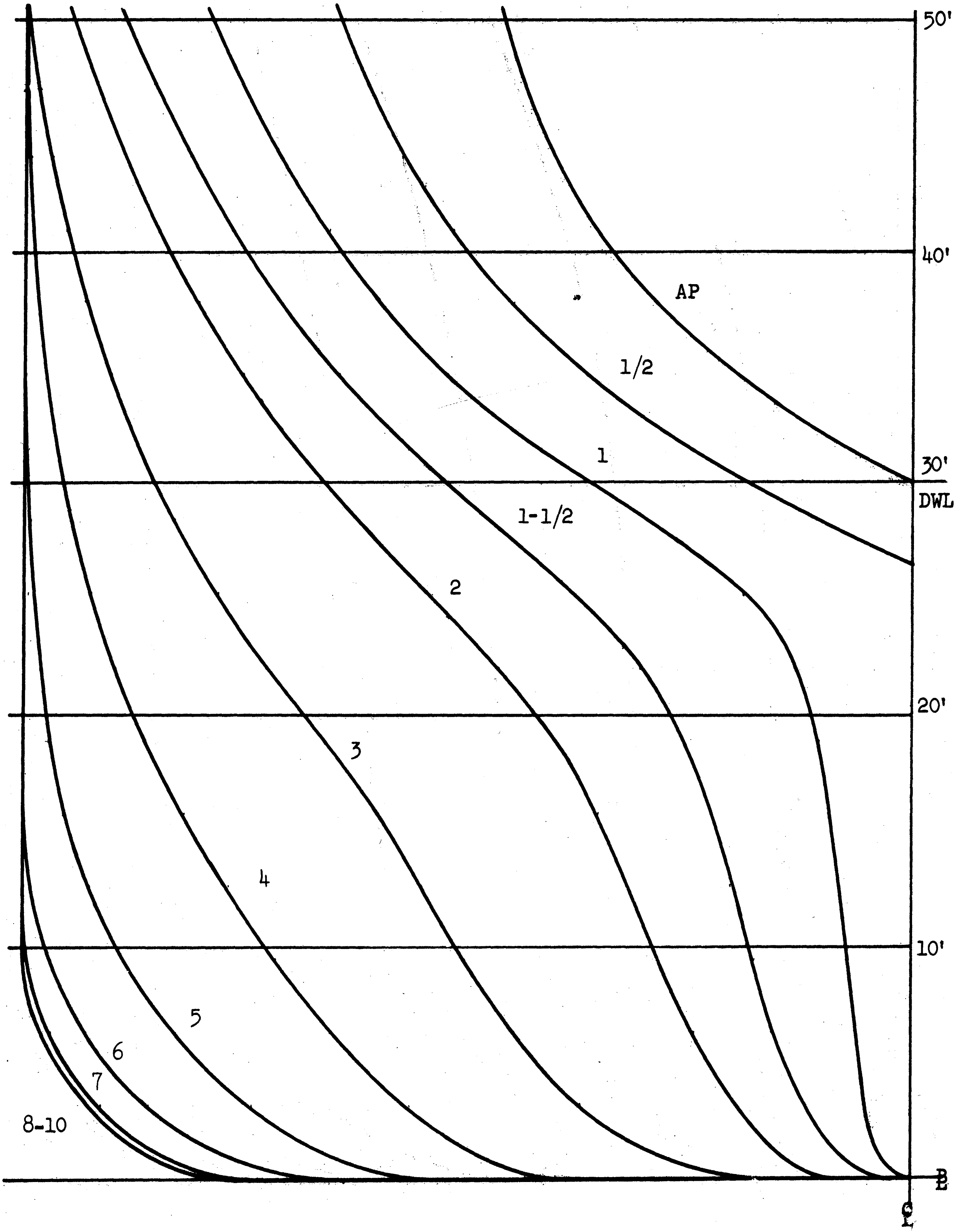

Fig. 2. Sections of conventional afterbody.

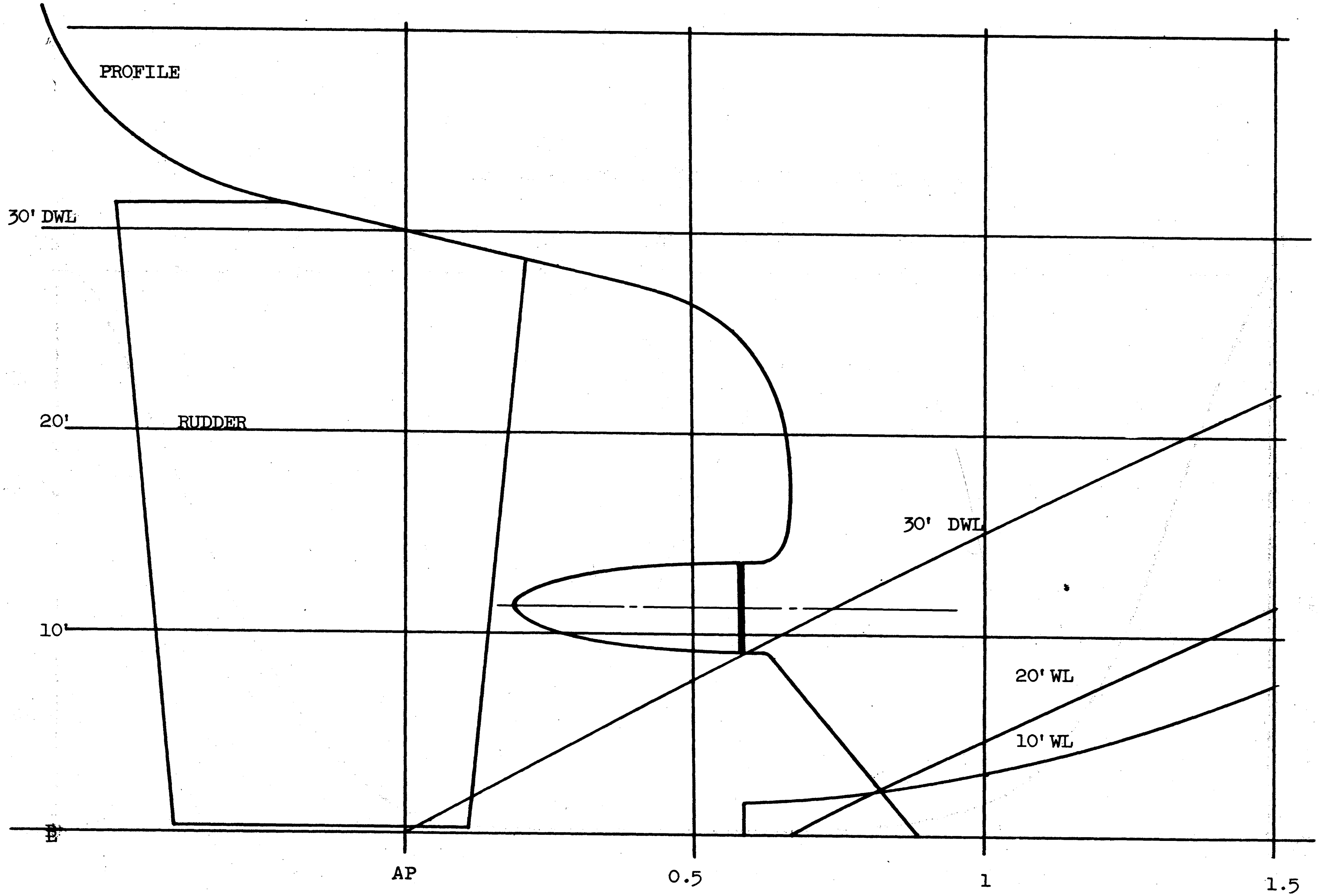

Fig. 3. Conventional stern profile.

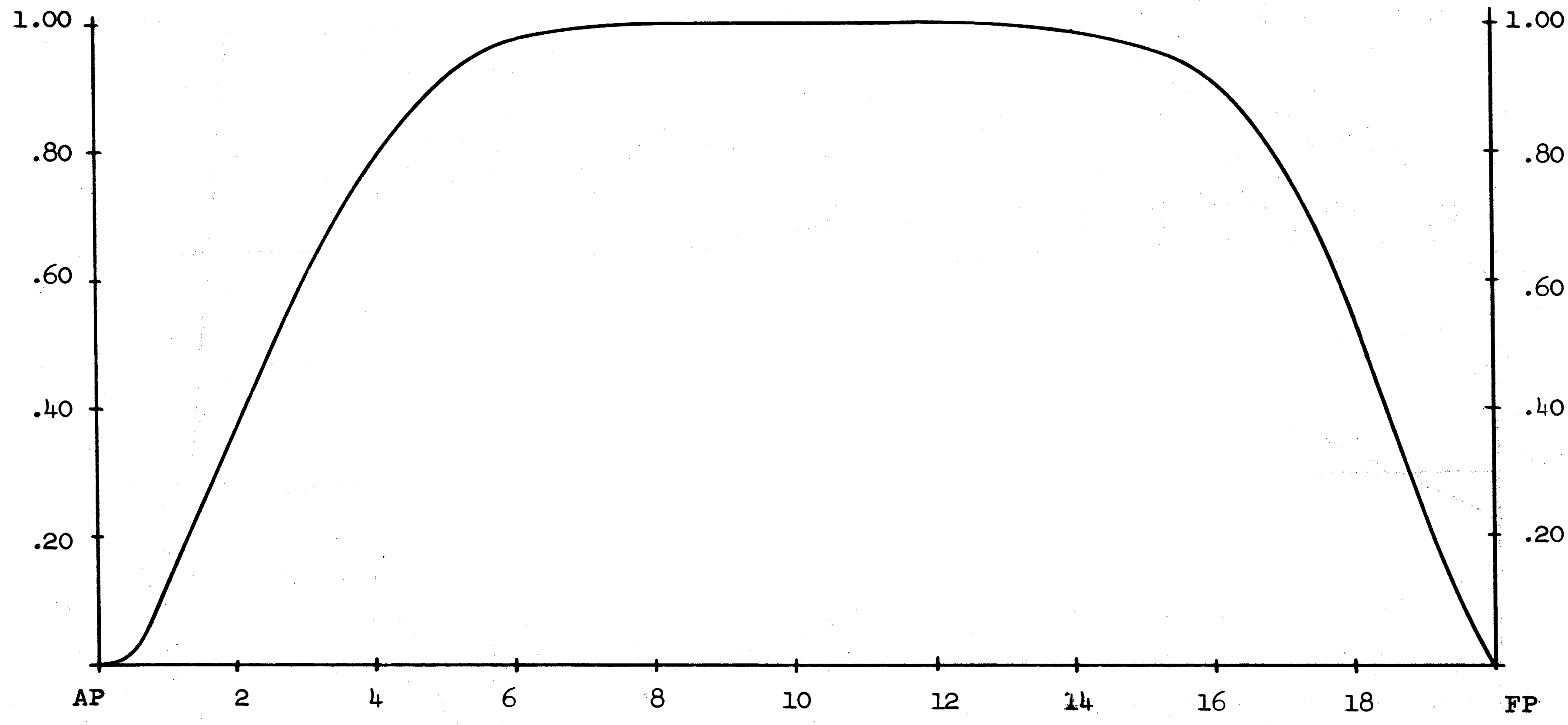

Fig. 4. Nondimensional section area curve of 75-cv.

BULBOUS BOW DESIGN

It is generally agreed that presently the most effective means of reducing a ship's total resistance is to minimized the wave-making resistance. Proposals have been made which would reduce the frictional resistance, but none have yet been made applicable for ships.

A most readily applicable method of minimizing the wave-making resistance, which is sufficiently well developed, is that of adopting a bulbous bow. Special bulbous sterns have been proposed and in some instances proven slightly effective.[3] No full scale application has yet been made, however. Inui, Kajitani, and Kasahara,[4] and Pien and Moore[5] have begun investigating low-resistance nonbulbous hull forms. The authors are of the opinon, however, that hull forms of minimum wave-resistance will exhibit a concentration of singularities at the ends. Thus one may as well start, *a priori*, with a bow bulb in an experimental study such as this.

Prior to the actual design of the bulb, extensive investigations of existing literature and into the results of other designs were carried out. A group of unrelated, relatively full-form ships, upon which bulbous bow experimentation had been carried out at The University of Michigan, was studied in detail.

The general result of these investigations was to learn that the bulb should be considered an integral part of the hull form, and to be utilized to the greatest extent, not designed as an appendage, or considered as an afterthought. The bulb-less (conventional) forebody of 75-CV was therefore designed with the forthcoming addition of a bulb in mind.

The problem of utilizing a bulbous bow design for this model proved unique and exeptional in many respects. Most ships having displacement length ratios greater than 160 are also slow or moderate-speed ships. Also, ships operating at comparable speeds are usually found to have ratios less than 130. Thus, any bulbous bow information gleaned from existing ships or models had to be used carefully because none of it was directly applicable, as noted. This situation merely substantiates the necessity for the model tests conducted in this development.

One basic difference between bulbs designed for finer, moderate-speed ships and those designed for fuller, slow-speed ships is that, in the former case, total resistance reduction is achieved primarily through a decrease of wave-making resistance, and in the latter, through a reduction of underside eddying and general reduction of unsteady flow around the forebody as well.[6]

It is generally agreed that choosing the relative size of some representative cross-sectional area of the bulb is the first step to a good bulb design. Usually either the area at the fore-perpendicular or at the longitudinal center of the bulb is nondimensionalized by dividing it by the midship-section area. (Since most midship-section coefficients are comparable, this is considered a consistant method.)

In this case, the area at the longitudinal center of the bulb is considered to be the area which will most effectively govern the resistance characteristics of the ship with the bulbous bow.

This longitudinal location should not, however, be considered the "effective" center of the bulb. The "effective wave-generating center" of the bulb can be considered as the fore-aft origin which enables us to view the bulb wave mathematically almost completely as a negative cosine wave. A similar "effective wave-generating center" of the ship enables us to regard the ship wave almost completely as a positive cosine wave. Maximum cancellation of waves occurs when the effective centers coincide and the wave amplitudes are equal. Because the waves are not exactly in phase with a cosine wave system and because the viscous interaction of the bulb and the ship upon each other's wave generating characteristics is presently not well known, it is extremely difficult to define the effective centers.

Of all the important parameters associated with the bulb, the desired longitudinal center is the most evasive. Although there may be consistency between similar ships in other parameters, generally the longitudinal center of the best bulb for each has been found to be different. For this reason it would have been informative to test several bulbs that were identical in most respects except for the longitudinal center. The limitations of funds and time prevented tests of this nature from being conducted.

Since almost all the waves generated by the ship arise at the forebody it is best to consider the problem of matching the bulb to the forebody, and not to the entire ship. (This does not rule out the possibility that the bulb effects the wake of the ship at the stern; but as investigations into that matter have not been conducted, it would only be speculation to discuss it at this time.) The effective center of the bulb volume, which is understood to include the fairing into the bulb-less hull, will depend on the shape of the main body of the bulb, and of the fairing. The effective wave-generating center of the forebody will depend on the relative fullness of water-lines near the stem, the shape of the waterlines in the forebody, and the rake of the stem. In view of this, it is quite easy to understand why the longitudinal center of the bulb is very difficult, if not impossible, to define in simple terms.

There are several possible shapes that the transverse section through a bulb may take. The three most distinctive ones are shown in Figure 5 which illustrates the relative widths necessary for the same section areas. Not

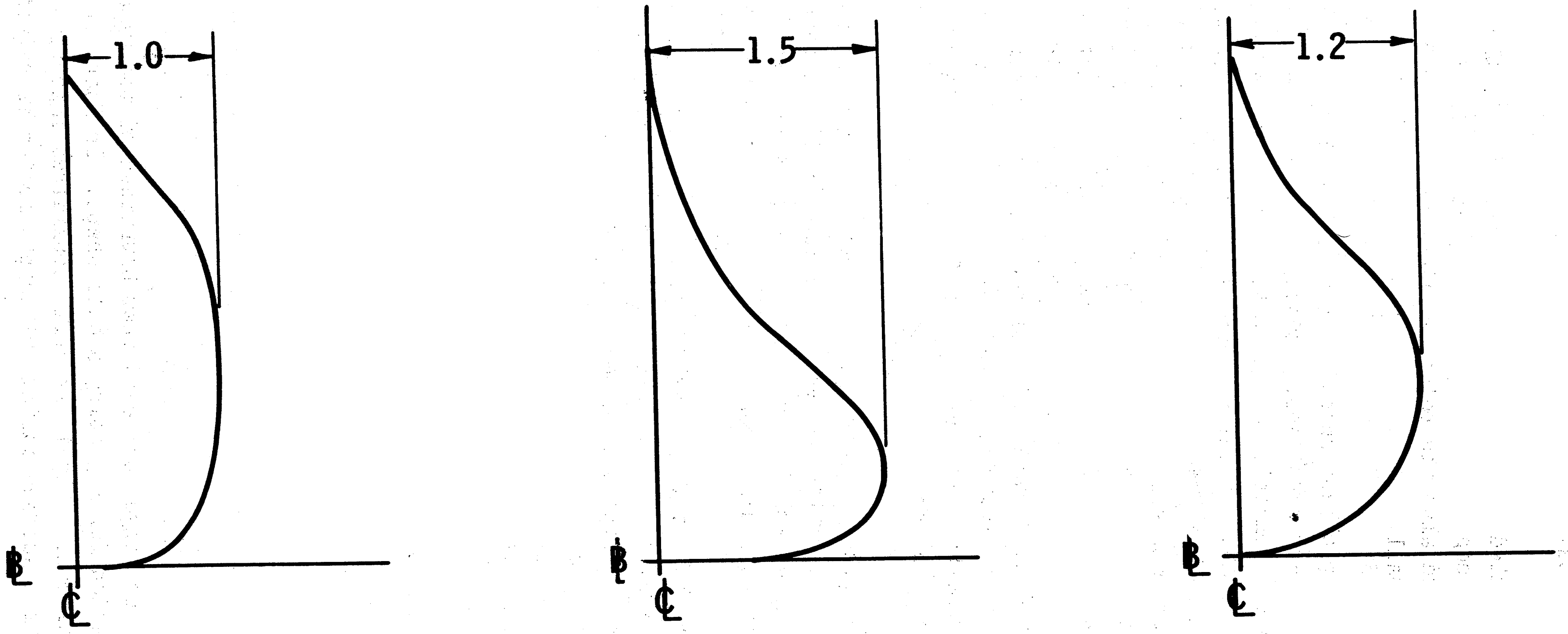

Fig. 5. Typical variations of bulbous-bow sections.

much is known about the effects on resistance that the various shapes of bulb sections will have. Thus, the circular shaped bulbs designed for this model were chosen for certain other considerations.

The vertically-oriented elliptical shape was rejected on the basis that the shape of the leading edge of the waterplane would be too blunt in lightly ballasted conditions,* and also the relative submerged bulb volume in ballast condition would be too small.

A solution to these problems encountered with the elliptical shape would be to use of the "tear-drop" shape, which would preserve suitable waterplane shapes in ballasted condition and also keep the submerged bulb volume a maximum in all conditions. If the required section area is large, however, the extra width of the bulb would prevent the smooth downward flow of water, as illustrated in Figure 6a, since the width of that bulb would be greater than either the elliptical or circular shaped bulbs. (This direction of flow was noted on subsequent flow studies using wool tufts.) The interference of the flow from the side of the hull to the bottom in the region of the wide bulb could be eliminated if we accepted a narrowing of the waterline, as shown by the solid line in Figure 6b. This shape might lead to a point of separation, however, somewhere just aft of the FP (as illustrated) because of an adverse pressure gradient.

The best solution appeared to be the circular section which would preserve suitable waterplanes at the surface for shallower drafts than the elliptical section, and which would permit easier downward flow aft of the bulb than the tear-drop section would allow.

The profile of the bulb is, by itself, not considered important in the design. However, for a given section shape and for a required bulb volume the profile will be amost completely determined. The profile could be cut shorter if part of the bulb volume is added to the fairing behind the main body of the bulb. But it is though that such a volume distribution would not be as effective for wave generation as it could be at the forward part of the bulb.

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*As noted later, it is no longer believed that bluntness of the waterplane is a valid criterion for rejecting a bulb shape. In fact, it may indeed prove to be desirable. But it is still considered important that the waterline at the free surface during the ship's motion be relatively fine.

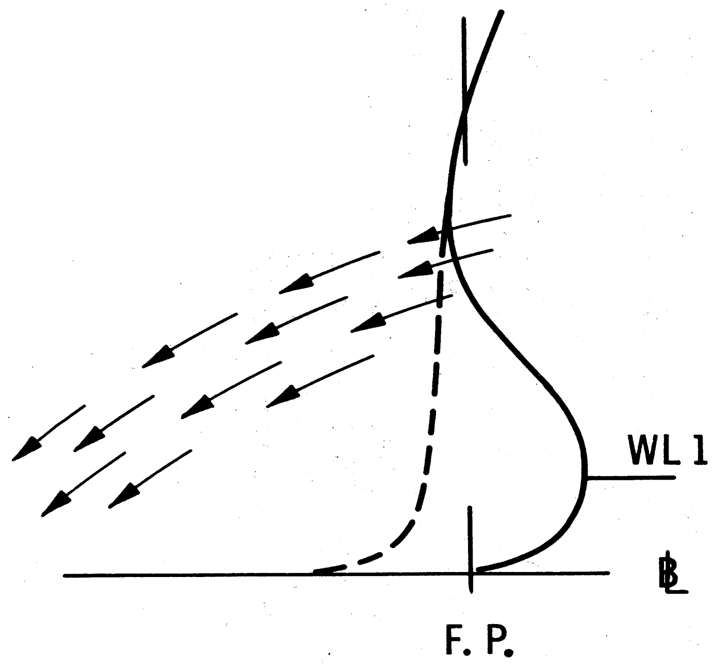


Fig. 6a. Typical flow in vicinity of bulbous bow.

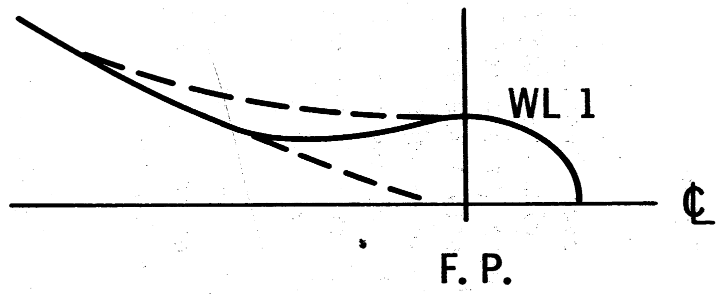


Fig. 6b. Variations of waterline through bulbous bow.

GEOMETRIC CHARACTERISTICS OF BULBS

In the course of this development, five configurations were developed. The last three were designed with the longitudinal center aft of the FP. Having previously decided upon the desired bulb area, the question arose as to whether the area should include the area of the conventional forebody at that position, or if it should be an added area. Recognizing that it would be the added bulb area that accounts for the reduction of the resistance of the parent form, the section area of the bulb is taken to be the area added to that of the corresponding section of the conventional forebody.

Continuing with the decision to maintain circular sections, the bulbs were designed by splitting the desired circular sections and appending the halves to either side of the conventional forebody at the appropriate longitudinal position.

The characteristics of the designed bulbs are listed in Table I. The characteristics are presented in an order which is considered to be of diminishing importance. Figures 7a and 7b show the actual designs. Further notation on the differences and similarities is in the section on sequential development.

In Table I, the longitudinal center and the bulb depth describes the position of a sphere, having as its radius the mean radius of the bulb, which can be positioned in the nose of the bulb. The longitudinal centroid describes the center of the volume added to the conventional forebody by the bulb and its fairing. The bulb volume includes the volume of the fairing.

At this point a brief summary of the resistance characteristics is presented. Figure 8 indicates the decrease of effective horsepower (EHP), as a percentage of the EHP of the ship fitted with the conventional bow, for each of the bulbs in the three standard test conditions. The graphs for the 100% displacement condition (no trim) are for the design speed of 19-1/2 knots ($v/\sqrt{L}$ = 0.85). Those for the 80% displacement condition (1% LBP trim) are for a speed of 20-1/2 knots (0.89). And the 60% displacement condition (2-1/2 LBP trim) graphs are for 21-1/2 knots (0.93).

TABLE I

CHARACTERISTICS OF BULBOUS BOWS
(PERCENTAGES)

Bulb	B1	B2	3A	3B	3C
Area at long'l center/A_x	11.4	11.4	18.0	18.0	18.0
Bulb depth below DWL/Draft	67	40	67	67	67
Long'l center fwd./LBP	+0.5	+0.5	-1.25	-1.25	-1.25
Long'l centroid fwd./LBP	-1.36	-0.80	-2.30	-2.34	-2.75
Bulb Volume/ Ship Volume	0.71	0.41*	1.26	1.22	1.44
Protrusion/LBP	2.16	2.16	1.79	1.79	1.79
Mean Radius/LBP	1.66	1.66	3.04	2.92	2.92
Bulb Beam/Ship	21	21	40	40	40

*Includes effect of cut-away forefoot.

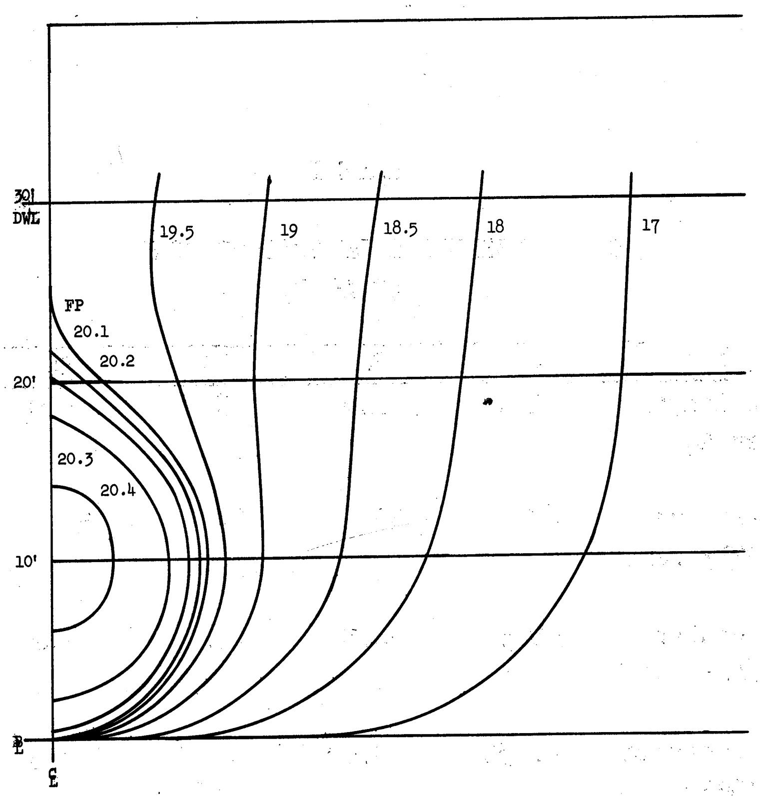


Fig. 7a. Sections of bulbous bow B1.

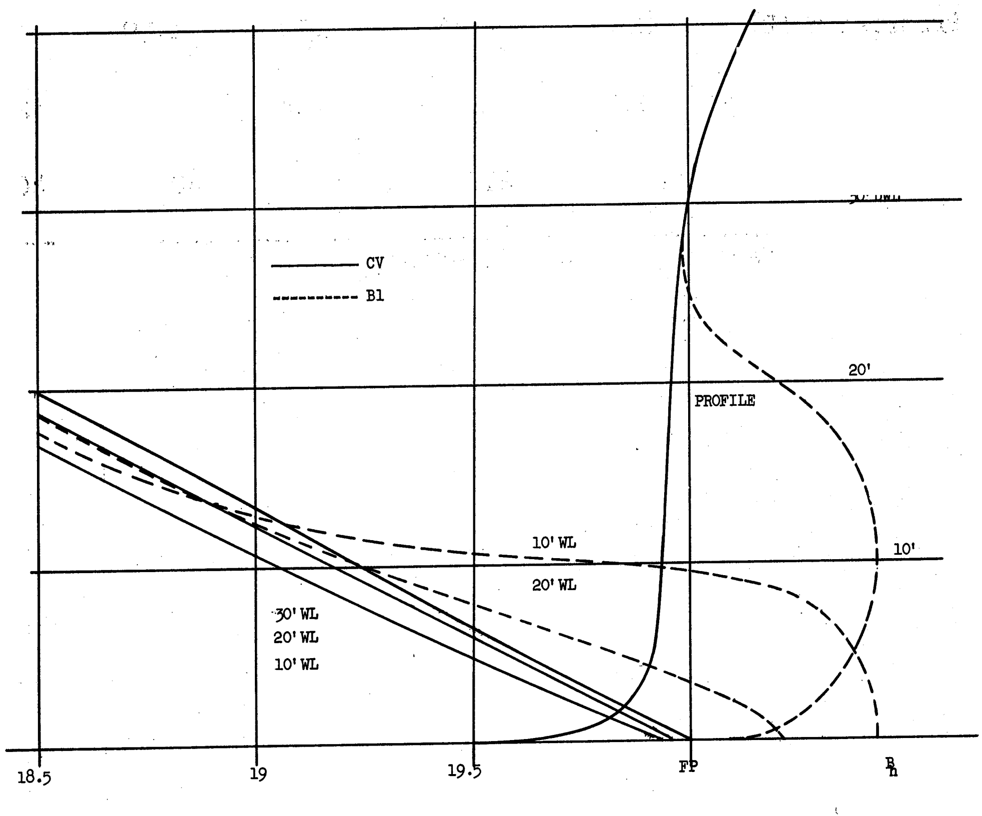


Fig. 7b. Conventional bow cv and bulbous bow B1 profiles.

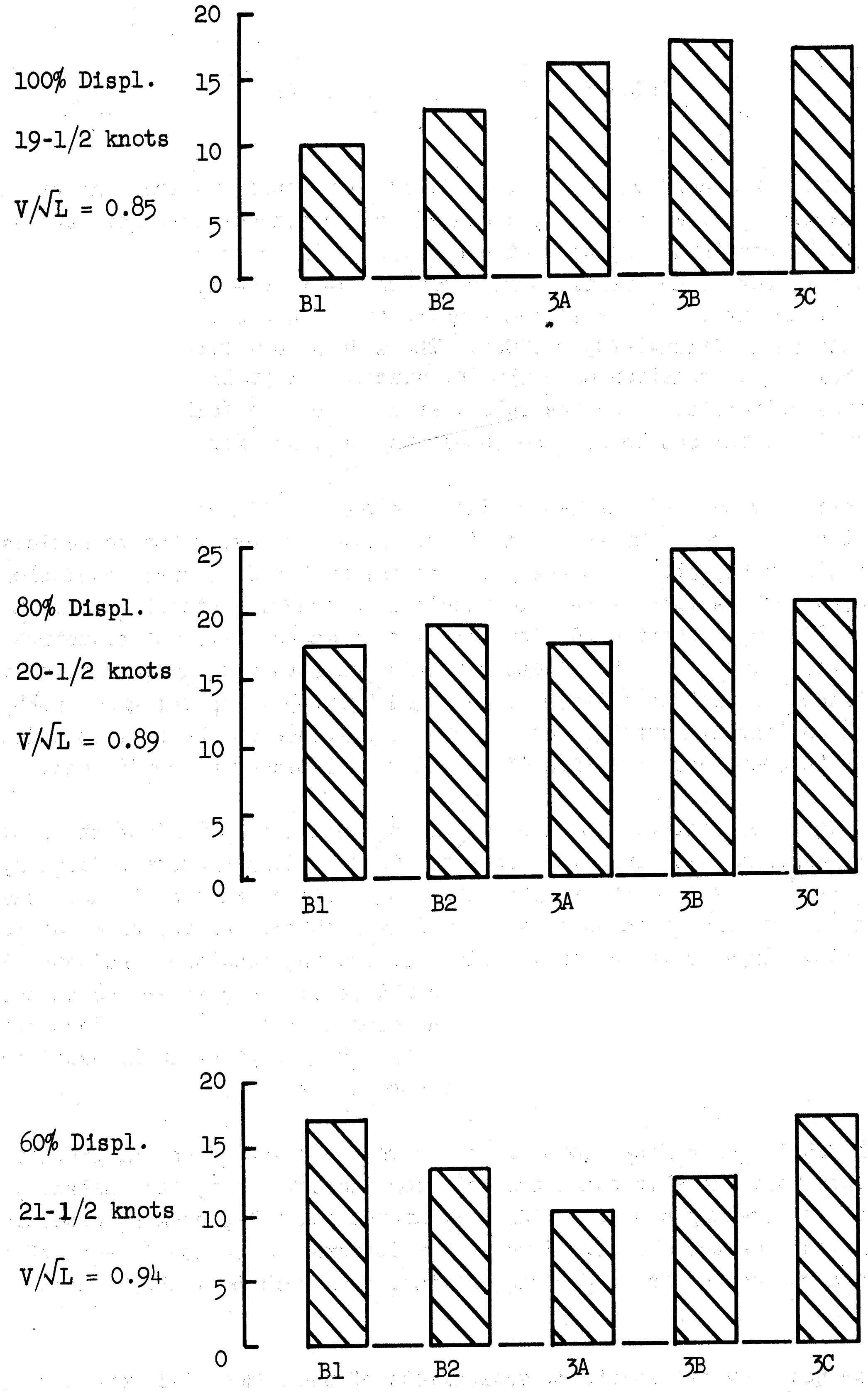


Fig. 8. Percent decrease of EHP due to addition of bulbs.

SEQUENTIAL DEVELOPMENT OF BULBS

As seen in Figure 8 each of the bulbous bow configurations has resulted in substantial decreases of EHP, compared to the conventional bow, at each of the three standard displacement conditions. Those results, as all others, are based on resistance tests carried out on 14-ft models, expanded to a 530-ft ship. Extrapolation was carried out using the ITTC model-ship correlation line, with an additional $\Delta C_F = .0004$. The models were fitted with a trip wire for turbulence stimulation of 0.036-in. diameter at 5% LBP aft of the FP for turbulence stimulation. On the bulbs, studs were used following normal practice for large bulbous bows. The rudder was in place for the resistance tests.

A brief summary of the sequential development will clarify the over-all systematic development of this hull form. After achieving the reductions by the first bulb B1, attention was given to the full displacement condition. The second bulb, a raised one, did result in a greater reduction of resistance in the 100% displacement condition, but with some sacrifice of reduction in the lightest condition. Still concentrating on attaining maximum reductions of resistance in full displacement, a third bulb, 3A, was designed which, as Figure 8 indicates, further decreased the resistance at the full load design speed, with continued sacrifice in both light displacement conditions.

Through observations noted below it was realized that minor changes in the form of that bulb could lead to the same full displacement reduction, and greater reductions over the rest of the range of loading conditions. That modification of the third bulb is denoted as bulb 3B. Again, observations of the flow characteristics in the lightest loading condition indicated that another modification of the third bulb could result in greater reductions of resistance in this loading condition. As seen in Figure 8, that last modification of the third bulb, denoted 3C, also had the effect of small sacrifices of reduction in the fuller displacement conditions.

The choice of a final form for a design would depend on the operating conditions that the ship owner predicts for his ship. If, for instance, it were to be operating almost exclusively at the full displacement condition, bulb 3B would be the choice. However, if it were to operate in each of the three conditions for equal periods of time, then bulb 3C might be most suitable.

The next several sections, subsections of the Sequential Development, note the step-by-step development, emphasizing the experimental observations, and delineating the differences between each of the five bulbous bow configurations. The results of thirty-three resistance tests are presented here in graphical form. An attempt has been made to keep to a minimum the number of non-graphical numberical values in the text of this report.

Along with the text of this report, at appropriate times, the changes of R_T/Δ and R_R/Δ are presented for each bulb in the three displacement conditions. Changes of C_T and C_R are given in Appendix A. Those curves will enable the reader to compare the several bulbs at a given displacement condition. To avoid a "clutter," there are two groups for each displacement condition: B1, B2, and 3A; 3A, 3B, and 3C. Also included in Appendix B are curves of the actual values of R_T/Δ, R_R/Δ, EHP, C_T, and C_R.

BULBOS BOW B1

The model with the first bulbous bow was tested over the same speed range as was done for the bulb-less hull. Figures 9 and 10 show the reductions of R_T/Δ and R_R/Δ, as a percentage of the corresponding value for the conventional bow. Comparable graphs of the changes in C_T and C_R are given in Appendix B.

In order to investigate the correctness of the bulb's longitudinal position and of the amplitude of the effective bulb wave, the wave profiles along the hull for the forward quarter of the length were recorded for the hull both with and without the bulb. It was noted from those wave profiles that the trough of the bulb-less hull wave occurred aft of the crest of the effective bulb wave. Thus, subsequent alternation in the longitudinal direction was to move the effective wave-generating center of the bulb aft.

It was also noted that the amplitude of the effective bulb wave in full displacement was insufficient to cause wave cancellation, and therefore something had to be done to increase the wave amplitude. In the 60% displacement condition, the amplitude of the effective bulb was sufficient. (Again, see Figures 9 and 10.)

At the 60% condition, the static waterline was near the vertical center of bulb B1, thus creating a very blunt waterplane. It was noticed, while conducting the resistance tests, that at low speeds the flow around the forebody was greatly impeded by the blunt waterplane. But at higher speeds, the stagnation pressure forward of the bulb's blunt end was sufficient to raise the level of the water in the immediate vicinity so that water flowed very smoothly above and around the bulb. The effect of that flow is seen in the pictures in Figure 11. The resistance comparisons clearly reflect this change in the mode of flow. It was then recognized that such a flow might be utilized in the fuller displacement conditions.

In pursuing the problem of wave amplitude, it was realized that the greater reduction of resistance in the 60% condition, compared to the reduction achieved in the 100% condition, was due to the depth of immersion of the bulb. A series of tests was then devised that would quickly simulate the variation of the depth of the bulb in the full displacement condition.

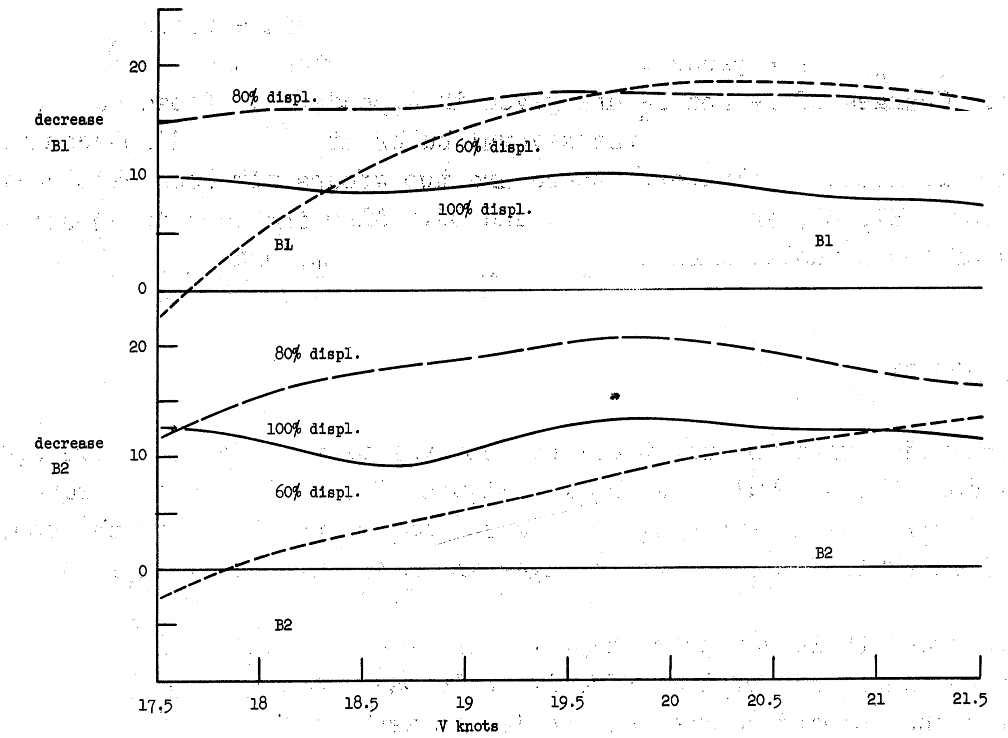


Fig. 9. Percent change of R_T/Δ due to addition of bulbs B1,B2.

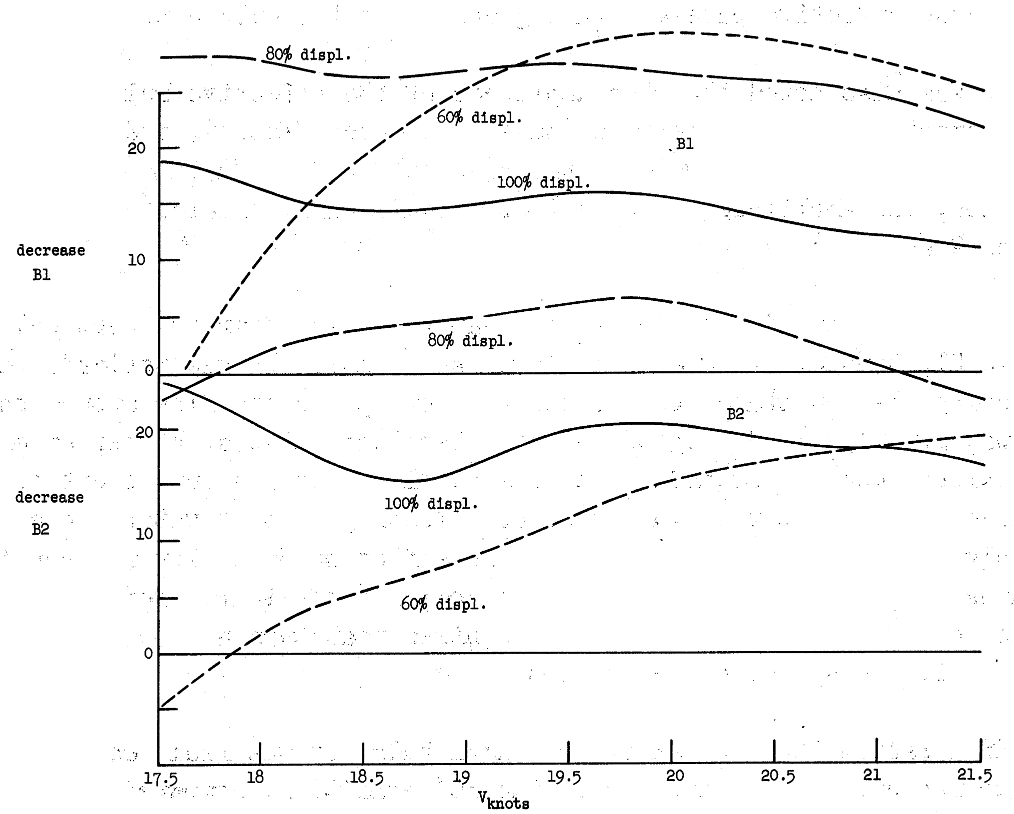
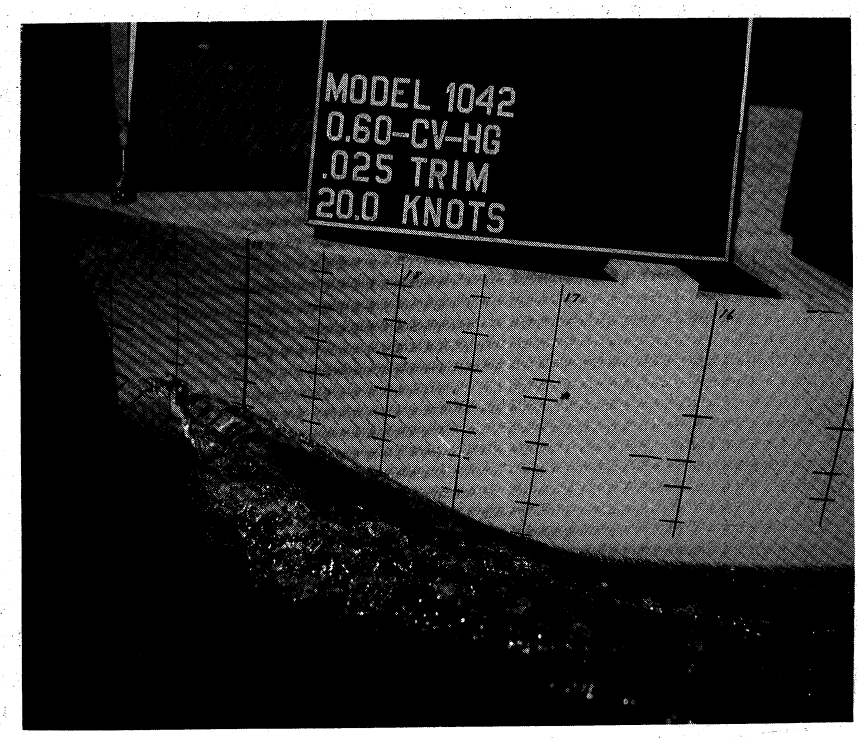


Fig. 10. Percent change of R_R/Δ due to addition of bulbs B1,B2.



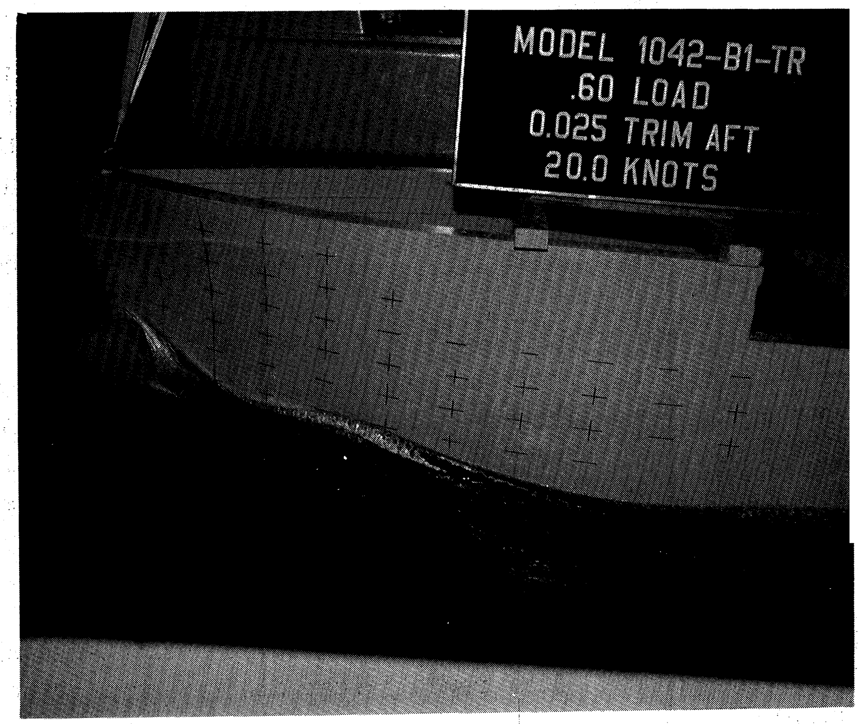


Fig. 11. Comparison of bow waves at 20 knots (60% displ., 2-1/2% trim).
Top: Conventional bow CV. Bottom: Bulbous bow B1.

Resistance tests were carried out on the model without the bulb in full displacement with several trim conditions. The trim ranged from 1% forward to 3% aft. Then with bulb B1, the same tests were run; thus varying the depth of the bulb from 76% to 40% of the mean draft. Hence comparisons were made for identical conditions.

The results showed that the most significant reductions were obtained when the bulb was closest to the surface. It appeared obvious that the next step in the development should then be to design and test a forebody having the bulb center closer to the surface than the 67% immersion of B1.

RAISED BULB B2

The subsequent design is shown in Figures 12a and 12b. In order to have the minimum number of parametric variations between bulbs B1 and B2, the longitudinal position and the area at the bulb center were kept the same, along with the actual sections forward of the bulb center. As noted in Table I, the nondimensional bulb volume, including the fairing of B2 is considerably less than that of B1. Actually, the bulb volumes are comparable, but the lower value for B2 is due to the cut-away forefoot (Figure 12b), and also reflects the quicker fairing into the conventional forebody at the higher waterlines.

Having found from the tests with B1 that the decreased immersion of the bulb would lead to greater resistance reductions in the full-displacement condition, the vertical position of B2 was chosen to be the same as the minimum value used in trimmed tests with B1. It was then expected that the level-keel, full displacement tests on B2 would lead to reductions of resistance comparable to those achieved in the 3% trim, full displacement condition with B1.

Although 75-B2 had less resistance in full displacement than did 75-B1 (Figures A1 and A2), the decrease was less than expected. Nevertheless, the reduction of resistance due to B2 is significant (over 13% at 19-1/2 knots). Comparative photographs of the waves appear in Figure 13. Figures 9 and 10 show reductions of R_T/Δ and R_R/Δ; and changes of C_T and C_R are given in Appendix B.

Specifically, the achieved difference in resistance between B1 and B2 was about 60% of the expected difference. That discrepancy may be accounted for by two effects:

1. The flow conditions around the raised bulb B2 are different from the flow conditions around the lowered bulb in trimmed condition.

2. In trimmed condition, the flow around the stern with the bulbous bows is different from the flow at the stern without a bulb.

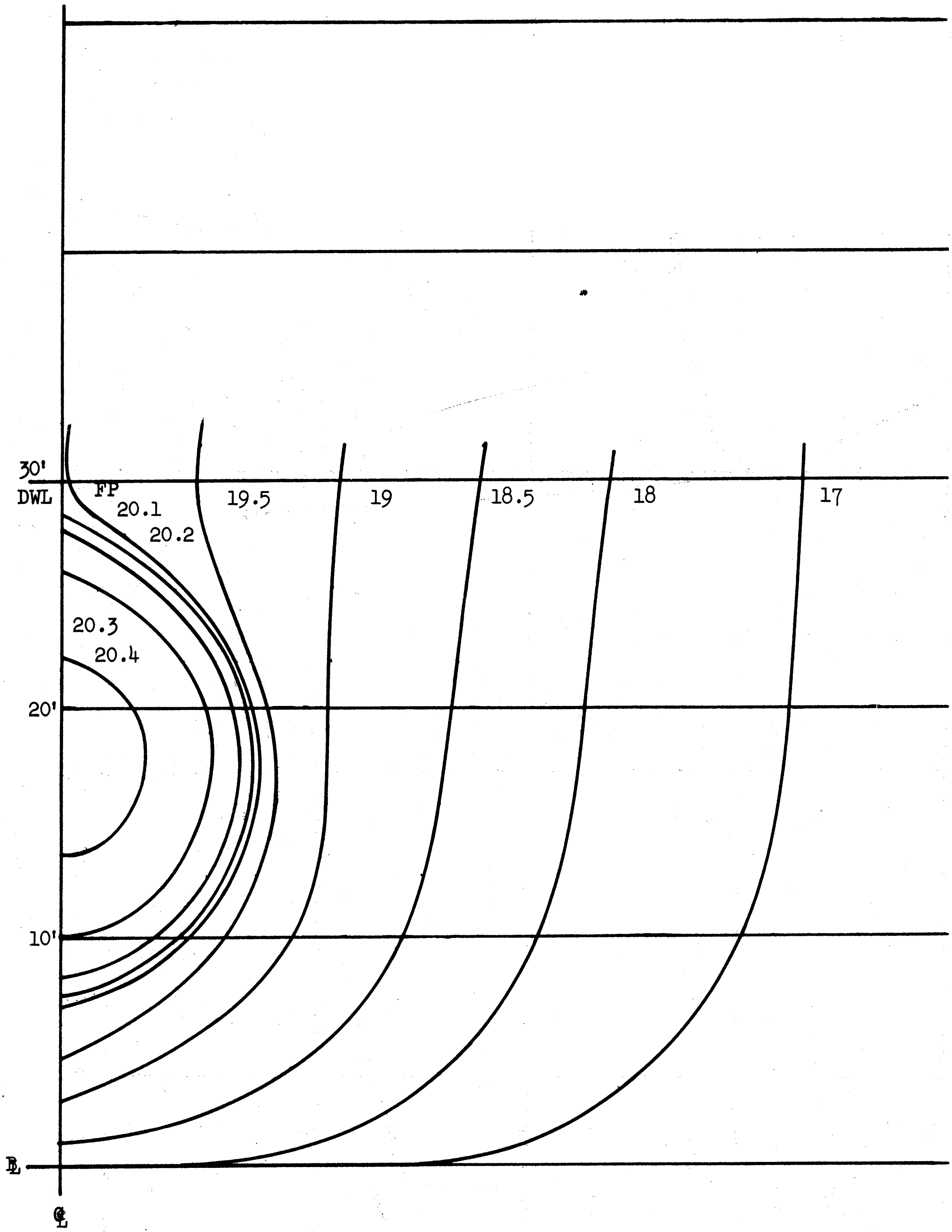


Fig. 12a. Sections of bulbous bow B2.

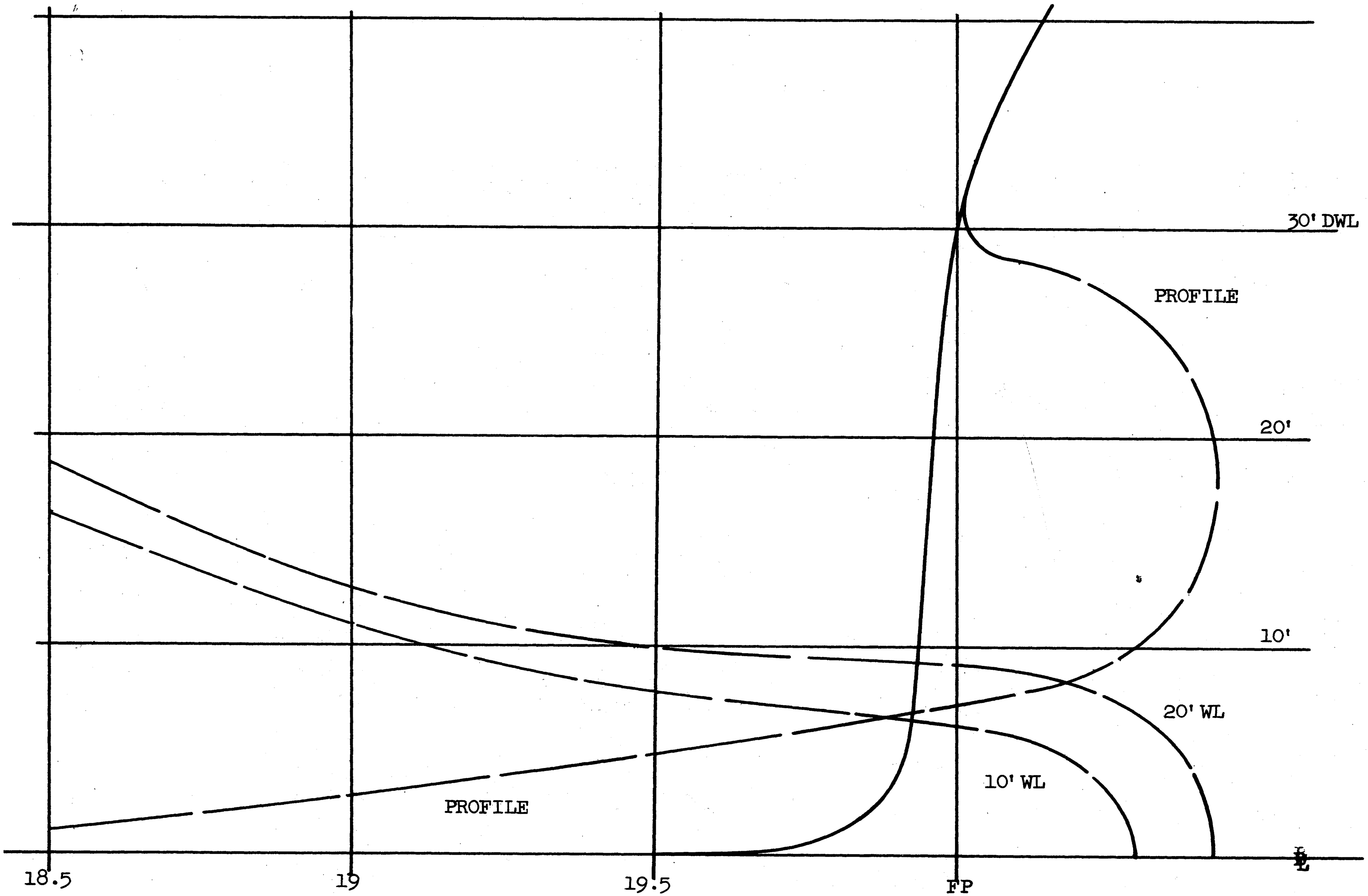
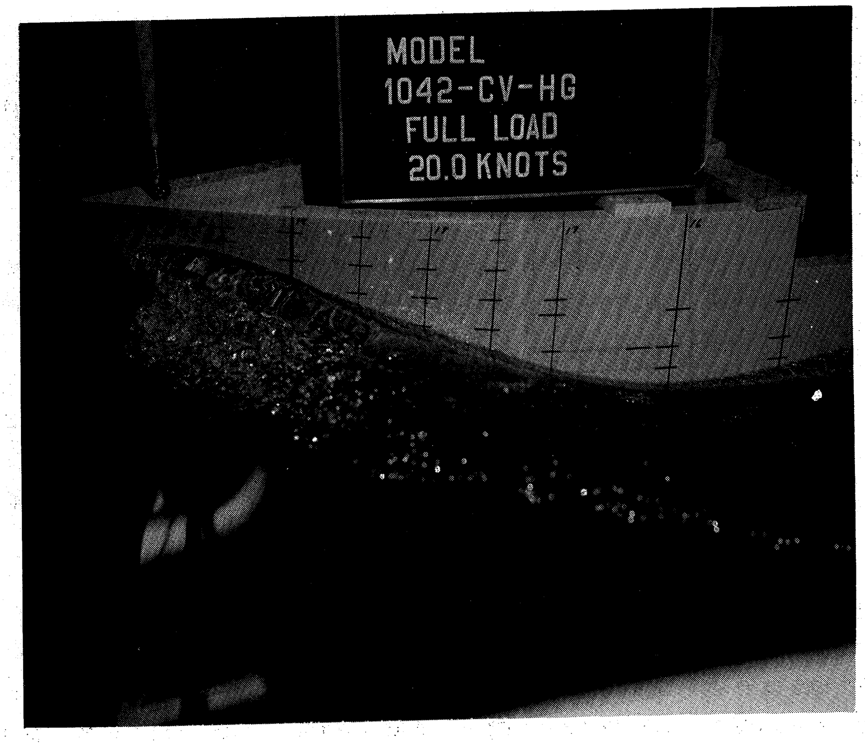


Fig. 12b. Bulbous bow B2 profile.



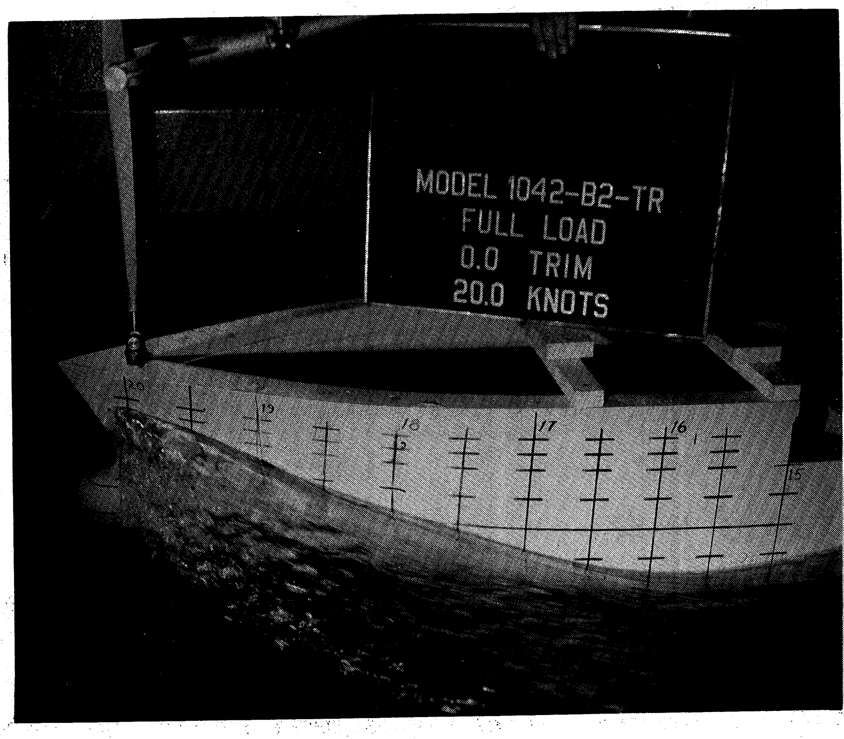


Fig. 13. Comparison of bow waves at 20 knots (100% displ., no trim).
Top: Conventional bow CV. Bottom: Bulbous bow B2.

But the most significant effect is that of the shape of the section area curve during both trimmed and level-keel conditions. Recalling that the volumes of the lowered bulb and the raised bulb are comparable, and noting that when the model is trimmed the section area curve becomes much finer in the forebody than at level keel, it is then seen that the ratio of bulb volume to forebody volume is much greater for B1 in the trimmed condition than it is for B2 in the level-keel condition. Generally, this means that the potential ability of the bulb to cancel the waves produced at the forebody is greater for B1 trimmed than for B2 in level-keel condition.

It was with this new insight that bulb B3 was designed, considering primarily the full-displacement condition. Prior to discussion of the next bulbous bow, however, attention is given to the lighter displacement conditions of 75-B2.

The raised bulb concept was pursued in this study was encouraged by the phenomena observed when B1 was tested at 60% displacement. In that test, the vertical center of the bulb was almost up to the static waterline; and the resistance reductions were very significant. The vertical position of B2 at 80% displacement is slightly below that for B1 at 60% displacement and so it was thought that comparable reductions would be obtained. In fact, the reductions of resistance were almost equal, as seen in Figures 9 and 10, in the range near and above the design speed.

In the 60% displacement condition, the static waterline on raised bulb B2 is at the lower quarter of the bulb. At the lower speeds, there is no smooth flow around the bulb. At the higher speeds, however, the flow is over the top of the bulb. The transition occurs near the design speed, as recorded visually in Figure 14. Although the reduction of resistance at 60% displacement due to the addition of B2 is not as great as that achieved by B1, the reduction is still positive and significant, as noted in Figures 8, 9, and 10.

CONCLUSIONS FROM B1 AND B2

After studying the results of the tests on the raised bulb B2, two tentative and seemingly contradictory conclusions were reached. The results of the 60% test on B1 and the 80% test on B2, which, respectively had the greatest reductions for the several displacement conditions, indicated the desirability of having the static waterline only slightly above the vertical center of the bulb. Yet the trimmed tests on B1, and subsequent trimmed tests on B2, indicated the favorable effects of having a larger bulb volume. Taken together, these would result in a large, raised bulb. But, reinterpreting, they could indicate that, if done appropriately, the decrease of bulb immersion could be exchanged for the increase in bulb volume.

Fig. 14. Comparison of flow around bulb B2. (60% displ., 2-1/2% trim).
Top: 19.1 knots. Bottom: 20.4 knots

The design of the next bulb tentatively substantiated that conclusion to a large degree. It could be a significant learning process, if the funds could be made available from the Maritime Administration or some other source, to test two more bulbs designed to prove the validity of that conclusion. Bulb 3A (and its modifications 3B and 3C) is a large lower bulb. It would be proposed that bulb B4 would be a large bulb raised to the position of B2; and bulb B5 would be a bulb the size of B2 raised even higher.

BULBOUS BOW 3A

As noted above, of the several design choices available at this point, a large lower bulb was chosen. The choice was made on the basis of seeking to substantiate the conclusion concerning bulb volume and vertical position as readily as possible. The apparently logical step was to create a lower bulb, like B1, but having a bulb-volume ratio like that for B1 in the full displacement, 3% trim condition. At the same time, the bulb's longitudinal position was moved aft in accord with the results of the earlier wave profile study. The design is shown in Figures 15a and 15b. Since the longitudinal position was now aft of the FP, this design utilized the "split" circular section at the bulb center, mentioned in the earlier section on geometric characteristics.

It would be appropriate, then, to expect that the reduction of resistance obtained with 3A in the full-displacement, level-keel condition would be comparable to that achieved by B1 in the 3% trim condition at full displacement.

As seen in Figure 8, the difference in the reduction of EHP between 3A and B2 at 100% displacement is greater than that between B2 and B1, thus the reduction achieved by 3A slightly surpassed the expected reduction. The changes of R_T/Δ and R_R/Δ due to the addition of 3A in all displacement conditions are given in Figures 16 and 17. Changes of C_T and C_R are given in Appendix B.

Due to the extreme width of the bulb, the possibility of separation in the down-flow region of the fairing, as sketched in Figure 6a, could not be neglected. Flow studies were conducted by the use of wool tufts attached to the surface of the hull. In all regions on and around the bulb and its fairing, the flow was found to be steady (indicating no separation) and in the directions predicted. Two photographs of these studies are shown in Figure 18.

It should be noted that although 75-3A had less resistance than 75-B2 at full displacement, the reductions in the lighter displacements were not as great, although they were still positive.

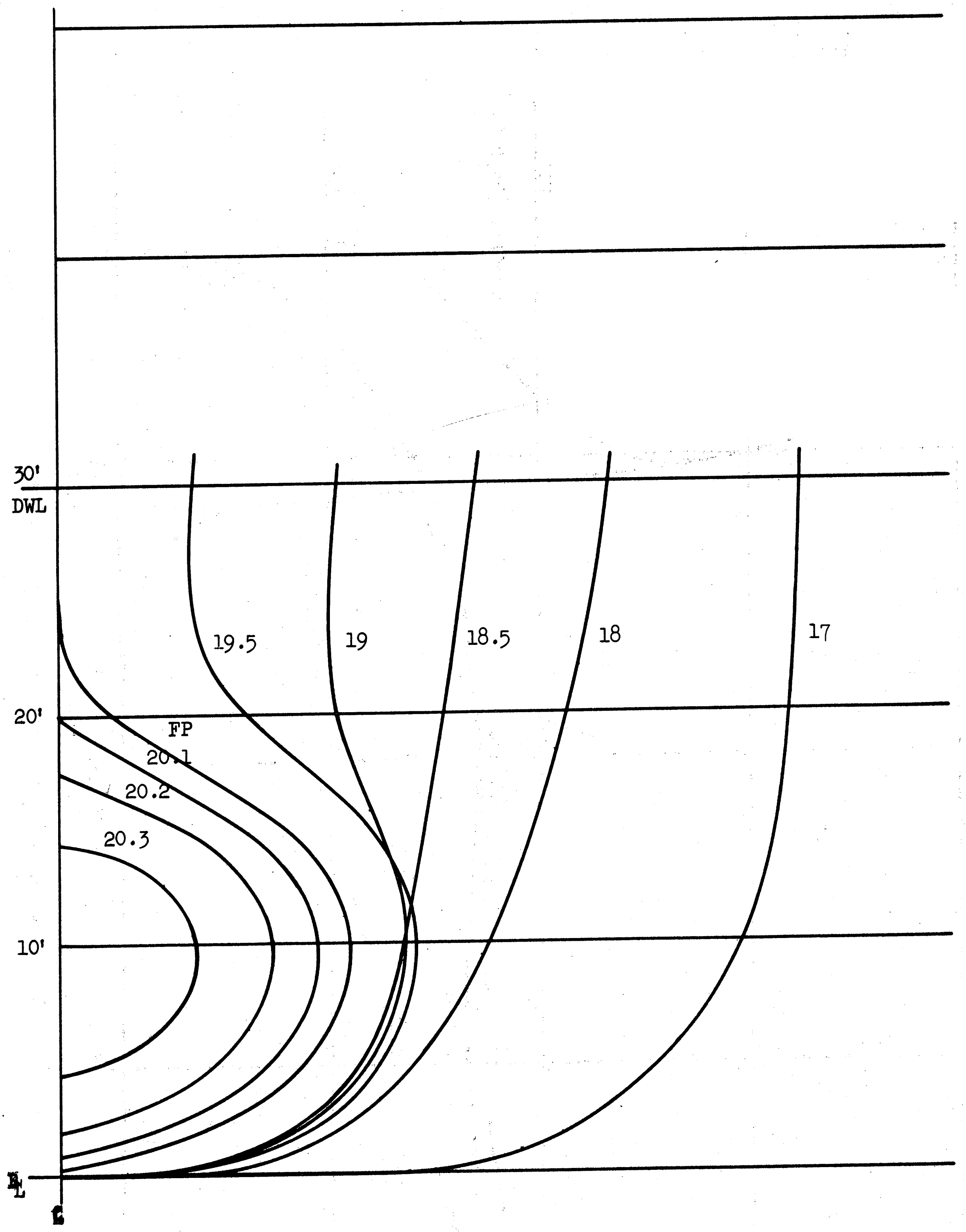


Fig. 15a. Sections of bulbous bow 3A.

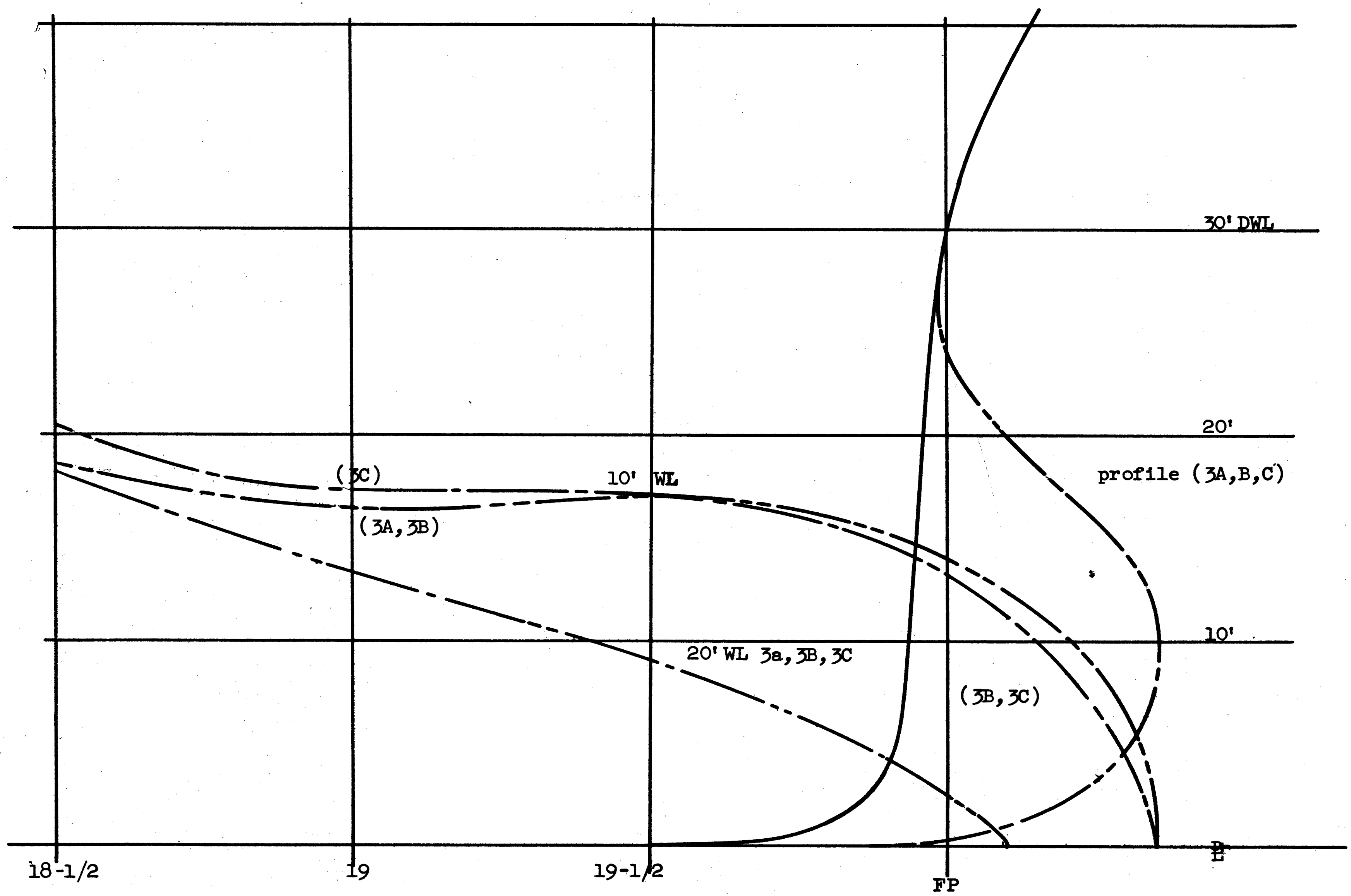


Fig. 15b. Bulbous bows 3A, 3B, 3C profiles.

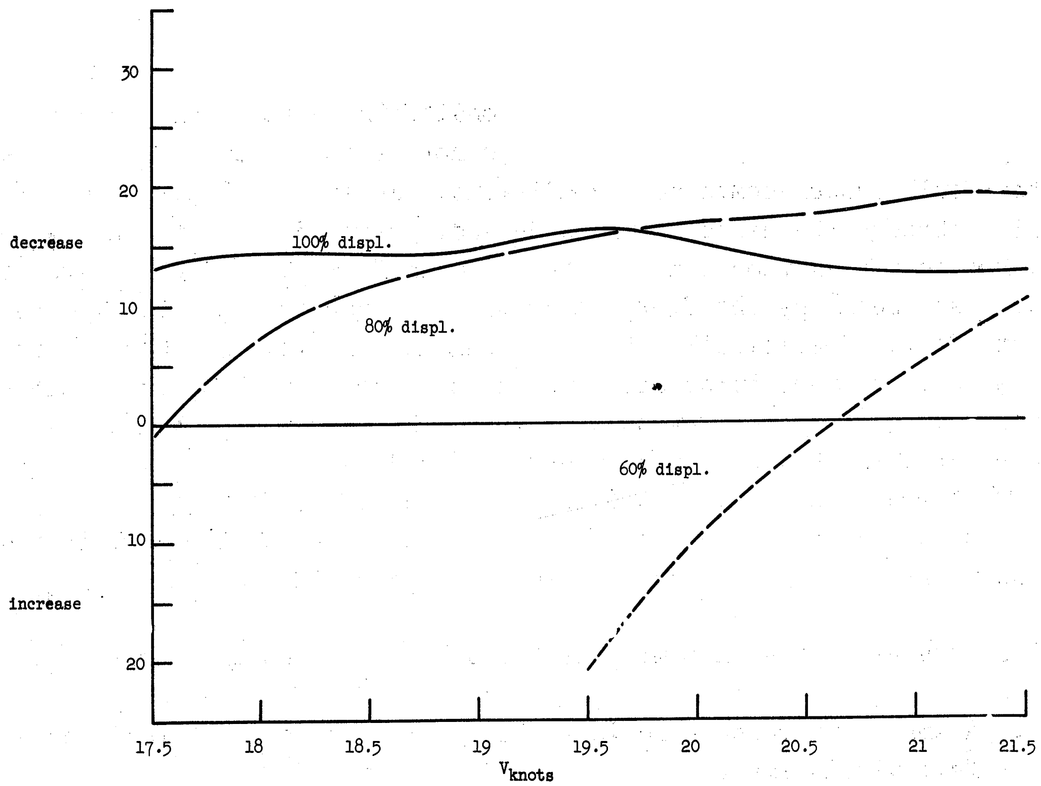


Fig. 16. Percent change of R_T/Δ due to addition of bulb 3A.

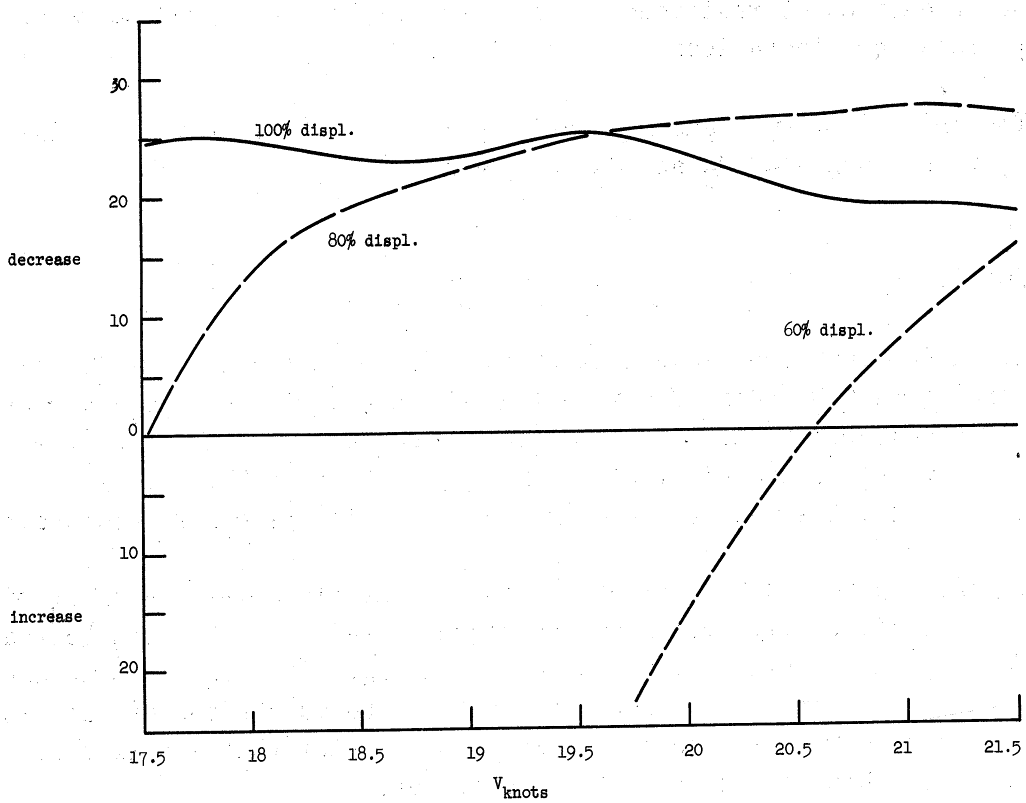


Fig. 17. Percent change R_R/Δ due to addition of bulb 3A.

MODIFICATION 3B

It was observed, in those lighter conditions, that the flow in the vicinity of the extremity of the bulb was not as smooth as had been observed for other bulbs under comparable conditions. As seen in Figure 15b, the waterline through the center of bulb 3A ended perpendicular to the centerline. Due to the extreme width of the bulb, a formidable frontal area of the bulb was "seen" by the flow, which was believed to attribute to the lack of smooth flow. Specifically, this "roughness" of flow was seen in the form of large-scale surface turbulence, which would undoubtedly cause "foaming" on the full-scale ship. Seeking to alleviate that condition, the tangent angles of the waterlines through the bulb were reduced, without altering the profile. That modification is noted in the different 10-ft waterlines forward of station 19-1/2 in Figure 15b. The change of sections is seen in Figure 19a, and the resulting bulbous bow sections appear in Figure 19b.

That change in the extremity of the bulb caused (as in Figure 8):

1. A small but measurable increase in the reduction of resistance at full displacement.
2. An additional 6% reduction of EHP at 80% displacement.
3. A moderate additional reduction at 60% displacement.

The significance of those results lies in the face that the large additional reduction of resistance in the 80% displacement conditions arose out of visual considerations.

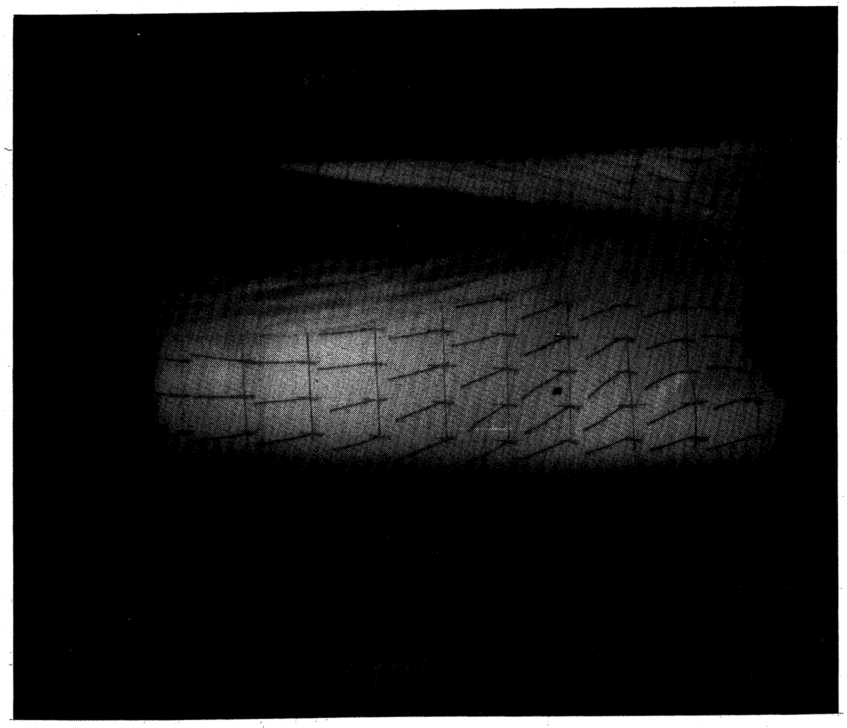
The changes of R_T/Δ and R_R/Δ due to the bulb 3B are given in Figures 19 and 20, with changes of C_T and C_R in Appendix B.

MODIFICATION 3C

At this point, the reductions of resistance in the two heavier displacement conditions (100% and 80%) were greater than had been obtained previously. But in the 60% condition, the reduction, although still positive, was significantly below that achieved with B1. It was hoped that this could be corrected without altering the resistance characteristics in the other two conditions.

In the lightest displacement condition, the flow over the front of the bulb was satisfactorily smooth at the higher speeds, but was considered unsatisfactory in the vicinity of the bulb fairing. That observation caused attention to be centered on the region aft of the bulb's center, and it appeared from an other wise unscientific point of view that a fuller fairing could correct that situation to a large degree.

The change that was made in the fairing is shown in Figure 22a, and the resulting bulbous bow sections appear in Figure 22b. As noted from Figure 8,



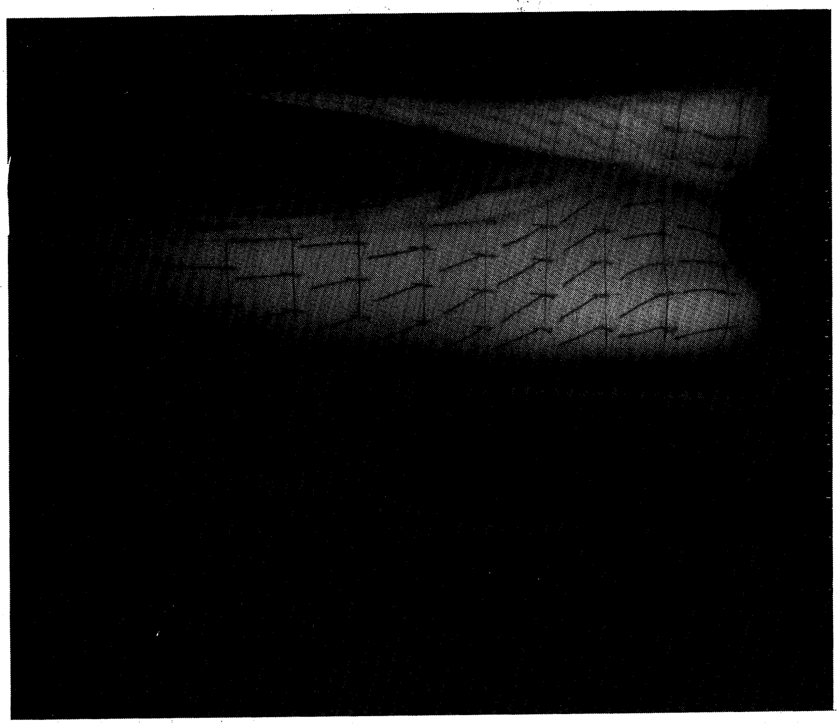


Fig. 18. Flow around bulbous bow 3A. Top: 20 knots at 100% displ., no trim. Bottom: 21 knots at 80% displ., 1% trim.

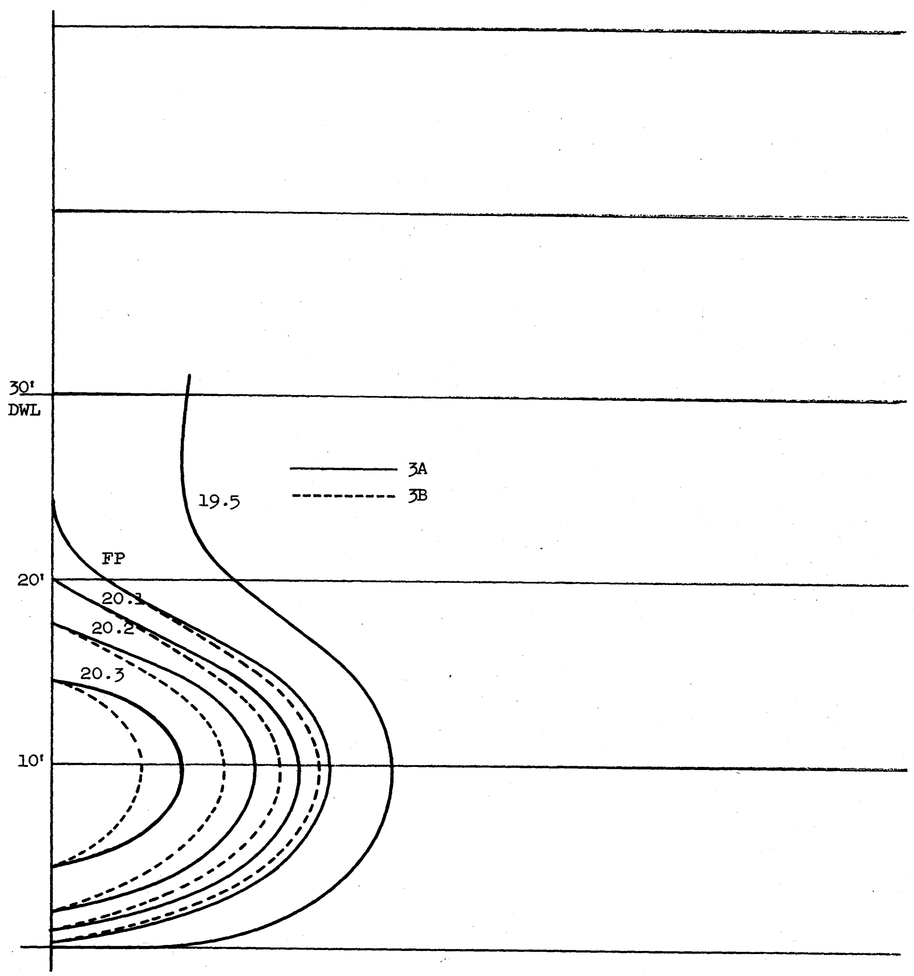


Fig. 19a. Changes of bulbous bow sections for finer extremity.

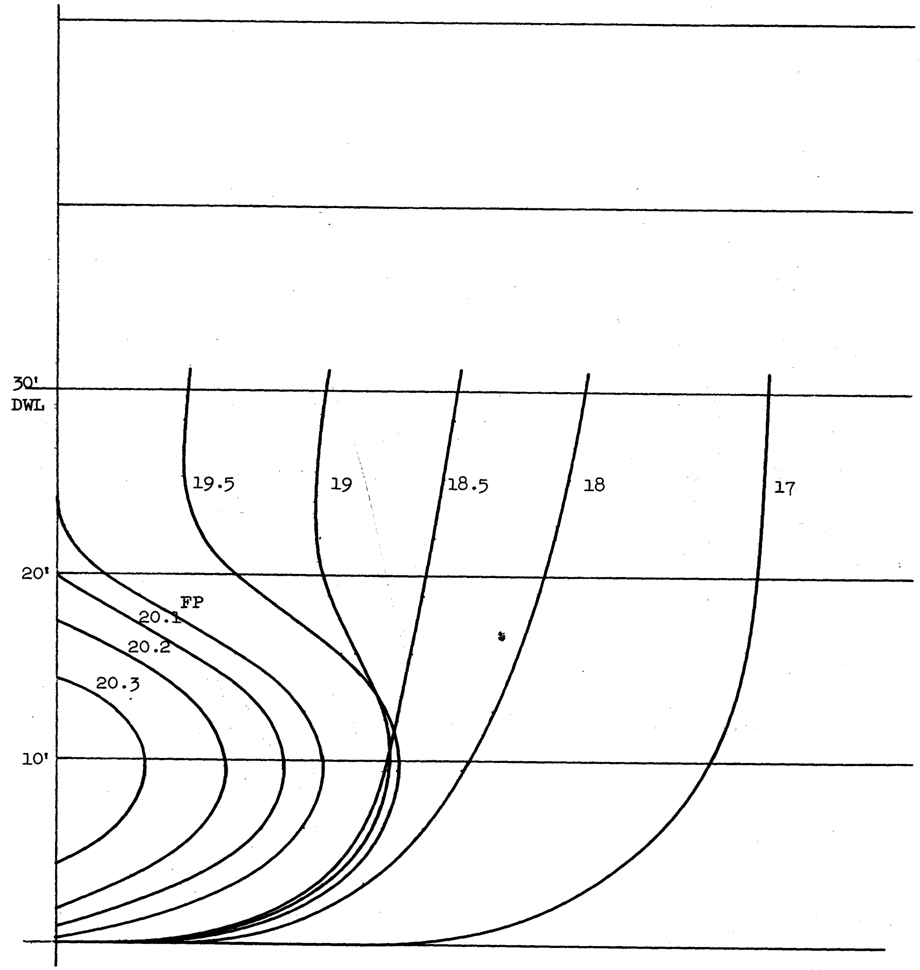


Fig. 19b. Sections of bulbous bow 3B.

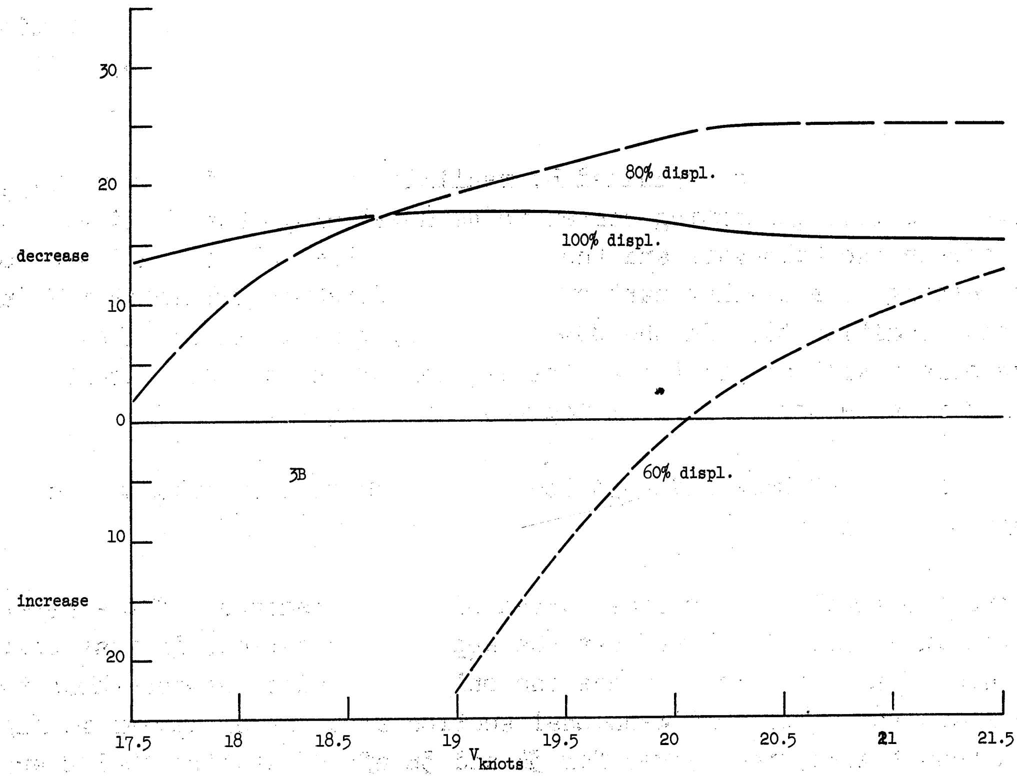


Fig. 20. Percent change of R_T/Δ due to addition of bulb 3B.

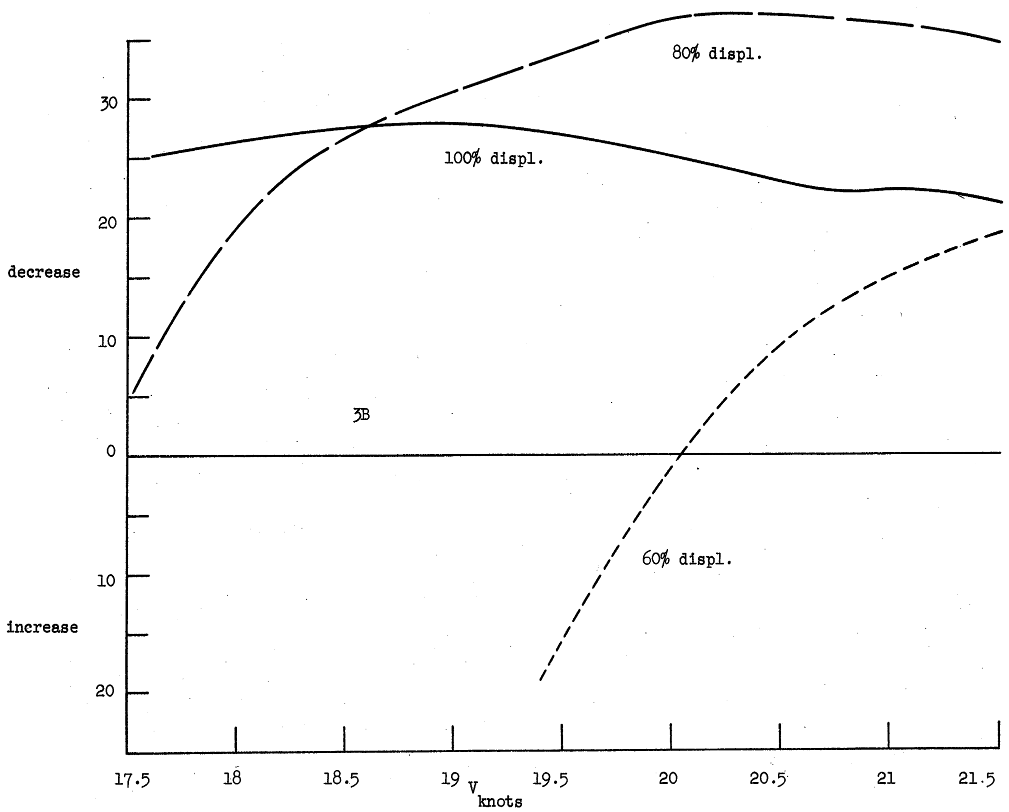


Fig. 21. Percent change of R_R/Δ due to addition of bulb 3B.

the effect of 3C at 60% displacement was to cause a resistance reduction as great as achieved by B1, with a very small loss, compared to 3B, at full displacement, and a moderate loss in the 80% displacement condition.

That consequence is explained by realizing that the fuller fairing causes the effective wave-generating center to be moved aft, thus causing a phase shift between the bulb-wave and the ship-wave. The volume added due to the fuller fairing is a smaller part of the total forebody volume in the full displacement condition than in the 80% condition; thus it is expected that the adverse effect will be greater at the lighter of the two displacement conditions for which the fuller fairing was not designed.

The changes of R_T/Δ and R_R/Δ due to the addition of bulb 3C are shown in Figures 23 and 24.

Nondimensional section area curves of the extremities of the several bulbs are given in Figure 25. Note that the appropriate curves, in that region, for 3B and 3C are identical, since the only difference between those two is the fairing, for which nondimensional section area curves appear in Figure 26. In that figure, the curves for 3A and 3B aft of station 19-1/2 are identical, since the only difference between the two of them is in the nose of the bulb.

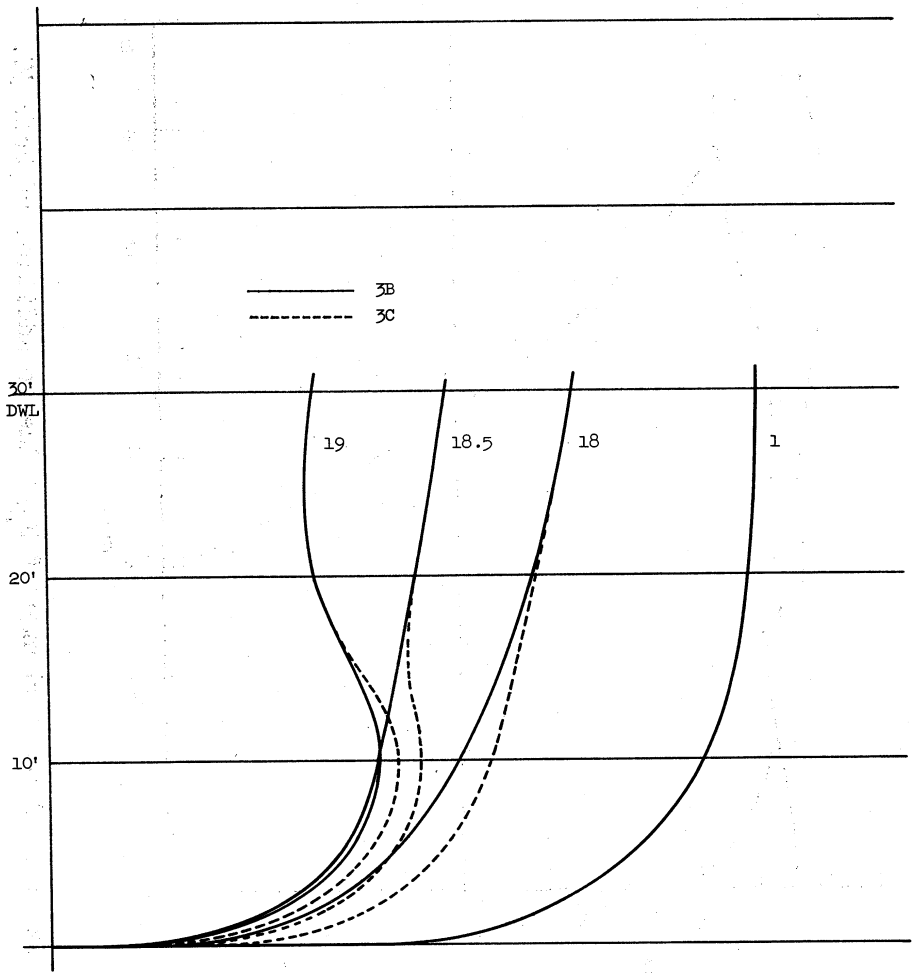


Fig. 22a. Change of bulbous bow sections for full fairing.

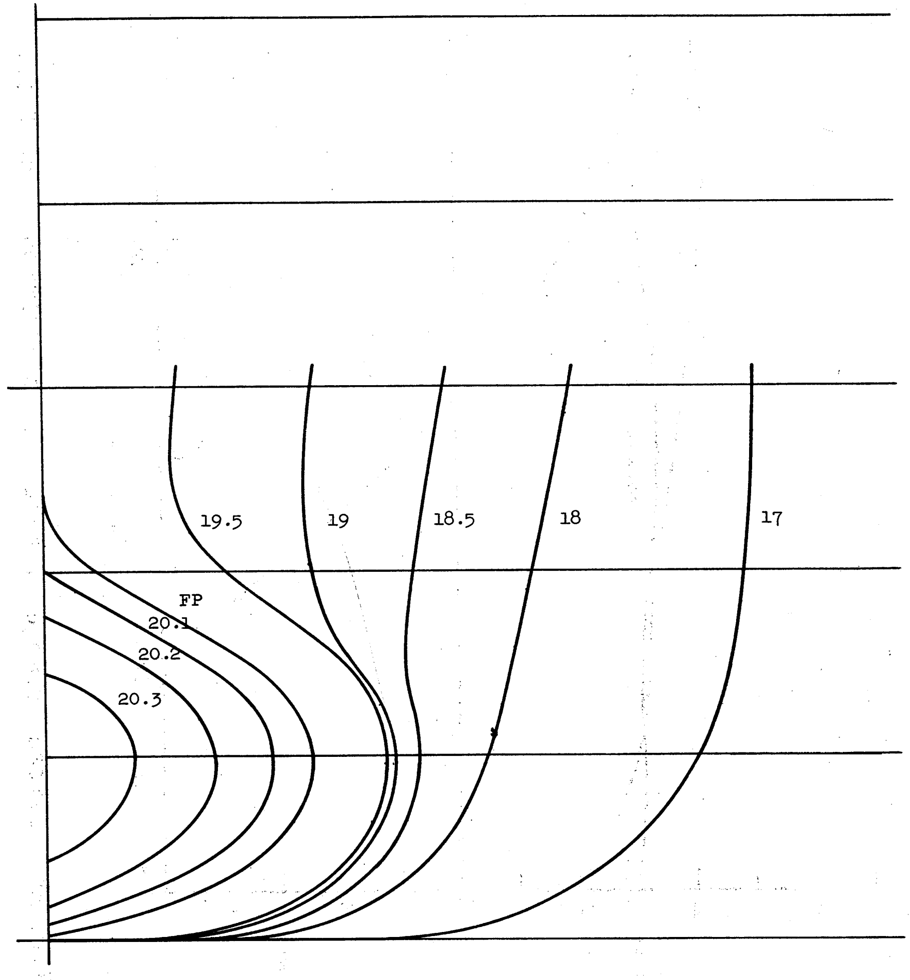


Fig. 22b. Sections of bulbous bow 3C.

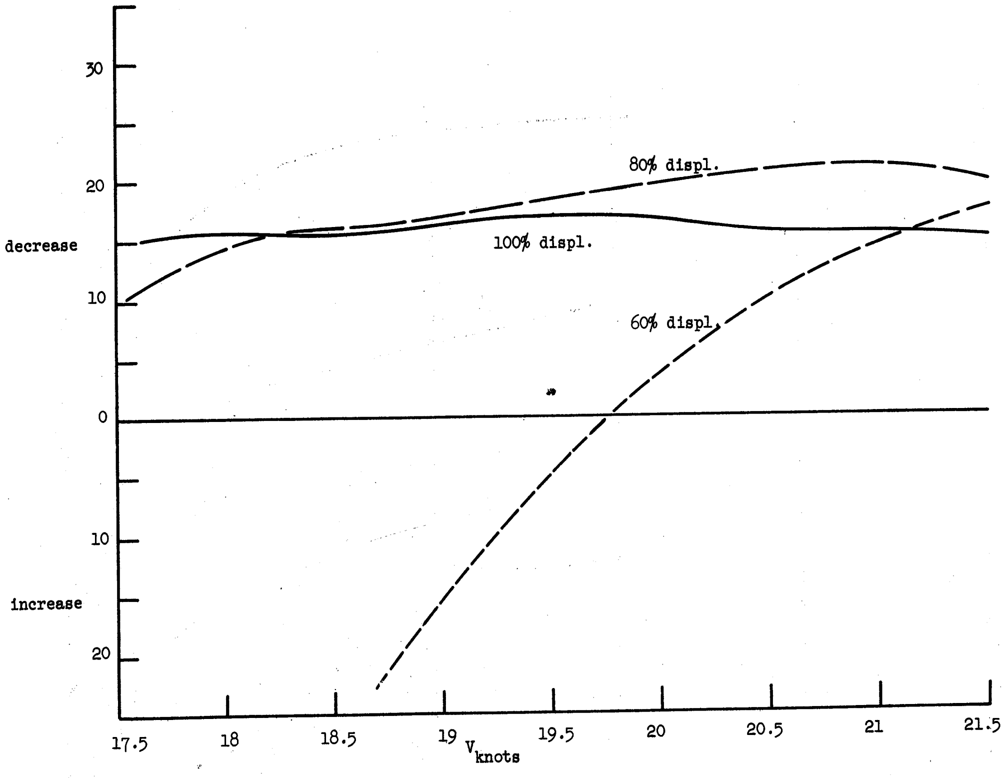


Fig. 23. Percent change of R_T/Δ due to addition of bulb 3C.

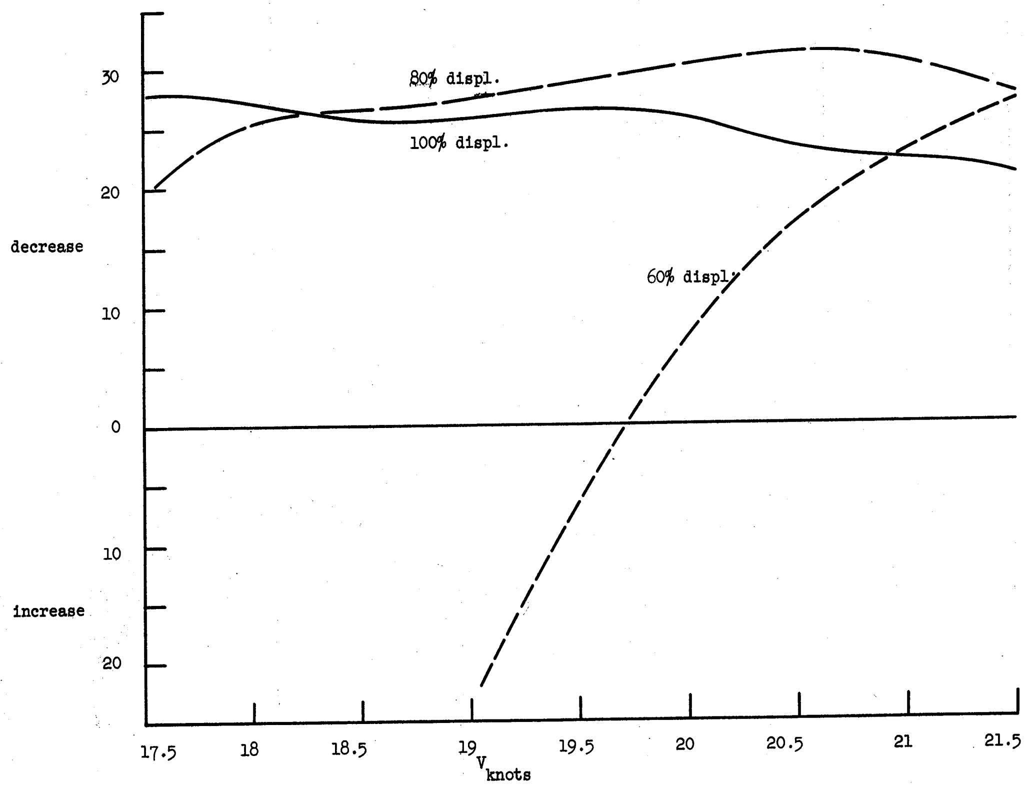


Fig. 24. Percent change of R_R/Δ due to addition of bulb 3C.

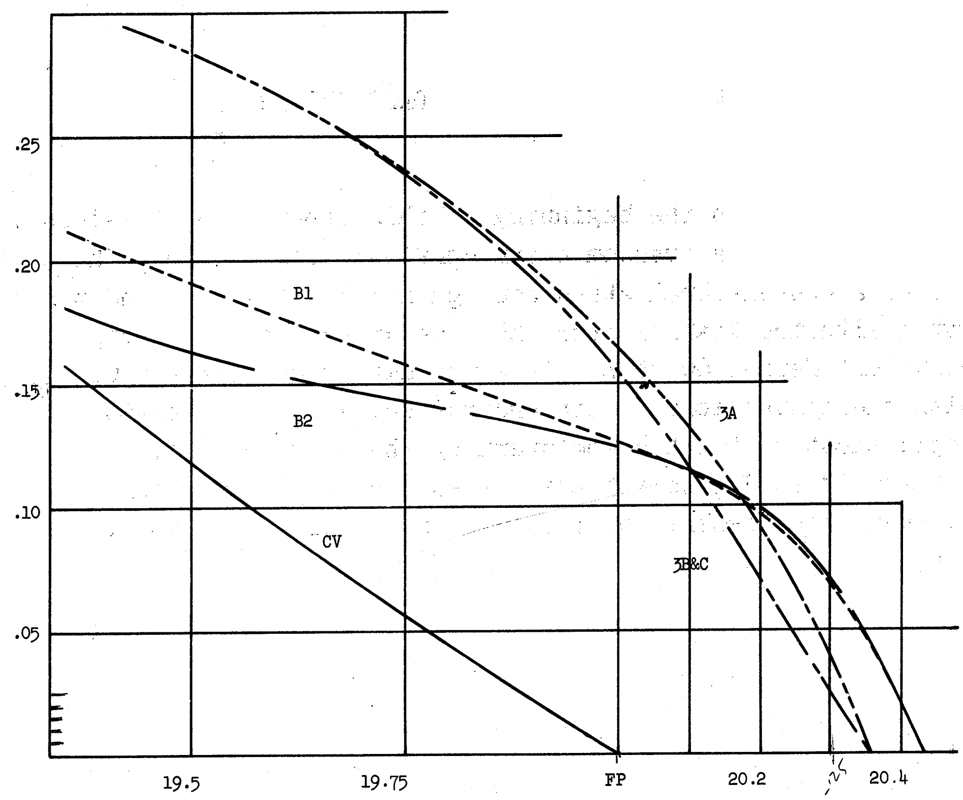


Fig. 25. Non-dimensional section areas of bulb extremities.

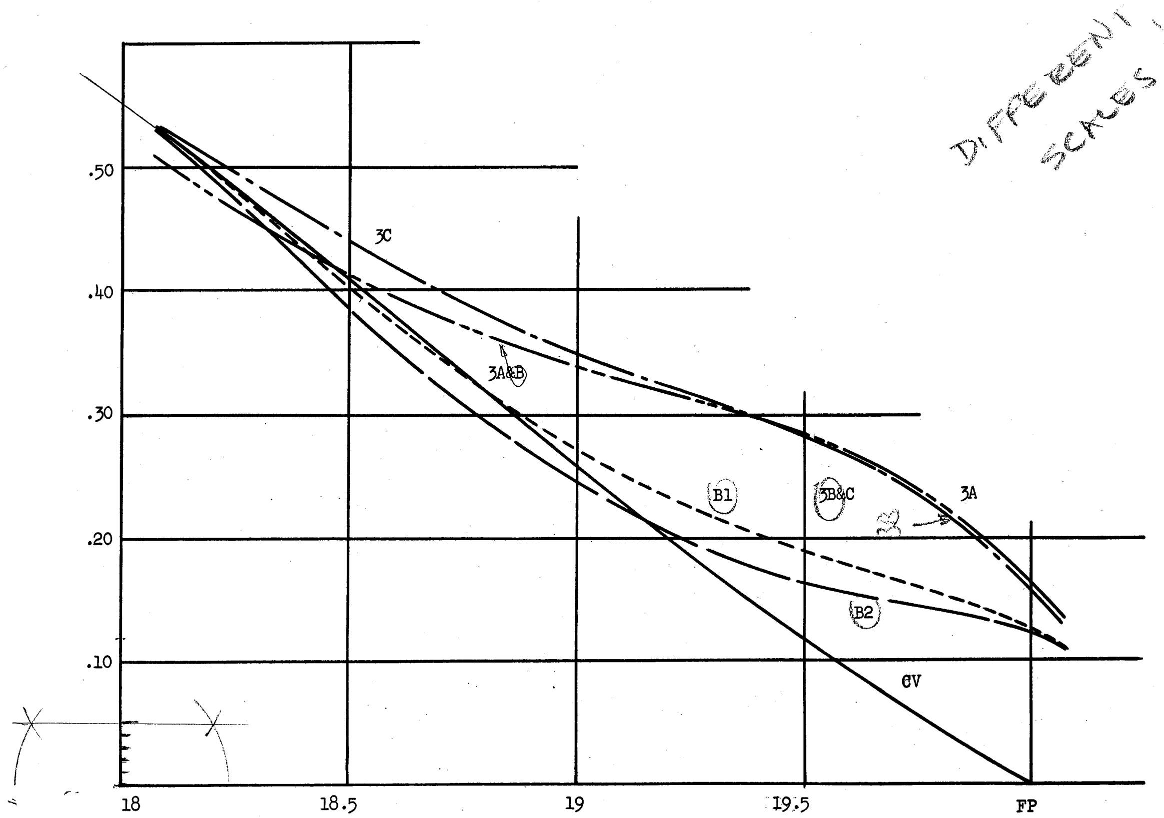


Fig. 26. Non-dimensional section areas of bulbous bow fairings.

COMPARISONS WITH STANDARD SERIES

It was mentioned in the beginning of this report that previous work had been carried out using a transom stern configuration, whereas the work reported here has used a conventional stern configuration. It was found that model 75-CV fitted with the transom stern had resistance characteristics the same as an equivalent Series-60 ship. Thus the difference between model 75-CV fitted with the conventional stern and the equivalent Series-60 ship is due to the replacement of the transom stern by the conventional. Included on Figures A1 and A2 in Appendix A are curves labeled S-60, which show the difference between the present model 75-CV and the slightly better Series-60 equivalent.

CONCLUDING REMARKS

Several specific conclusions have been reached concerning the design of bulbous bow for ships of the type under consideration here, which are probably equally valid for ships of other finesses at comparable speeds.

1. Fuller fairings of the bulb into the forebody are appropriate for the lighter displacement conditions.
2. Finer fairings are appropriate for the heavier displacement conditions. (Note: in no case did any of the bulb fairings used in this study "neck down" such that a waterline had reverse sloped. In some cases, however, the waterlines were parallel to the centerline.)
3. Waterlines through the bulb center with end tangent angles less than 90° have had beneficial effects in all displacement conditions.

Other conclusions have been reached from this study which are not expected to be quantitatively valid for all ships with finer forms, but which are certainly qualitatively valid.

4. The extremely large bulbs are most effective in the heavier displacement conditions.
5. The extremely large bulbs produce positive resistance reductions at the lighter displacement conditions, although not as great as those produced by the moderately sized bulbs.

Some tentative conclusions have been reached, and these along with other observations, have prompted the growth of ideas on how to continue the experimental research into the potential abilities of bulbous bows. Primarily, as expressed earlier in the section titled "Conclusions from B1 and B2," it is considered desirable to design and test at least two more bulbs which could give ample verification of the tentative conclusion that, if appropriately done, the extremely large size of the bulbs encountered here could be exchanged for less immersion of the smaller bulbs.

The one problem that would be encountered there, of course, is the resulting configuration in the lighter displacement conditions.

Inasmuch as bulb 3B achieved a 24% reduction of EHP in the 80% condition, it is thought that perhaps that bulb is not large enough to achieve resistance reductions of the same magnitude in the full displacement condition. Consequently, it is considered desirable to design and test a bulb, in addition to those proposed above, having a bulb-volume/forebody-volume ratio at full displacement equal to that of 3B in the 80% displacement condition.

Such a design probably exceeds the imagination of many readers. But it is strongly felt by the authors that preconceived notions about how a ship "ought to look" must be cast aside. These designs can really not be called bulbs and yet be consistent with the previous use of the term. Such "bulbous bows" have now been shown to be effective, and there is substantial evidence indicating that upper limits have not yet been reached, regardless of what these forms are called.

ACKNOWLEDGMENTS

The authors wish to acknowledge the extensive aid rendered by Mr. Bernard Young, without whose help the project would never have gotton off the ways, nor maintained headway throughout the past two years.

The authors are also indebted to Mr. J. Thomas Bringloe, whose computer programs for data analysis and graphical representations have significantly aided this program.

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APPENDIX A

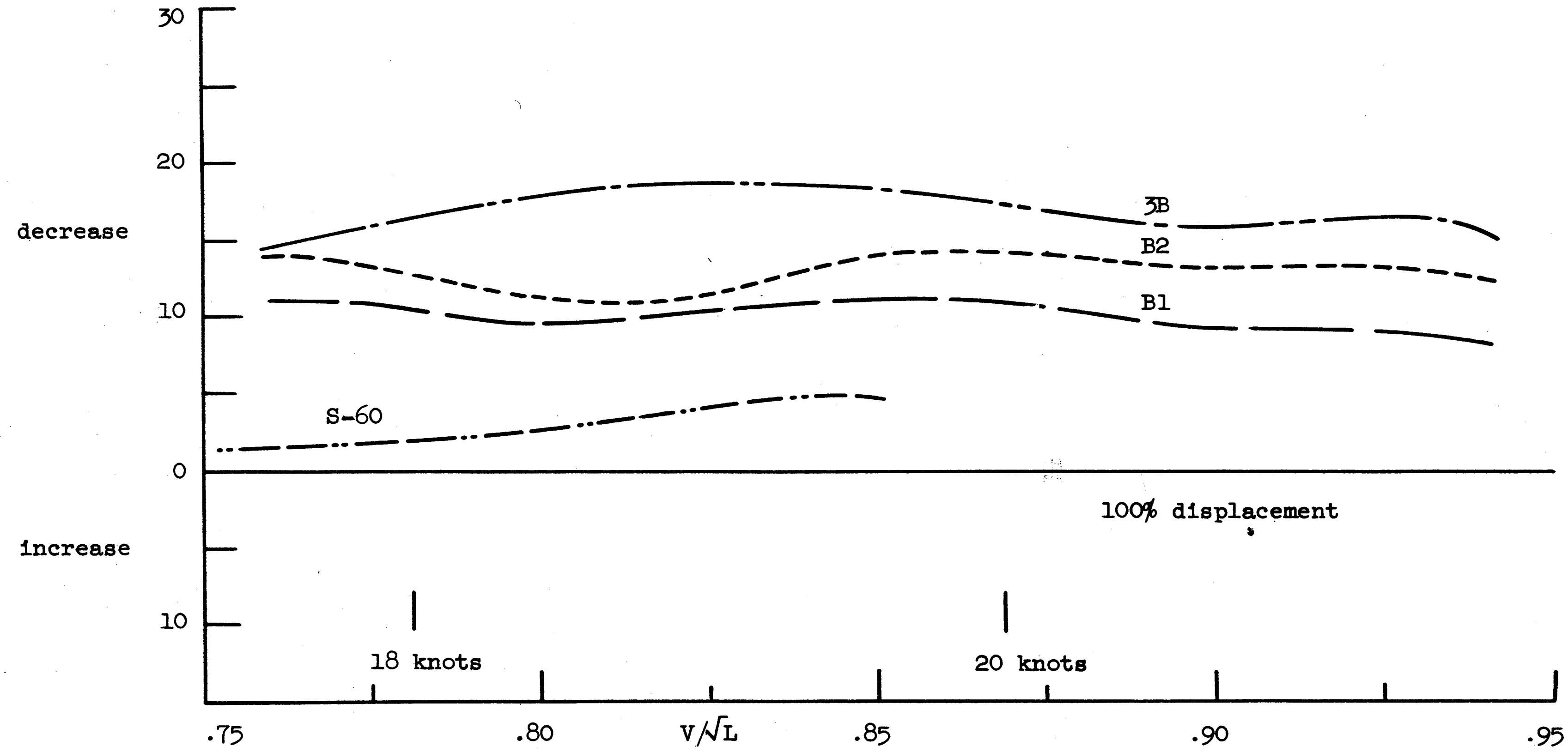

Fig. A1. Percent change of C_T due to addition of bulbs B1,B2,3B; S-60 comparison (100%).

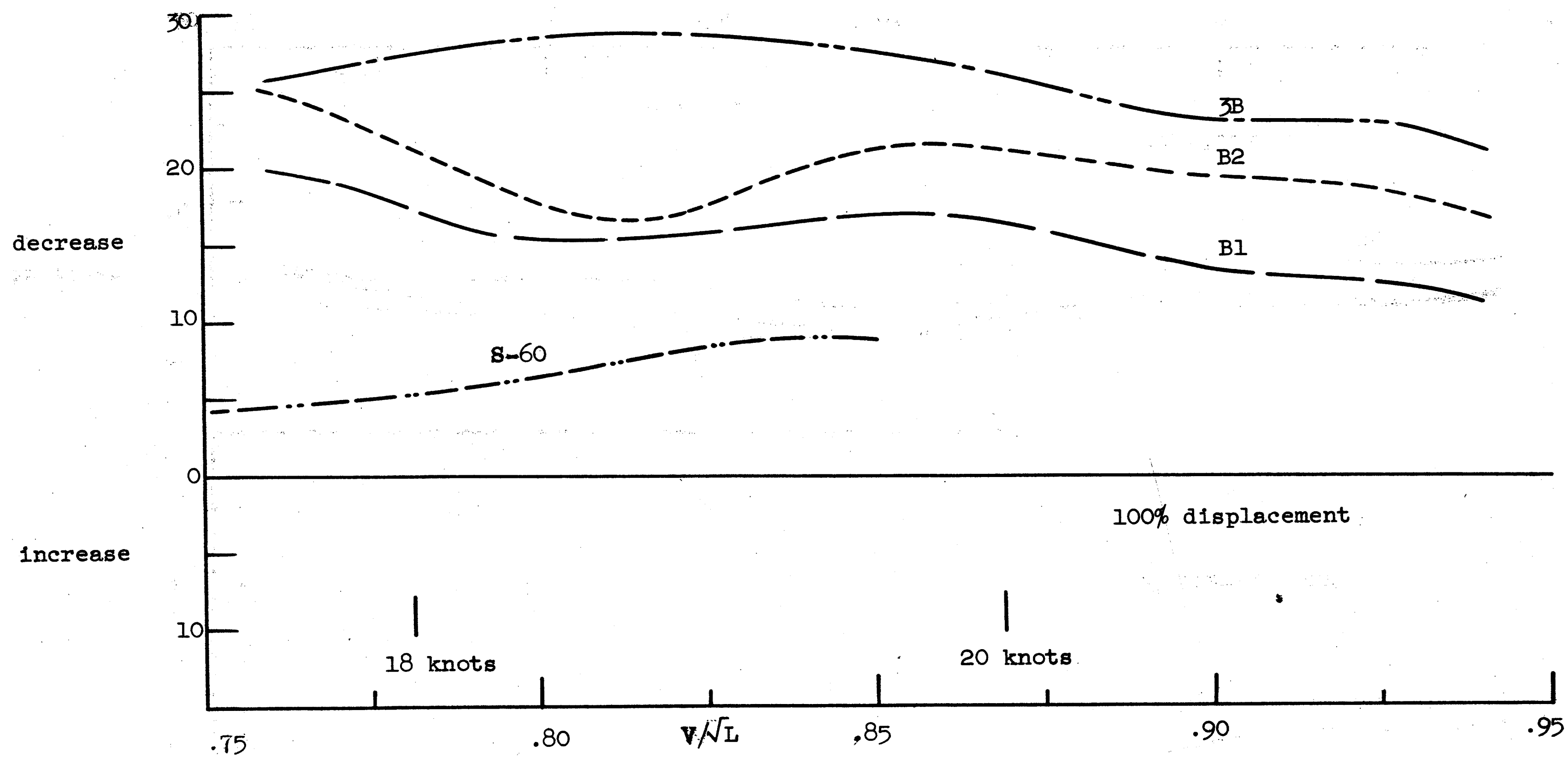

Fig. A2. Percent change of C_R due to addition of bulbs B1, B2, 3B; S-60 comparison (100%).

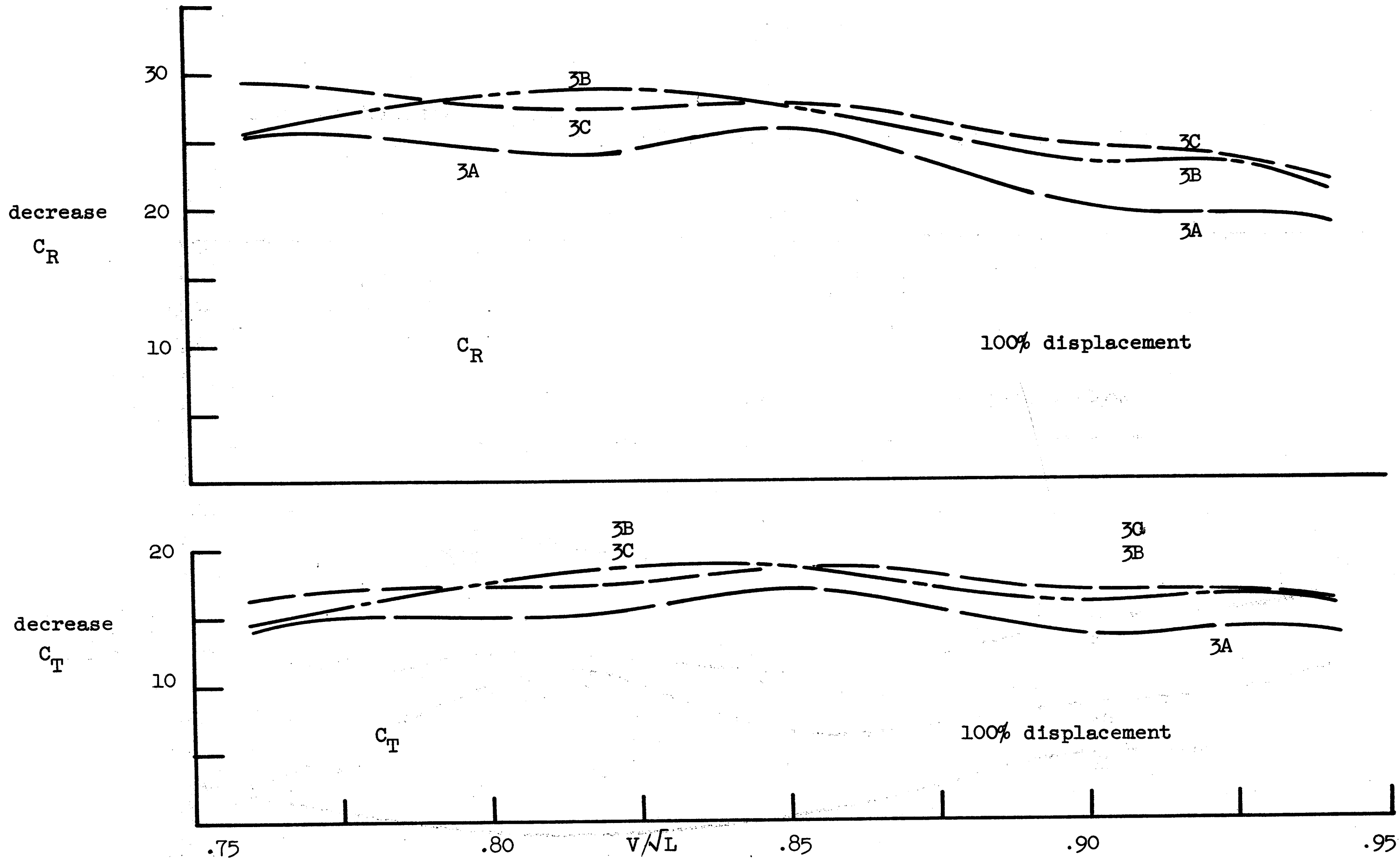

Fig. A3. Percent change of C_R and C_T due to addition of bulbs 3A, 3B, 3C (100%).

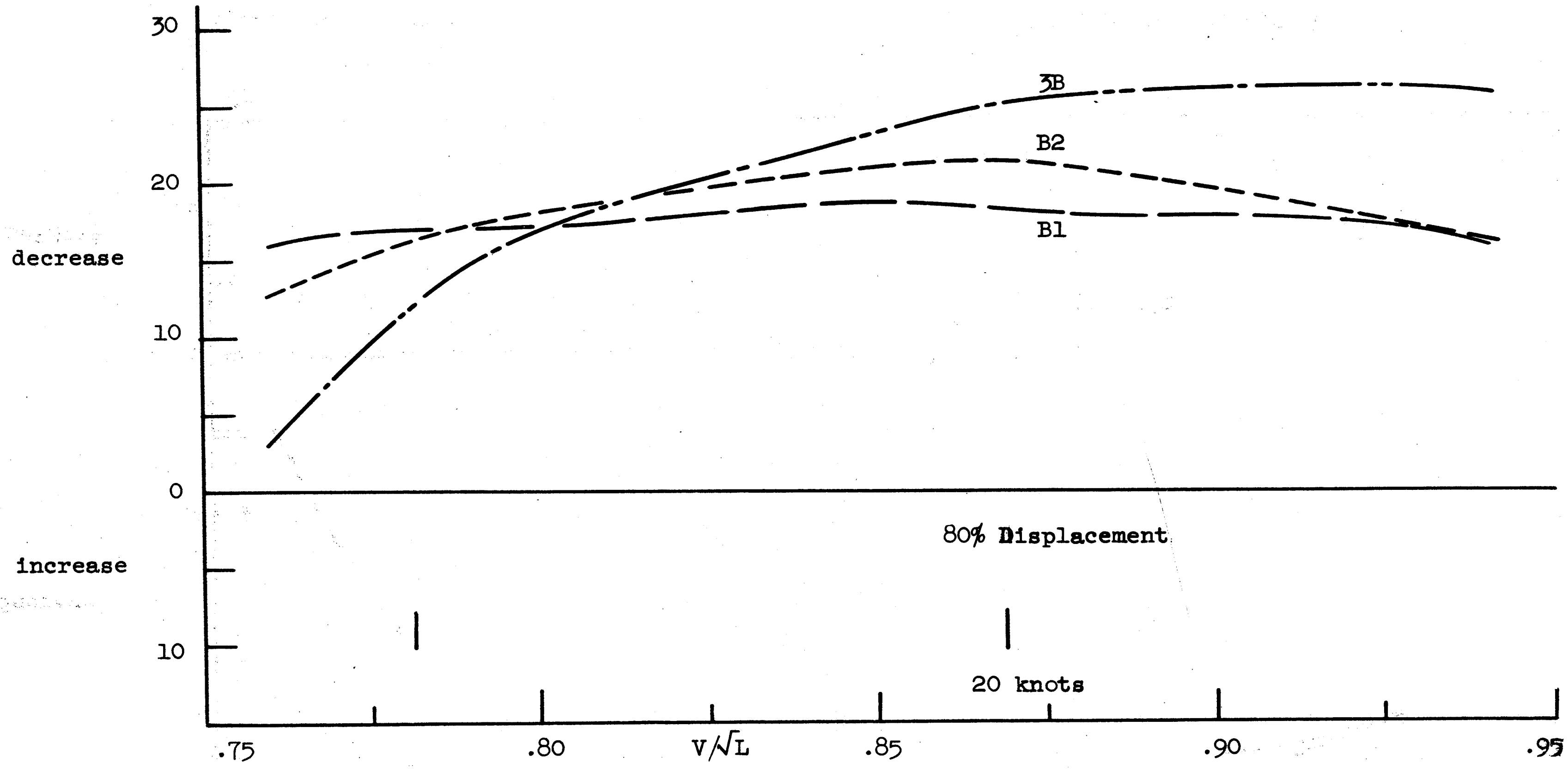

Fig. A4. Percent change of C_T due to addition of bulbs, B1, B2, 3B (80%).

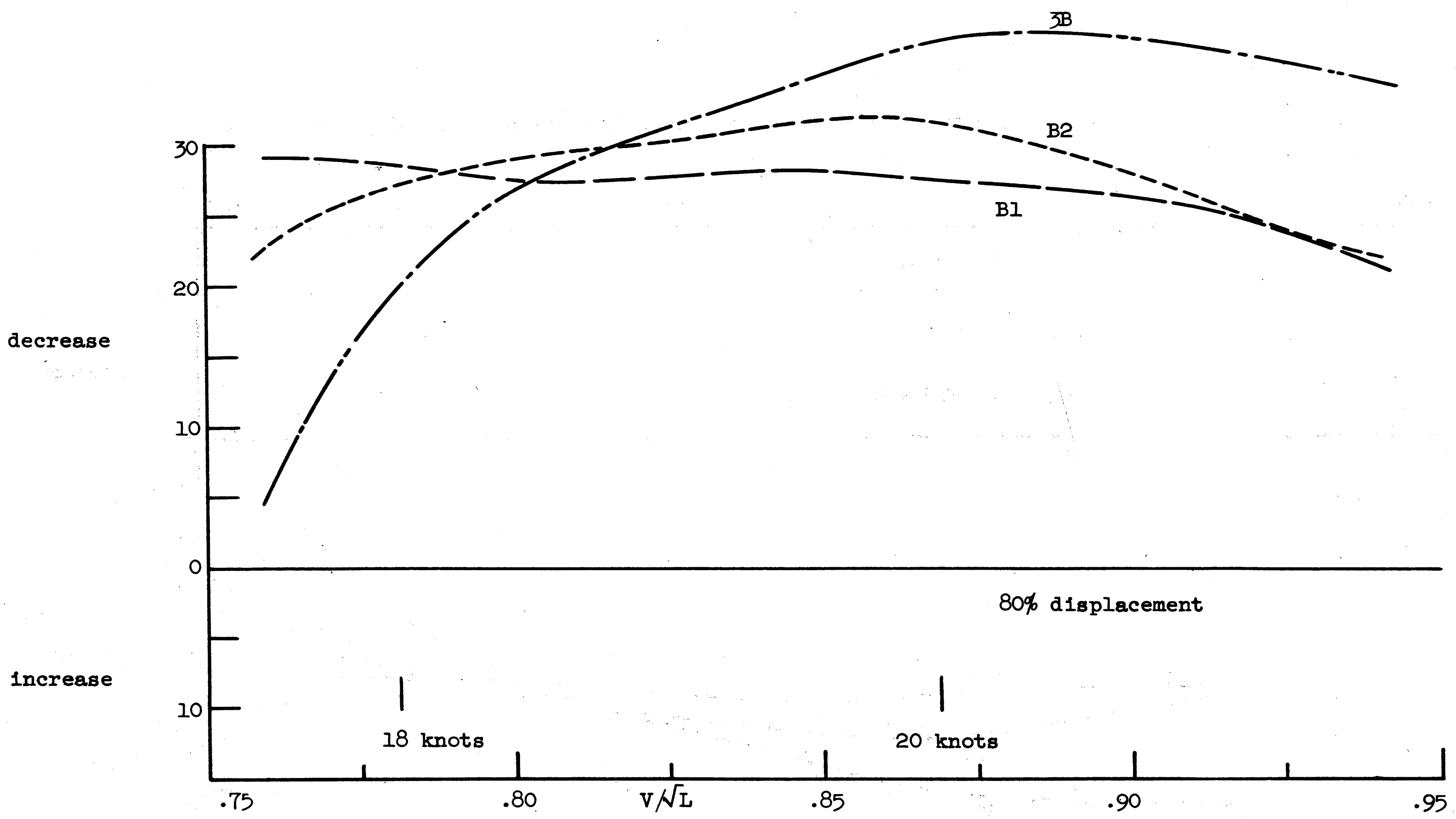

Fig. A5. Percent change of C_R due to addition of bulbs B1, B2, 3B (80%).

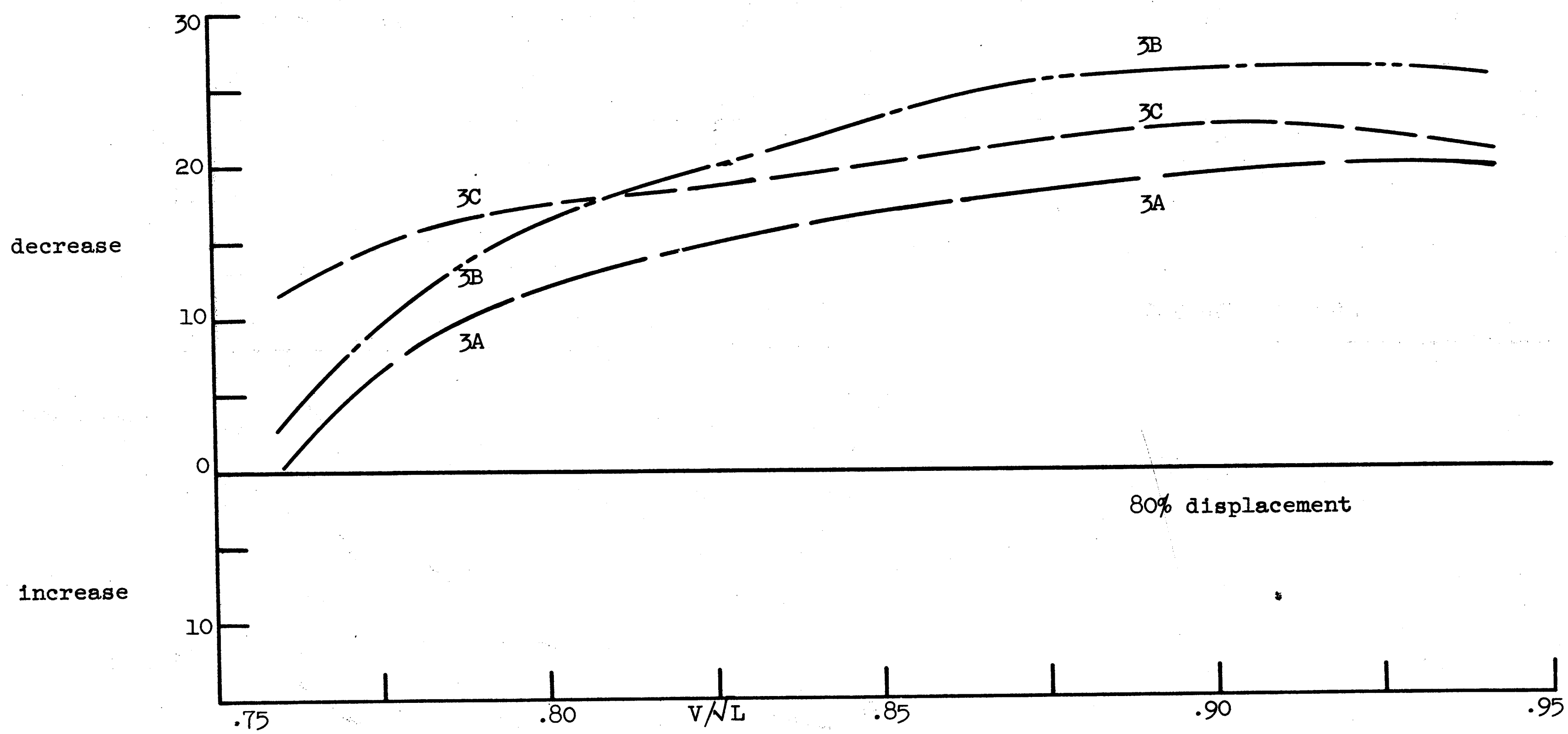

Fig. A6. Percent change of C_T due to addition of bulbs 3A, 3B, 3C (80%).

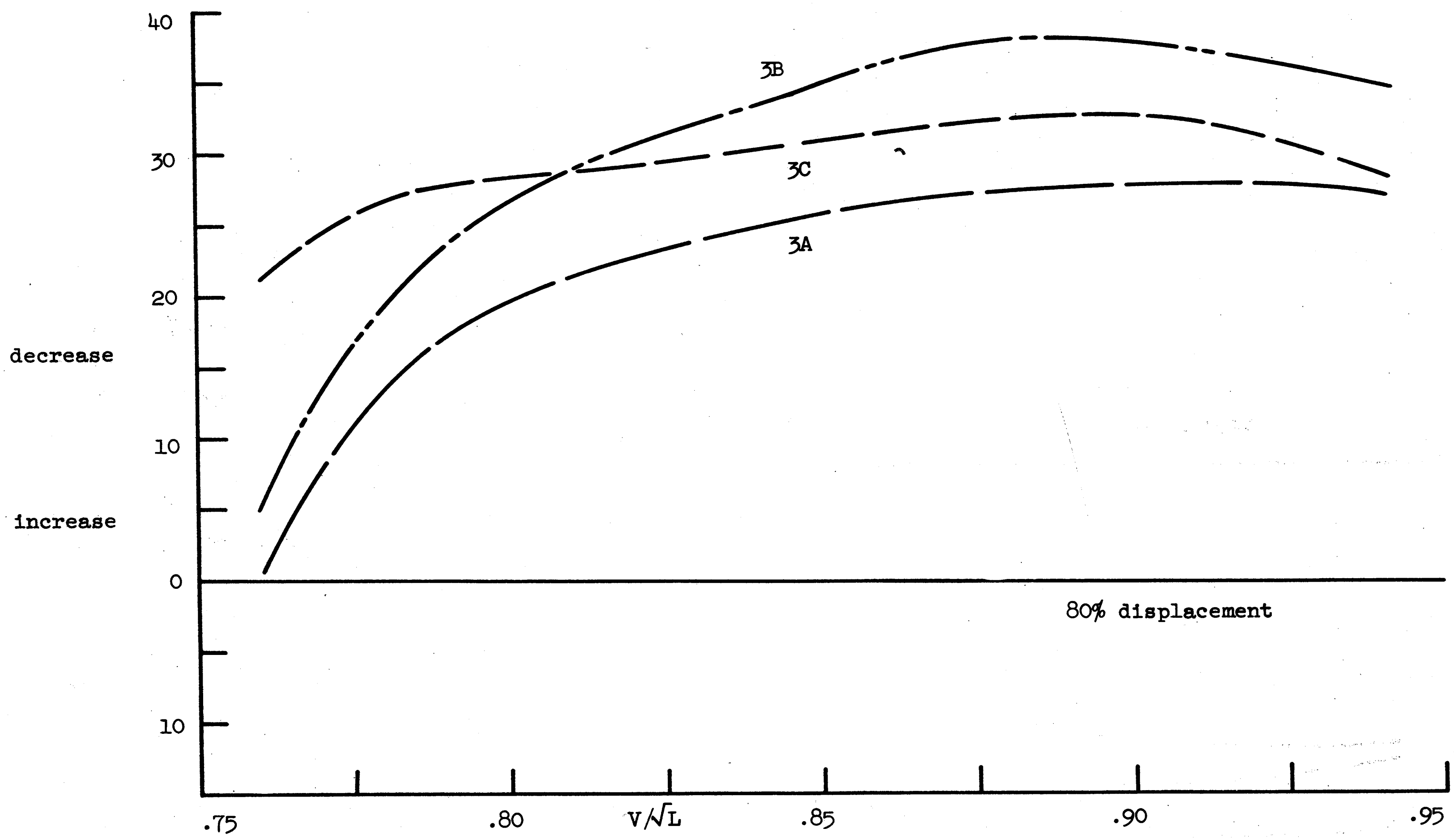

Fig. A7. Percent change of C_R due to addition of bulbs 3A, 3B, 3C (80%).

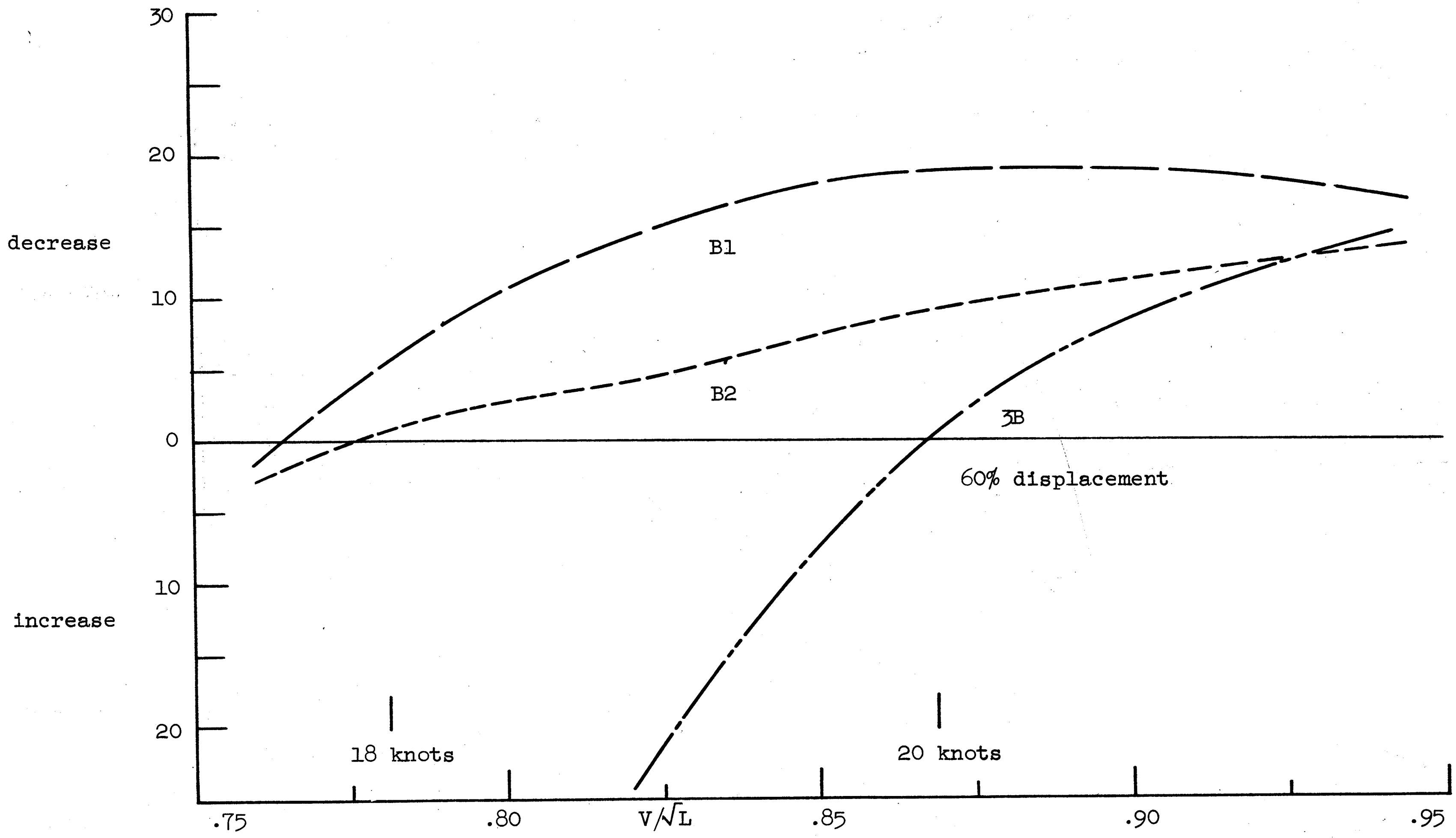

Fig. A8. Percent change of C_T due to addition of bulbs B1, B2, 3B (60%).

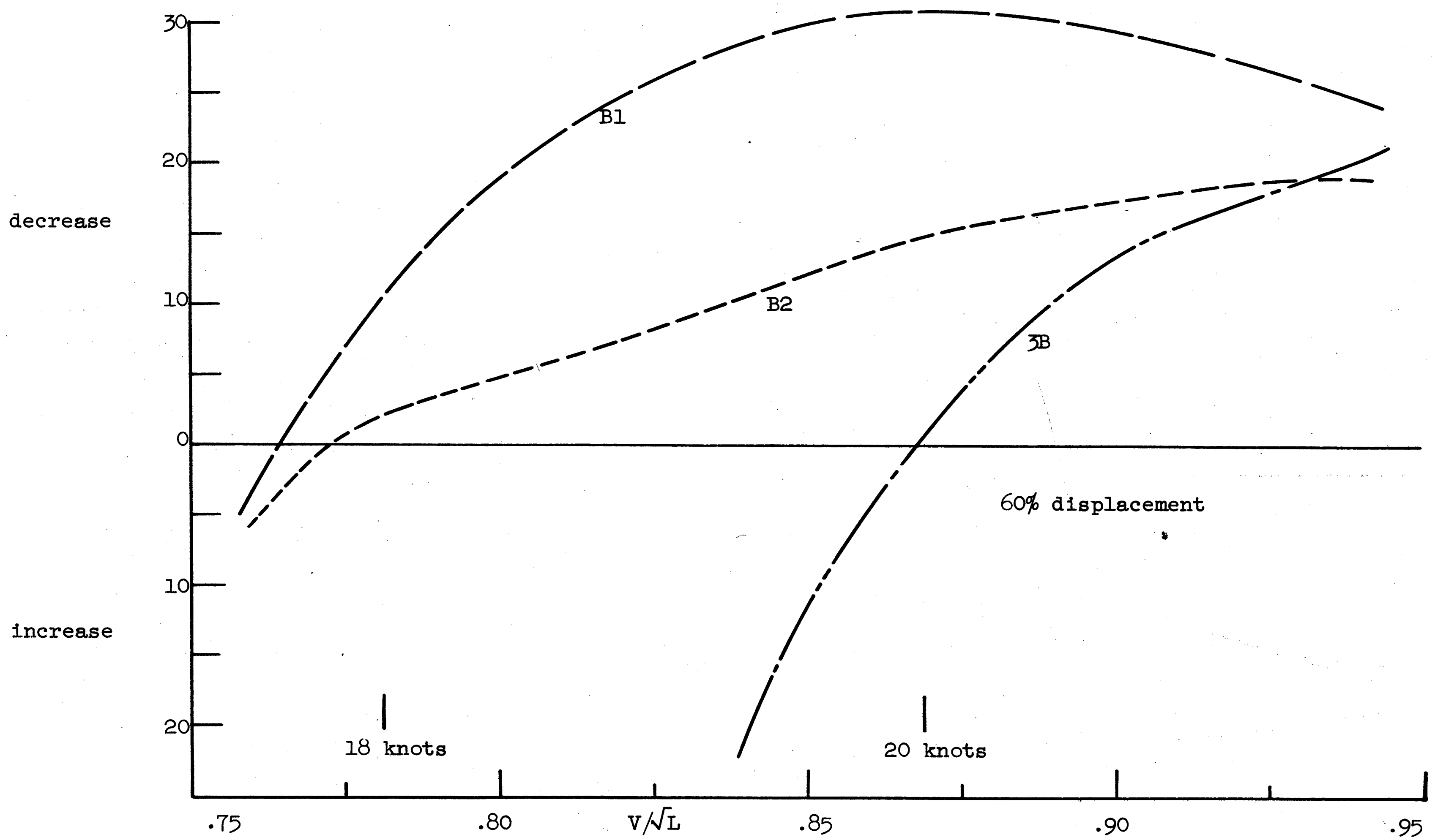

Fig. A9. Percent change of C_R due to addition of bulbs B1,B2,3B (60%).

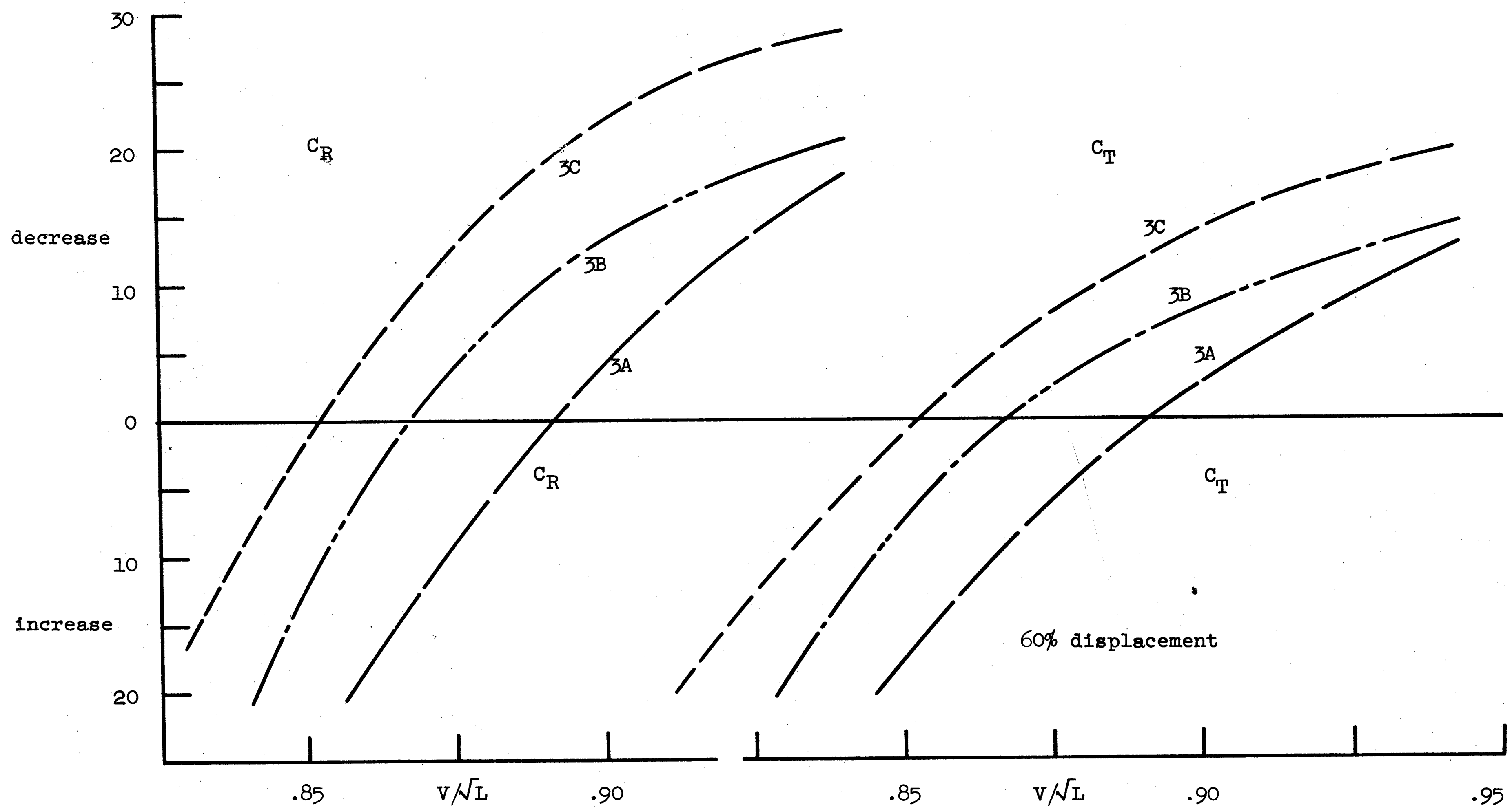

Fig. A10. Percent change of C_R and C_T due to addition of bulbs 3A, 3B, 3C (60%).

APPEXIDX B

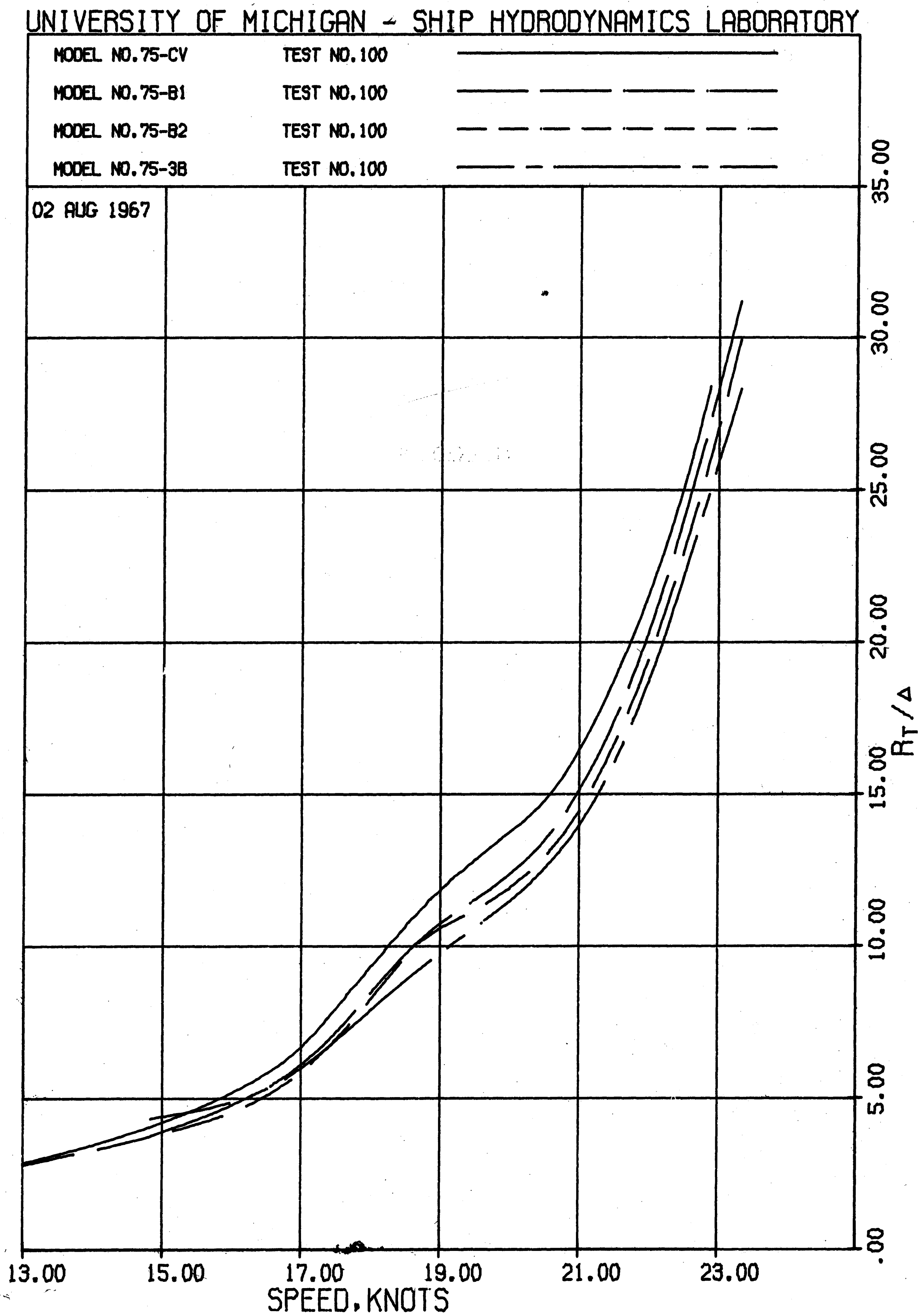

Fig. B1. R_T/Δ for 75-CV, B1,B2,3B (100%).

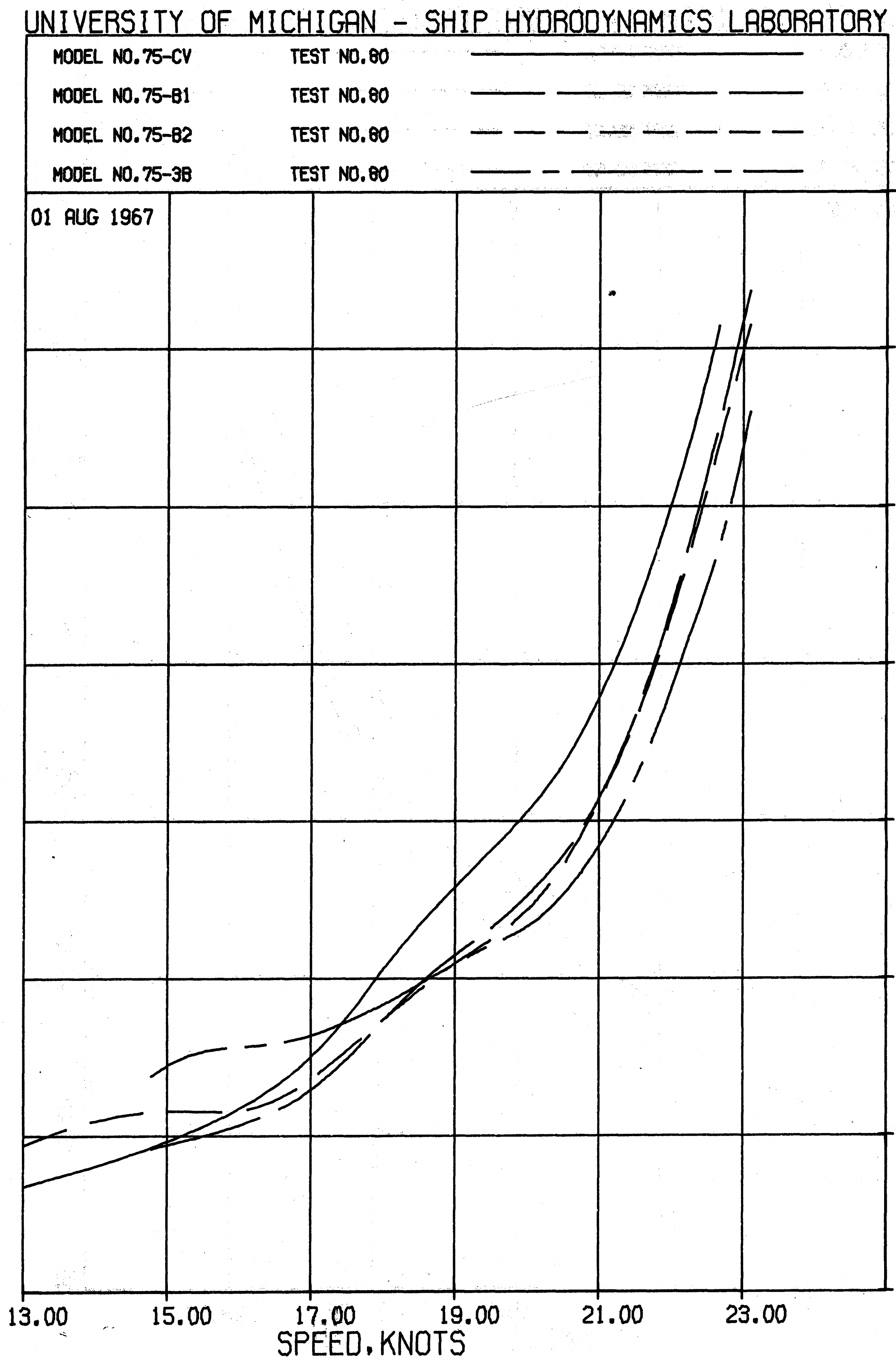

Fig. B2. R_T/Δ for 75-CV, B1,B2,3B (80%).

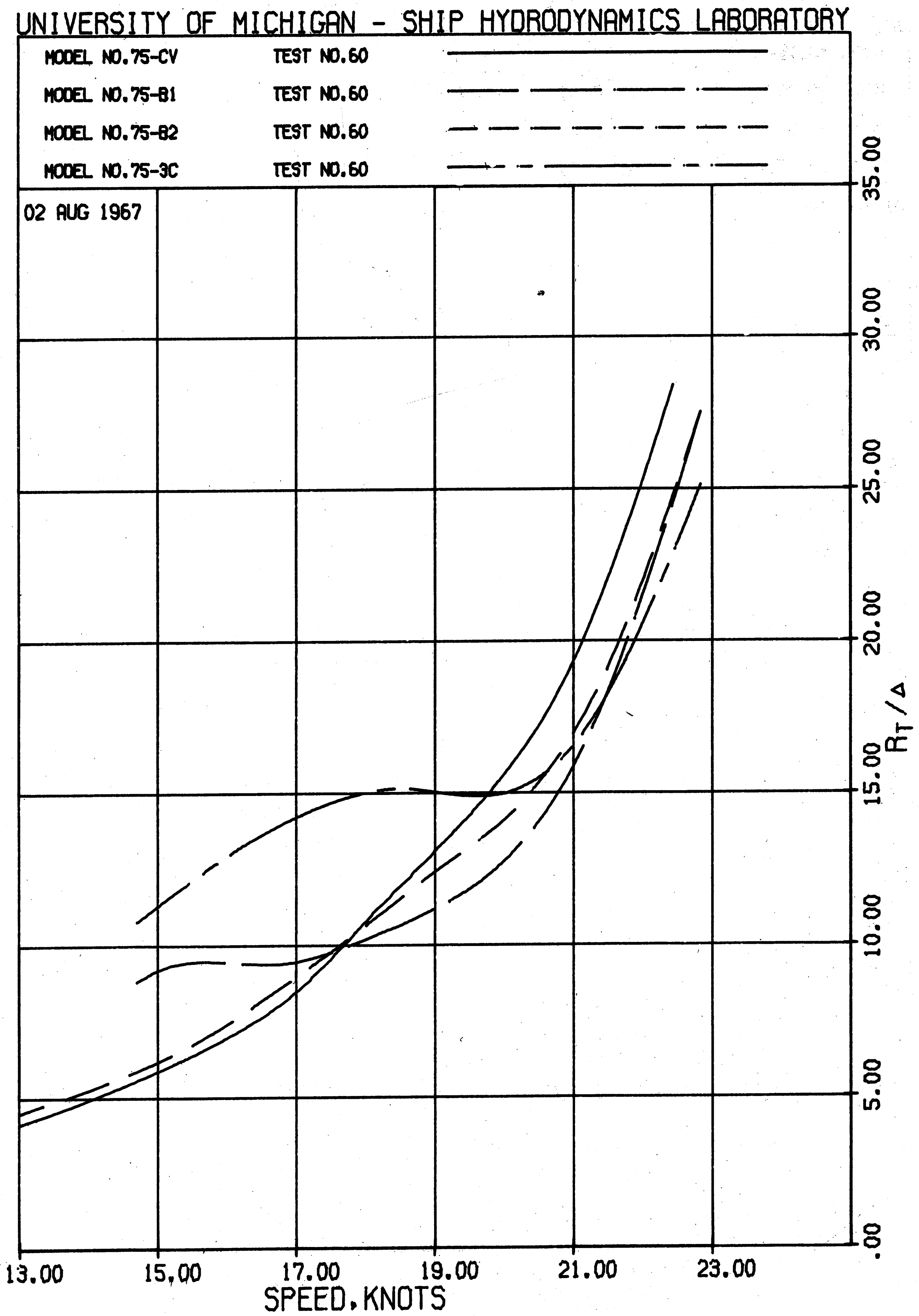

Fig. B3. R_T/Δ for 75-CV, B1,B2,3C (60%).

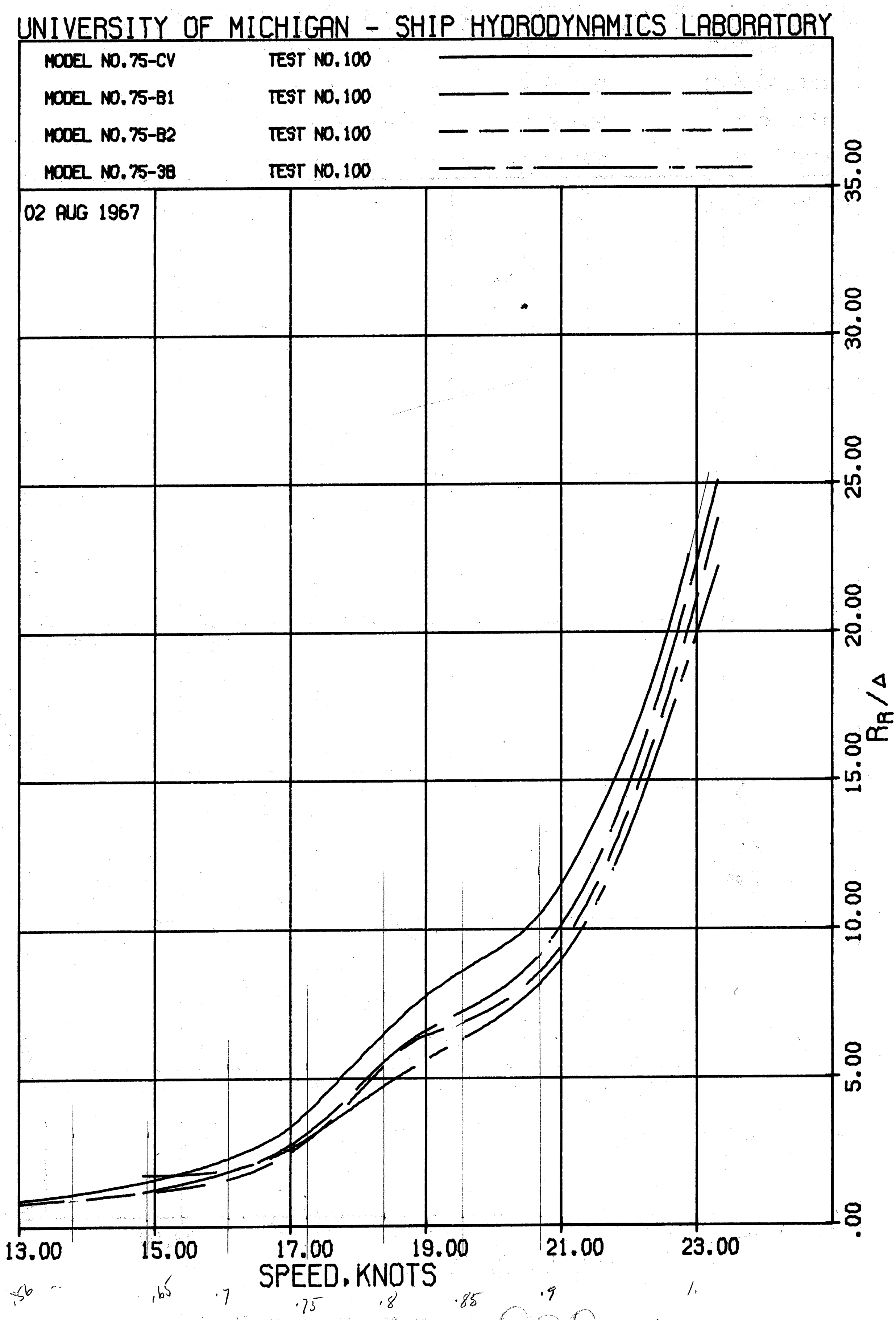

Fig. B4. R_R/Δ for 75-CV, B1, B2, 3B (100%).

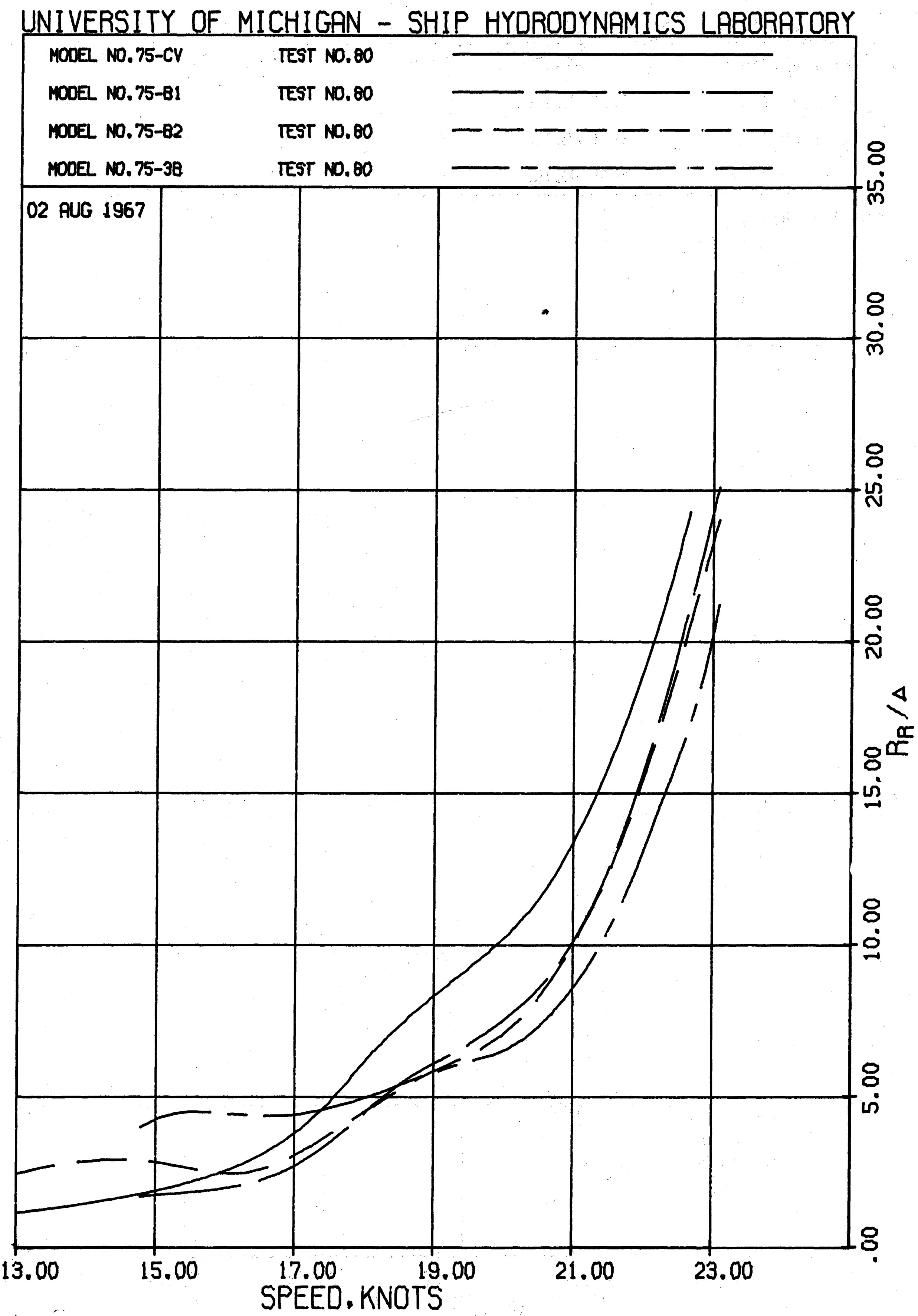

Fig. B5. R_R/Δ for 75-CV, B1,B2,3B (80%).

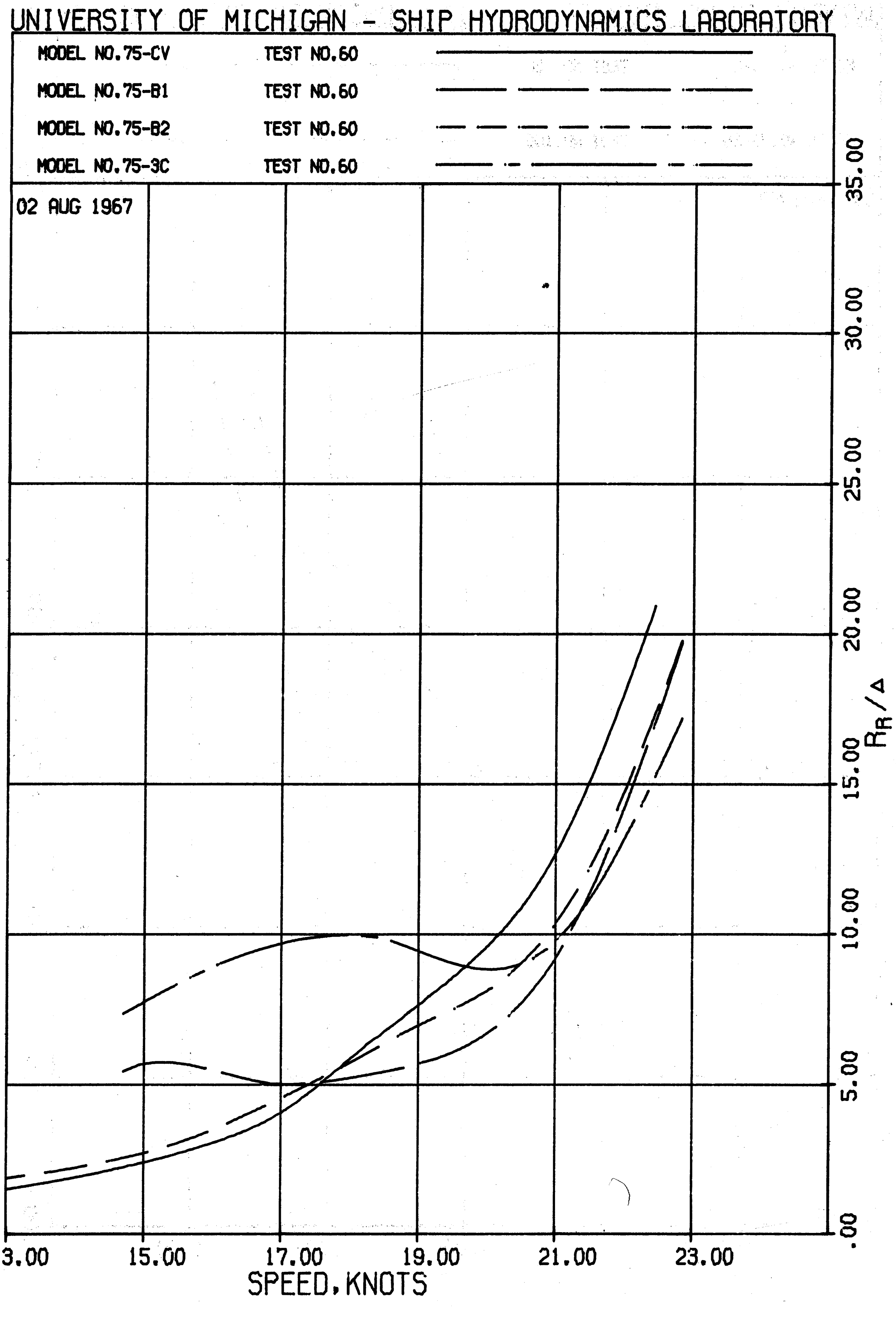

Fig. B6. R_R/Δ for 75-CV, B1,B2,3C (60%).

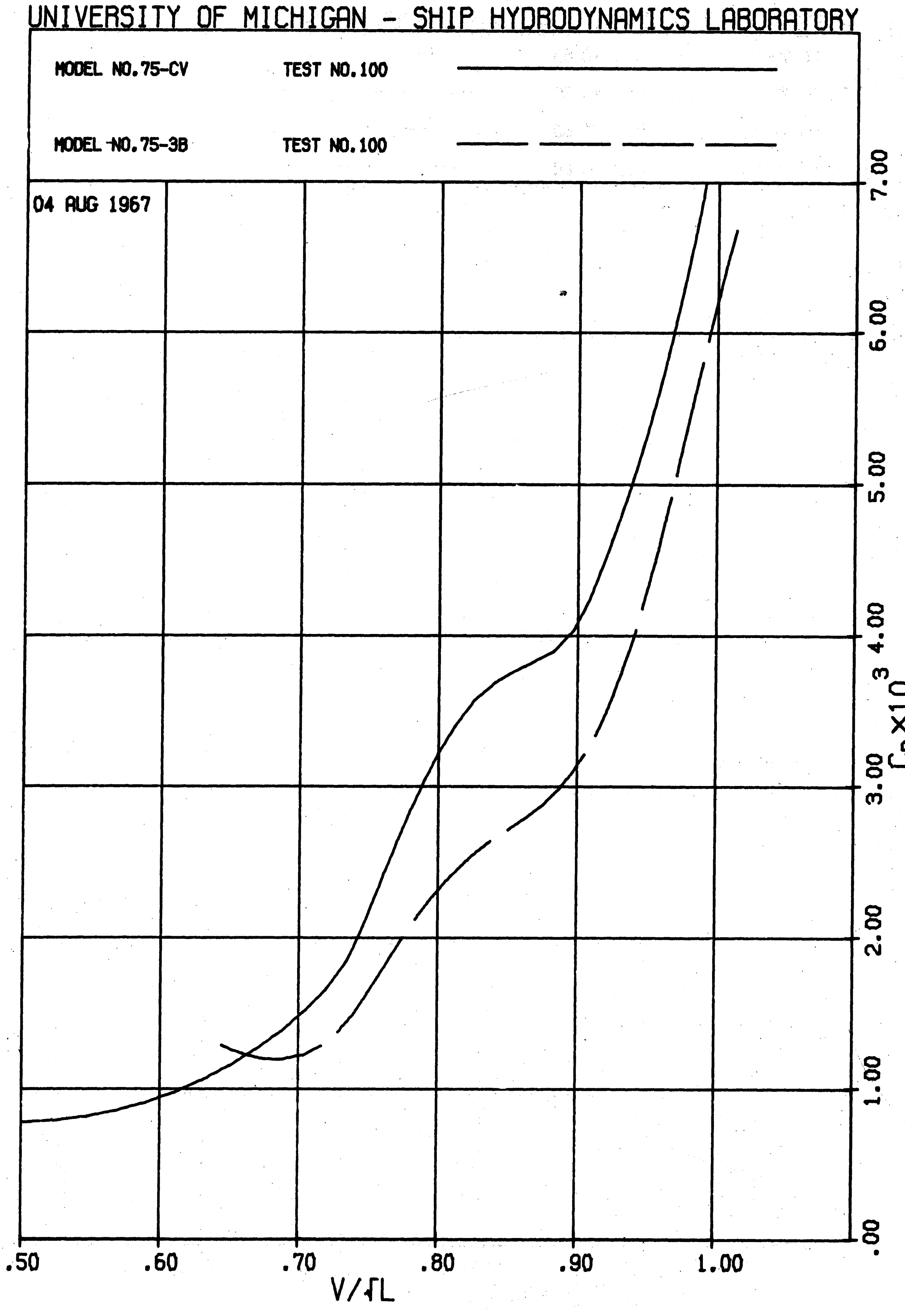

Fig. B7. C_R for 75-CV, 3B (100%).

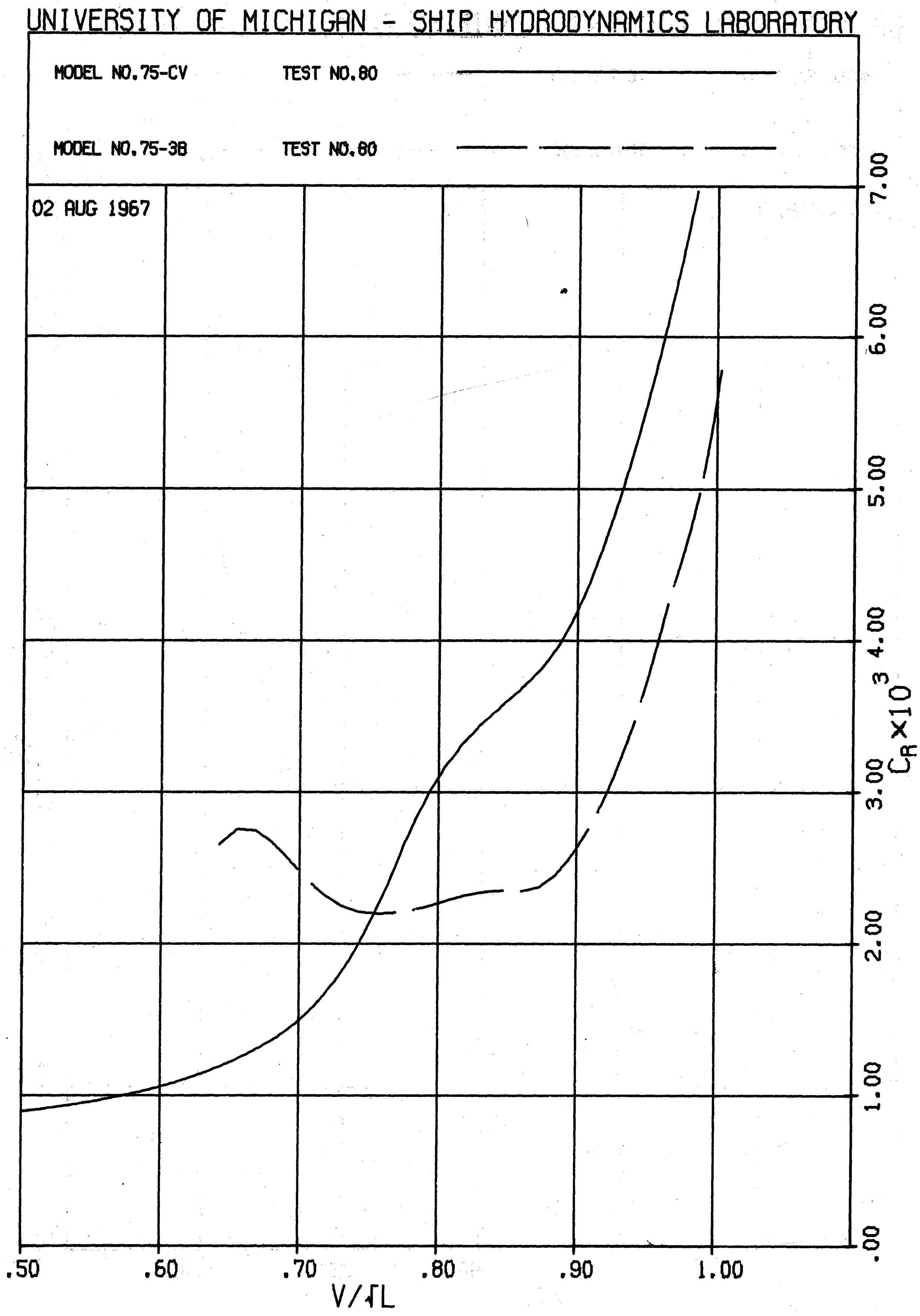

Fig. B8. C_R for 75-CV, 3B (80%).

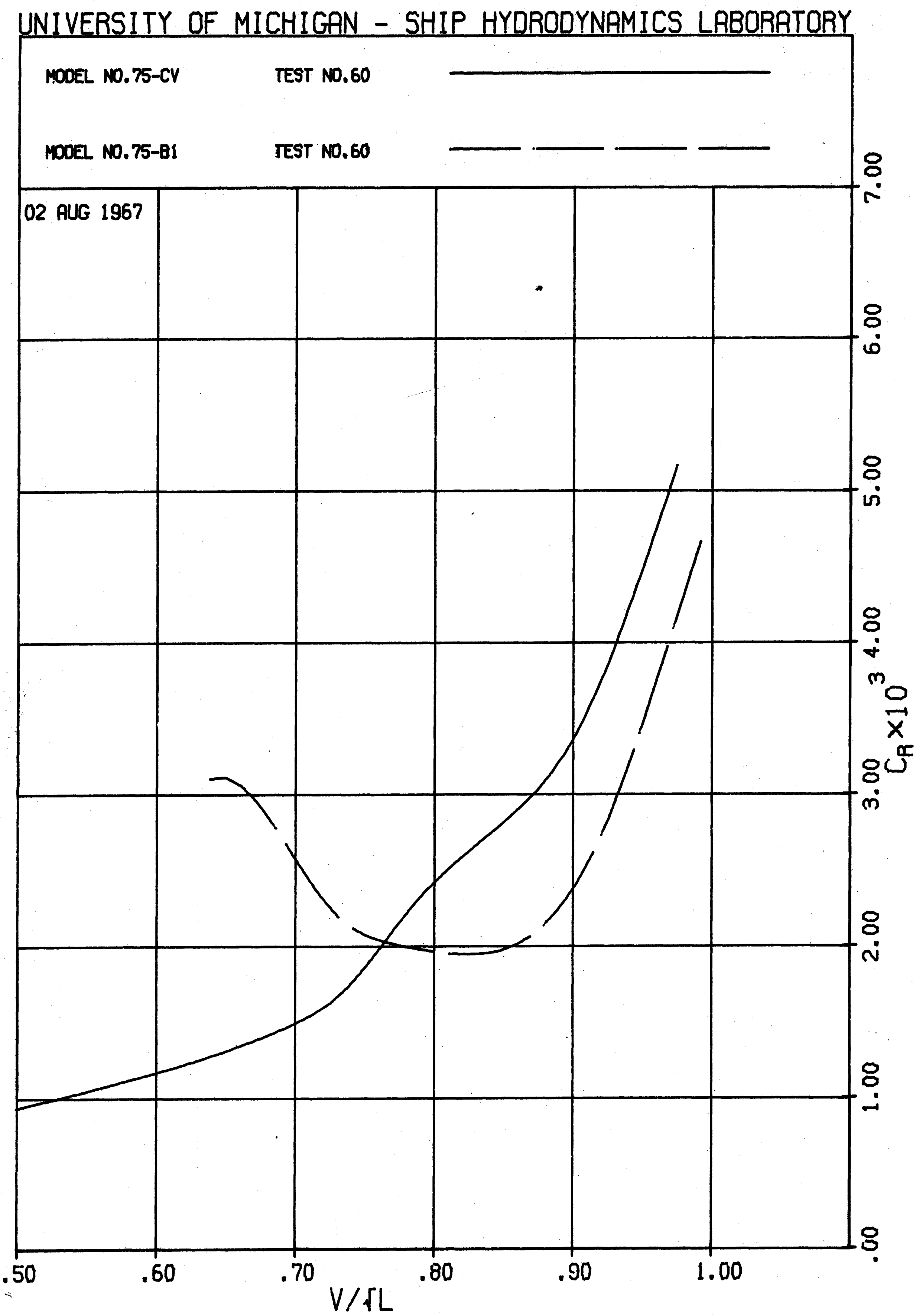

Fig. B9. C_R for 75-CV, B1 (60%).

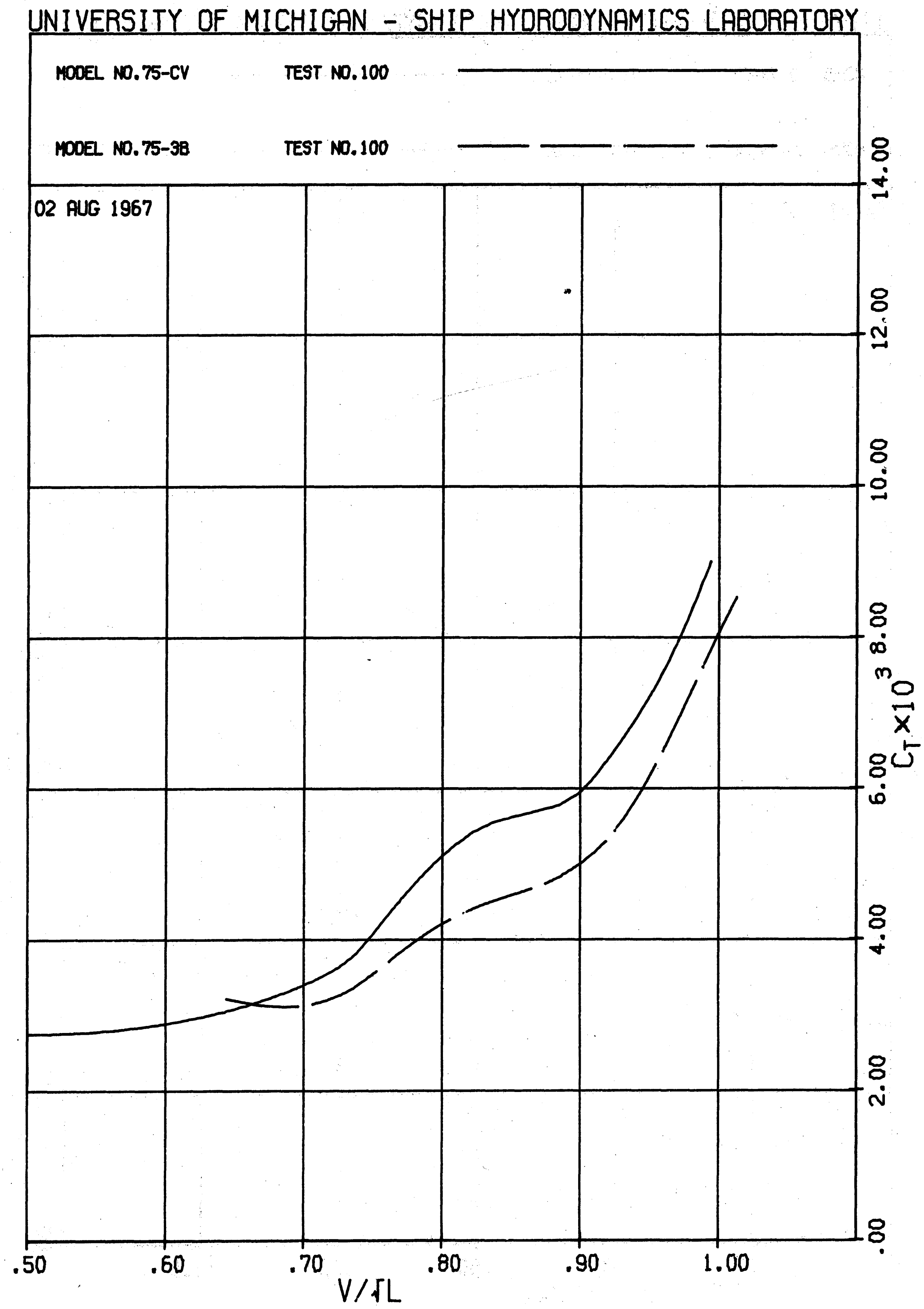

Fig. B10. C_T for 75-CV, 3B (100%).

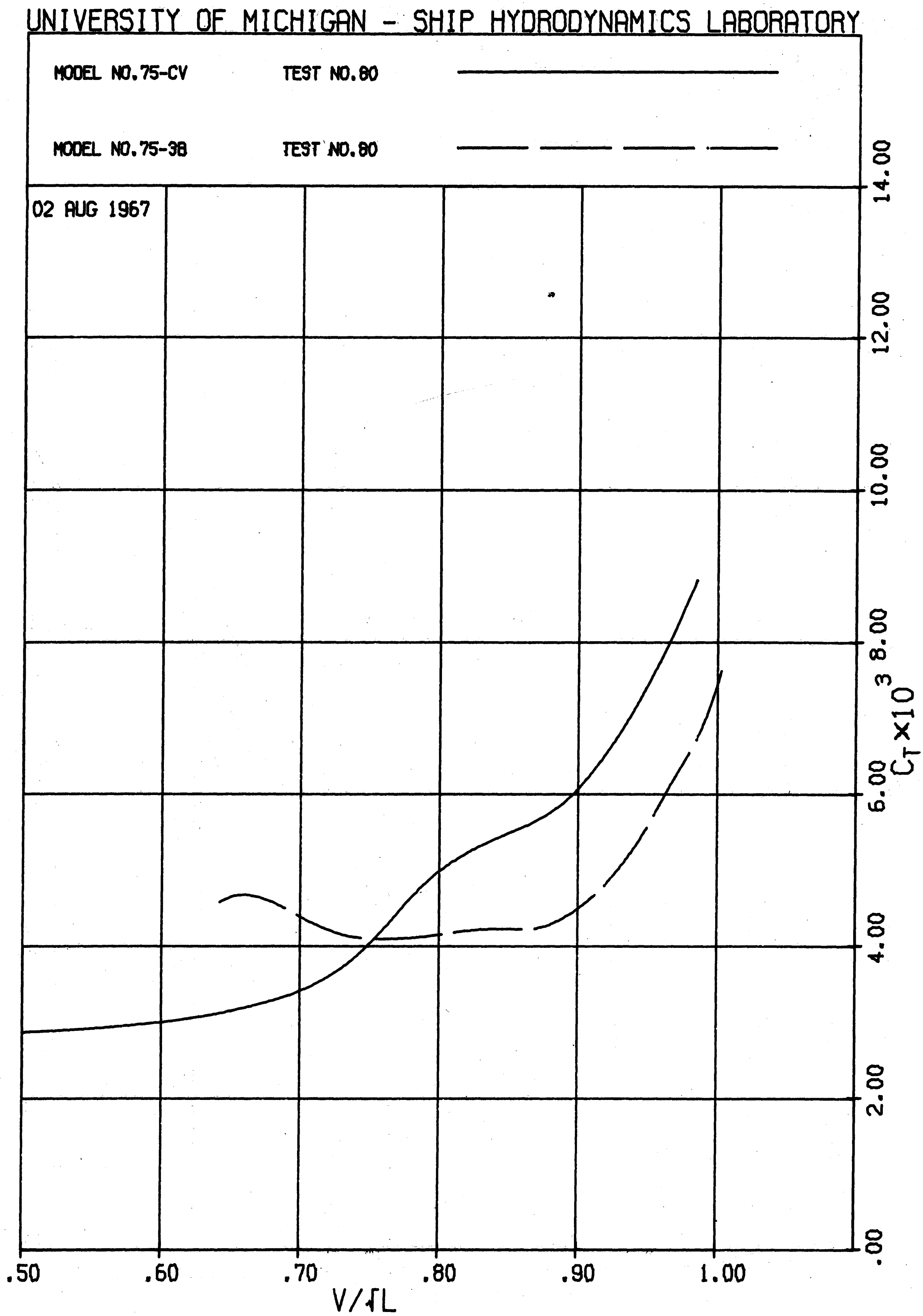

Fig. B11. C_T for 75-CV, 3B (80%).

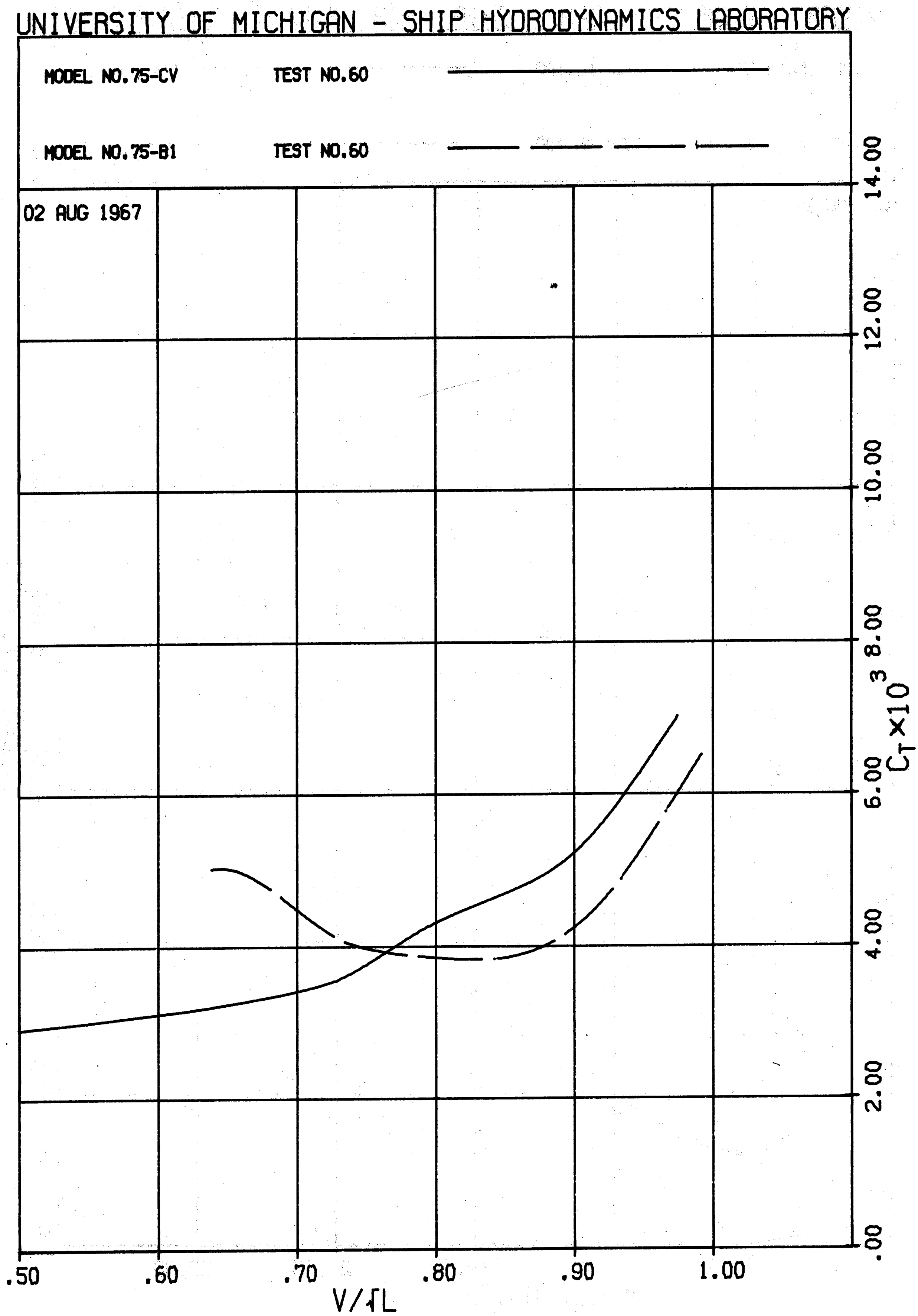

Fig. B12. C_T for 75-CV,B1 (60%).

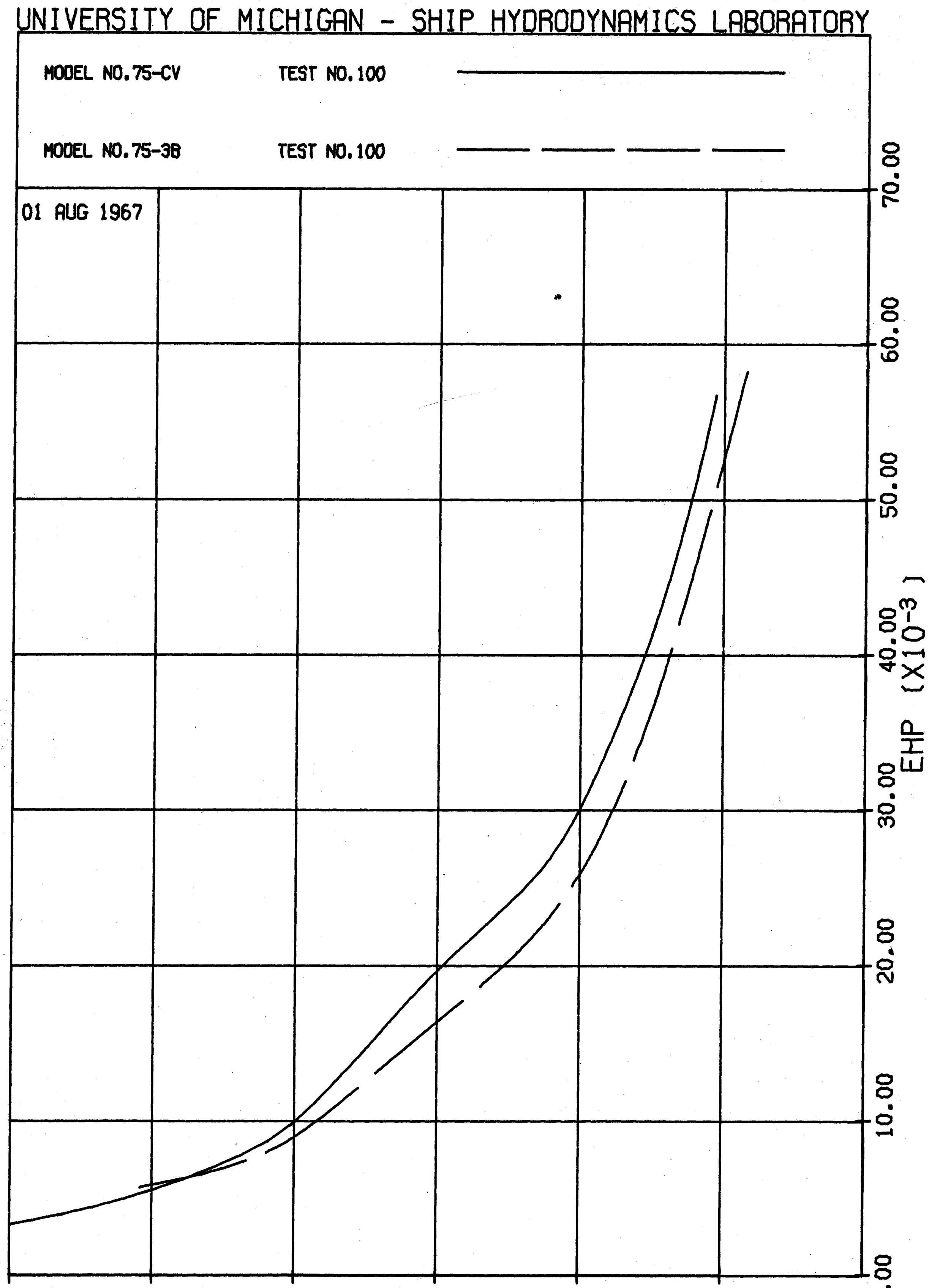

Fig. B13. EHP for 75-CV,3B (100%).

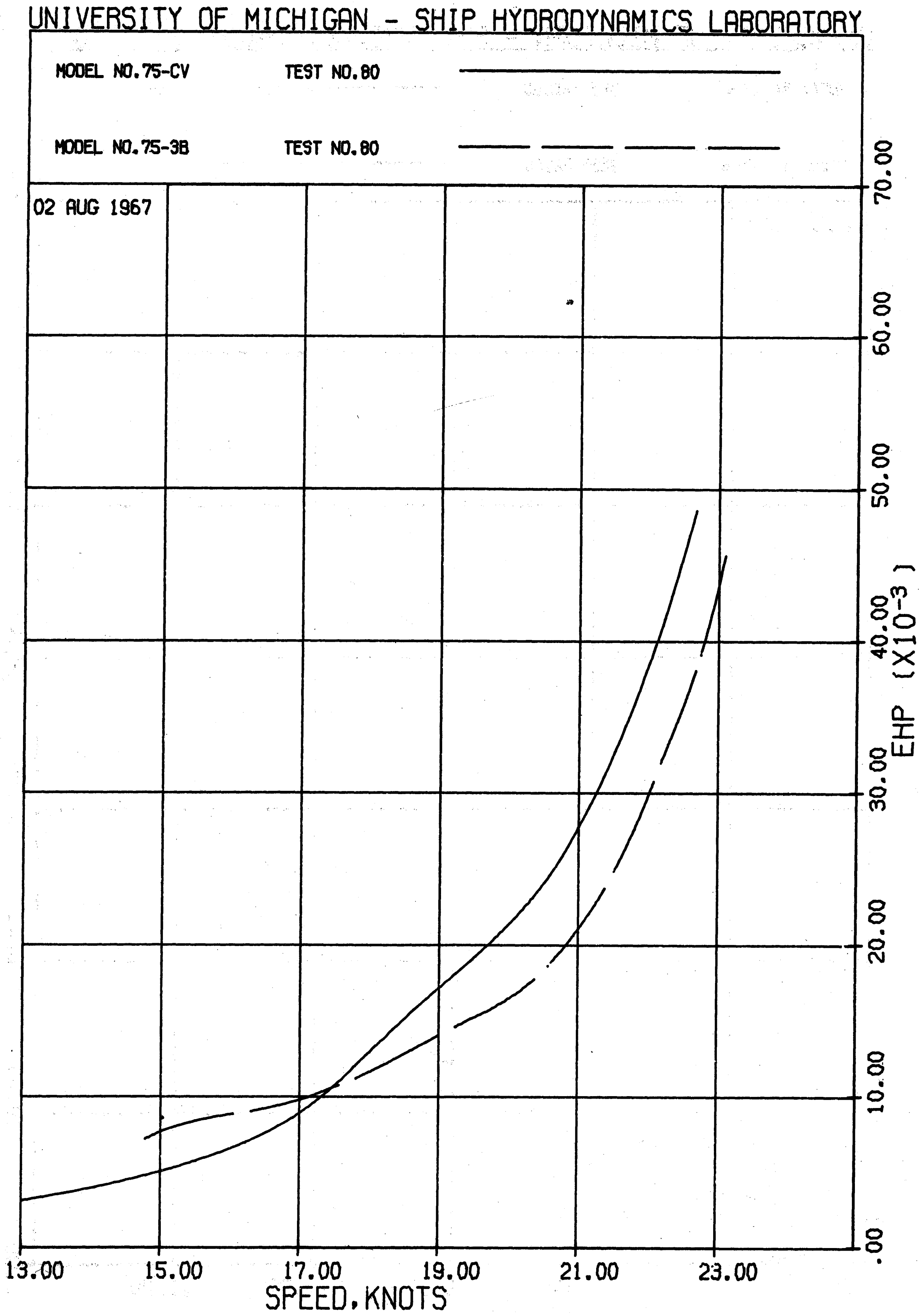

Fig. B14. EHP for 75-CV, 3B (80%).

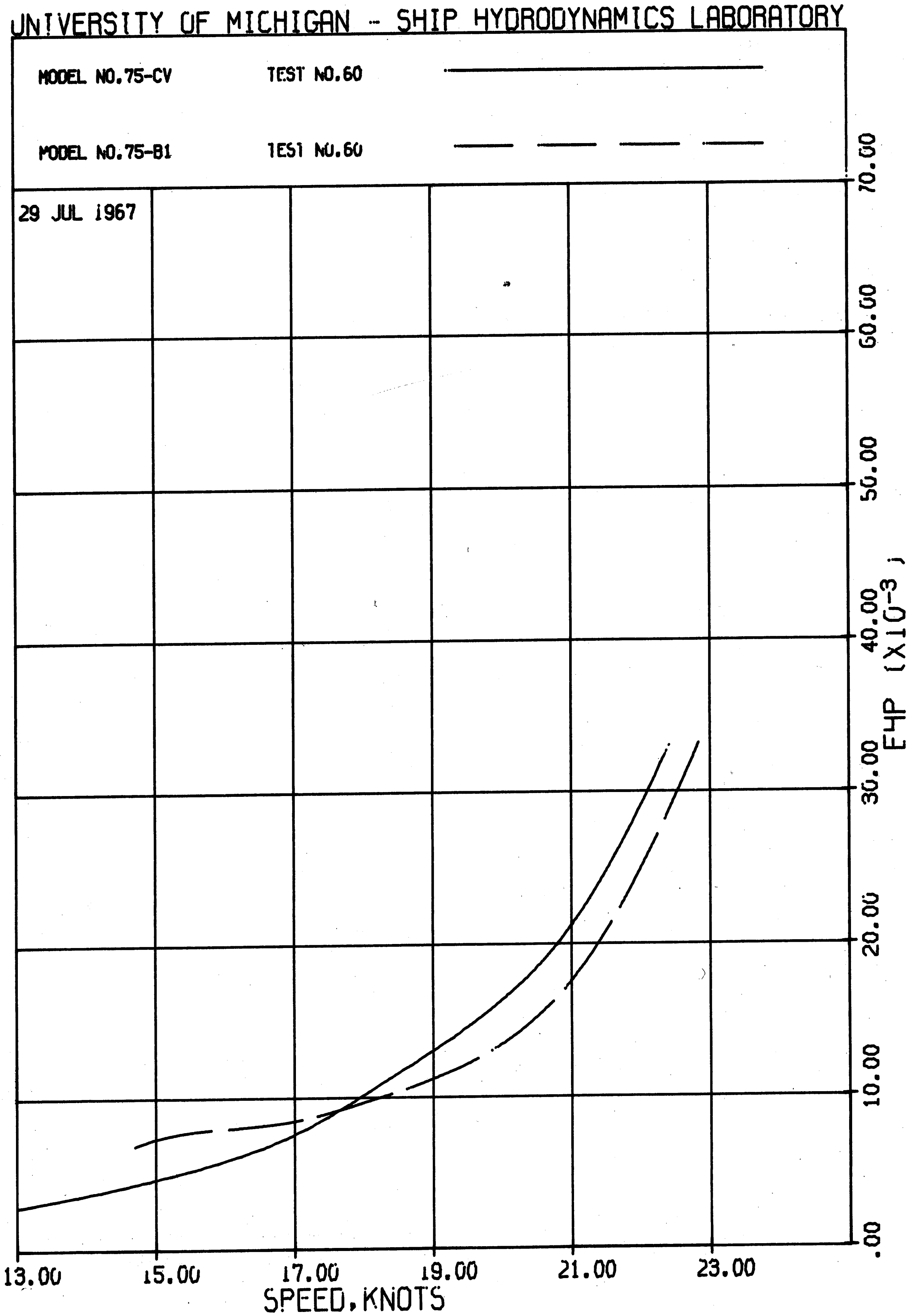

Fig. B15. EHP for 75-CV,B1 (60%).