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No. 104

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THE DEPARTMENT OF NAVAL ARCHITECTURE AND MARINE ENGINEERING

THE UNIVERSITY OF MICHIGAN
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College of Engineering
The University of Michigan
ORA Project No. 01491

CONTENTS

NOMENCLATURE

The standard nomenclature adopted by the Presentations Committee of the International Towing Tank Conference in 1966 has been used throughout with the following exceptions.

$C_w = 2\underline{R}_w/\rho V^2 S$	Coefficient of wave resistance
$E(u)$	Nondimensional amplitude spectrum
$F(u)$	Sine component of $E(u)$
$G(u)$	Cosine component of $E(u)$
$\underline{L}$	Dimensional model length
$L = \underline{L}g/V^2$	Nondimensional model length
P or p	Relative bulb size
Q or q	Relative bulb location
$\underline{R}_w$	Dimensional wavemaking resistance
$R_w = \underline{R}_w g^2/\rho V^6$	Nondimensional wavemaking resistance
R_{wm}	Wavemaking resistance of main hull alone
R_{wt}	Wavemaking resistance of system hull and bulb
s	Nondimensional longitudinal wave number
u	Nondimensional transverse wave number
$\eta = R_{wt}/R_{wm}$	Bulb influence factor

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INTRODUCTION

Several techniques have recently become available for determining the wavemaking characteristics of a hull form from a suitable analysis of wave profiels measured in a model experiment [1].* The most promising application of this new experimental tool seems to be in the area of wave resistance reduction by the use of optimal multi-hull configurations. The term multi-hull may be used to denote any assembly of hulls or hull components, each of which can be considered as a separate entity from the point of view of wavemaking. Examples of simple multi-hulls to which this technique has already been applied are bulbous bow hulls [2], twin-hull catamarans [3], and semi-submerged ships (submarine hulls with surface piercing superstructures) [4]. In view of current shipbuilding practice, the most urgent of these problems is probably the optimization of bulbous bows.

Basically, one might distinguish two different approaches to the problem of bulb design for a given main hull. First, there is the possibility of model testing several randomly or systematically chosen alternative bulbs and measuring the comparative values of resistance or propulsive power. This seems to be the favorite current practice. However, in view of the enormous number of model tests required for a truly exhaustive search, this is clearly an uneconomical and therefore unsatisfactory approach. Second, one could apply a purely computational

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*Numbers in square brackets denote references listed at the end of the report.

procedure based on the analytical theory of wave resistance for determining hull-bulb combinations of low wave resistance. Pioneering attempts of Wigley [5] and Weinblum [6] in this direction have been followed up by many others recently. However, as a result of the approximations implicit in the linearized theory of wave resistance, such calculations invariably lead to overly optimistic predictions which are at unacceptable variance with experimental facts [7].

The present approach to bulb design may be regarded as a synthesis of the experimental with the theoretical method. The basic wave patterns of the main hull and the bow bulb are obtained from measurements in the model tank. The theory is then applied for predicting the effect of changes in bulb size and location on the wave pattern and for calculating the wavemaking resistance from the wave pattern. This combination allows the extraction of maximum useful information from a minimum number of experiments. The original conception of this method should probably be attributed to Inui [8] but the technique actually used here is the one devised by Sharma [2].

A crucial hypothesis in this method is the approximate theoretical principle of simple linear superposition of the free-wave spectra of the main hull and bow bulb to yield the total free-wave spectrum of the composite bulbous bow hull form. A practical problem lies also in deciding just how a bulb shape should be altered so as to effect any desired changes in the amplitudes and phases of the bulb wave spectrum. The purpose of the present study was to verify by a few simple experiments the actual validity of this method as a practical design tool.

THEORY OF BULB OPTIMIZATION

The present method of bulb optimization starts from the assumption that the free-wave spectra of the main hull and of a suitable trial bulb are known. In practice, these spectra will be obtained from a Fourier transform analysis of suitable transverse or longitudinal wave profiles measured in the model tank by methods described in [1]. However, in principle, one or both of the spectra could also be derived from purely analytical theory. Main disadvantages of the latter approach are i) restriction to mathematically simple forms and ii) unrealistic estimates of spectrum due to fundamental simplifications in the analytical theory.

The significance of the free-wave spectrum lies in that it determines for all practical purposes the wavemaking characteristics of the object in question. Suppose, for instance, that $F(u)$ and $G(u)$ represent the sine and cosine spectrum (as functions of transverse wave number u) respectively of a certain hull form in unrestricted deep water at a definite Froude number. Then the wavemaking resistance is given by

$$R_W = \frac{1}{16\pi} \int_{-\infty}^{\infty} \{F^2(u) + G^2(u)\} \frac{\sqrt{1 + 4u^2}}{(1 + \sqrt{1 + 4u^2})}\, du \tag{1}$$

Moreover, in a righthanded Cartesian coordinate system O_{xyz} moving with the ship (with x pointing forward and z vertically upwards) the free-surface deformation

$$z = \zeta(x,y) \tag{2}$$

can be expressed asymptotically in terms of the free-wave spectrum:

$-x \to \infty$:

$$\zeta(x,y) = \frac{1}{4\pi} \int_{-\infty}^{\infty} \{F(u) \sin(sx + uy) + G(u) \cos(sx + uy)\} du \tag{3}$$

where $s = \{(1 + \sqrt{1 + 4u^2})/2\}^{1/2}$

is the longitudinal wave number [1].

In the preceding equations the nomenclature of references [1,2] has been used and all quantities are understood to have been rendered nondimensional by use of a fundamental unit system comprising the ship speed $\underline{V}$, acceleration due to gravity $\underline{g}$ and water density $\underline{\rho}$. Note, however, that the present definitions of $F(u)$ and $G(u)$ differ from those of [2] by a factor 4π.

Suppose now that the spectrum $F_m(u)$, $G_m(u)$ of the main hull and the spectrum $F_{to}(u)$, $G_{to}(u)$ of the hull fitted with a trial bulb have been determined from measured model wave profiles. Then from the principle of linear superposition of wave patterns (which can be justified as a first approximation in potential flow wave theory) the spectrum of the trial bulb itself becomes

$$\begin{aligned} F_{bo}(u) &= F_{to}(u) - F_m(u), \\ G_{bo}(u) &= G_{to}(u) - G_m(u) \end{aligned} \tag{4}$$

One may now reasonably assume that for small suitable changes in bulb size the wave heights will be uniformly changed in the same ratio. Moreover, if the bulb is shifted in the longitudinal direction, it will simply carry its wave pattern with it and hence by virtue of equation (3) the spectrum will experience a mere phase shift. On this hypothesis, the spectrum of a new bulb of arbitrary size p (relative to the trial bulb) and longitudinal location q (relative to the trial bulb, but expressed as a fraction of hull length L) becomes

$$\begin{aligned} F_b(u) &= p\{F_{bo}(u)\cos(sqL) + G_{bo}\sin(sqL)\} \\ G_b(u) &= p\{G_{bo}(u)\cos(sqL) - F_{bo}\sin(sqL)\} \end{aligned} \tag{5}$$

Again from the principle of linear superposition the spectrum of a hull fitted with this new bulb becomes

$$\begin{aligned} F_t(u) &= F_m(u) + F_b(u) \\ G_t(u) &= G_m(u) + G_b(u) \end{aligned} \tag{6}$$

and the wave resistance can be computed from the general formula (1).

One might introduce a bulb influence factor

$$\eta = \frac{R_{w_t}}{R_{w_m}} \tag{7}$$

defined as the ratio of the wave resistance of the hull with bulb to the wave resistance of the main hull. By plotting contours of η in the feasible domain of the p, q plane one can obtain a complete picture of the wave resistance modifications to be expected for any size or longitudinal location of that type of bulb. As is evident from the form of equation (1), these contours will show effects of interference between hull and bulb wave systems and, in general, there will be a point of minimum wave resistance in the feasible p,q range. The effect of other changes in bulb configuration (a vertical shift of the centroid for instance) must be determined, of course, from new experiments.

It is appropriate at this point to refer to one fundamental difficulty which arises in the practical application of this method. Suppose, for example, that the η contours in a given case reveal it to be desirable to change the "size" of the trial bulb by a factor p_1 and move its "location" by a fraction q_1 of hull length. The practical question is, what physical changes to bulb geometry are necessary to effect the precise change in spectrum implied by equation (5)? A practical answer to this question can only be obtained from experiments, but some guidance is available from the theory of waves generated by solid bodies in steady translation.

First, consider the question of changes in "size." There is no known general theory to determine how an arbitrarily shaped body should be modified so that its wave pattern will remain unchanged in phase but be scaled in amplitude by a constant prescribed factor. However, there exist approximate theories for special classes of bodies. For a thin body, one might apply the classical Michell approximation. Thus in case of a thin bulb one would keep the longitudinal and vertical offsets unchanged and just change all transverse offsets in the ratio p_1 to yield an affine transformation of the old bulb. If the bulb appears to be an axi-symmetric slender body, one might use the slender body approximation, i.e., keep the axis of symmetry fixed and change the cross-sectional area throughout by the factor p_1. If the bulb is nearly spherical, the deeply submerged body approximation requires that the centroid be kept fixed and the volume changed in the ratio p_1. A generalization of this method to spheroids is possible [9]. In this case an isofocal, rather than a geometrically similar transformation is required. The foci must be held constant and the dipole moment (rather than volume) changed by factor p_1. In practice, one would have to use one or the other of these approximations depending on the general shape of the given trial bulb.

Next comes the question of changes in location. At first sight it might seem trivial, because if a body is simply shifted in the horizontal plane, it is just like moving the origin of the coordinate system. However, the necessity of fairing the bulb into the hull makes it very difficult to implement pure changes of location. In fact, the effect of fairing on the wave interference between hull and bulb is so complicated that it can be assessed only by experiment. It is evident then that in the actual application of this method certain elements of personal judgement cannot be avoided.

EXPERIMENTS

The basic plan of these experiments was to carry out bulb optimization calculations on the basis of several different trial bulbs and then compare these predictions against each other. Models of a suitable main hull (Model 1094) and a reasonably good bulb (B2) were already available at The University of Michigan from a previous investigation [10]. Two further bulbs, designated B4 and B5 were designed for this study. Bulb B4 has the same size and shape as B2, but is located 2% of hull length forward of B2. Bulb B5 has the same location as B4, but is 50% larger in size. All three bulbs have an approximately hemispherical nose. It is assumed that the center and volume of this hemisphere determine the bulb location and size respectively. The main dimensions and basic form parameters of the four models are listed in Table 1, and the bow lines are shown in Figures 1 through 4.

Basically, two different experiments were carried out with each of the four models: the standard resistance test over a large speed range, and longitudinal wave profile measurements at two selected speeds. The resistance was measured in the usual way by means of a strain-gage dynamometer and weights. The models were allowed to float freely, and turbulence was stimulated by rows of studs near the bow.

The wave profile measurements required new equipment. A conductance wire type wave probe was constructed by Mr. W. H. Roth following the Hamburg design [11]. This probe is capable of measuring both wave height and slope simultaneously, but only the former was recorded in the present tests. The probe was mounted at a fixed point in the towing tank, and as the model passed by, a time record of the wave height at the location of the probe was taken on a Sanborn strip chart recorder. Assuming steady state conditions, a simple transformation of the time scale yielded the desired longitudinal wave cuts in a coordinate system moving with the model. The relative position of the model was fixed by recording (on a separate channel) an event signal generated by the passage of the model across a sharply controlled light beam spanning the tank width. Owing to the relative narrowness of the towing tank the models had to be towed 2 feet off center, and the wave cuts were taken at a transverse distance of about 4 feet from the model center plane. The two speeds selected for wave measurements were 5.01 and 5.36 ft/sec corresponding to Froude numbers of 0.250 and 0.267 respectively.

Wave measurements on Models 1094 and 1094-B2 were conducted in July and August 1968. Resistance values were already available from previous work [10]. Wave and total resistance tests on Models 1094-B4 and 1094-B5 were carried out in March and May 1969 respectively.

ANALYSIS

The topic of primary interest in this study is, of course, the wave profile analysis. But it is simpler to begin with the resistance component analysis based on measured total resistance. The original test data (measured values of speed and resistance) are listed in Table 2 for all models. The total resistance values were analysed to achieve an empirical breakdown into viscous and wavemaking components. For this purpose, the ITTC-1957 friction line

$$C_F = \frac{0.075}{(\log_{10} R_n - 2)^2} \tag{8}$$

was used and a graphical technique due to Hughes and Prohaska [12] was employed to determine the viscous form factors based on this line. The final results of this analysis are shown in Figures 5 through 8. The empirical wave resistance coefficients determined in this way for the four models are compared in Fig. 9. Also added for the sake of interest is a design oriented resistance comparison in Fig. 10 for an assumed full scale ship length of 680 ft [10]. It is evident that all three bulbs lead to a significant reduction in total resistance for $F_n > 0.2$. The low resistance of bulb B5 at the design Froude number is obtained, however, at the expense of an unusual hump at low Froude numbers. It should be mentioned that the actual wetted surface area and displacement of each model has been used in the preceding analyses. However, the Reynolds and Froude numbers are based on a common length of 12.5 ft for the model and 680 ft for full scale.

The measured wave profiles were analysed by the longitudinal cut method described in References [2] and [1]. The first step in this method is to obtain the free-wave spectrum by a modified Fourier analysis of the wave profile. The results are displayed in Figures 11-12 for Model 1094, in Figures 13-14 for Model 1094-B2, in Figures 15-16 for Model 1094-B4 and in Figures 17-18 for Model 1094-B5. For each model and each of the two speeds tested, two alternative diagrams are provided, one showing the variation of the sine component F, the cosine component G and the total amplitude $E = \sqrt{(F^2+G^2)}$ with transverse wave number u, and the other showing the same quantities as a function of the corresponding longitudinal wave number s. It may be observed that the basic wave length of $2\pi F_n{}^2$ clearly shows up in the variation of amplitude with longitudinal wave number s, as one would expect from simple considerations of wave interference between bow and stern. It is also evident that each of the three bulbs is to some extent effective in reducing wave amplitudes at both speeds tested.

The next step is to calculate the nondimensional wave resistance R_w from the free-wave spectrum by use of equation (1). The results are listed in Table 3 and show clearly the significant reduction in wavemaking resistance achieved by each of the three bulbs. The table also provides a comparison of the results of wave analysis with corresponding numbers derived from a form-factor analysis of measured total resistance using the relations

$$C_w = C_t - (1 + k)C_f \tag{9}$$

and

$$R_w = (g^2S/2V^4)C_w \quad . \tag{10}$$

Obviously, our wave analysis underestimates the quantity (C_t-C_v) at these Froude numbers. The reason for this is not yet understood. However, it is only of side interest in the present study which is concerned mainly with the prediction of *relative* effects produced by the bulb.

Once the spectra are available, it is easy to combine them in pairs (main hull and any given bulb) and generate predictions of wavemaking resistance, or better still of the bulb influence factor $\eta = R_{wt}/R_{wm}$, for feasible variations of bulb size and location as explained in a previous section. This was attempted for all six possible combinations, namely main hull 1094 with bulbs B2, B4 and B5 at F_n=0.250 and at F_n=0.267. The results appear as Figures 19 through 24. Assuming the wave profile measurements to be sufficiently accurate and the principle of linear superposition of free-wave spectra to be strictly valid, the three diagrams at each Froude number should be perfectly equivalent. This will be discussed further in the next section.

Incidentally, the preceding analysis is almost fully automated. As described in Reference [13] our computer programs will accept digitized wave profile data as input and produce numerical and graphical output of spectrum (as a function of wave number) and of bulb influence factor (as a function of bulb size and location), as exemplified by Figures 11 through 24 which are all entirely computer generated.

DISCUSSION

The basic question to be examined here is whether the three different trial bulbs tested lead to identical, or at least similar, predictions of optimum bulb size and location. As noted above, the crucial test lies in examining the three supposedly equivalent Figures 19, 20 and 21 (or 22, 23 and 24) for mutual consistence. In comparing these diagrams however, it should be remembered that while the contour function η always has the same meaning, the scales for size p and location q are, in general, not the same everywhere for they are reckoned relative to the bulb on which the particular diagram is based.

For the ease of comparison, therefore, certain cross curves have been taken from the η contours and plotted on a common base. Thus Figure 25 illustrates the effect of change in bulb size for a fixed bulb location, assumed for instance to be coincident with B4. Since B4 and B5 have the same location, vertical cross curves were taken at $q = 0$ from Figs. 20 and 21, but at $q = 0.02$ from Fig. 19 as B2 is 0.02 L aft of B4. After adjusting the p values (only necessary for B5 as B2 and B4 are of same size) and replotting, Fig. 25 is obtained. In theory, the three curves should have collapsed into one. Actually, the three curves diverge with increasing p and there are appreciable differences in the η predictions. However, the optimum value of bulb size p is roughly the same in all cases.

Similarly, Figure 26 displays a comparison of horizontal cross sections taken from Figures 19-21 at $p = 1$, 1 and 2/3 respectively after a suitable adjustment in the q scale of B2. Again, it is evident that there is some divergence between the three curves, but their minima (the points of optimum bulb location) are fairly close to each other.

Finally, one might go a step further and compare the η predictions only at certain selected values of p and q corresponding to the cases actually tested. This results in the two matrices of cross prediction presented in Table 4. Since total resistance values were also available at these points the corresponding η values based on the form-factor analysis are also included as the last row of each matrix marked "EHP". It is encouraging that the discrepancies in the η values from wave analysis and from form-factor analysis are not as bad as the discrepancies between the corresponding R_W values of Table 3. The cross predictions of η values themselves are pretty good with a few exceptions.

In summary, one can conclude that the semi-empirical technique of optimizing bow bulb configurations by linear superposition of free-wave spectra (derived from measured longitudinal wave profiles) holds promise as a useful design tool for economically predicting optimum bulb size and location with a minimum of model experiments. Although the absolute values of wave resistance are considerably underestimated by this method, the predicted ratios of wave resistance reduction seem to be fairly reasonable.

ACKNOWLEDGEMENTS

The authors are grateful to Professor F. C. Michelsen for initiating this project, and take pleasure in acknowledging the special help of Messrs William H. Roth and Arthur M. Reed without whose contributions this study would not have been possible. W. H. Roth constructed the wave probe and carried out the wave profile measurements on the first two models: 1094 and 1094-B2. A. M. Reed wrote Fortran IV computer programs for wave analysis and bulb optimization. Thanks are also due to David C. Lowery who programmed the spectrum and contour plotting subroutines.

The general cooperation of the staff of the Ship Hydrodynamics Laboratory, University of Michigan, in carrying out the experiments is appreciated. Besides the sponsoring agency noted on the title page, this work was also supported by the Department of Naval Architecture and Marine Engineering, and the Office of Research Administration of The University of Michigan.

REFERENCES

[1] K. W. H. Eggers, S. D. Sharma, and L. W. Ward, "An assessment of some experimental methods for determining the wavemaking characteristics of a ship form," Trans. SNAME vol. 75 (1967) pp. 112-144, 157.

[2] S. D. Sharma, "An attempted application of wave analysis techniques to achieve bow-wave reduction," Proc. Sixth Symposium on Naval Hydrodynamics, Washington, D.C., 1966, pp. 731-773.

[3] J. T. Everest, "Some research on the hydrodynamics of catamarans and multi-hulled vessels in calm water," Trans. NECIES vol. 84 (1967-68) pp. 129-148, D29-34.

[4] S. D. Sharma, "Der Wellenwiderstand eines flach getauchten Körpers und seine Beeinflussung durch einen aus dem Wasser herausragenden Turmaufbau," Schiffstechnik vol. 15 (1968) pp. 88-98.

[5] W. C. S. Wigley, "The theory of the bulbous bow and its practical application," Trans. NECIES vol. 52 (1935-36) pp. 65-88.

[6] G. Weinblum, "Theorie der Wulstschiffe," Schiffbau 1936 pp. 55-65.

[7] A. Kracht, "Lineartheoretische Abhandlung über die optimale Verringerung des Wellenwiderstandes gegebener Schiffsformen durch einen Wulst in symmetrischer oder asymmetrischer Anordnung," Institut für Schiffbau, Hamburg, Bericht Nr. 183, 1967.

[8] T. Inui, "Wavemaking resistance of ships," Trans. SNAME vol. 70 (1962) pp. 282-326, 353.

[9] T. H. Havelock, "The wave resistance of a spheroid," Proc. Royal Society A vol. 131 (1931) pp. 275-285.

[10] F. C. Michelsen, J. L. Moss, and B. J. Young, "Some aspects of hydrodynamic design of high-speed merchant ships," Trans. SNAME vol. 76 (1968) pp. 214-230, 237.

[11] H. Luft, "Wave probes for model tanks," Hamburg Model Basin Report No. F46/67 Translated from German by W. H. Roth and S. D. Sharma, University of Michigan, Department of Naval Architecture, July 1968.

[12] G. Hughes, "An analysis of ship model resistance into viscous and wave components," Trans. RINA vol. 108 (1966) pp. 289-297, 302. Discussion by C. W. Prokaska, p. 301.

[13] A. M. Reed, "Computer programs for the analysis of longitudinal ship wave profiles," University of Michigan, Department of Naval Architecture, May 1969.

TABLE 1—MODEL PARTICULARS

MODEL

$L_{PP} = 12.5$ ft

$T = 6.25$ in

$\lambda = 54.4$

SHIP

$L_{PP} = 680$ ft

$T_{FL} = 28.333$ ft

$B = 100$ ft

MODEL	C_B	C_M	C_P	MODEL		SHIP	
				S (ft^2)	∇ (ft^3)	S (ft)	Δ (tons-59°F)
1094	.521	.976	.534	24.228	6.2312	71,700	28,680
1094-B2	.525	.976	.538	24.701	6.2844	73,100	28,925
1094-B4	.526	.976	.539	24.910	6.2904	73,720	28,950
1094-B5	.527	.976	.540	24.991	6.3020	73,960	29,010

NOTE: Reference [10] gives the following for model 1094:

$C_B = 0.517$

$C_M = 0.976$

$C_P = 0.530$

Data under test conditions gives values calculated above using:

$$C_B = \frac{\nabla}{LBT}; \quad C_P = \frac{C_B}{C_M}$$

TABLE 2—MEASURED TOTAL RESISTANCE VALUES

MODEL	1094		1094-B2		1094-B4		1094-B5	
∇-ft^3	6.2312		6.2844		6.2904		6.3020	
S-ft^2	24.228		24.701		24.910		24.991	
TEMP °F	69.5°F		68°F		66°F		72°F	
SERIAL NO.	V (ft/sec)	R_T (lbs)	V	R_T	V	R_T	V	R_T
1	1.98	.355	2.28	.535	2.01	.45	*1.99	.42
2	2.07	.39	2.74	.76	2.22	.55	2.00	.44
3	2.29	.49	3.32	1.07	2.41	.63	2.22	.51
4	2.51	.58	3.54	1.19	2.62	.73	*2.23	.51
5	2.84	.75	3.64	1.28	2.80	.82	2.43	.62
6	3.09	.87	4.05	1.56	3.00	.93	2.62	.70
7	3.32	1.01	4.53	1.93	3.20	1.05	2.84	.84
8	3.52	1.13	5.07	2.48	3.42	1.18	3.00	.93
9	3.84	1.35	5.65	3.10	3.62	1.30	*3.22	1.06
10	4.12	1.55	6.05	3.65	3.82	1.44	3.38	1.175
11	4.43	1.80	6.13	3.79	4.02	1.57	3.59	1.32
12	4.63	2.25	6.49	4.31	4.20	1.73	*3.60	1.29
14	4.85	2.00	6.99	5.82	4.42	1.91	*3.78	1.40
14	5.13	2.53			4.61	2.05	*4.01	1.55
15	5.49	2.91			4.80	2.24	4.03	1.57
16	5.64	3.08			5.01	2.40	4.18	1.70
17	5.83	3.32			5.21	2.69	4.29	1.75
18	6.12	3.72			5.41	2.88	4.66	2.05
19	6.48	4.35			5.61	3.15	4.78	2.16
20	6.75	5.03			5.82	3.40	5.03	2.42
21	6.98	5.88			6.00	3.67	5.18	2.58
22	7.09	6.37			6.43	4.32	5.39	2.77
23	7.30	7.40			6.83	5.28	5.51	2.90
24					7.21	6.93	5.79	3.23
25							5.95	3.51
26							6.25	3.90
27							6.38	4.05
28							*6.65	4.70
29							*7.00	5.90
30							*7.20	6.75

* denotes data taken at 74°F.

TABLE 3—COMPARISON OF R_W

MODEL	R_W FROM EHP TESTS $F_N = 0.250$	R_W FROM WAVE CUTS $F_N = 0.250$	R_W FROM EHP TESTS $F_N = 0.267$	R_W FROM WAVE CUTS $F_N = 0.267$
1094	0.0127	0.0050	0.0106	0.0039
1094-B2	0.00567	0.0022	0.00570	0.0024
1094-B4	0.00306	0.0015	0.00457	0.0016
1094-B5	0.00409	0.0015	0.00419	0.0017

TABLE 4---CROSS PREDICTION MATRICES

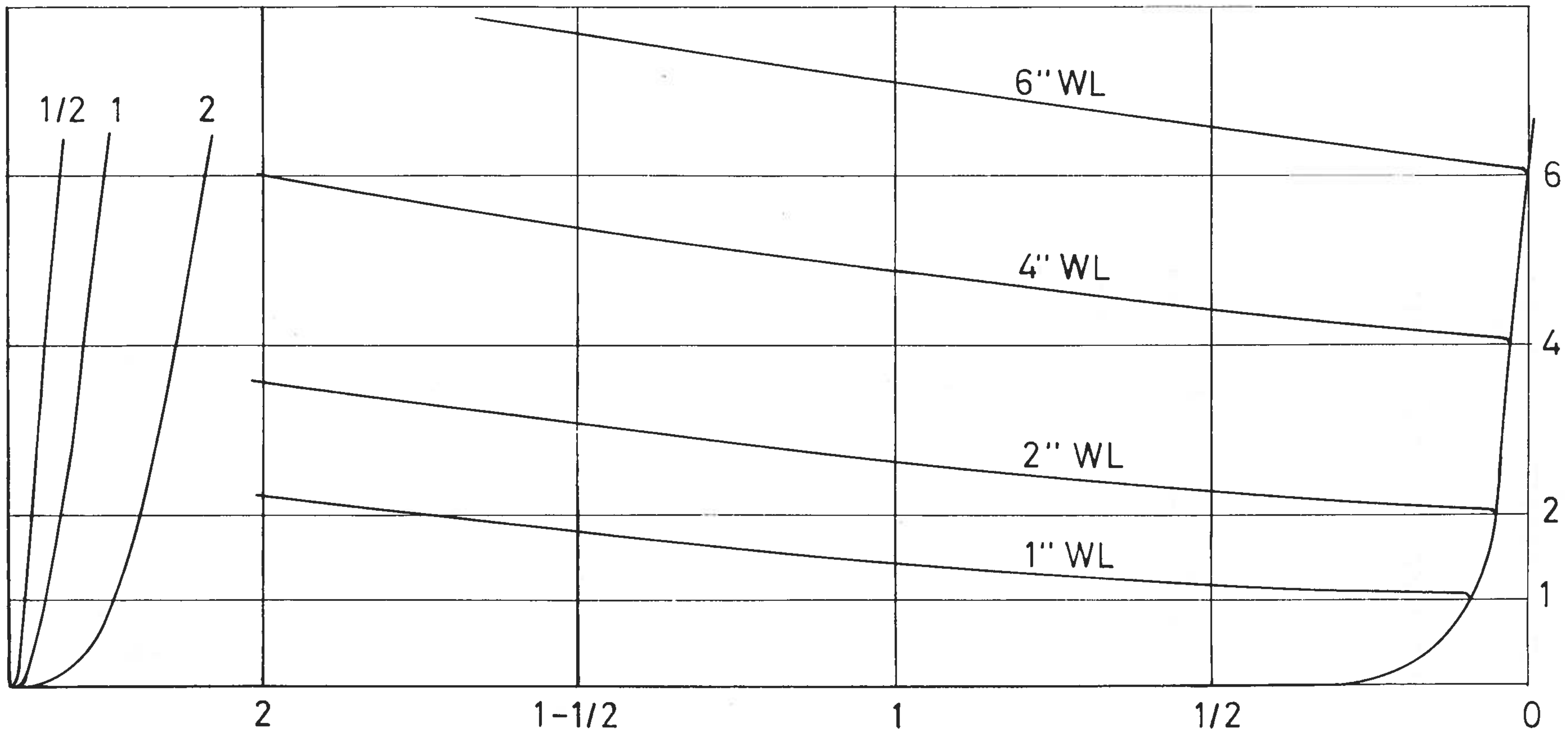
Summary of results of wave analysis and bulb optimization for Model 1094

I. $F_n = 0.250$ (V = 5.01 ft/sec)

	η PREDICTED FOR		
η PREDICTED FROM	B2	B4	B5
B2	0.44	0.43	0.36
B4	0.58	0.32	0.24
B5	0.53	0.39	0.29
EHP	0.446	0.241	0.322

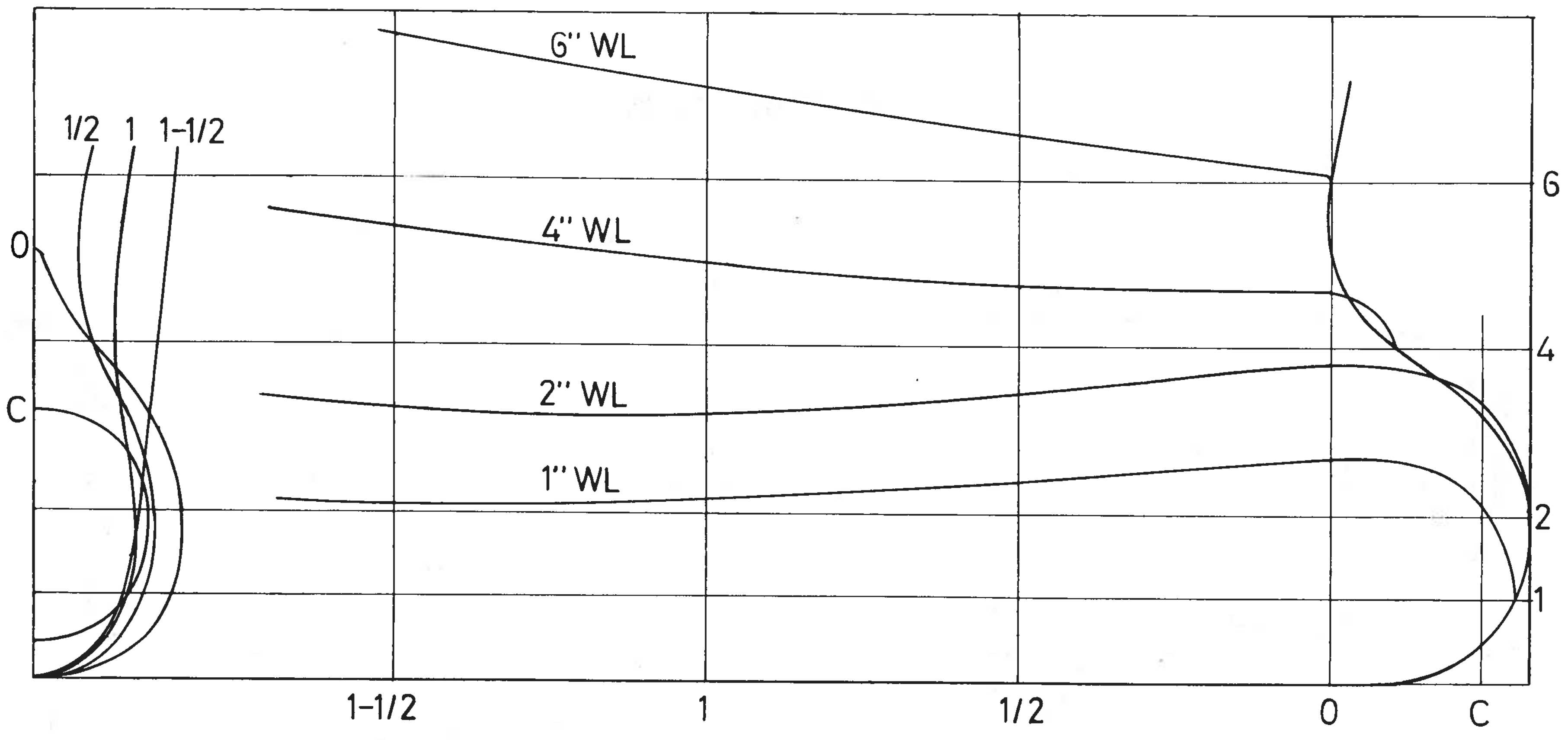
II. $F_n = 0.267$ (V = 5.36 ft/sec)

	η PREDICTED FOR		
η PREDICTED FROM	B2	B4	B5
B2	0.61	0.72	0.76
B4	0.53	0.42	0.34
B5	0.64	0.51	0.44
EHP	0.538	0.431	0.395



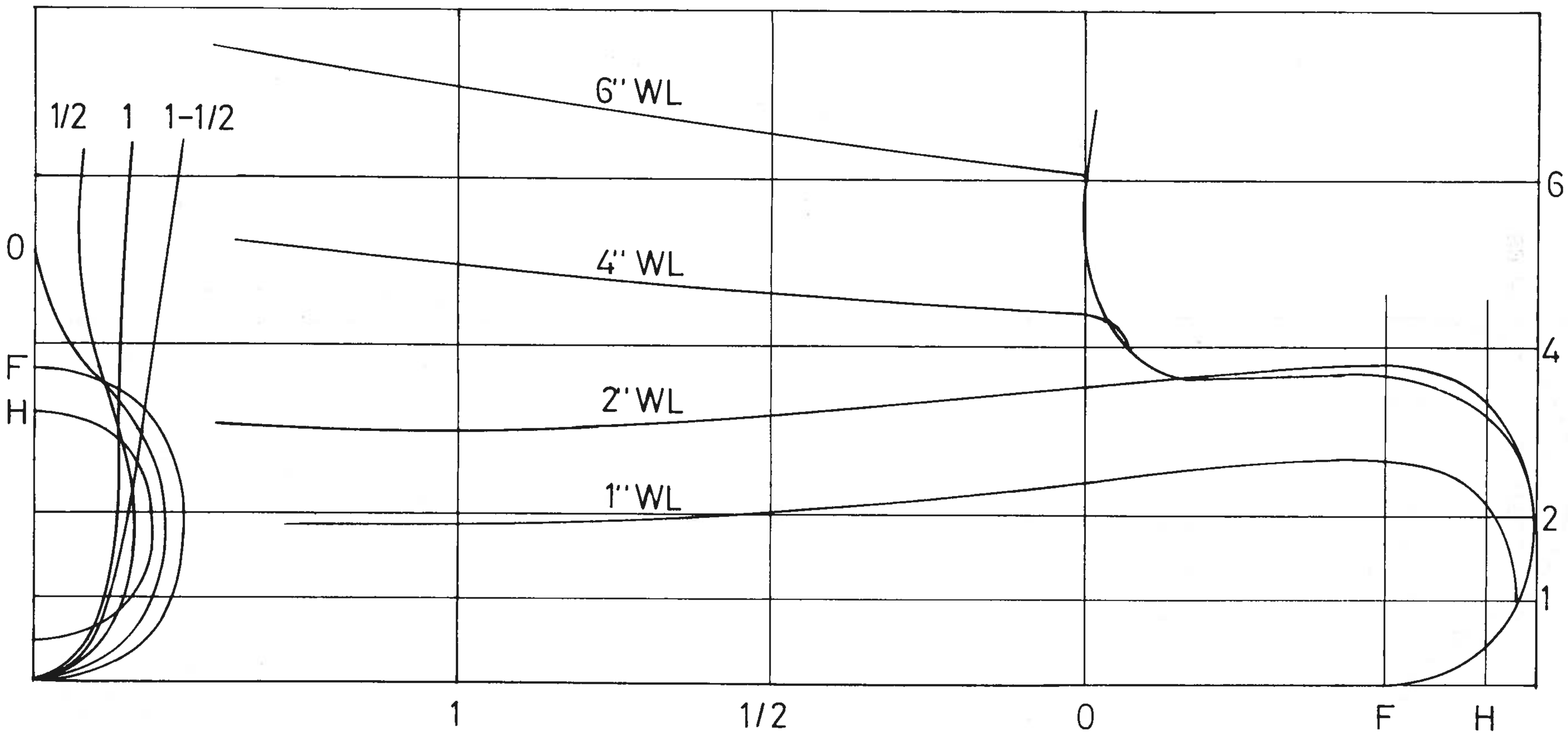
MODEL 1094

FIGURE 1



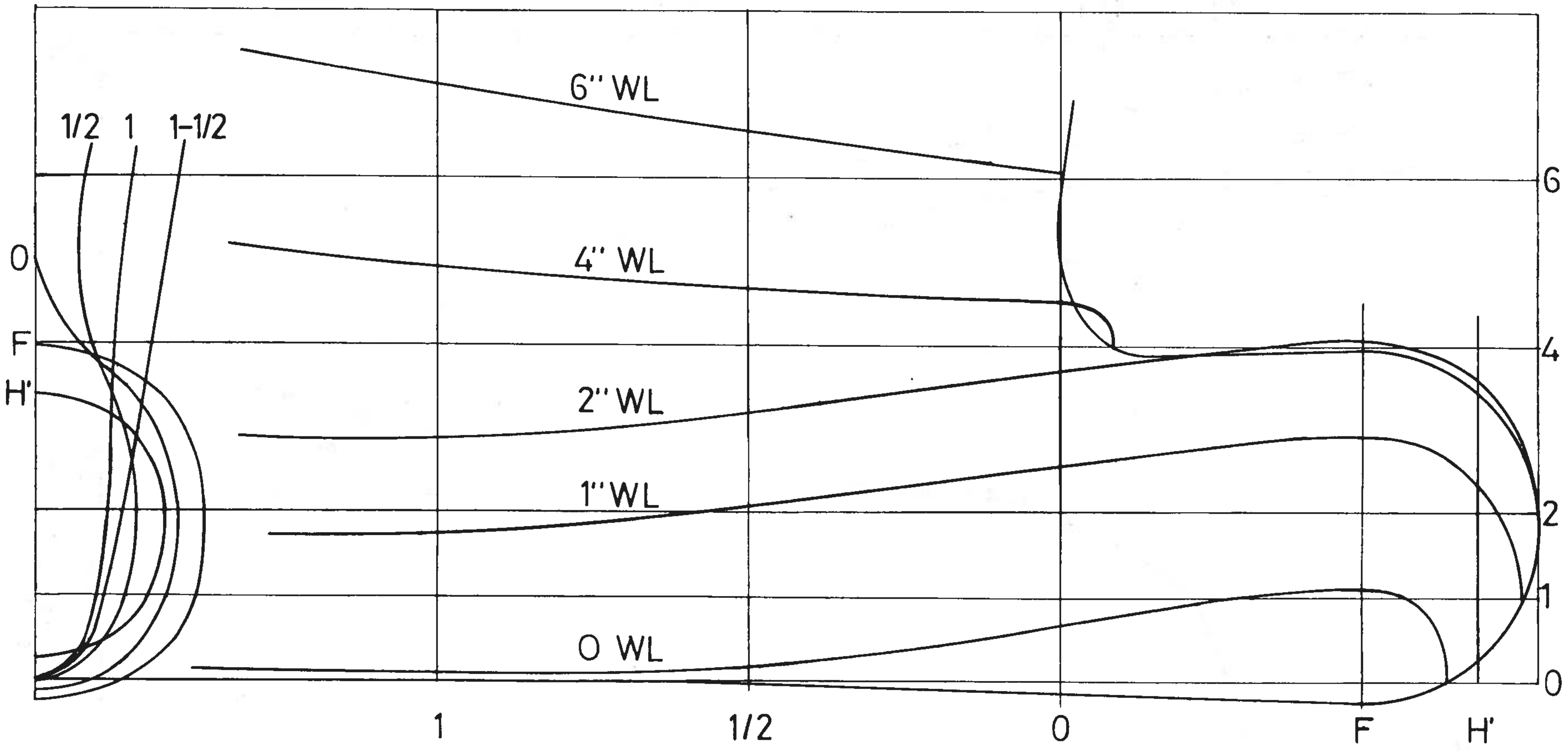
MODEL 1094-B2

FIGURE 2



MODEL 1094-B4

FIGURE 3



MODEL 1094-B5

FIGURE 4

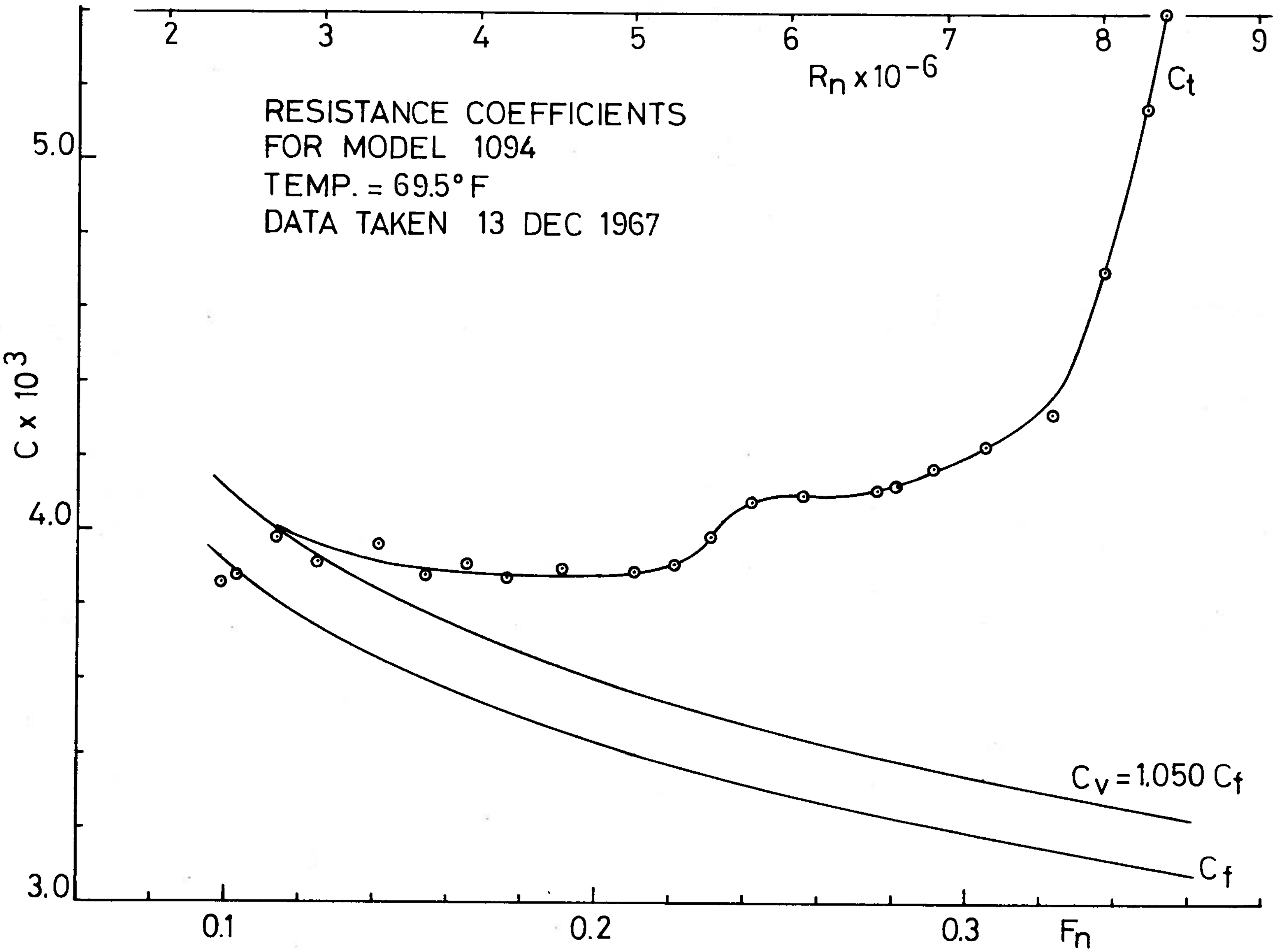
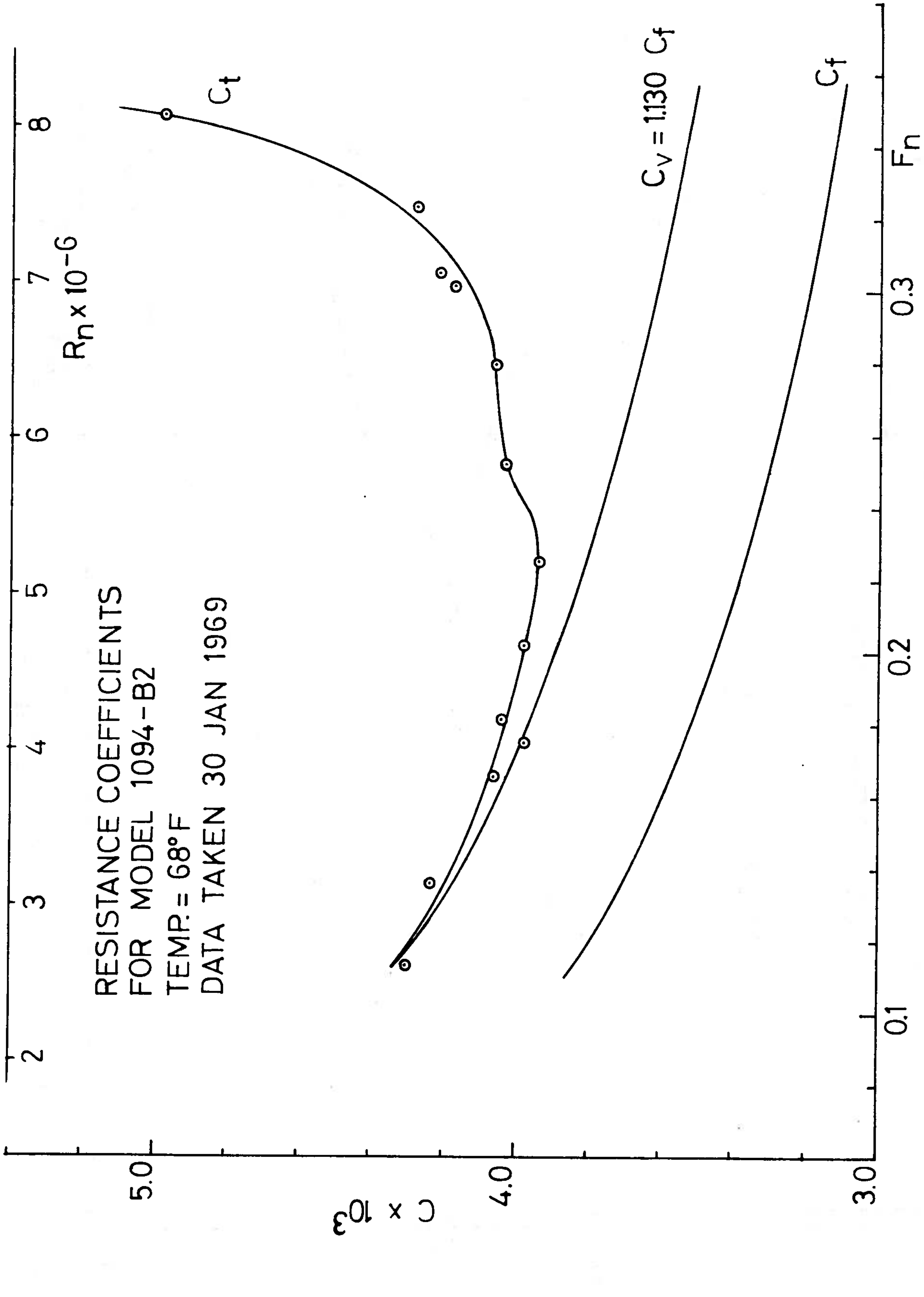

RESISTANCE COEFFICIENTS
FOR MODEL 1094
TEMP. = 69.5° F
DATA TAKEN 13 DEC 1967
2
3
4
5
6
7
8
9
$R_n \times 10^{-6}$
C_t
5.0
4.0
3.0
$C \times 10^3$
$C_V = 1.050\ C_f$
C_f
0.1
0.2
0.3
F_n

FIGURE 5



RESISTANCE COEFFICIENTS
FOR MODEL 1094-B2
TEMP. = 68°F
DATA TAKEN 30 JAN 1969

FIGURE 6

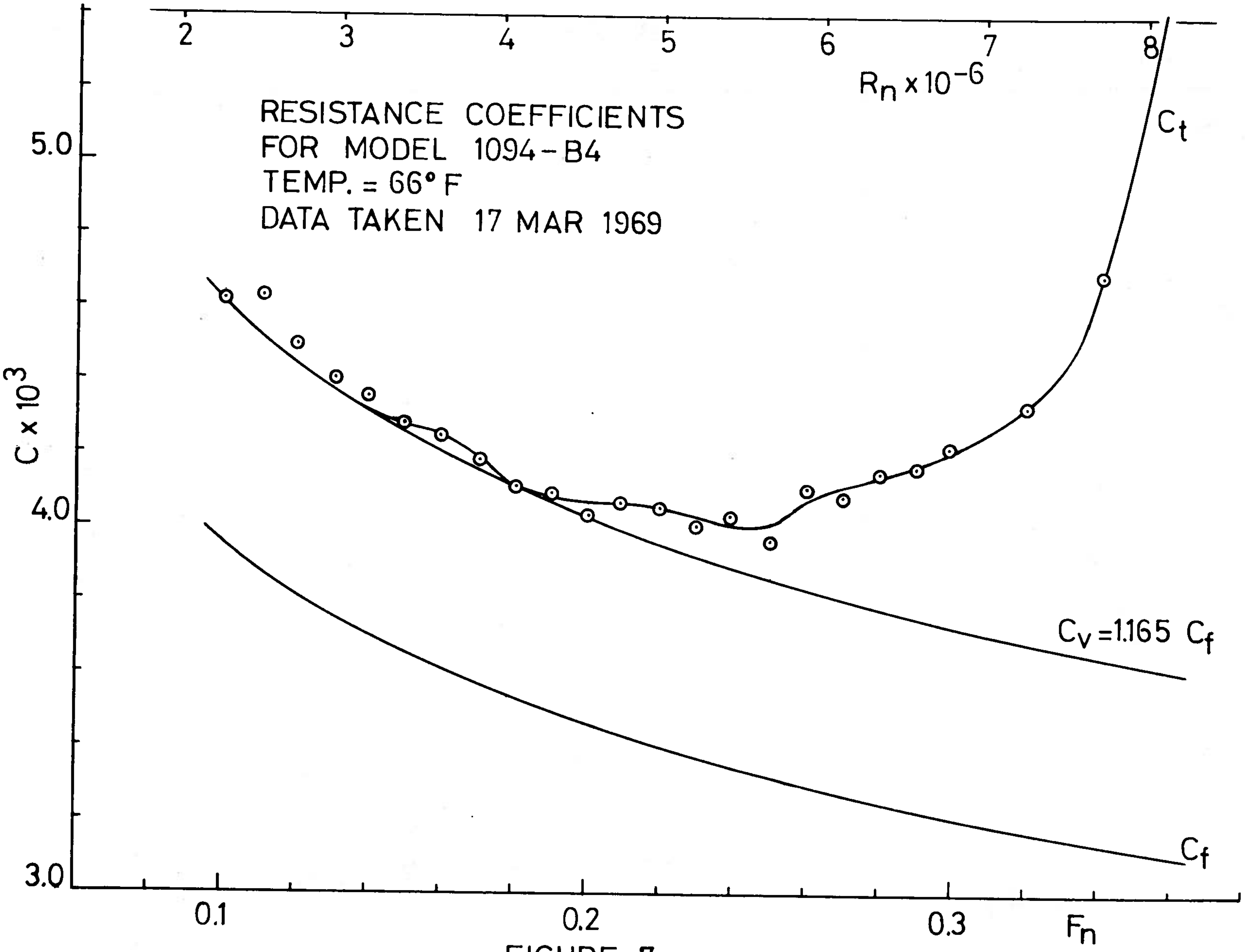

RESISTANCE COEFFICIENTS
FOR MODEL 1094-B4
TEMP. = 66° F
DATA TAKEN 17 MAR 1969
2
3
4
5
6
7
8
$R_n \times 10^{-6}$
C_t
$C_v = 1.165\ C_f$
C_f
5.0
4.0
3.0
$C \times 10^3$
0.1
0.2
0.3
F_n

FIGURE 7

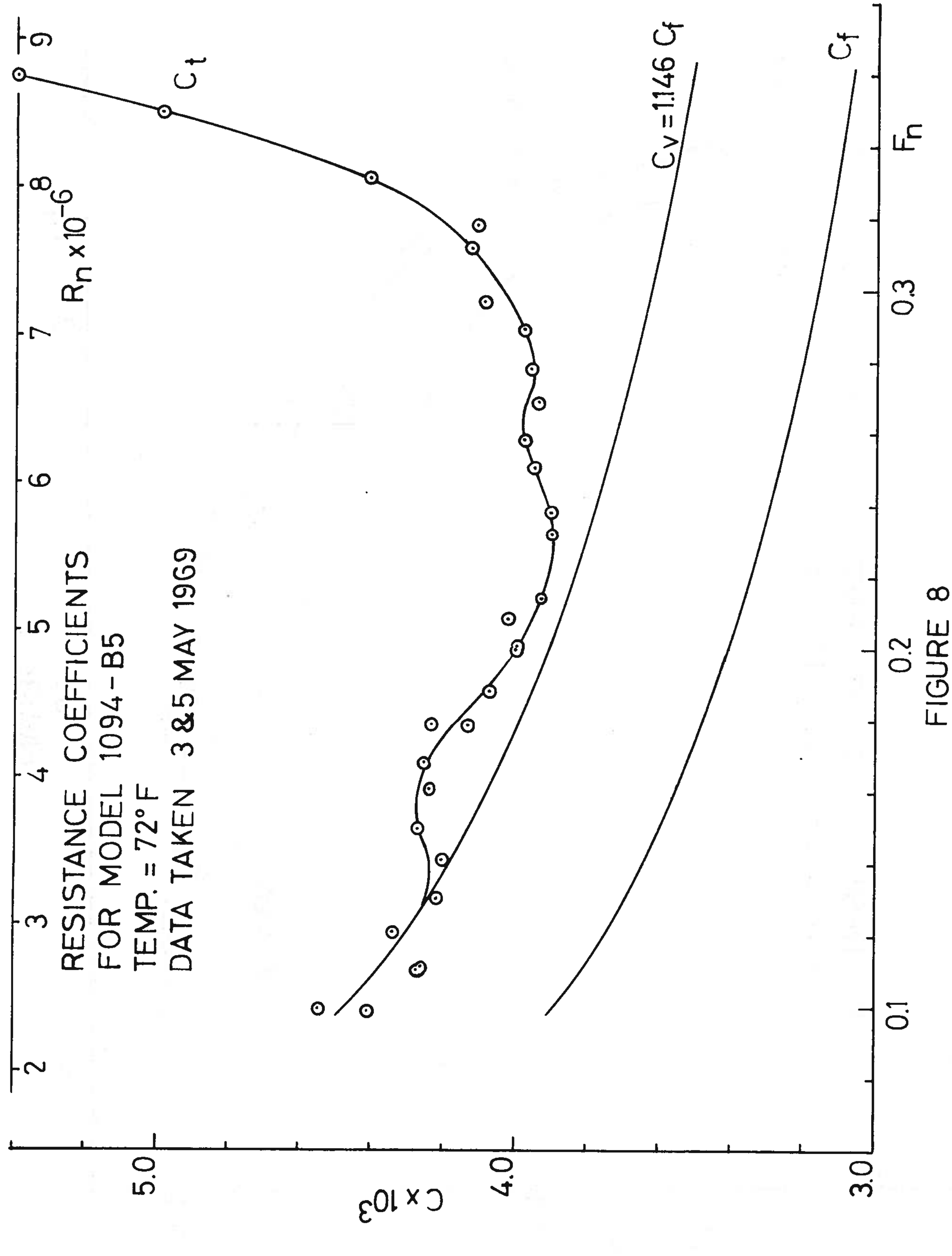
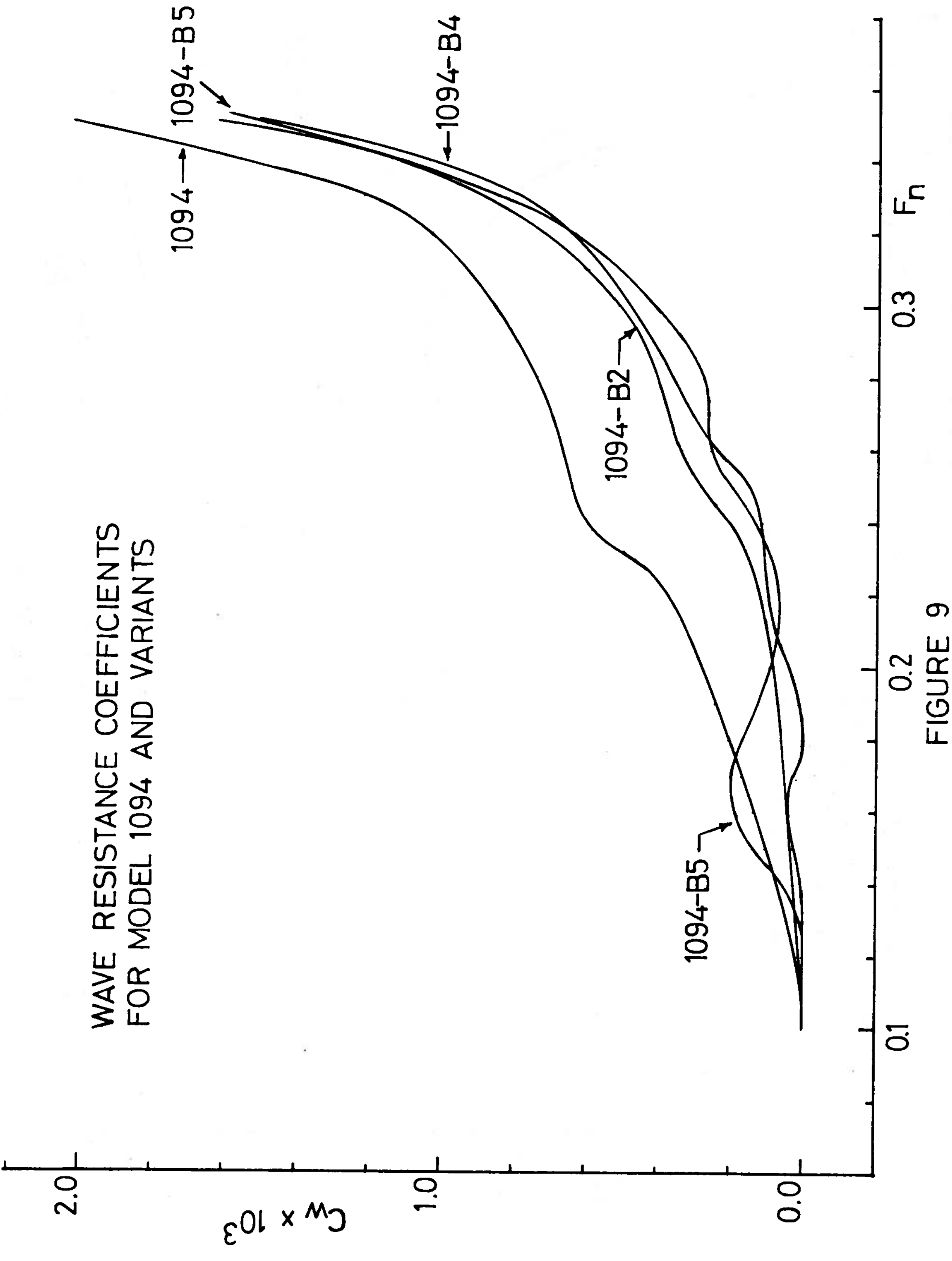

RESISTANCE COEFFICIENTS
FOR MODEL 1094-B5
TEMP. = 72° F
DATA TAKEN 3 & 5 MAY 1969

FIGURE 8



WAVE RESISTANCE COEFFICIENTS FOR MODEL 1094 AND VARIANTS

FIGURE 9

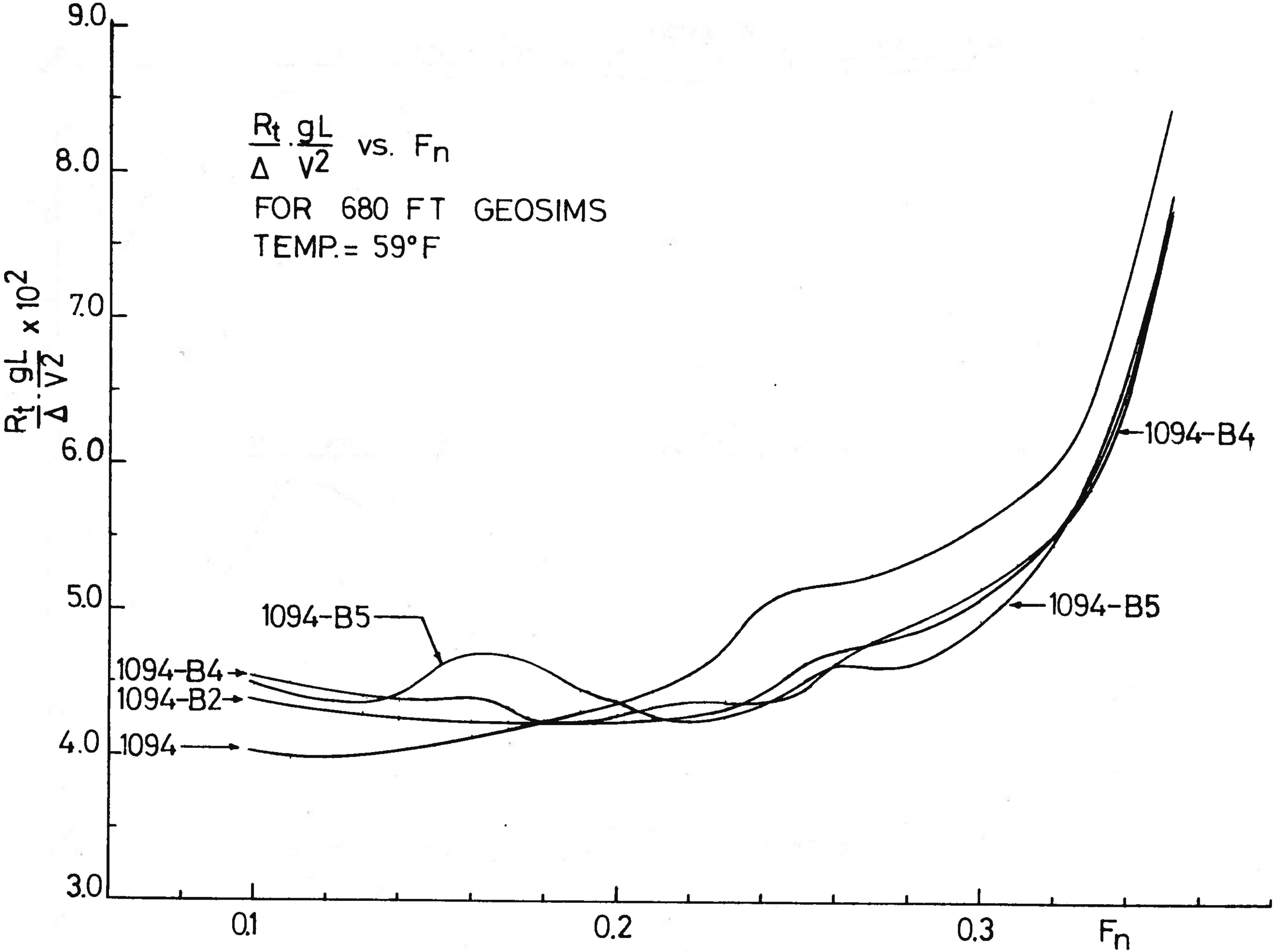

$\frac{R_t}{\Delta} \cdot \frac{gL}{V^2}$ vs. F_n
FOR 680 FT GEOSIMS
TEMP.= 59°F
$\frac{R_t}{\Delta} \cdot \frac{gL}{V^2} \times 10^2$
9.0
8.0
7.0
6.0
5.0
4.0
3.0
0.1
0.2
0.3
F_n
1094-B4
1094-B5
1094-B5
1094-B4
1094-B2
1094

FIGURE 10

WAVE SPECTRA FOR MODEL 1094 AT V=5.01 FT/SEC AUG.6,1968

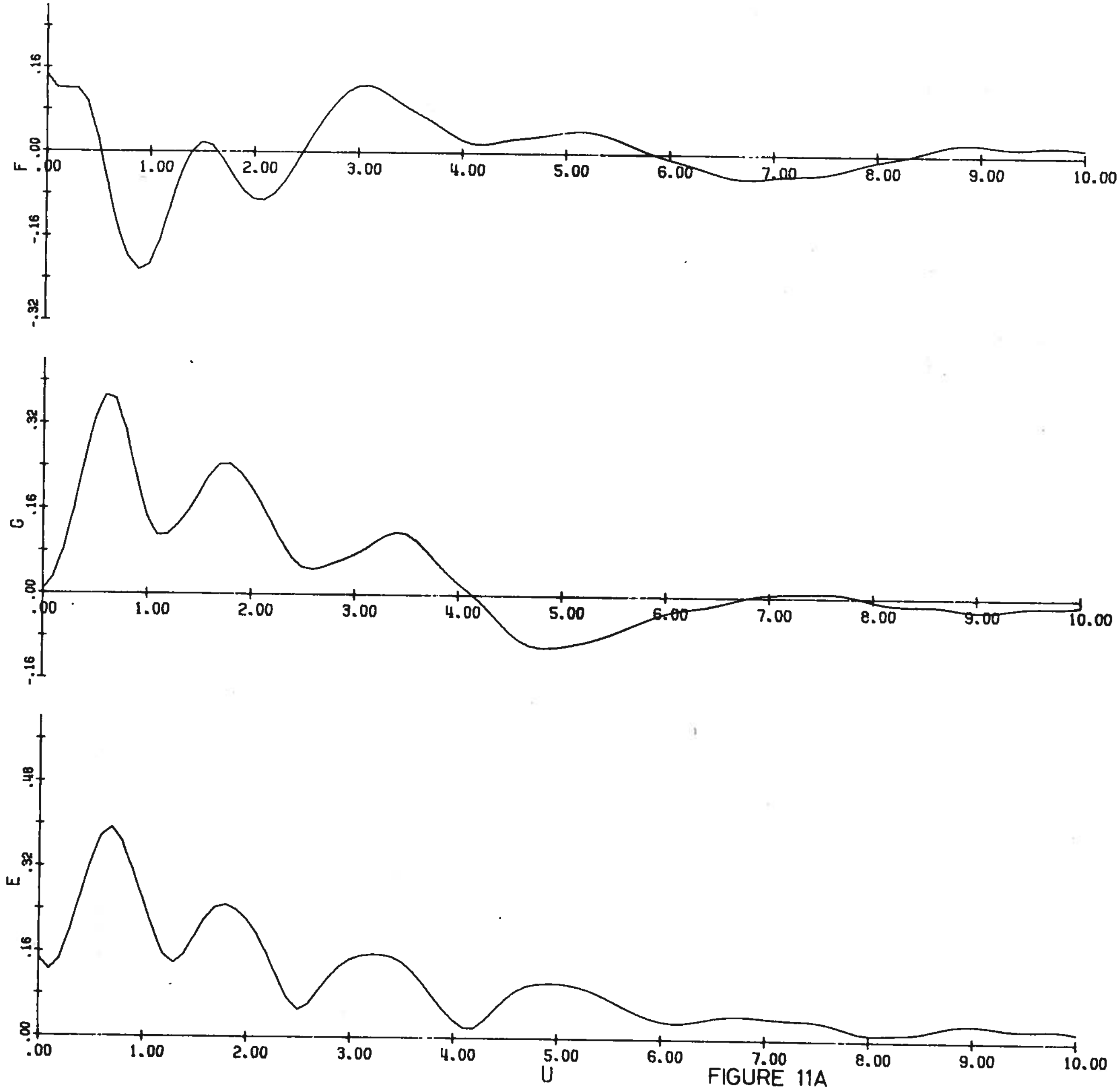


FIGURE 11A

WAVE SPECTRA FOR MODEL 1094 AT V=5.01 FT/SEC AUG.6,1968

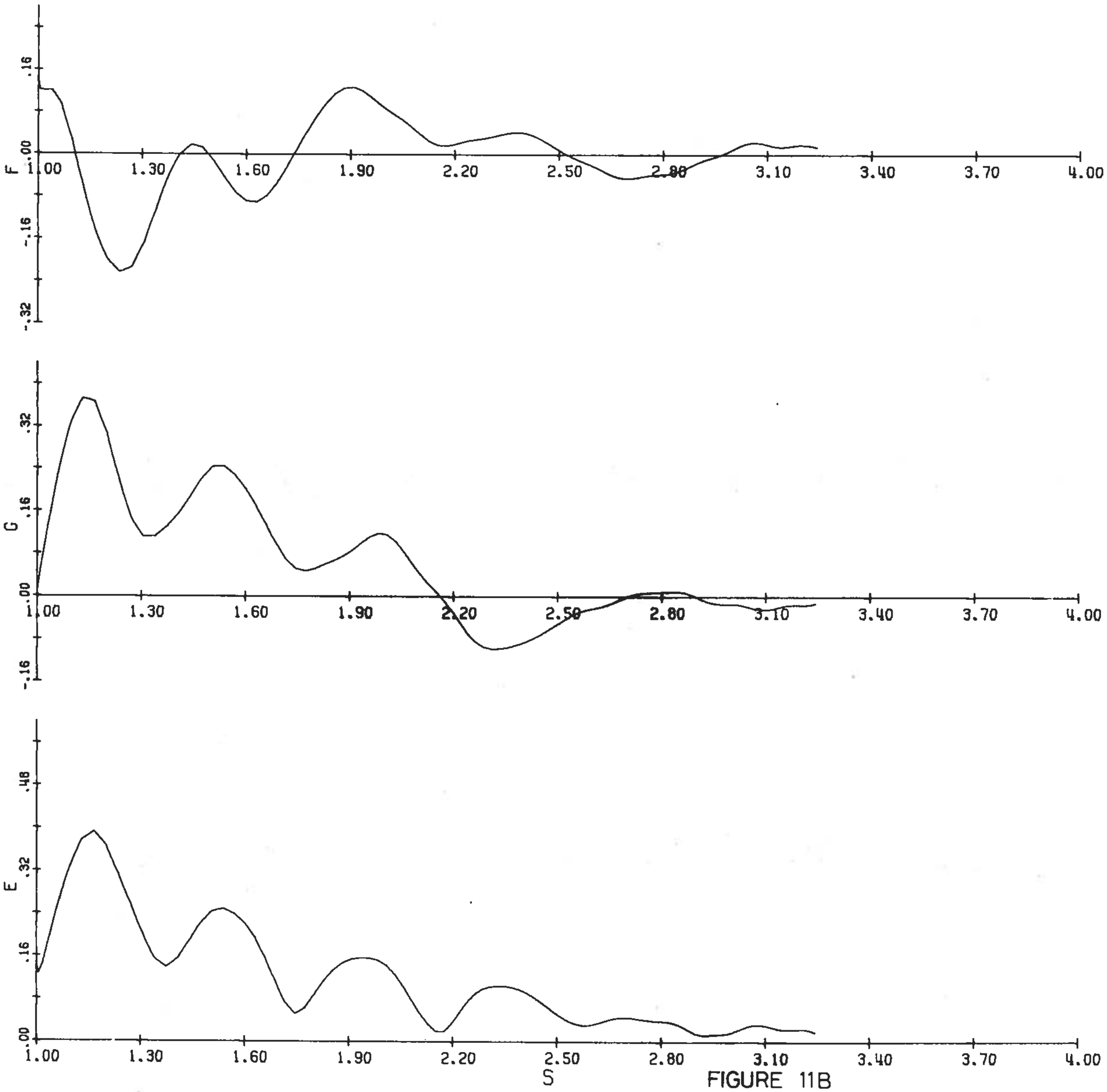


FIGURE 11B

WAVE SPECTRA FOR MODEL 1094 AT V=5.36 FT/SEC AUG.6,1968

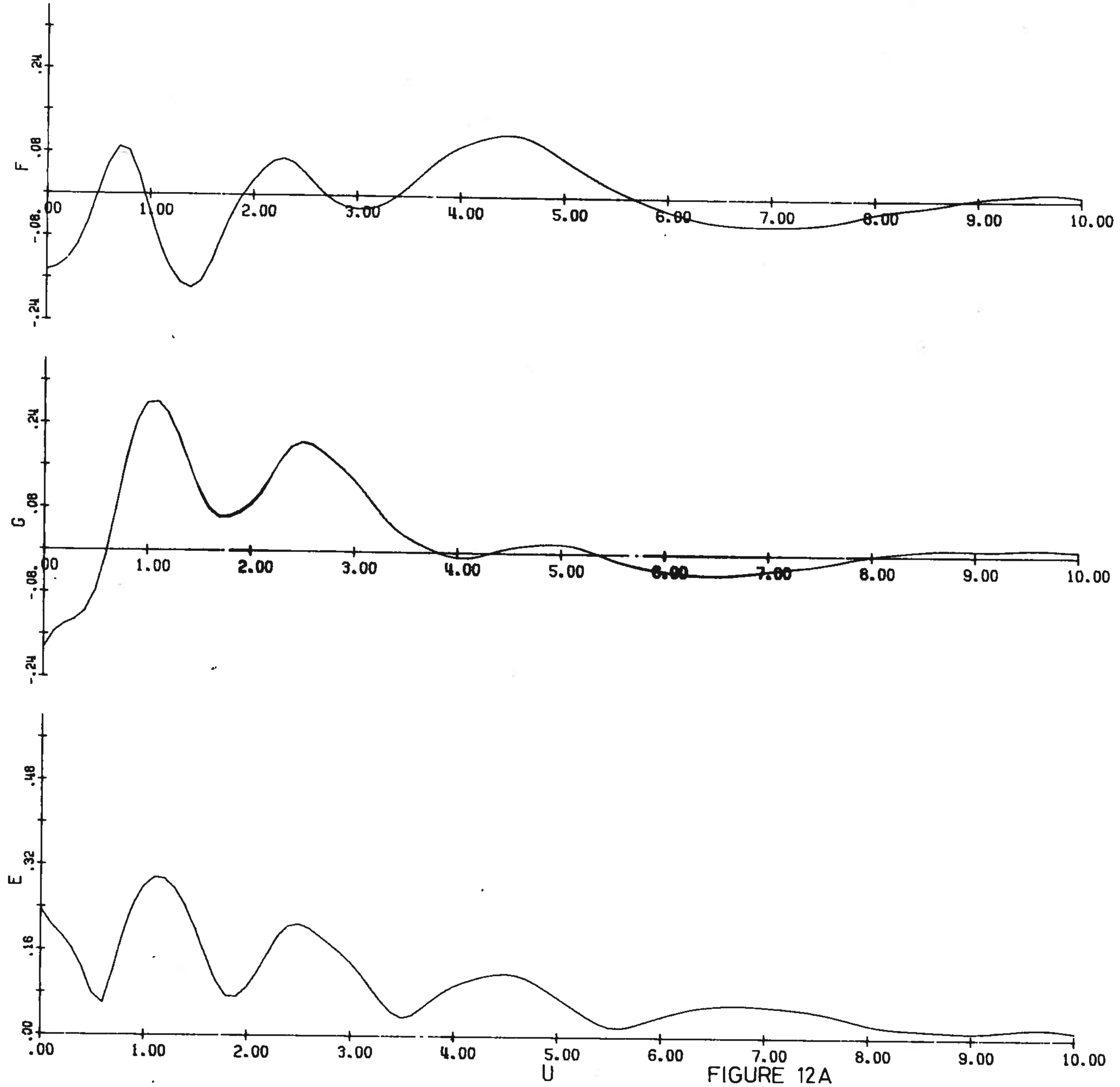


FIGURE 12A

WAVE SPECTRA FOR MODEL 1094 AT V=5.36 FT/SEC AUG.6,1968

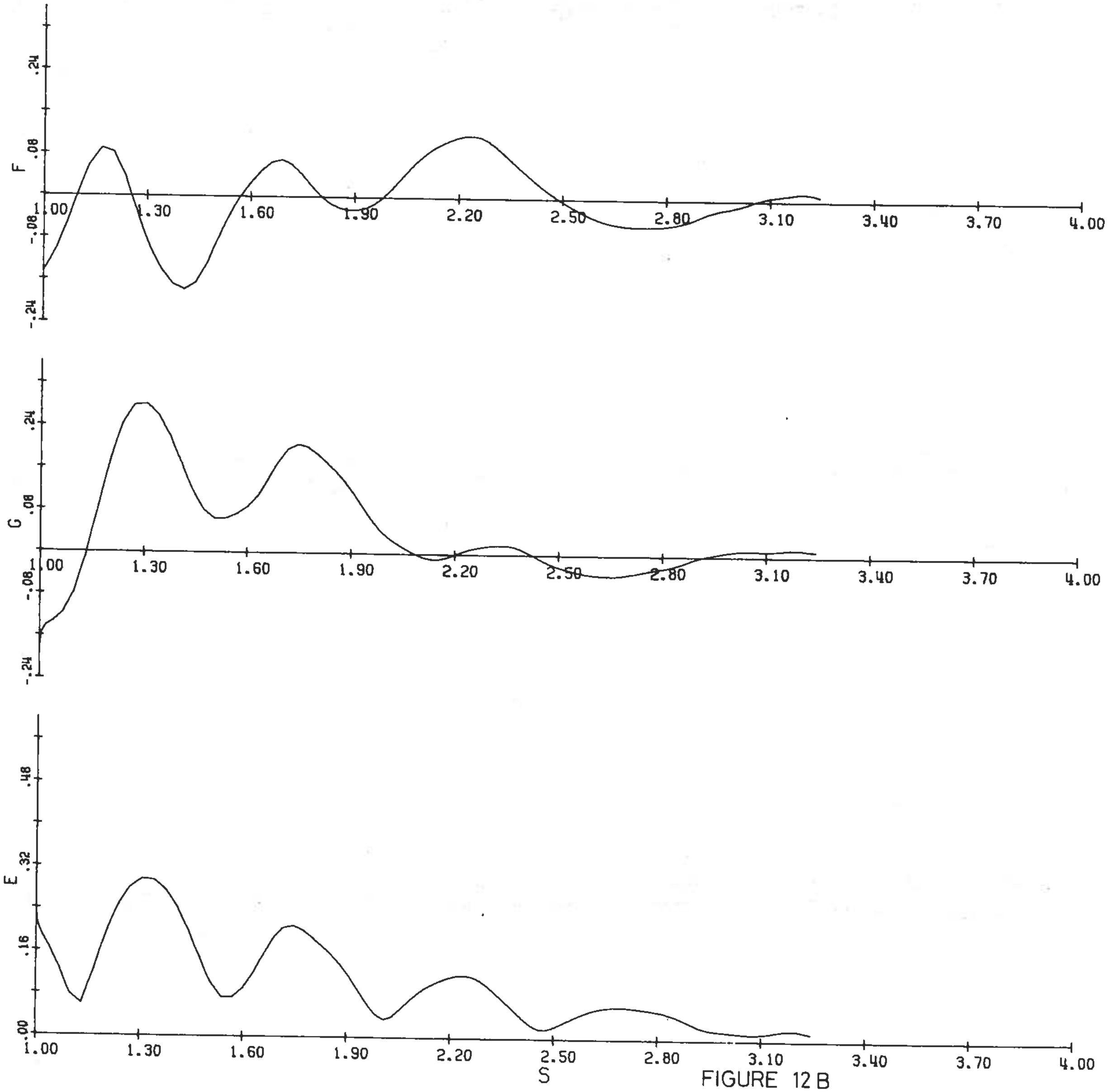


FIGURE 12 B

WAVE SPECTRA FOR MODEL 1094-B2 AT V=5.01 FT/SEC AUG.8,1968

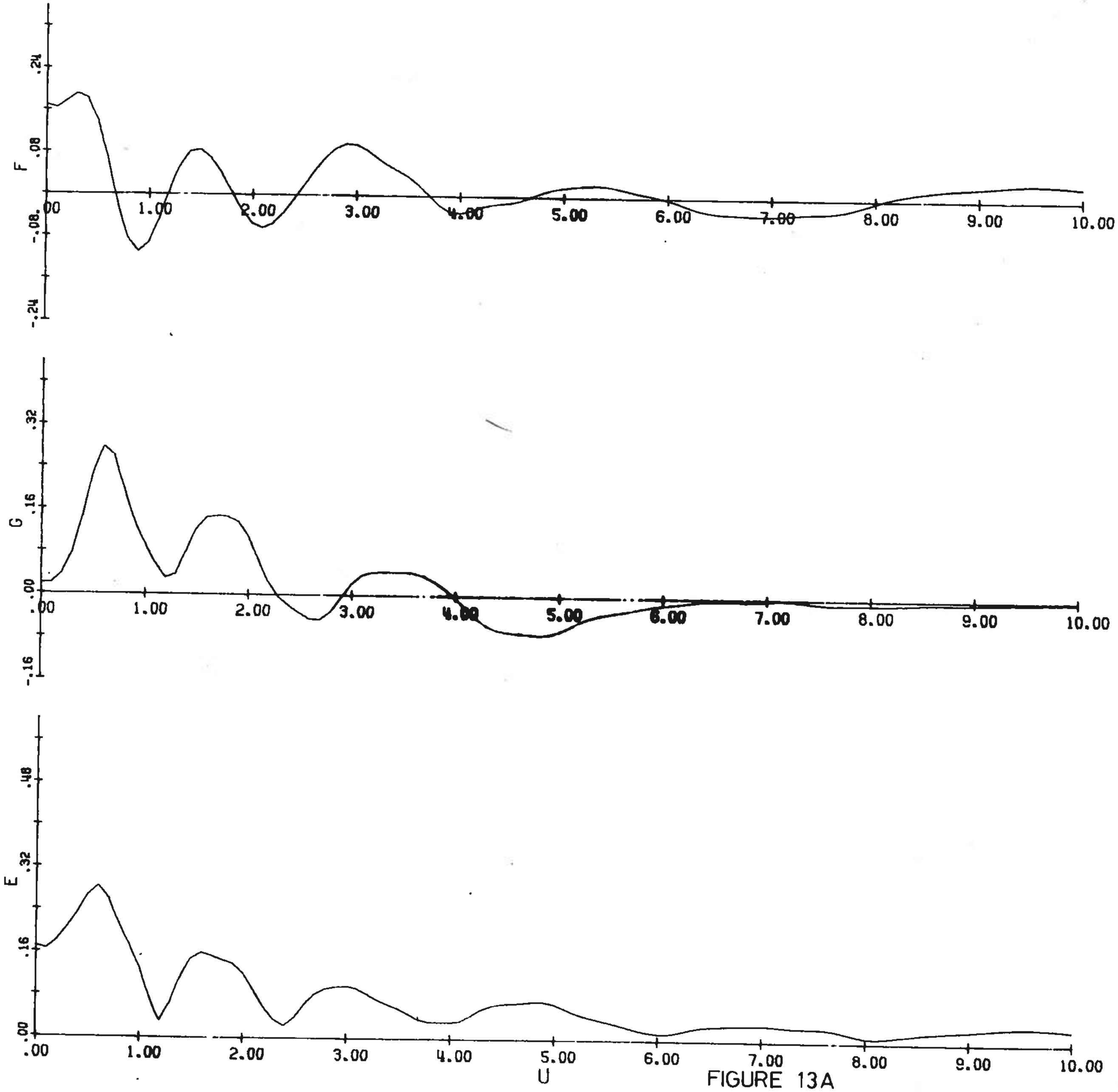


FIGURE 13A

WAVE SPECTRA FOR MODEL 1094-B2 AT V=5.01 FT/SEC AUG.8,1968

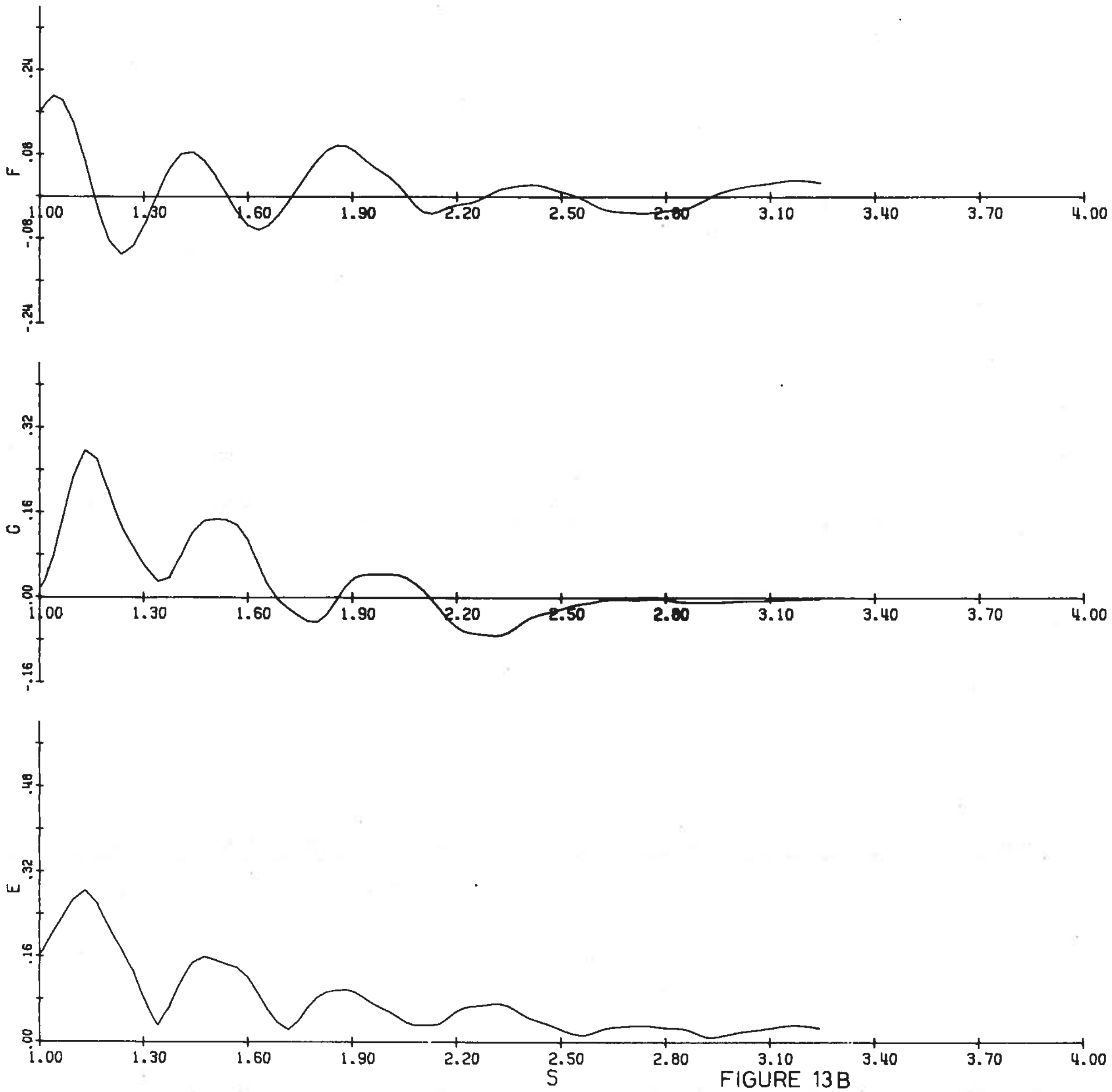


FIGURE 13B

WAVE SPECTRA FOR MODEL 1094-B2 AT V=5.36 FT/SEC AUG.8,1968

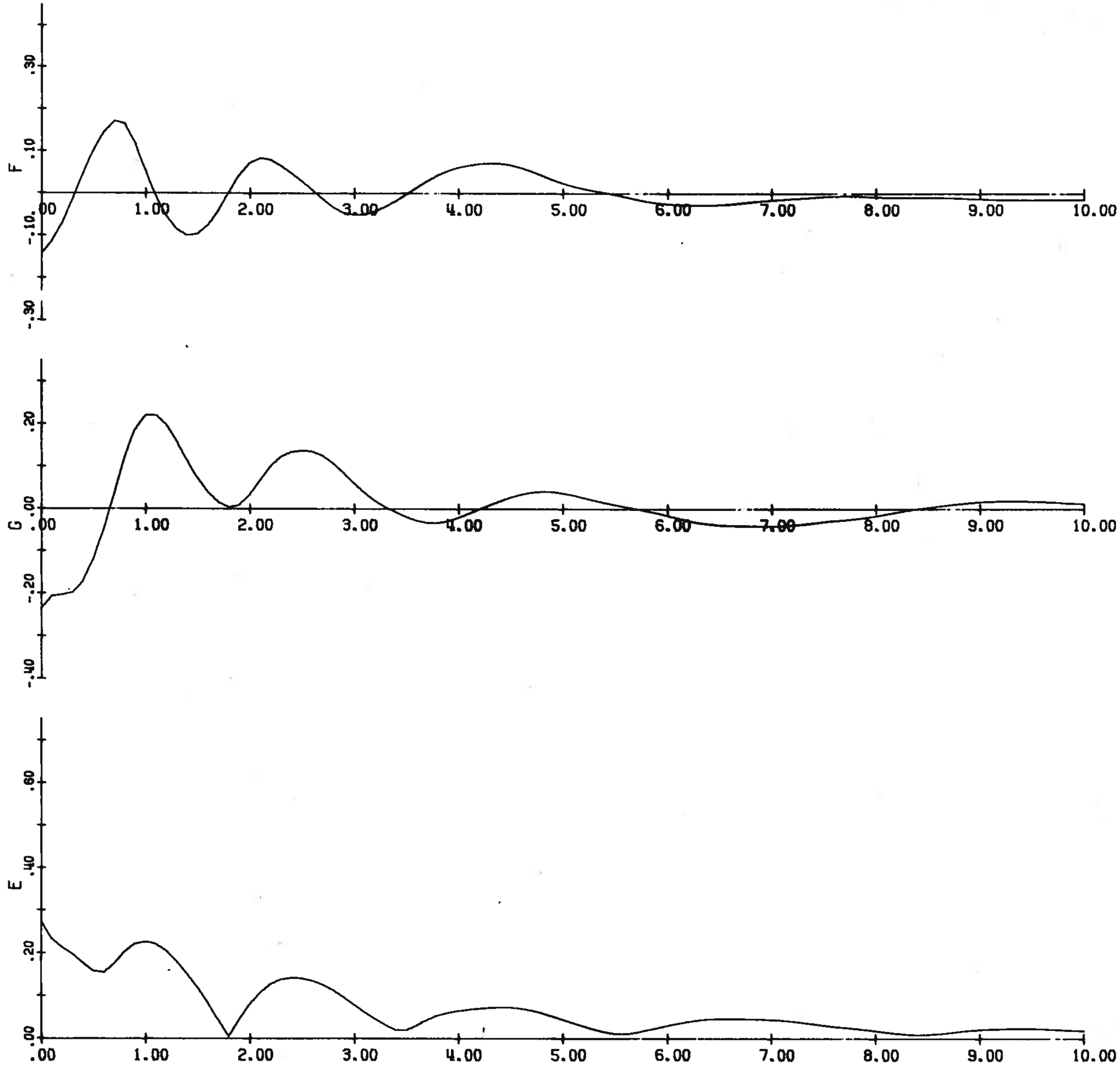


FIGURE 14A

WAVE SPECTRA FOR MODEL 1094-B2 AT V=5.36 FT/SEC AUG.8,1968

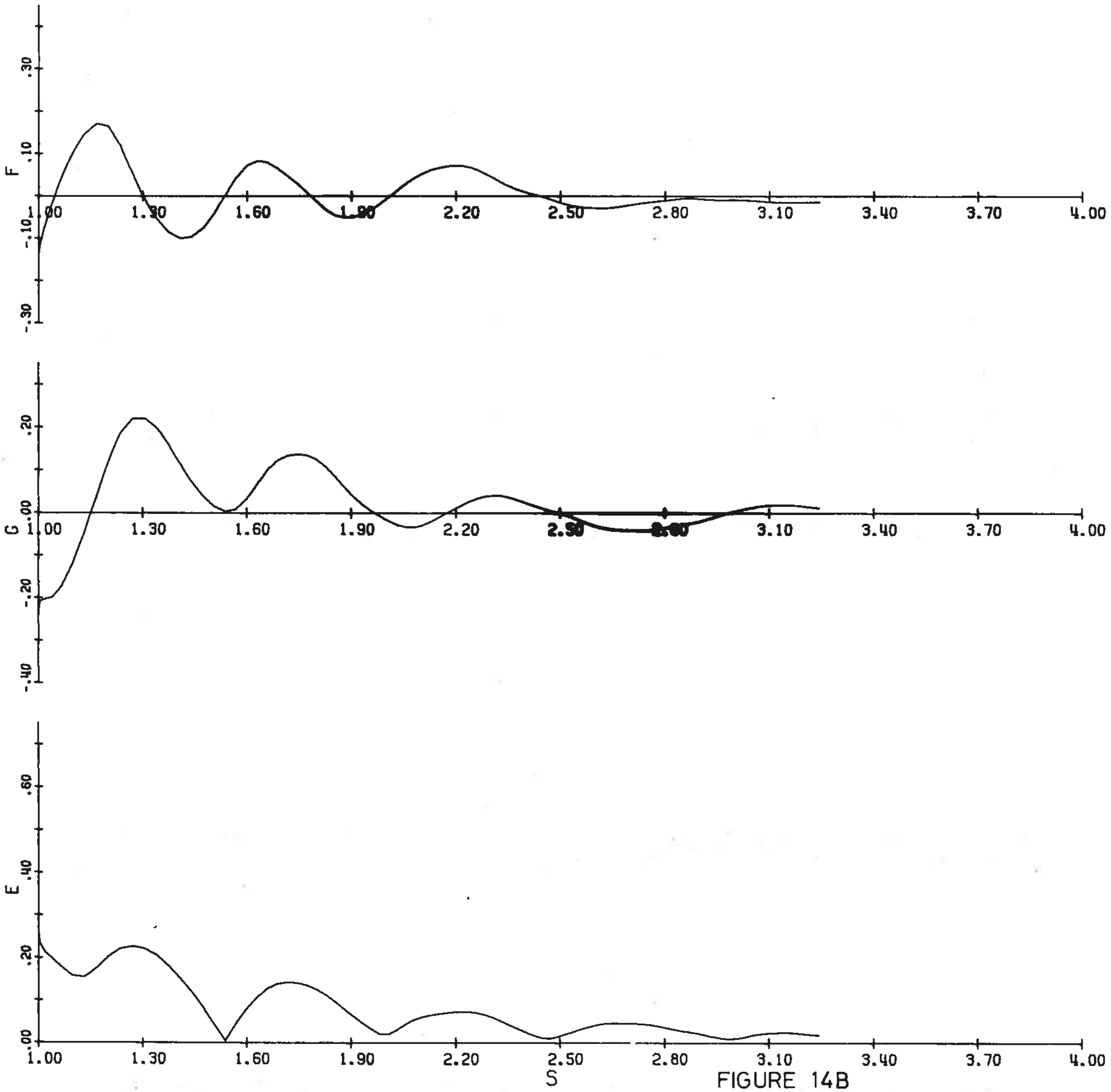


FIGURE 14B

MODEL 1094-B4 RUN NO.2 18 MAR 1969 V=5.01 FT/SEC

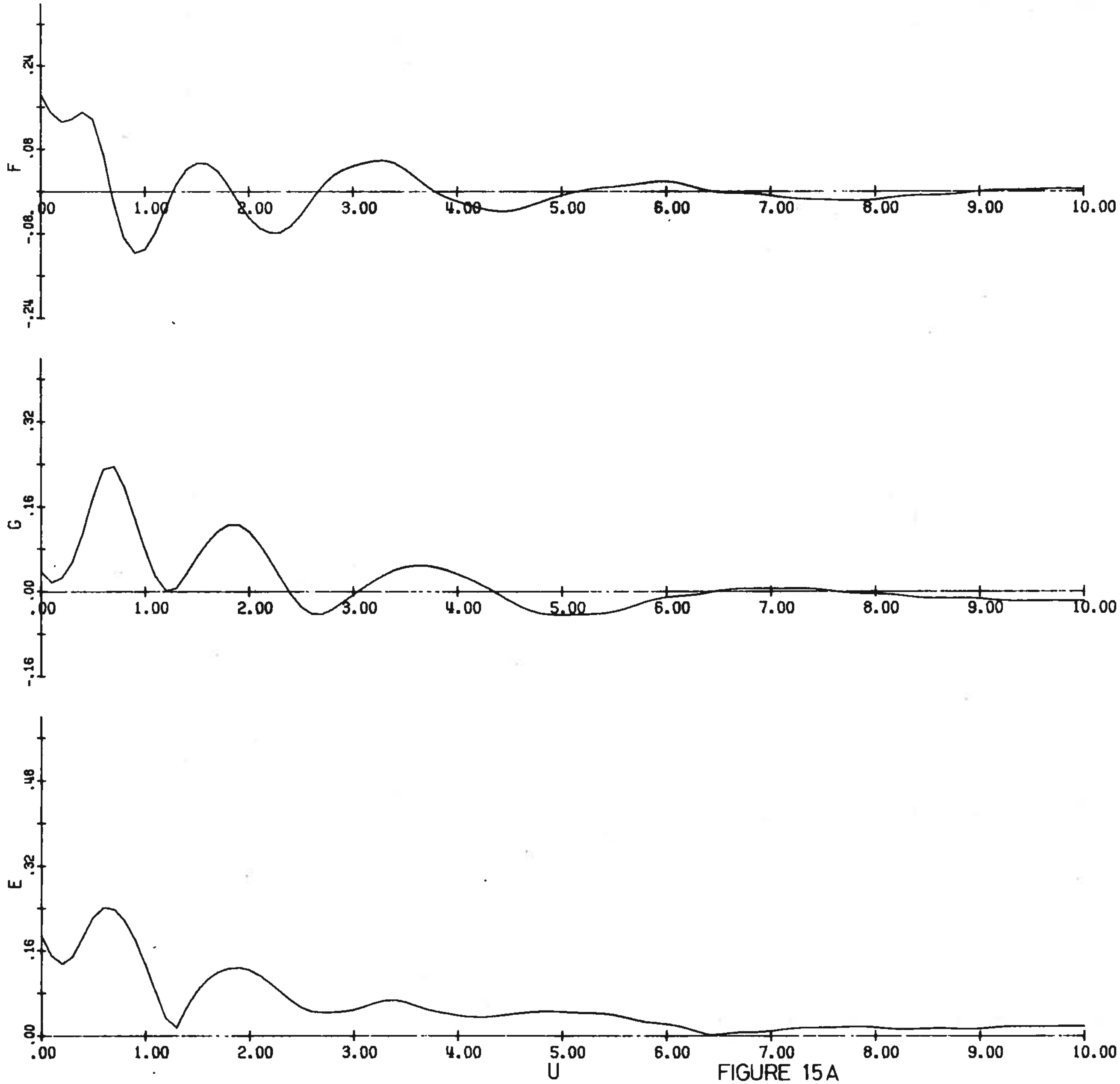


FIGURE 15A

MODEL 1094-B4 RUN NO.2 18 MAR 1969 V=5.01 FT/SEC

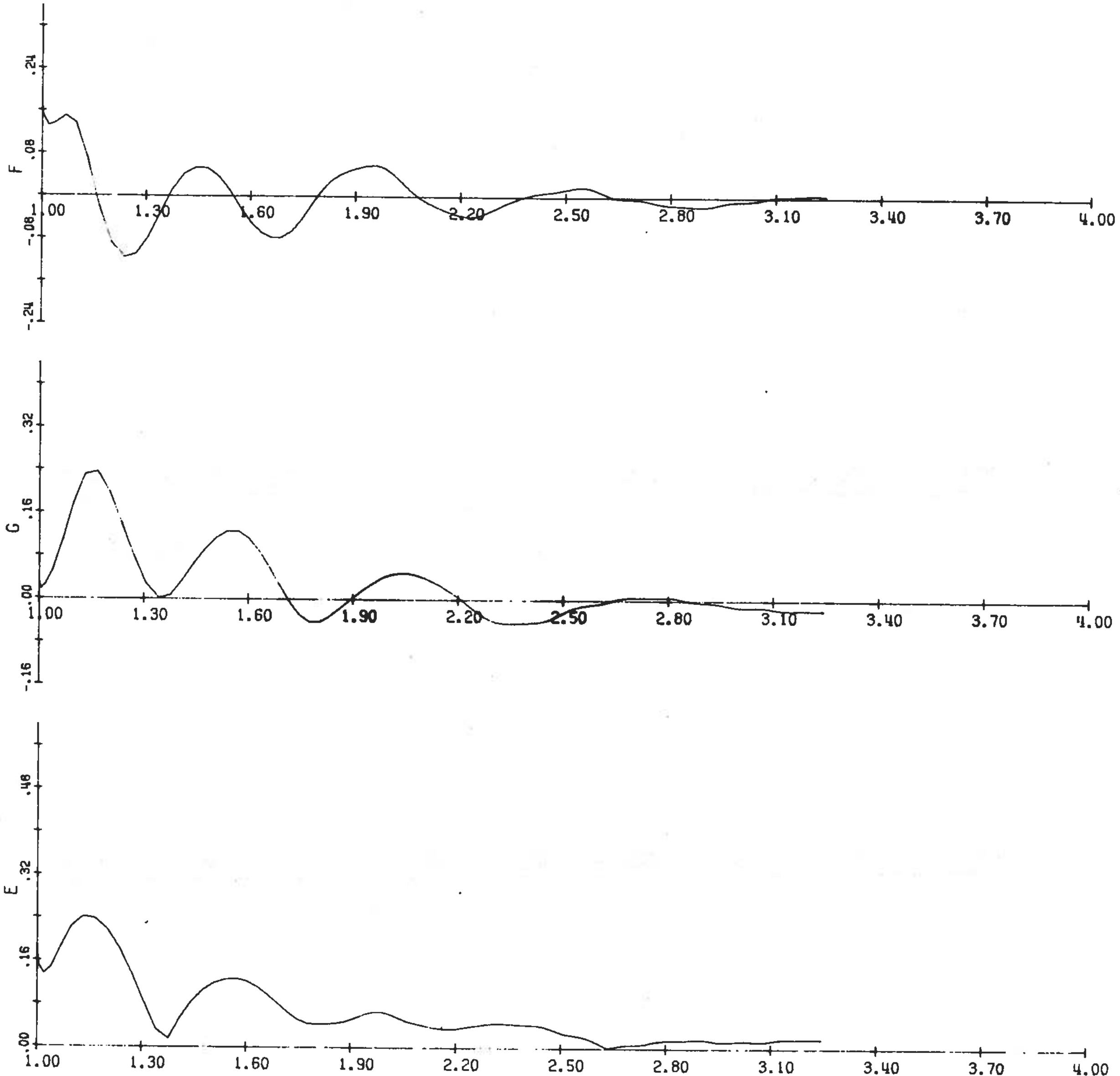


FIGURE 15B

MODEL 1094-B4 RUN NO.3 18 MAR 1969 V=5.36 FT/SEC

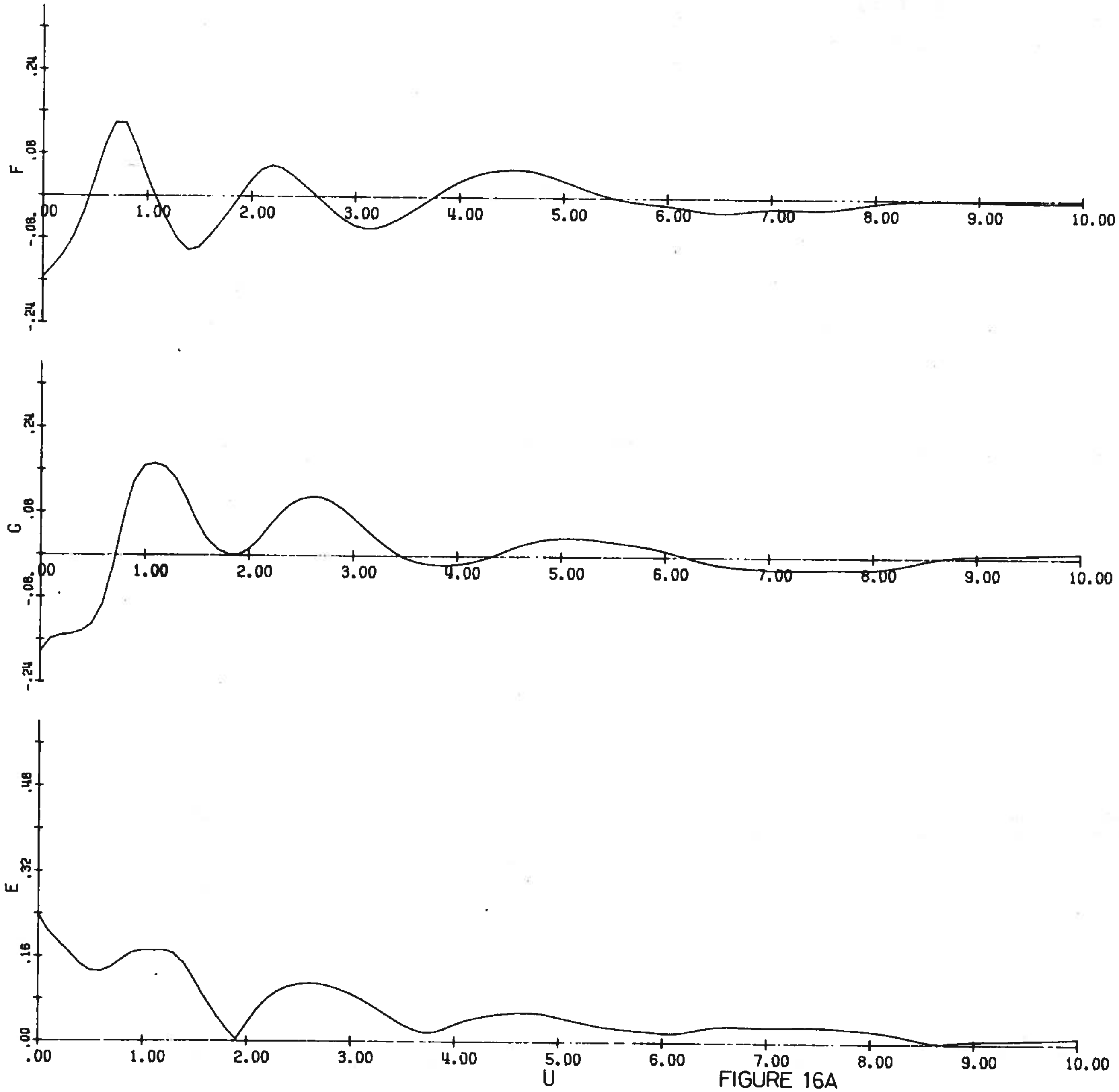


FIGURE 16A

MODEL 1094-B4 RUN NO.3 18 MAR 1969 V=5.36 FT/SEC

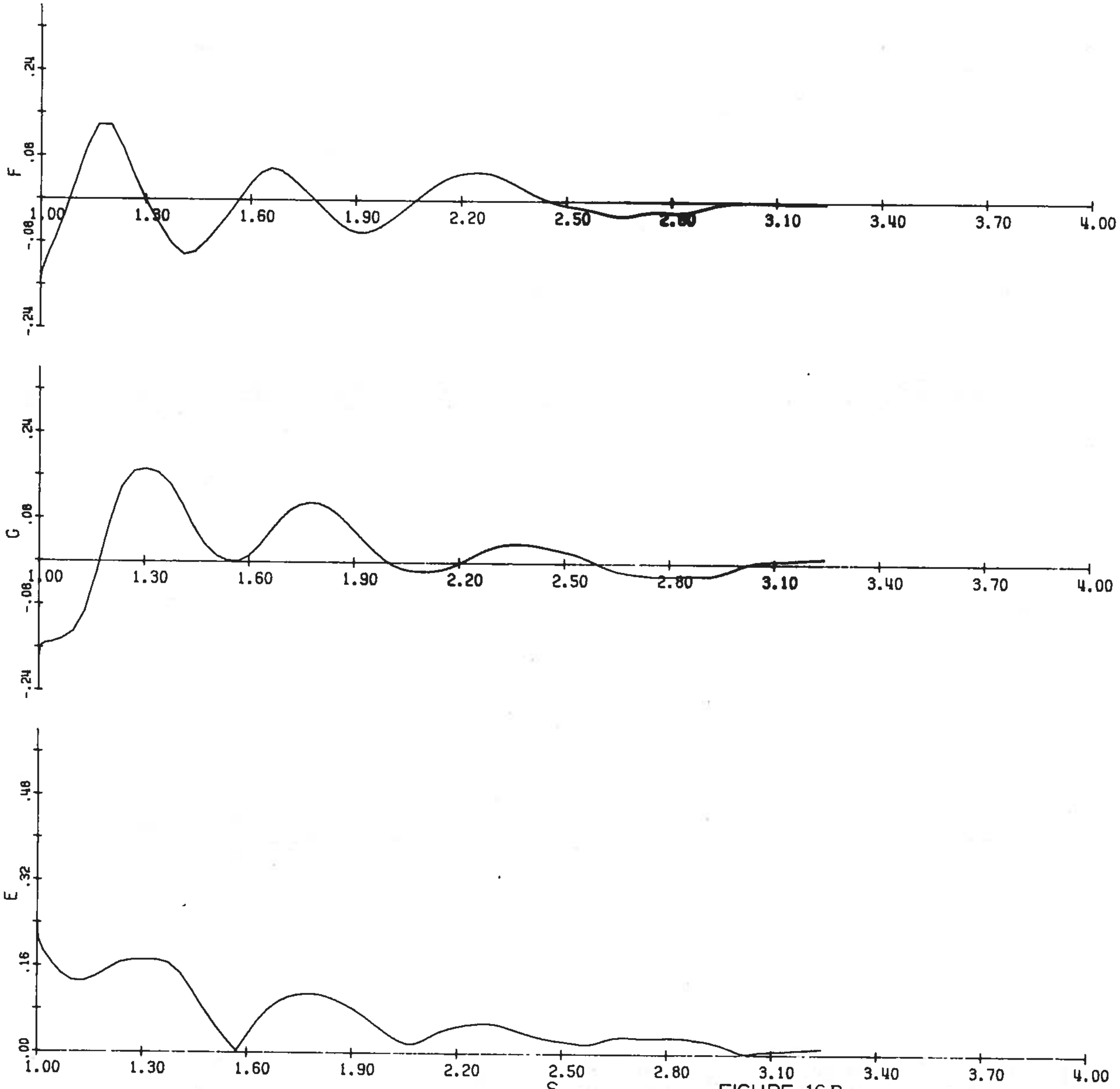


FIGURE 16B

WAVE SPECTRA FOR MODEL 1094-B5 AT V=5.01 FT./SEC. MAY 3,1969

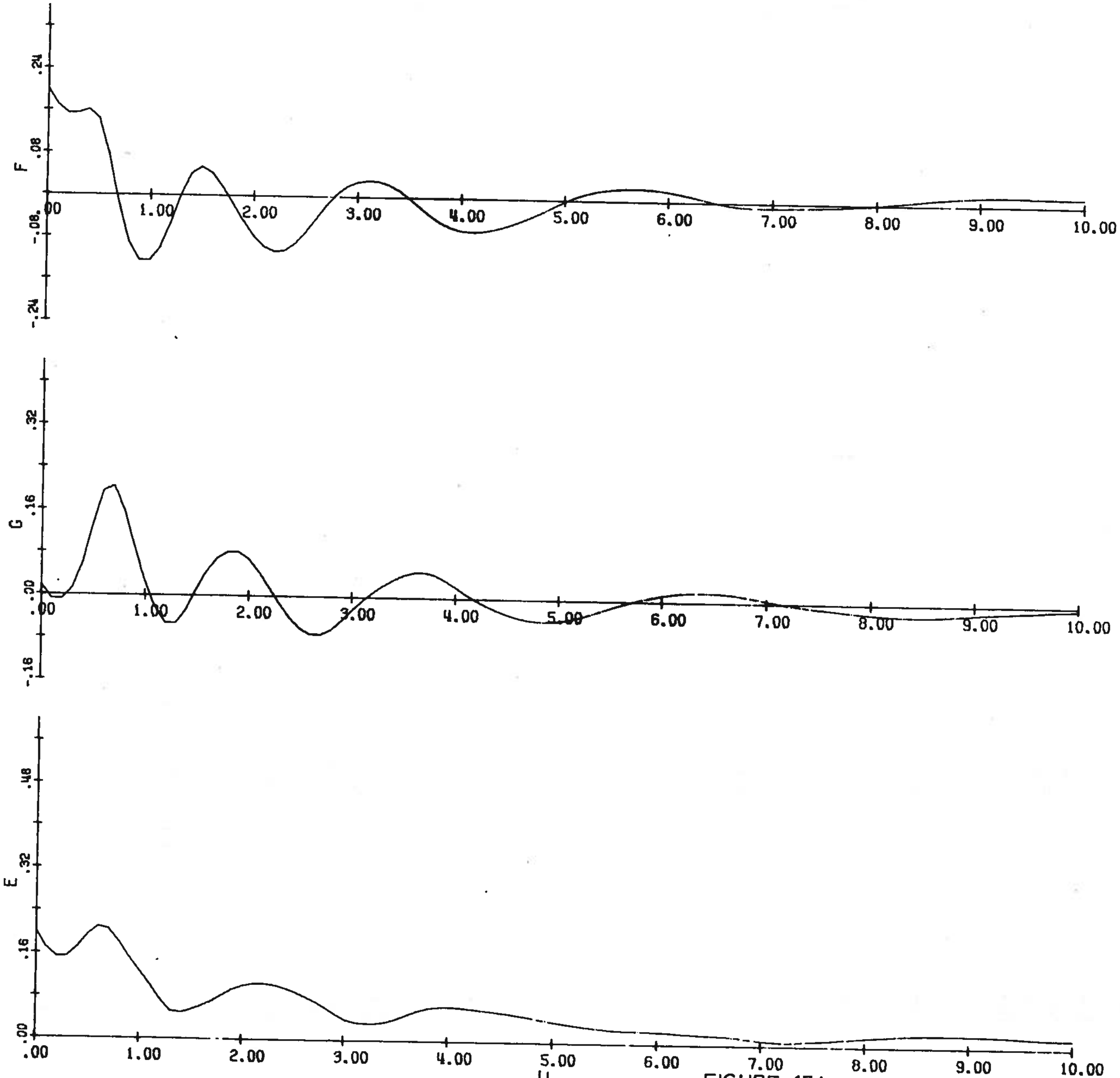


FIGURE 17A

WAVE SPECTRA FOR MODEL 1094-B5 AT V=5.01 FT./SEC. MAY 3,1969

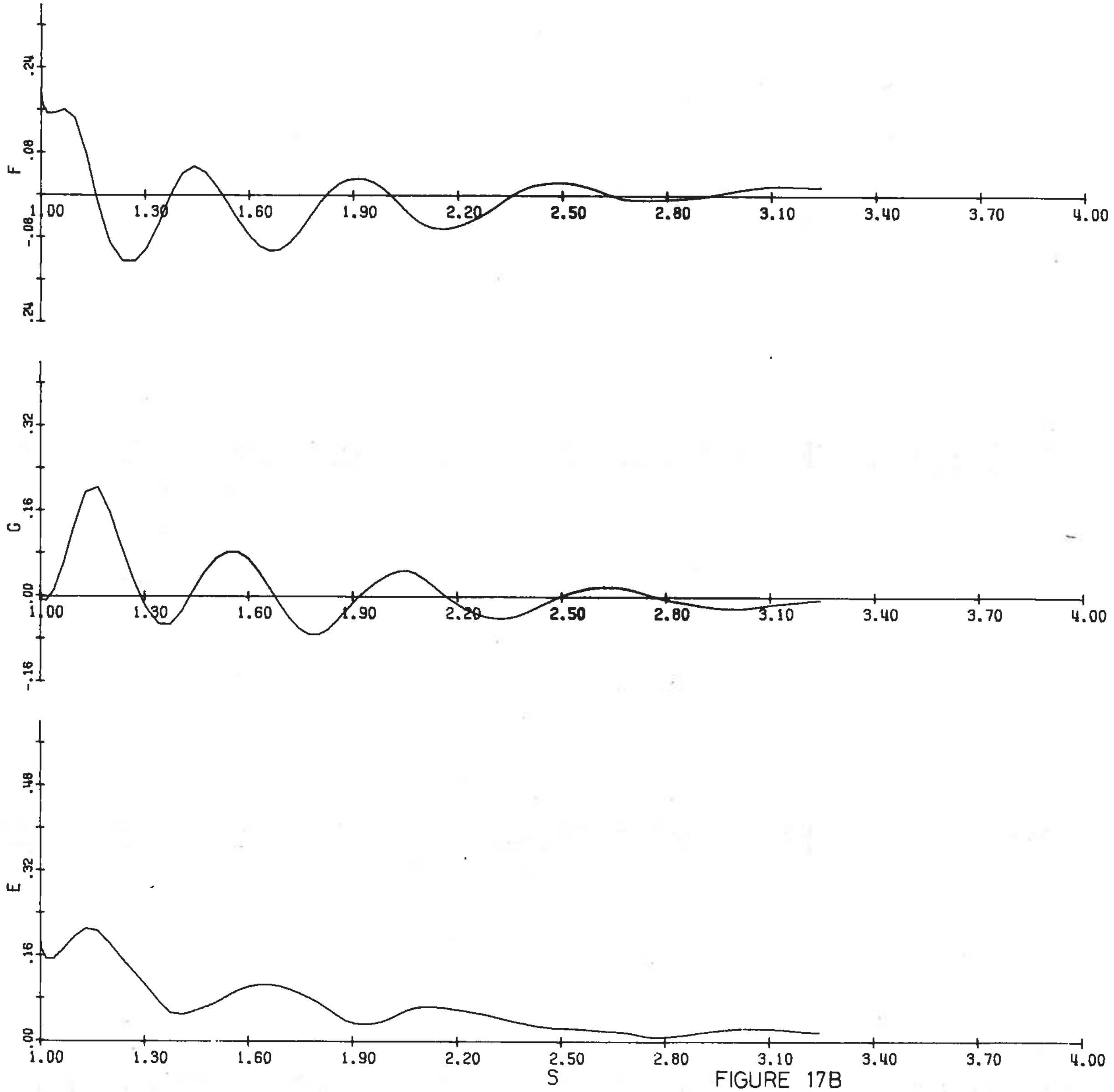


FIGURE 17B

WAVE SPECTRA FOR MODEL 1094-B5 AT V=5.36 FT./SEC. MAY 3,1969

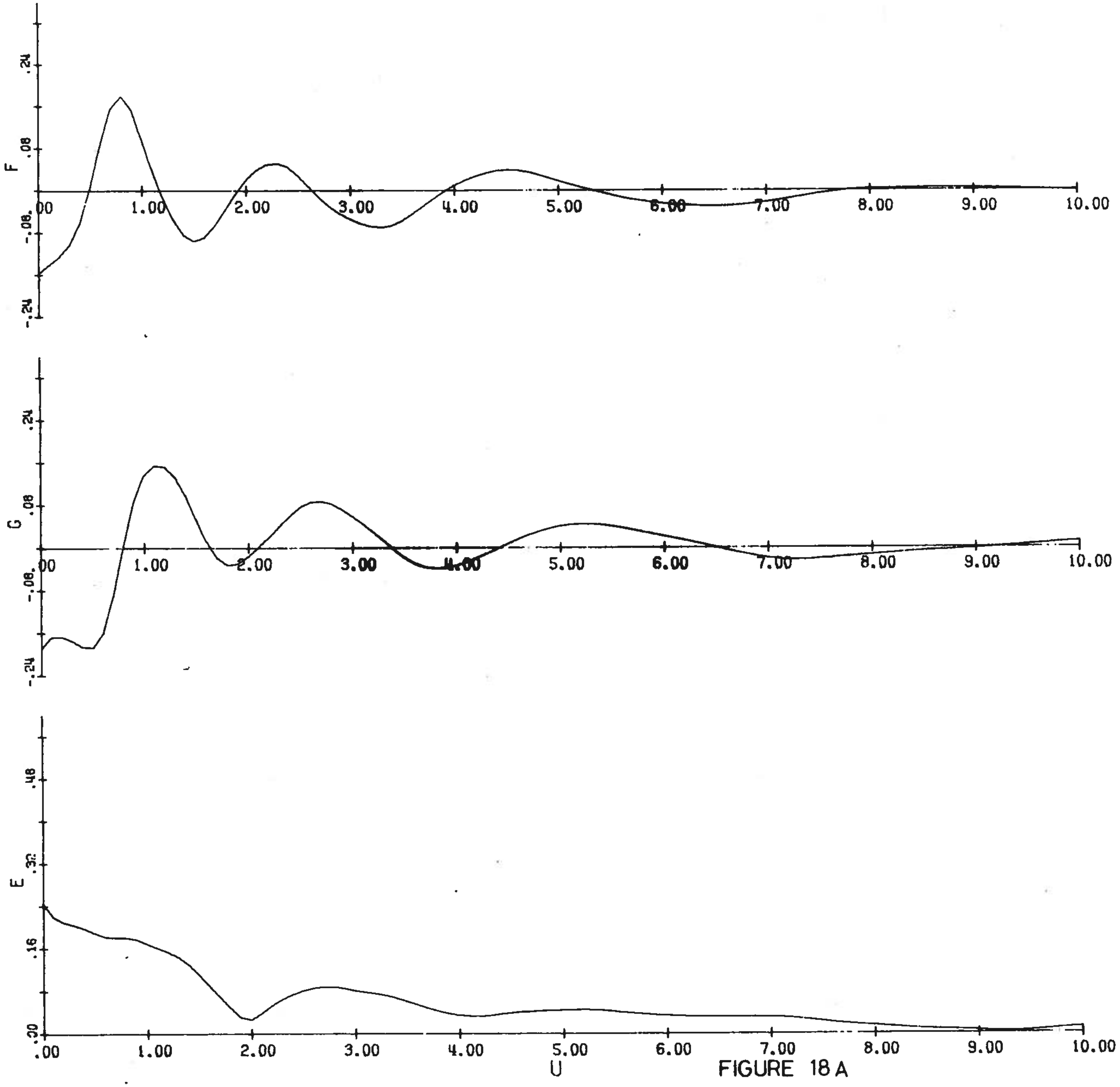


FIGURE 18 A

WAVE SPECTRA FOR MODEL 1094-B5 AT V=5.36 FT./SEC. MAY 3,1969

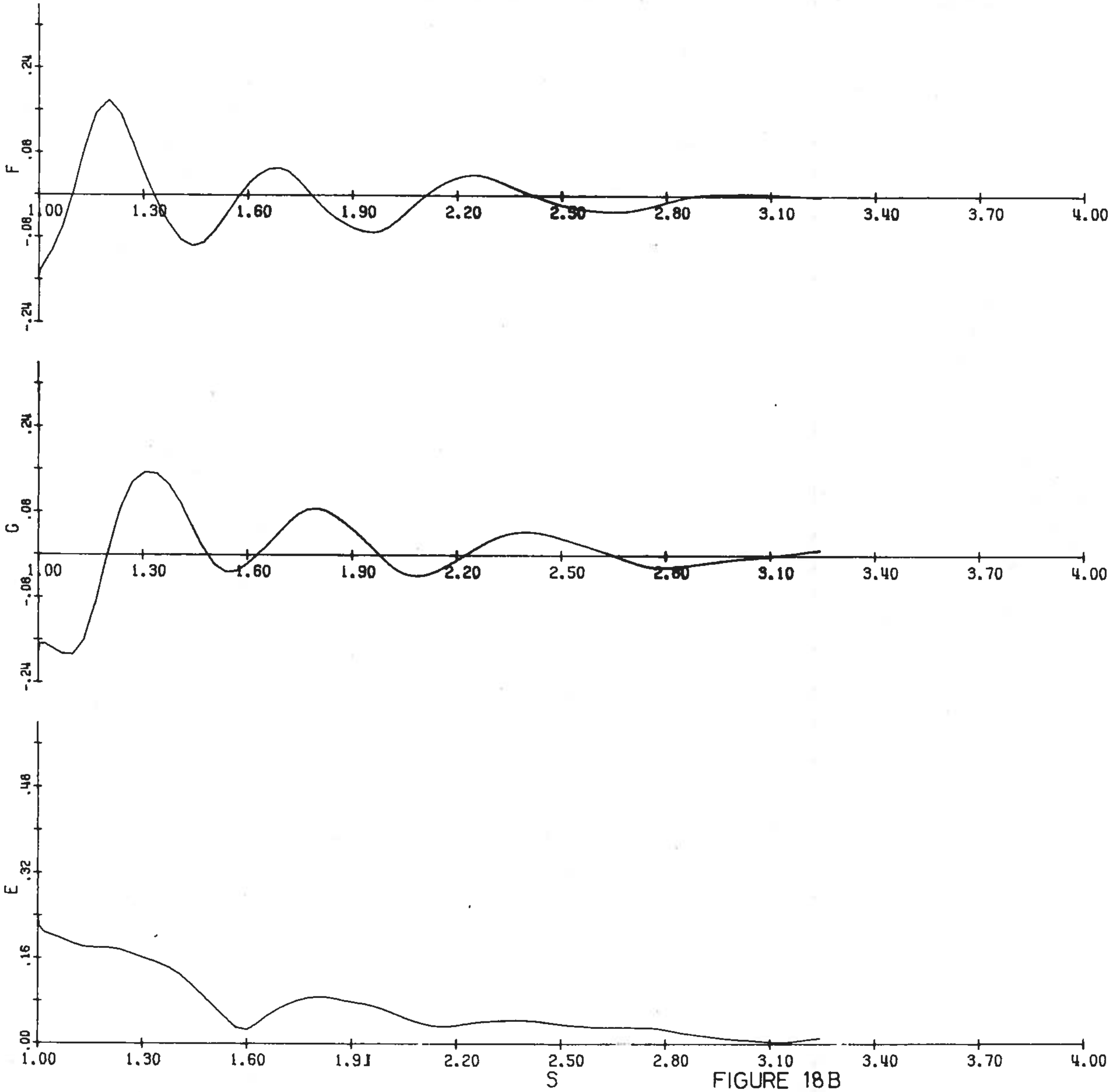
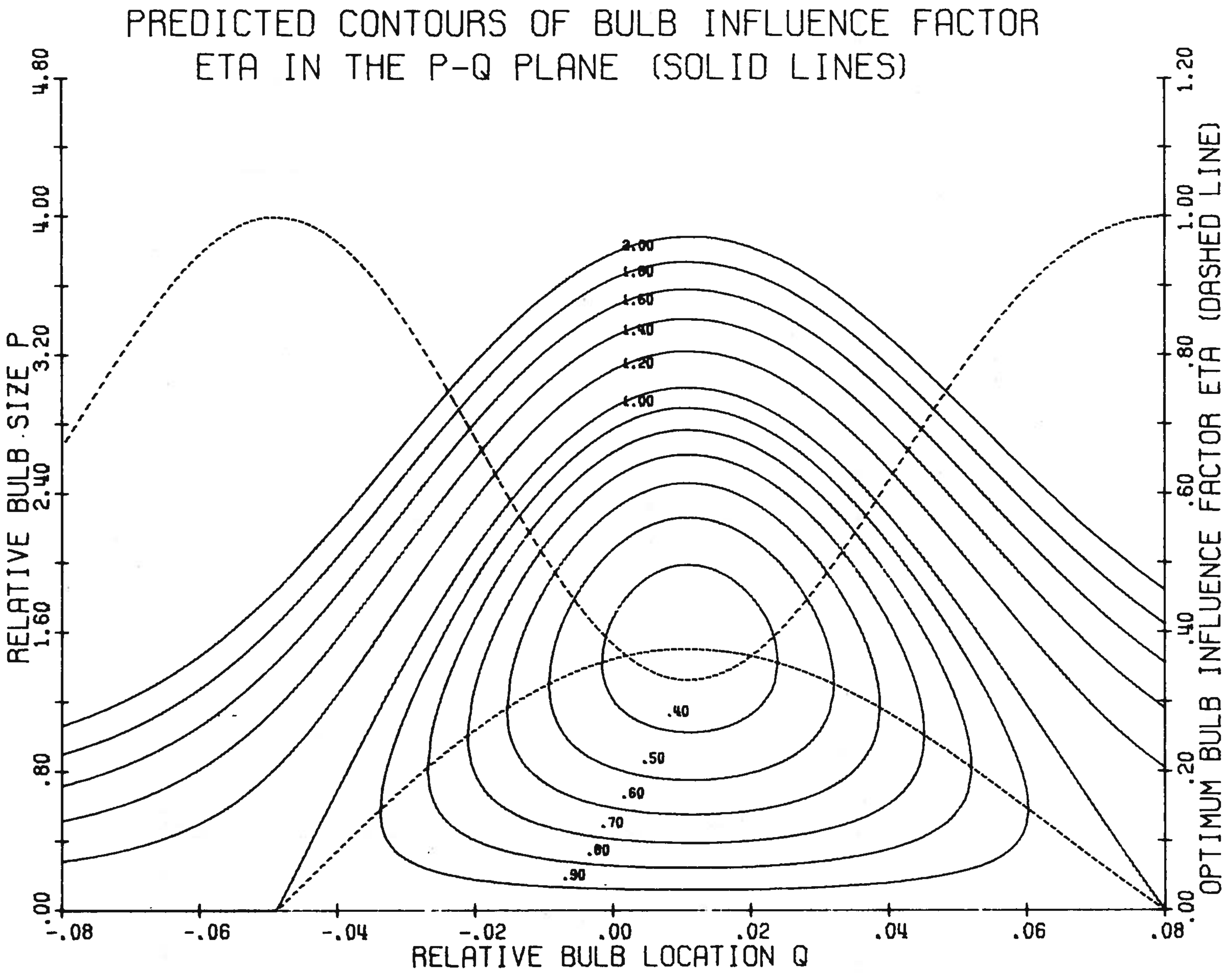
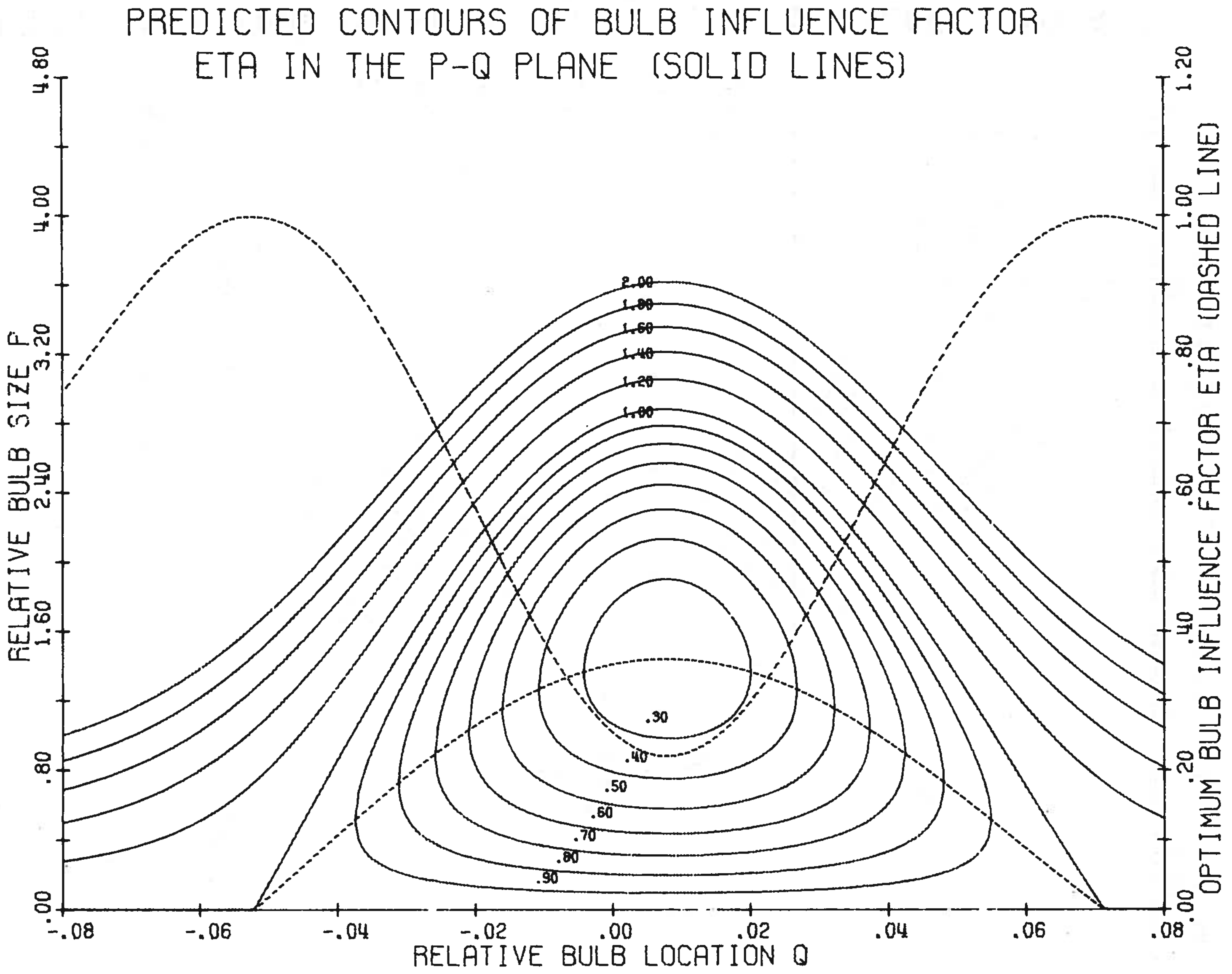


FIGURE 18B



PREDICTED CONTOURS OF BULB INFLUENCE FACTOR
ETA IN THE P-Q PLANE (SOLID LINES)

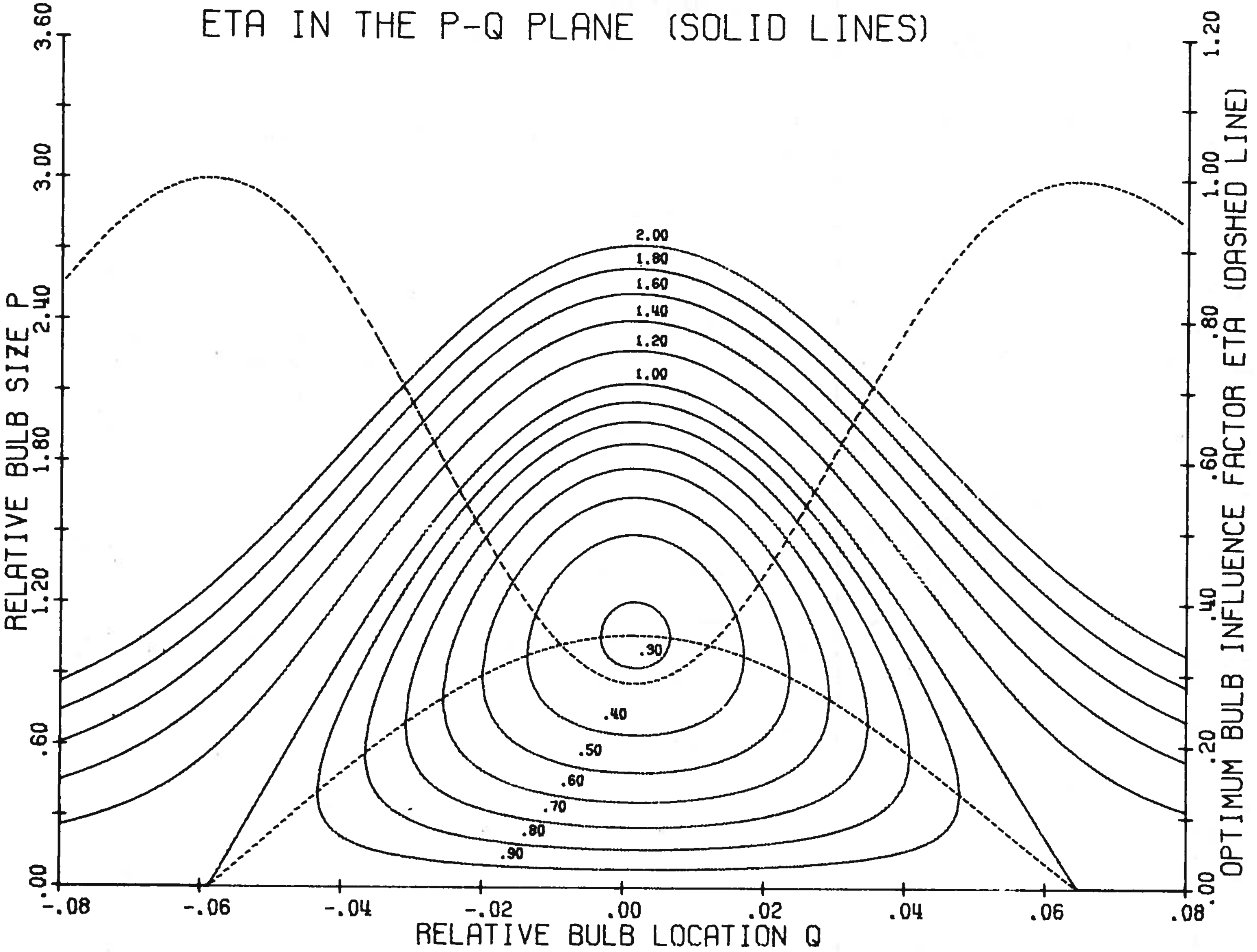
FROM MODELS 1094 AND 1094-B2 AT V=5.01 FT/SEC (AUG. 1968)
FIGURE 19



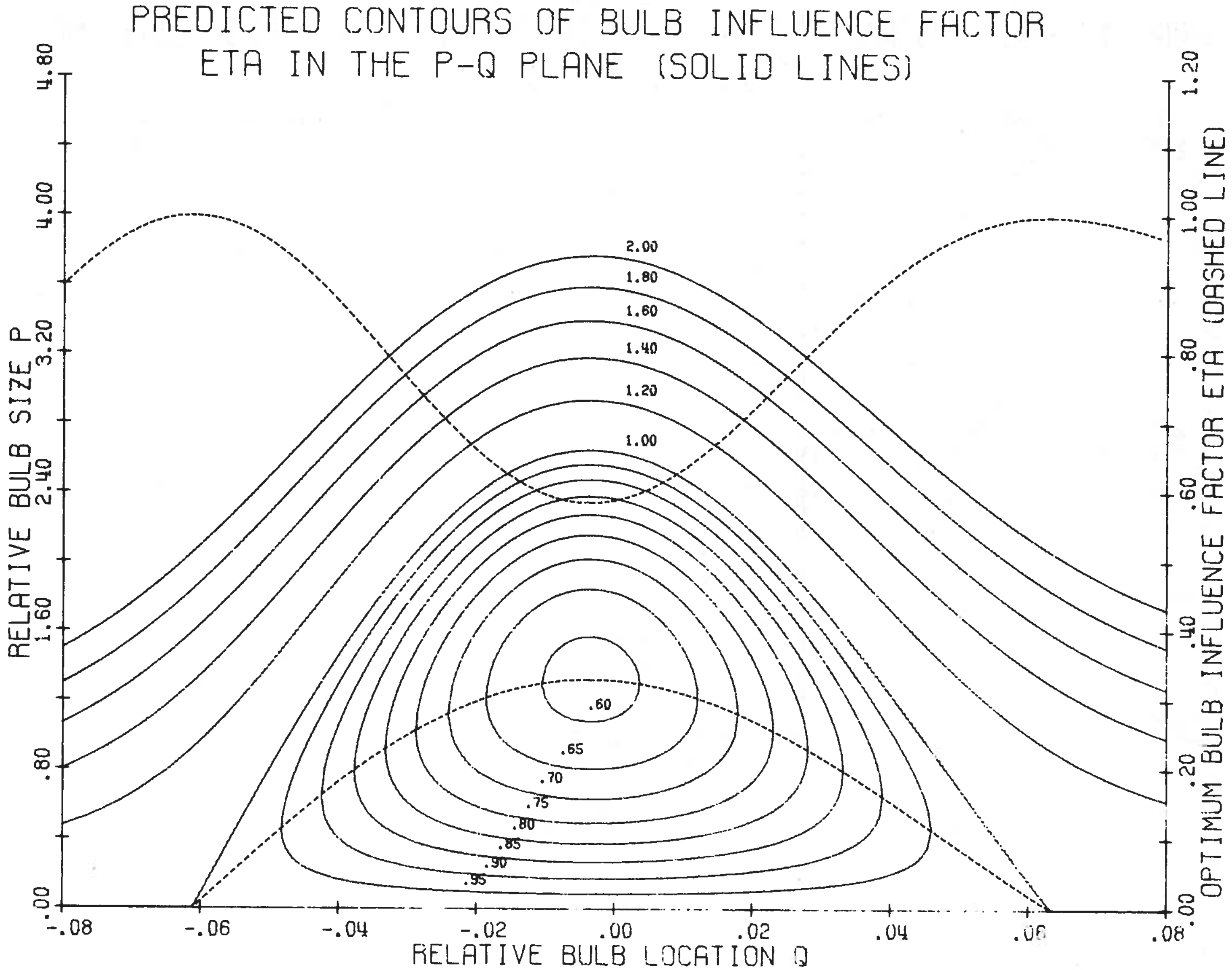
PREDICTED CONTOURS OF BULB INFLUENCE FACTOR
ETA IN THE P-Q PLANE (SOLID LINES)

MODEL 1094 AND 1094-B4 AT 5.01 FT./SEC. (AUG. '68 & MAY '69)
FIGURE 20

PREDICTED CONTOURS OF BULB INFLUENCE FACTOR
ETA IN THE P-Q PLANE (SOLID LINES)



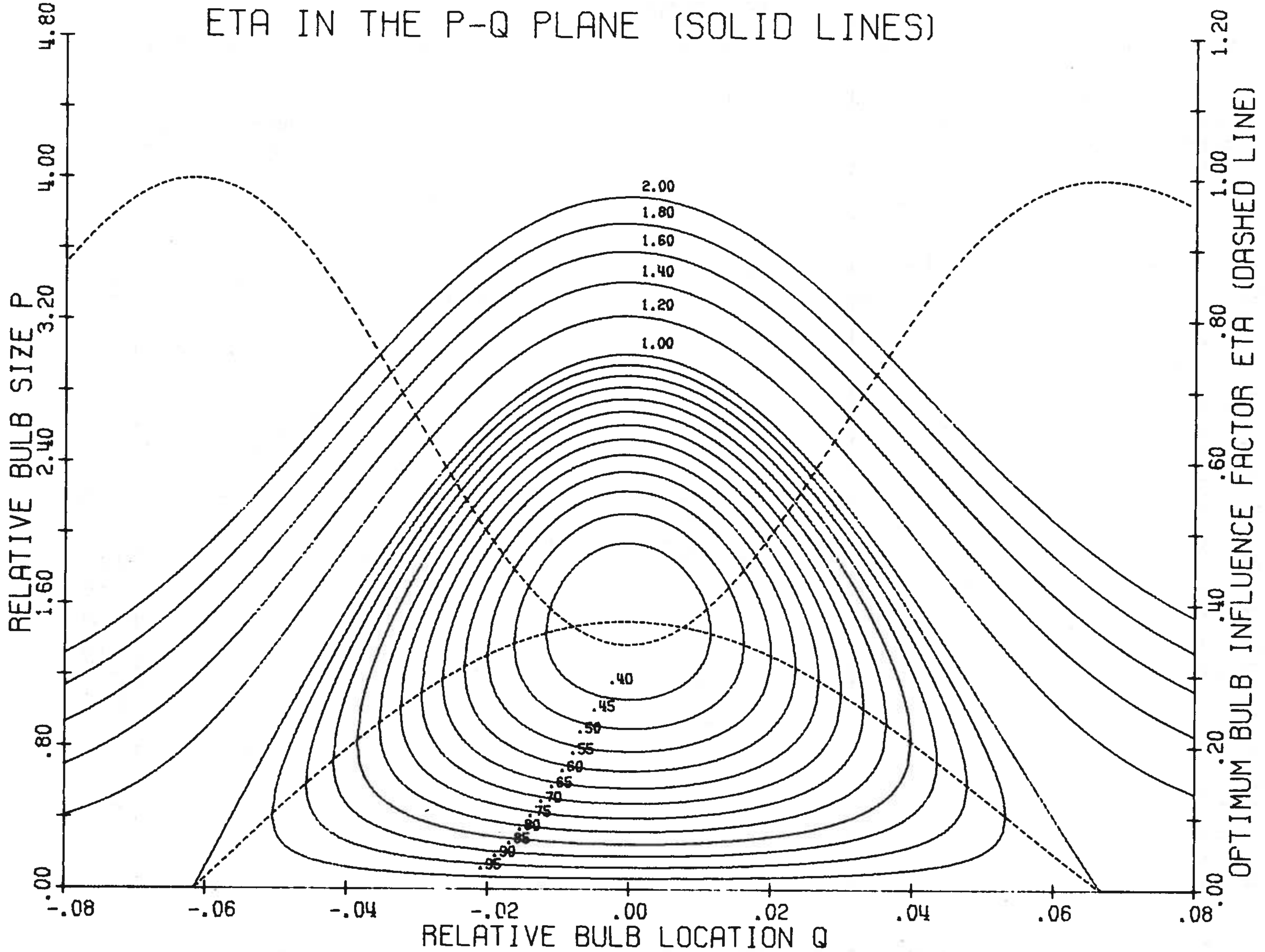
MODEL 1094 AND 1094-B5 AT 5.01 FT./SEC. (AUG. '68 & MAY '69)
FIGURE 21



PREDICTED CONTOURS OF BULB INFLUENCE FACTOR
ETA IN THE P-Q PLANE (SOLID LINES)

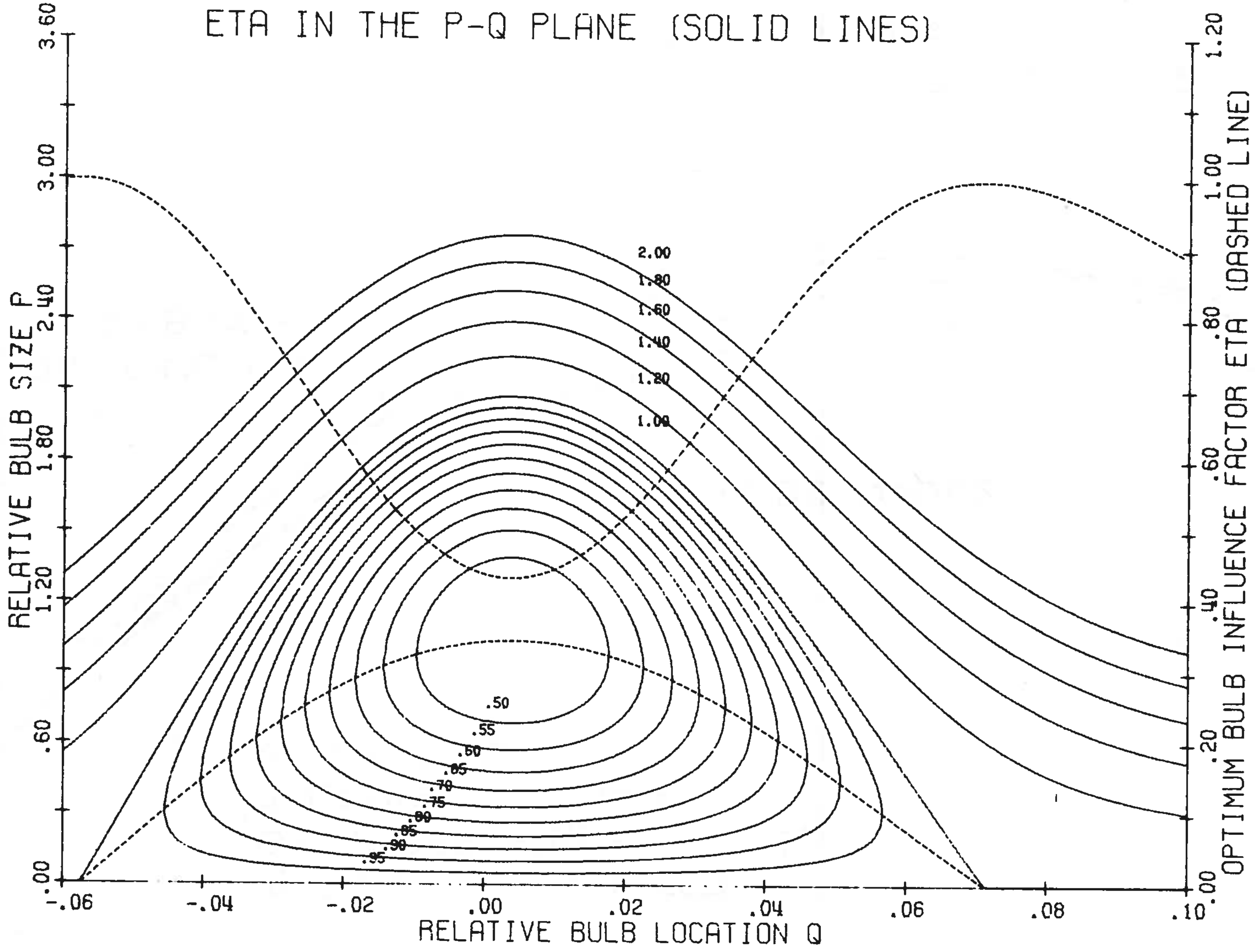
FROM MODELS 1094 AND 1094-B2 AT V=5.36 FT/SEC (AUG. 1968)
FIGURE 22

PREDICTED CONTOURS OF BULB INFLUENCE FACTOR
ETA IN THE P-Q PLANE (SOLID LINES)



MODEL 1094 AND 1094-B4 AT 5.36 FT./SEC. (AUG. '68 & MAY '69)
FIGURE 23

PREDICTED CONTOURS OF BULB INFLUENCE FACTOR
ETA IN THE P-Q PLANE (SOLID LINES)



MODEL 1094 AND 1094-B5 AT 5.36 FT./SEC. (AUG. '68 & MAY '69)
FIGURE 24

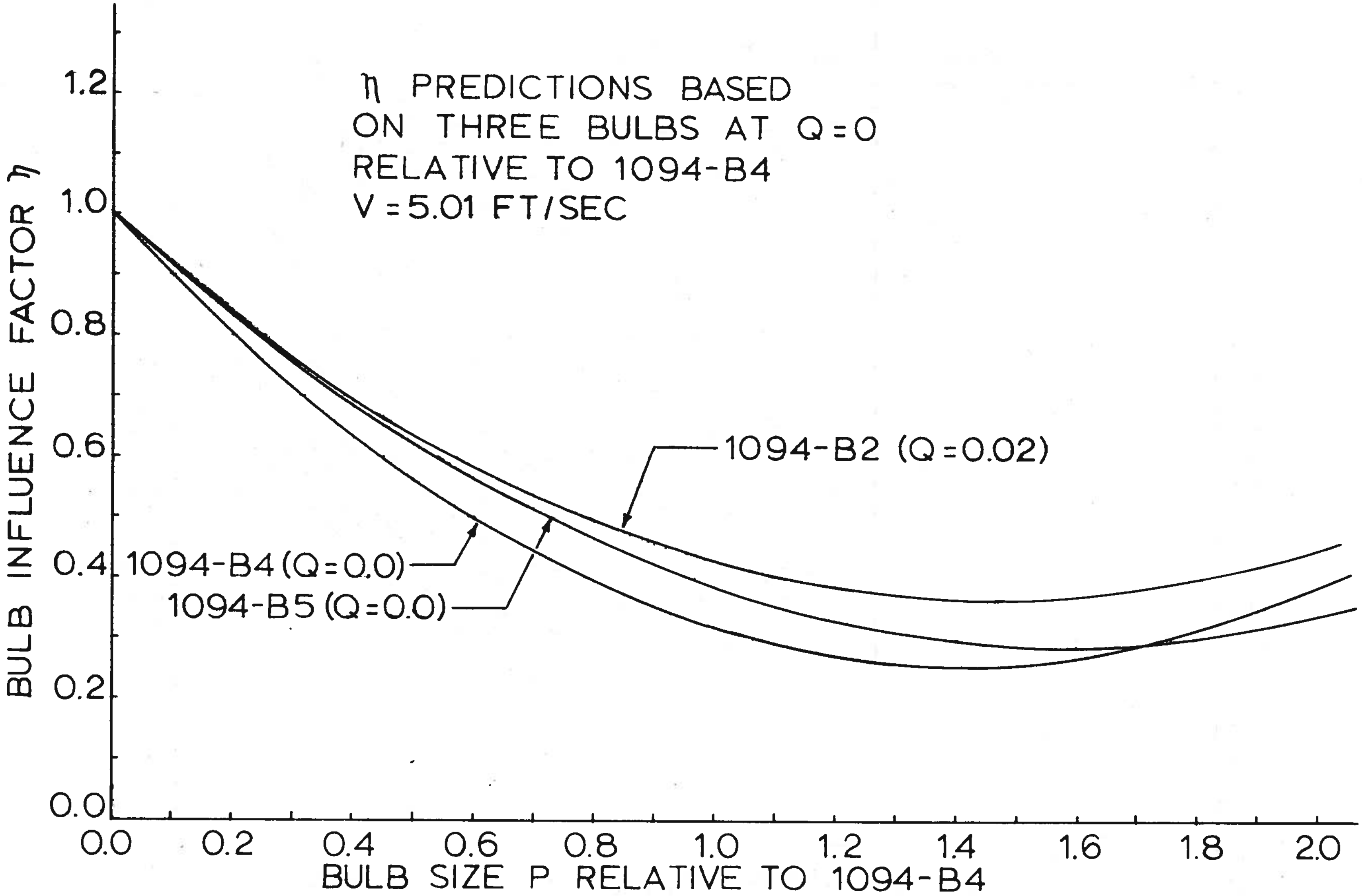

η PREDICTIONS BASED
ON THREE BULBS AT Q=0
RELATIVE TO 1094-B4
V=5.01 FT/SEC
1094-B2 (Q=0.02)
1094-B4 (Q=0.0)
1094-B5 (Q=0.0)
BULB INFLUENCE FACTOR η
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
BULB SIZE P RELATIVE TO 1094-B4

FIGURE 25

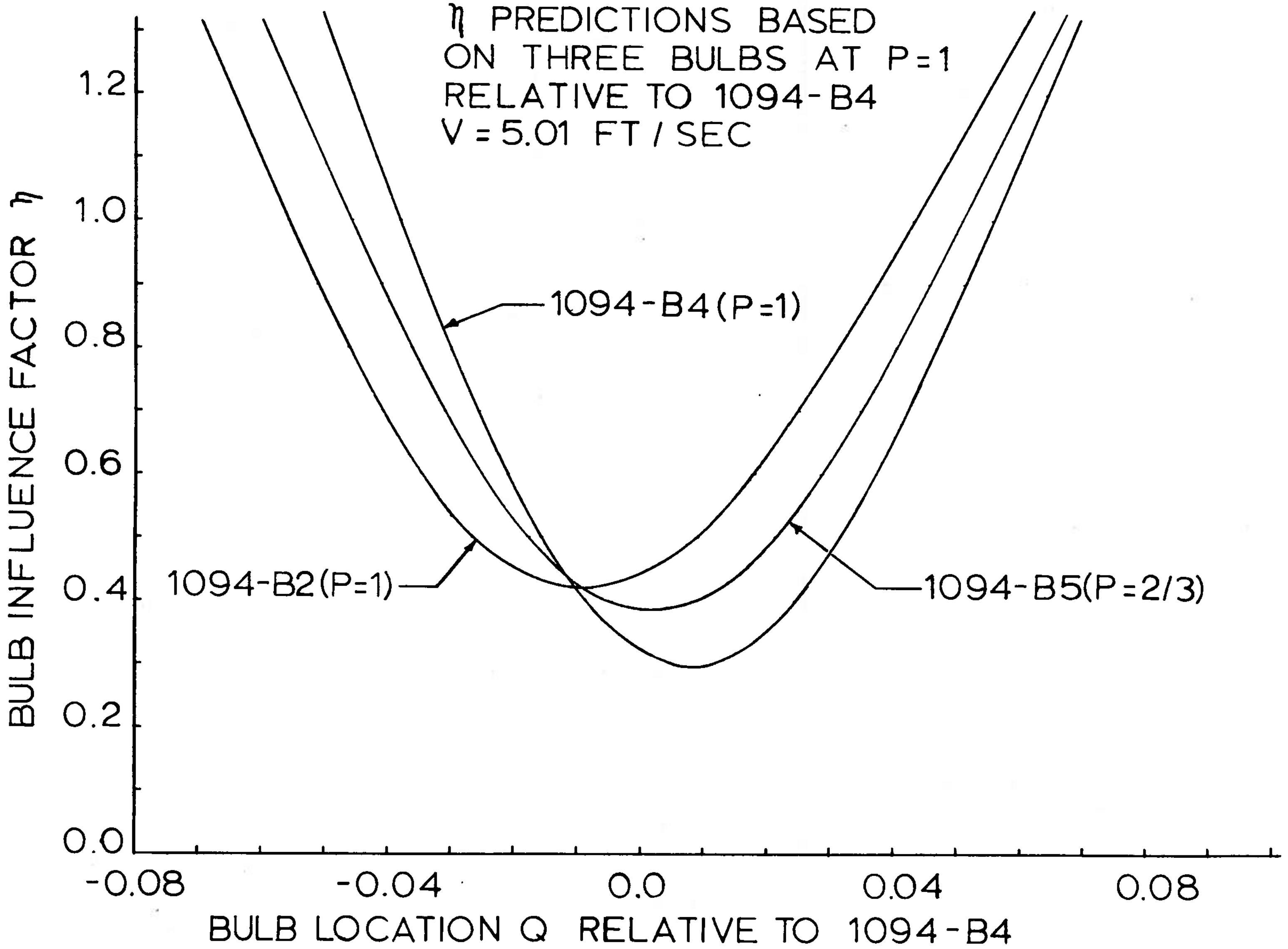

η PREDICTIONS BASED
ON THREE BULBS AT P=1
RELATIVE TO 1094-B4
V=5.01 FT / SEC
1094-B4(P=1)
1094-B2(P=1)
1094-B5(P=2/3)
BULB INFLUENCE FACTOR η
0.0
0.2
0.4
0.6
0.8
1.0
1.2
-0.08
-0.04
0.0
0.04
0.08
BULB LOCATION Q RELATIVE TO 1094-B4

FIGURE 26

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DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* The University of Michigan College of Engineering Department of Naval Architecture	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

OPTIMIZATION OF BOW BULB CONFIGURATIONS ON THE
BASIS OF MODEL WAVE PROFILE MEASUREMENTS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Final Technical Report

5. AUTHOR(S) *(First name, middle initial, last name)*

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6. REPORT DATE December 1970	7a. TOTAL NO. OF PAGES 60	7b. NO. OF REFS 13

8a. CONTRACT OR GRANT NO. N00014-67-A-0181-0009	9a. ORIGINATOR'S REPORT NUMBER(S) 104
b. PROJECT NO. SR 009 01 01	
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	Project No. 01491

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Naval Ship Systems Command General Hydromechanics Research Program

13. ABSTRACT

A semi-empirical method for designing bow bulb configurations of low wave resistance on the basis of wave profile measurements in the model basin is critically examined. The fundamental assumption under investigation is the principle of linear superposition of the individual free-wave spectra of the main hull and the bow bulb to yield the free-wave spectrum of the composite bulbous bow hull form. It is concluded that wave resistance predictions based on this hypothesis are reasonably accurate so as to encourage the use of this method as a heuristic design tool.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Bow bulb design						
Ship wave resistance						
Wave profile measurement						
Wave pattern analysis						
Wave resistance reduction						