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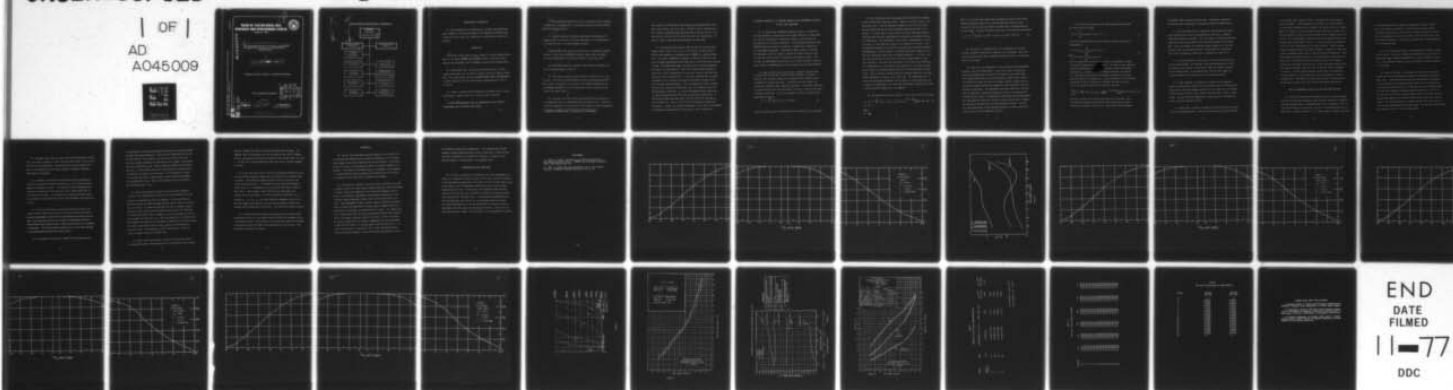
DAVID W TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CE--ETC F/G 13/10  
HULL FORM MODIFICATIONS TO THE LSD-41 DESIGN BASED ON LONGITUDI--ETC(U)  
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HULL FORM MODIFICATIONS TO THE LSD-41 DESIGN BASED ON LONGITUDINAL WAVE CUTS AND WAVE RESISTANCE MINIMIZATION

# DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084



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HULL FORM MODIFICATIONS TO THE LSD-41 DESIGN BASED ON LONGITUDINAL WAVE CUTS AND WAVE RESISTANCE MINIMIZATION

by

P. C. PIEN W. G. DAY, JR.

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SHIP PERFORMANCE DEPARTMENT

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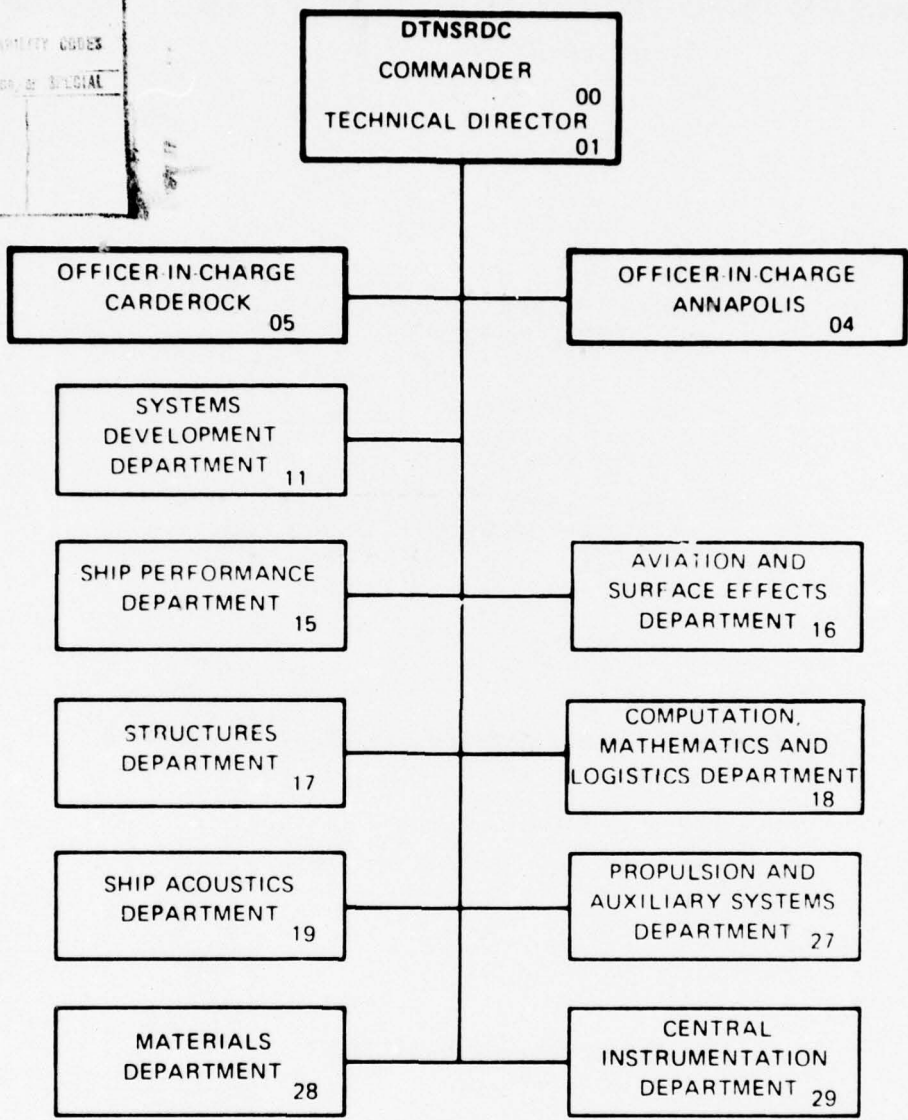
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**MAJOR DTNSRDC ORGANIZATIONAL COMPONENTS**



## ADMINISTRATIVE INFORMATION

(U) This investigation was authorized by the Naval Ship Engineering Center (NAVSEC) in Work Requests N6519777 WR 75554 and WR 75554-A1 dated 17 March 1977 and 7 June 1977, respectively, and identified as Work Unit 1524-627.

## INTRODUCTION

(U) As part of the effort in direct support of concept design development for the LSD-41, NAVSEC authorized the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) to perform the following tasks:

(a) Modify Model 5011, representing the LSD-36 Class, to create a concept design model for the LSD-41 by adding a section of parallel middle body. This altered model has been designated Model 5011-1 and represents an LSD-41 design with an LPP (length between perpendiculars) of 557.74 ft (170 m).

(b) Conduct resistance (EHP) experiments using Model 5011-1 at three displacements, namely 14,100 tons, 14,900 tons and 16,500 tons.

(c) Conduct longitudinal wave-cut experiments at the 14,900 ton displacement and at 22 knots, ship scale;

*over*

(d) Develop low-wave-drag hull forms as variations from the geometry of Model 5011-1 by making use of a wave-drag minimization theory and the wave-cut data from Item (c).

(e) Conduct additional resistance experiments investigating the change in EHP as a function of varying displacement in the neighborhood of 14,900 tons and at the design speed (22 knots).

(f) Develop an additional low-wave-drag hull form using an approach similar to that of Item (d) without change in beam, draft and length, but with a displacement increase from 14,900 to 15,500 tons; and

(g) Perform an analytical estimate of EHP and SHP requirements for the hull form developed in Item (f).

(U) This report contains results obtained for Items (c), (d), (f), and (g). The results from other tasks have been reported previously<sup>[1]</sup> 1.

This report also presents a discussion of the combined theoretical and experimental approach to hull form improvement used to improve the hull form of the LSD-41 Class.

(U) Initially, four hull forms were generated from the analysis of the longitudinal wave cut experimental data from Model 5011-1. These hull forms are represented by sectional area curves ( $A/A_x$ ) for each configuration.

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1. Numbers in brackets refer to references in bibliography.

For purposes of identification these designs are designated Hulls 5011-1 Mod A, 5011-1 Mod B, and 5011-1 Mod C, and 5011-1 Mod D, representing a hull form with a maximum design waterline beam of 82 feet (25.0 m), 83.3 feet (25.4 m), 84 feet (25.6 m) and 86 feet (26.2 m), respectively. No specific lines or body plans were developed for these hulls.

(U) Resistance predictions were made for each of the hulls represented by 5011-1 Mod A, 5011-1 Mod B, 5011-1 Mod C, and 5011-1 Mod D. Results were presented to representatives of NAVSEC in a meeting in May 1977. As a result, DTNSRDC was requested to develop a fifth hull form which increased displacement from 14,900 tons to 15,500 tons with no change in beam. This newest development from Model 5011-1 has been designated Hull 5011-2 for identification. Hull 5011-2 has the same afterbody as Model 5011-1, and is represented in this report by both a sectional area curve and a set of forebody lines. It was also requested that a complete estimation of the resistance and powering requirement be made for Hull 5011-2 without model experiments. Thus, an approach was taken to assume that the total resistance coefficients,  $C_T$ , is an algebraic sum of the wave-resistance coefficient,  $C_w$ , and the viscous-resistance coefficient,  $C_v$  (which contains both the frictional and form-drag coefficients). It was further assumed that Model 5011-1 and Hull 5011-2 have the same  $C_v$ , but a different  $C_w$ . The  $C_w$  of Hull 5011-2 was obtained by theoretical calculation. Finally, the powering requirement of Hull 5011-2 was estimated by assuming the same propulsion coefficient as that of Model 5011-1.

THE GENERAL PRINCIPLE OF A COMBINED THEORETICAL AND EXPERIMENTAL APPROACH  
TO HULL FORM IMPROVEMENT

(U) In recent years, wavemaking resistance theory, in combination with the technique of measuring the wave height produced by a towed model, has been used successfully to determine changes in a hull form which will improve its resistance performance. At Mitsubishi Experimental Tank, Baba<sup>[2]</sup> obtained good results by using such a combination of theoretical and experimental approaches. Encouraged by Baba's results, an attempt has been made to use this method to improve the LSD-41 Class hull form. In this part of this report a discussion of the theory is given. Then the wave cut experimental and resistance test results are given. Based on these results a recommended hull form for LSD-41 Class has been developed.

(U) When a surface ship is moving with a constant velocity ahead, a trailing free-surface wave system is always observed. As shown by Havelock, this free-wave system can be decomposed into elementary waves propagating in various directions. To maintain this wave system, the moving ship constantly feeds energy into the water. This energy represents the work done due to the wave resistance of the ship. Hence the ship wave resistance coefficient,  $C_w$ , can be expressed in terms of elementary wave amplitudes as follows:

$$C_w = 2\pi \int_0^{\frac{\pi}{2}} [A_c^2(\theta) + A_s^2(\theta)] \cos^3 \theta d\theta \quad (1)$$

where  $A_c(\theta)$  and  $A_s(\theta)$  are amplitude functions normalized by ship length.

(U) For a given hull form, these amplitude functions can be computed by the thin-ship wave-resistance theory. However, a practical ship is far from being "thin". The wave amplitudes computed by the thin ship theory are not accurate and the ship wave resistance obtained from them is not reliable. In recent years, various methods have been developed to obtain these amplitude functions experimentally by measuring wave heights produced by a towed model. This measurement is made along a longitudinal cut, which is parallel to the centerline of motion, but displaced to one side. Once the amplitude functions of a given hull form have been accurately determined experimentally, it may be possible to determine what small changes in hull form will effectively improve the resistance performance. It is well known that small alteration in ship offsets can produce large changes in ship wave resistance. Since the small alteration in hull form can be considered as a superposition of a thin-ship on the original hull, the desired changes in hull form can be obtained theoretically by the thin-ship wave resistance theory. This is the basic thought behind the combined theoretical and experimental approaches to improve a given hull form. The experimental part involves the wave height measurement when the model of a given ship hull form is towed in an experimental tank. From wave measurements, amplitude functions  $A_c(\theta)$  and  $A_s(\theta)$  of Equation (1) are computed.

(U) The theoretical free wave height of a thin ship is given as follows:

$$A_s'(\theta) = -\frac{2K_0^2}{\pi} \sec^4 \theta \int_0^1 dx' \int_{-t}^0 \eta(x', z') e^{-K_0 z' \sec^2 \theta} \frac{\cos(K_0 x' \sec \theta)}{\sin(K_0 x' \sec \theta)} dz' \quad (2)$$

$$A_c'(\theta) = +$$

where

$$K_0 = \frac{g}{V^2}$$

$\eta(x', z')$  is the thin ship offset which represents one half of the surface doublet distribution density on a central plane with the axis in the direction of ship motion, and  $t=d/L$  is the ship draft non-dimensionalized by ship length. The wave resistance coefficient of the modified ship becomes

$$C_w = 2 \pi \int_0^{\frac{\pi}{2}} \left\{ [A_c(\theta) + A_c'(\theta)]^2 + [A_s(\theta) + A_s'(\theta)]^2 \right\} \cos^3 \theta d\theta \quad (3)$$

(U) Our task is to determine  $\eta(x', z')$  of Equation (2) such that the wave resistance coefficient in Equation (3) is minimized. After this is done, the given hull form is modified according to  $\eta(x', z')$  and tested again for resistance.

(U) There are a few rough spots in this theoretical and experimental approach to hull form improvement. In the first place, the thin ship offsets are computed from the doublet distribution on the center plane in a uniform stream while the hull modification is made on both sides of the original hull where the flow is no longer uniform. Because of this, the thin ship amplitude functions computed by theory may differ from that obtained by experiment. The experimental amplitude functions of the thin ship are obtained by taking the differences of that of the original and the modified hull forms. By comparing the theoretical and the experimental thin ship amplitude functions, correction factors may be found to improve the accuracy of the predicted thin ship amplitude functions. A second hull form modification is then applied according to a more accurate prediction of the thin ship amplitude functions.

(U) To obtain the optimum thin ship, Baba represented the thin ship by a cosine series as follows:

$$\eta(x', z') = \sum_{m=1}^N C_m \cos(mx'), \text{ for } 0 \leq x' \leq 1, \quad (4)$$

With the following constraints of zero thickness at midship and zero net displacement as:

$$\eta(x', z') \Big|_{x'=0.5} = \sum_{m=1}^N C_m \cos(m \cdot 0.5) = 0,$$

and

$$\int_0^1 \eta(x', z') dx' = \sum_{m=1}^N \frac{1}{m} C_m \sin(m) = 0. \quad (5)$$

Here the thickness of the thin ship is assumed to be independent of depth.

By substituting Equation (4) into Equation (2), one term at a time, amplitude functions corresponding to each term are obtained in terms of the unknown coefficient  $C_m$ . By substituting these amplitude functions into Equation (3), these unknown coefficients are determined by minimizing the  $C_w$  value under the constraints of Equation (5). Instead of Equation (2), the following expressions are used for computing the amplitude functions of the thin ship if the correction functions  $h(x')$  and  $\delta(x')$  are known:

$$\left. \begin{matrix} A'_s(\theta) \\ A'_c(\theta) \end{matrix} \right\} = \mp \frac{2K_0}{\pi} \sec^4 \theta \int_0^1 dx' \int_{-t}^0 dz' \frac{\eta(x')}{h(x')} e^{K_0 z' \sec^2 \theta} \begin{Bmatrix} \cos \\ \sin \end{Bmatrix} [K_0 (x' - \delta(x')) \sec \theta], \quad (6)$$

where  $h(x')$  and  $\delta(x')$  are correction functions for the thin ship. They are obtained by comparing the theoretical and the experimental influence functions as discussed in reference (a). The necessary computer programs

to implement Baba's work have been achieved. Furthermore, additional features have been incorporated in the present work as discussed below:

1. If the thin ship offset is negative at the end where the offset of the original hull is zero, the modified hull would have a negative offset which cannot be tolerated. For this reason, two possible additional conditions on thin ship offsets at both ends are provided in the present work. Also, the original two conditions given by Equation (5) can take non-zero values on the right-hand side. Among these four constraints, one is free to choose any combination of constraints or none at all.

2. For various reasons, one may wish to limit the hull modification within certain regions. For instance, since the existing theory is more applicable to the forebody, one may wish to apply the present procedure to the forebody alone. In the present work, the thin ship length and location relative to the original hull can be specified freely.

3. In some instances, for stability or general deck arrangement reasons, one may wish to modify the hull form only below the load waterline. There are four thin ship elements provided in the present work, the offsets of which vary as the zero, first, second, and third power of draft, respectively. One may choose any combination of those four basic thin ship elements to form the desired thin ship.

4. In many cases, a bulbous bow added to a given hull form can improve the hull performance greatly. Hence, such an option has also been included

in the present work. Usually a bulb is represented by a point doublet near the forefoot. From a geometrical view point, it is more desirable to have a bulb represented by a horizontal line doublet instead of a single point. By doing so, it is much easier to fair a bulb into the main hull. The main question is how to find the location and the strength of the line doublet. At a chosen depth, a number of points are specified along a line starting from a point ahead of the F.P.. This starting point represents the limit of bulb protrusion which one would tolerate. Then an optimum doublet strength to minimize the wave resistance is computed at each point. A positive strength means a bulb at that point would be beneficial. After such computation has been done for all the chosen points along this horizontal line, the reduction of wave resistance as well as the doublet strengths at each point are printed out. After eliminating doublet points with negative strengths, the sum of all the positive doublet strengths is computed. Then the doublet strength at each point is multiplied by the ratio between its own strength and the total strength, to form an elongated bulb. With doublet strengths and locations of various points, one may make a further choice for overall bulb doublet distribution.

#### WAVE CUT EXPERIMENTAL RESULTS AND HULL FORM MODIFICATIONS

(U) Model 5011 was modified by adding 0.825 feet of parallel middle body for the resistance experiments which have been reported in reference 1. The modified model which is designated Model 5011-1, represents a 586.7 ft (170.0 m) LBP ship at a scale ratio of 21.50. The sectional area curve of Model 5011-1 is shown in Figure 1. At a chosen number of speeds, resistance

and wave measurements were conducted simultaneously. Figure 2 shows a plot of the residual resistance  $C_r$  coefficient and the wave pattern resistance coefficient  $C_w$  of Hull 5011-1. These curves are for conditions corresponding to the 19.4-foot draft of the full scale ship. The wave pattern resistance coefficient  $C_w$  of Model 5011-2 shown on Figure 1 will be discussed later.

(U) At the higher speed range, the repeatability of model  $C_w$  values was quite good. There was a considerable scattering of  $C_w$  values at the lower speed range. Generally speaking, the  $C_w$  curve followed the trend of  $C_r$ . The difference between  $C_r$  and  $C_w$  is assumed to be due, primarily, to a form drag.

(U) Based on the wave cut information at the 22-knot ship speed, several wall sided thin ships were computed for modifying the offsets of Model 5011-1. These modifications were done under several constraints. In the first place, the modification was confined to the forebody only. Each thin ship extended from F.P. to mid-ship so that the existing afterbody with its propulsive arrangement could be kept intact. Also it is believed that the thin ship wave resistance theory has a better chance of success when applied to the forebody, where viscous effects are less pronounced. The thin ship offsets at forward end were also kept at zero so that the bow construction could be kept simple. All hull form modifications were made for the 19.4 ft (5.91m) design draft.

(U) Sectional area curves for three of the four modifications to Model 5011-1 are shown in Figures 3,4, and 5 for Hulls 5011-1 Mod A, 5011-1 Mod B, and 5011-1 Mod C respectively. The sectional area curve for Model 5011-1 Mod D is not presented since the large increase in beam was considered undesirable by the sponsor.

(U) A summary of the LSD-41 hull form modifications including the predicted wave pattern resistance coefficients  $C_w$ , at the 22-knot design speeds are presented in Table 1. The increase in ship displacement associated with the addition of the thin ship to the original Model 5011 is also shown in this table. For reference, the flatplate frictional resistance coefficient calculated from the 1957 ITTC Ship-Model Correlation Line is given.

(U) At the review meeting to discuss the modified hull forms, the sponsor requested another hull form be developed for LSD-41 which would displace approximately 15,500 tons but would maintain the 82-foot (25.0 m) beam. The design goal was that the increase in displacement should be accomplished without change in beam or draft and with little or no increase in resistance. This was considered feasible since the thin ship would add to the displacement as shown by Hull 5011-1 Mod A.

(U) The problem to develop this "optimum" 82-foot beam ship with

a displacement of 15,500 tons was solved by using the hull-form improvement technique with some modification. Since only the forward half of the hull form was modified, the offsets at the after end of the thin ship were kept zero so that the beam of the ship would not be changed. The original model had a small bulb at bow. Table 2 shows the offsets of the optimum thin ship. If these offsets were used, the modified hull form would have a maximum section forward of the mid ship. It was necessary to change the thin ship offsets on a drawing board to ensure satisfactory geometry of the modified hull form. Table 3 gives station areas of the optimum and the modified thin ship.

(U) Before the modified thin ship could be used with confidence, a  $C_w$  value of the modified hull, obtained by using the modified thin ship instead of the optimum thin ship, was computed. It was found that the modified thin ship was quite acceptable and was used to obtain the new hull form, Hull 5011-2. It should be mentioned here that the present computer program can take a given thin ship together with the wave cut information of a given hull form as input to compute  $C_w$  value if the given thin ship is used to modify the given hull form. With this capability, the modified thin ship together with the wave cut information of Model 5011-1 at various speeds were used as input data to predict the  $C_w$  values of the modified hull form, Hull 5011-2. The predicted  $C_w$  curve of Hull 5011-2 is shown in Figure 2 compared with that for Model 5011-1.

(U) Figure 6 give the body plan of the new hull form, Hull 5011-2. For comparison purpose, these stations are at the positions of the original

stations of Model 5011 before the parallel mid body was introduced. The computed effective horsepower curve for the modified hull form is compared with the extrapolated curve from the resistance test of Model 5011-1 in Figure 7. The EHP curve of the modified hull form, Hull 5011-2, has been computed as follows:

(U) In the first step a plot of the total resistance coefficient  $C_T$  and the wave-pattern resistance coefficient  $C_w$  of Model 5011-1 is made as shown in Figure 8. The difference between these two curves is plotted as the viscous drag coefficient  $C_v$ . To estimate the total effective horsepower of Hull 5011-2, it is assumed that its  $C_v$  values are the same as those of Model 5011-1. The  $C_w$  values of Hull 5011-2, on the other hand, were computed strictly from theory. The total resistance coefficient,  $C_T$ , is obtained by:  $C_T = C_w + C_v$ . The total effective horsepower of Hull 5011-2 has been computed by using this  $C_T$  and the wetted surface area which was computed from the body plan of Hull 5011-2. The results are shown in Figure 7.

(U) A prediction of the propulsion performance for the LSD-41 Design represented by Hull 5011-2 was made by using the effective horsepower predictions shown in Figure 7 and the values of the propulsion coefficient obtained from propulsion tests with Model 5011 representing the LSD 36 Class. This prediction is presented in Figure 9.

## DISCUSSION

(U) The hull form improvement procedure appears to be a useful tool in evaluating and optimizing the resistance performance of a hull design where changes in major hull dimensions may not be tolerable. It may also be used, of course, to investigate the effects of sizeable changes in dimensions. To establish a reasonable degree of confidence in this approach it is almost mandatory that the predictions for Model 5011-2 be verified by experiments with a model built to represent that design.

(U) With specific reference to the use of this technique for the LSD 41 design it may be seen from the wave pattern resistance coefficients shown in Figure 2 and by the comparison of the effective horsepower curves in Figure 7 a considerable improvement in performance is predicted for the "improved" design represented by Hull 5011-2 at the design speed of 22 knots. This improvement is about 9 percent based on effective horsepower. Rather typically the improvement at design speed is somewhat offset by a degradation in performance at speeds below 19 1/2 knots. At a speed of 18 knots, roughly half power, the design represented by Model 5011-1 requires about 6 1/2 percent less power than for Hull 5011-2. This is not quite as bad as it might seem as it should be remembered that the displacement of Hull 5011-2 is about 41/2 percent greater than for Model 5011-1. It should also be noted, in retrospect, that it would have been possible, using the existing technique, to specify resistance optimization at both

an intermediate speed and at design speed. It is possible that the performance at design speed would not be quite as good, but it should be within the realm of possibility to minimize the increase in resistance of the improved design at cruising speed to an acceptable level.

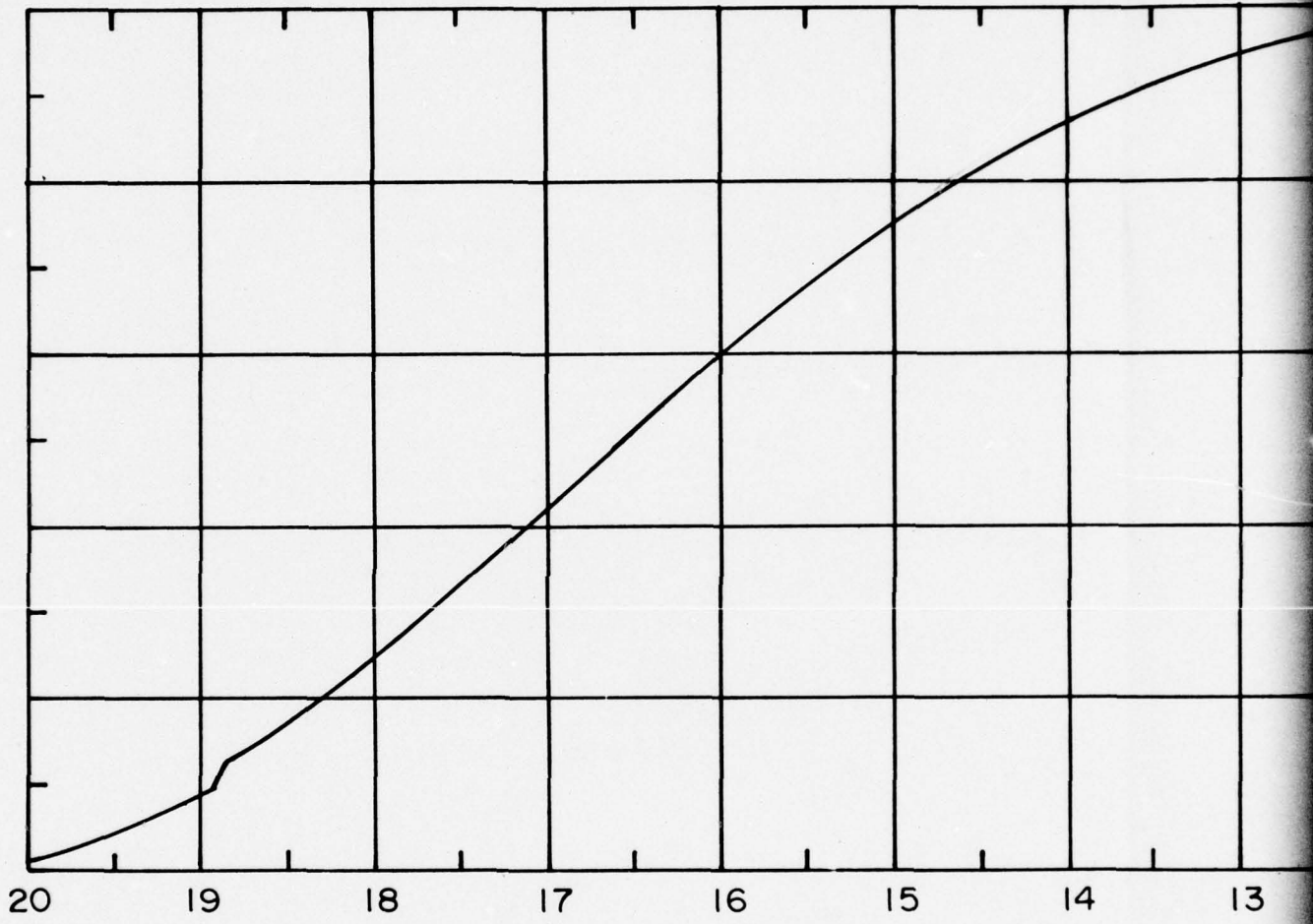
#### RECOMMENDATIONS FOR FUTURE WORK

(U) In order to evaluate this technique of hull form improvement procedure, it is essential to build a model for Hull 5011-2 and test it exactly in the same manner as Model 5011-1 was tested. Not only the test speeds should be the same but also instrumentation installation must be kept the same between these two tests. At each speed, the experimental wave amplitude function of the thin ship can be obtained by taking the difference between that of Model 5011-2 and Model 5011-1. By comparing the experimental thin ship wave amplitude functions and the corresponding theoretical values, the required information to close the gap between the theoretical and the experimental thin ship amplitude functions may be found. After there has been some definitive comment on this procedure, hull improvement can be made.

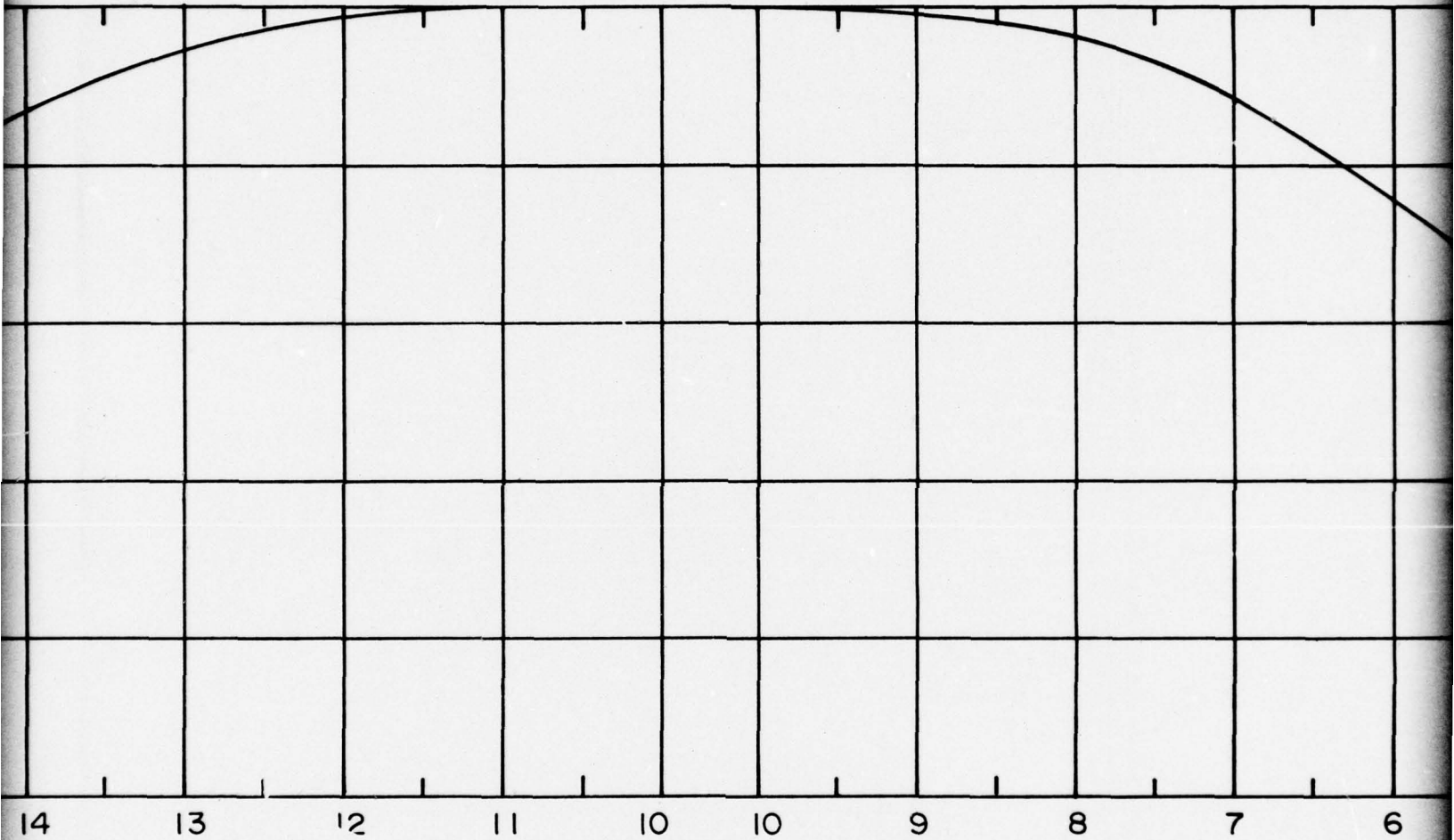
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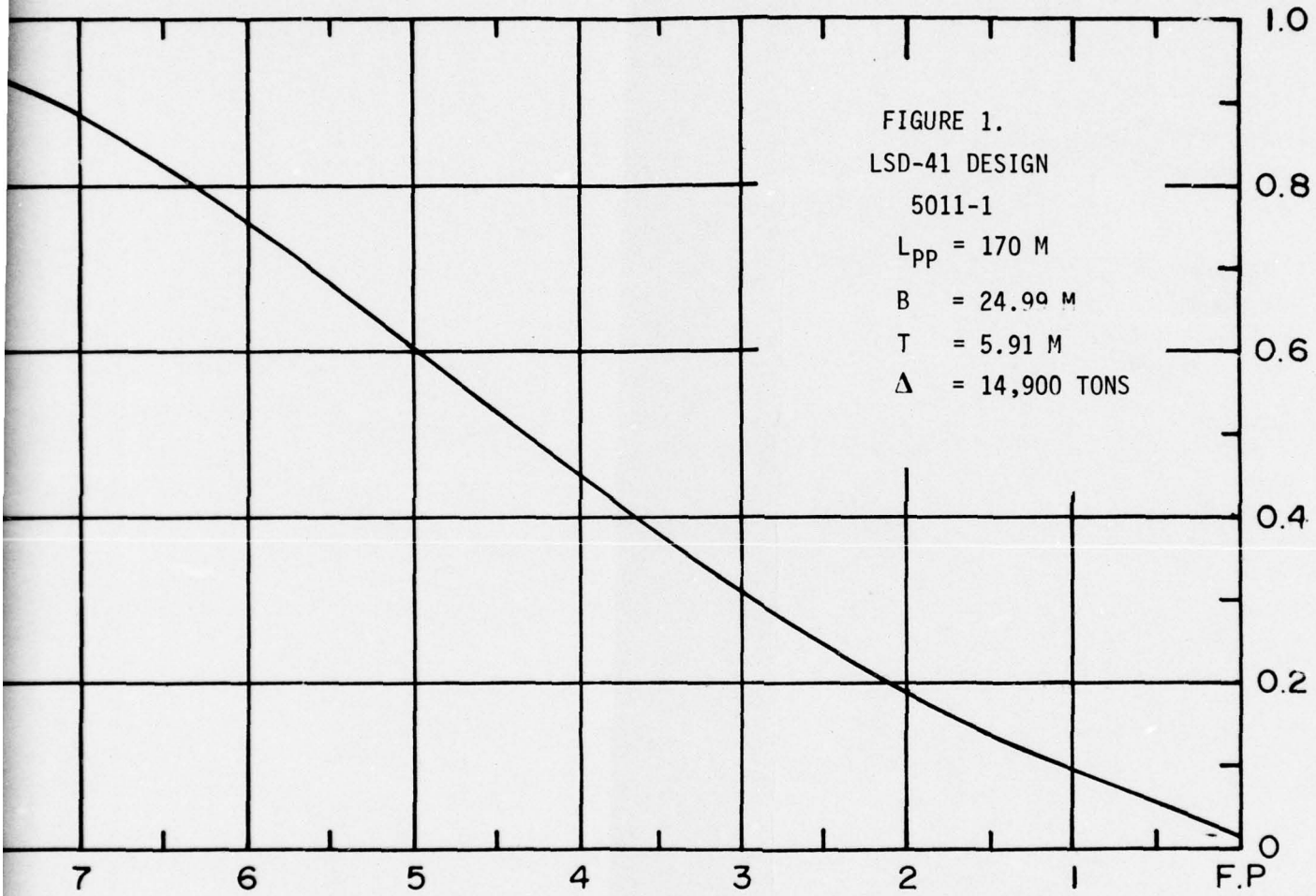
[2] Baba, E. (1973) Ship Form Improvement by use of Wave Pattern Analysis, Mitsmbishi Technical Bulletin No. 85, pp. 10.



2



$A/A_x$  (WITH SKEG)



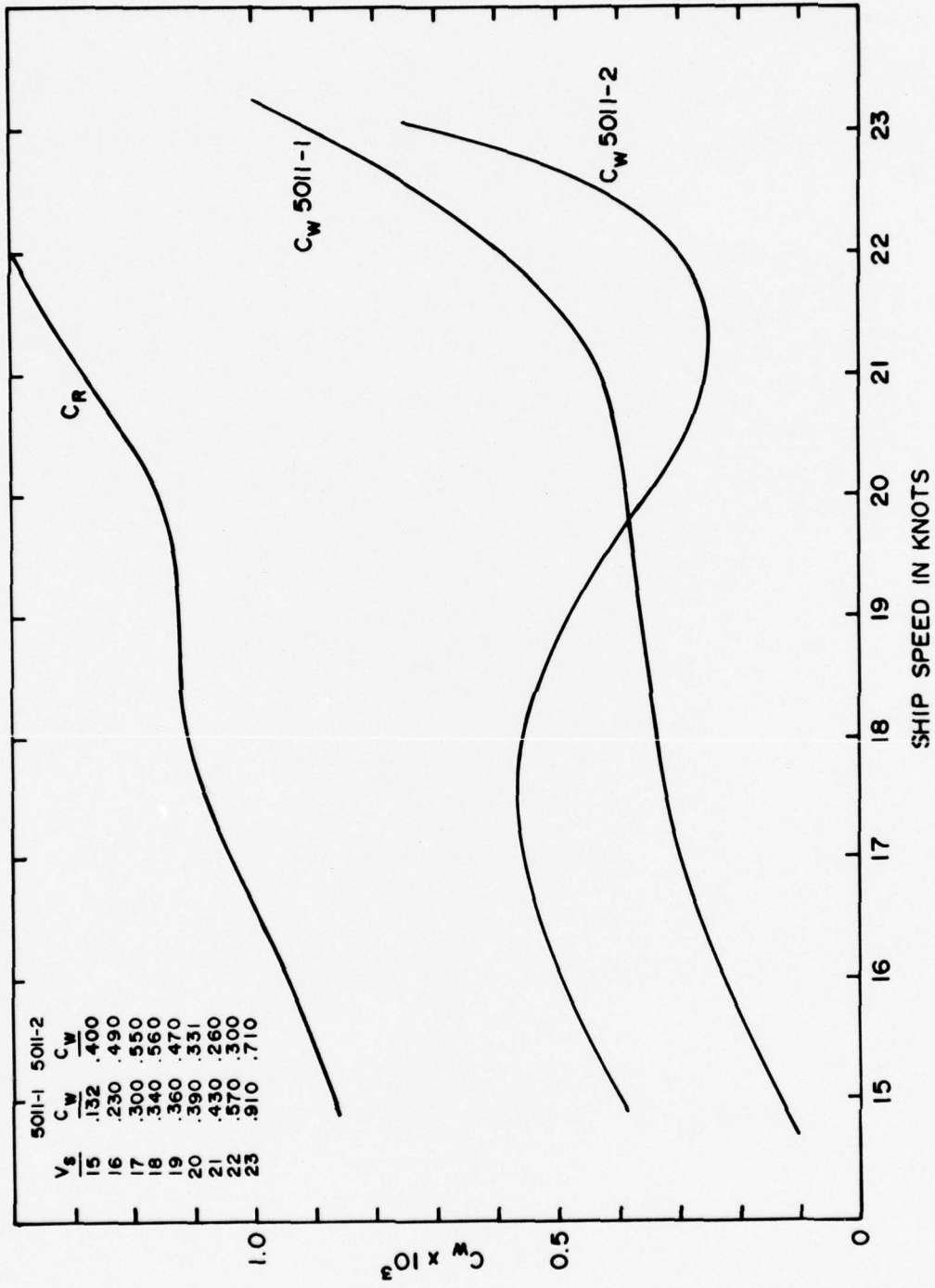
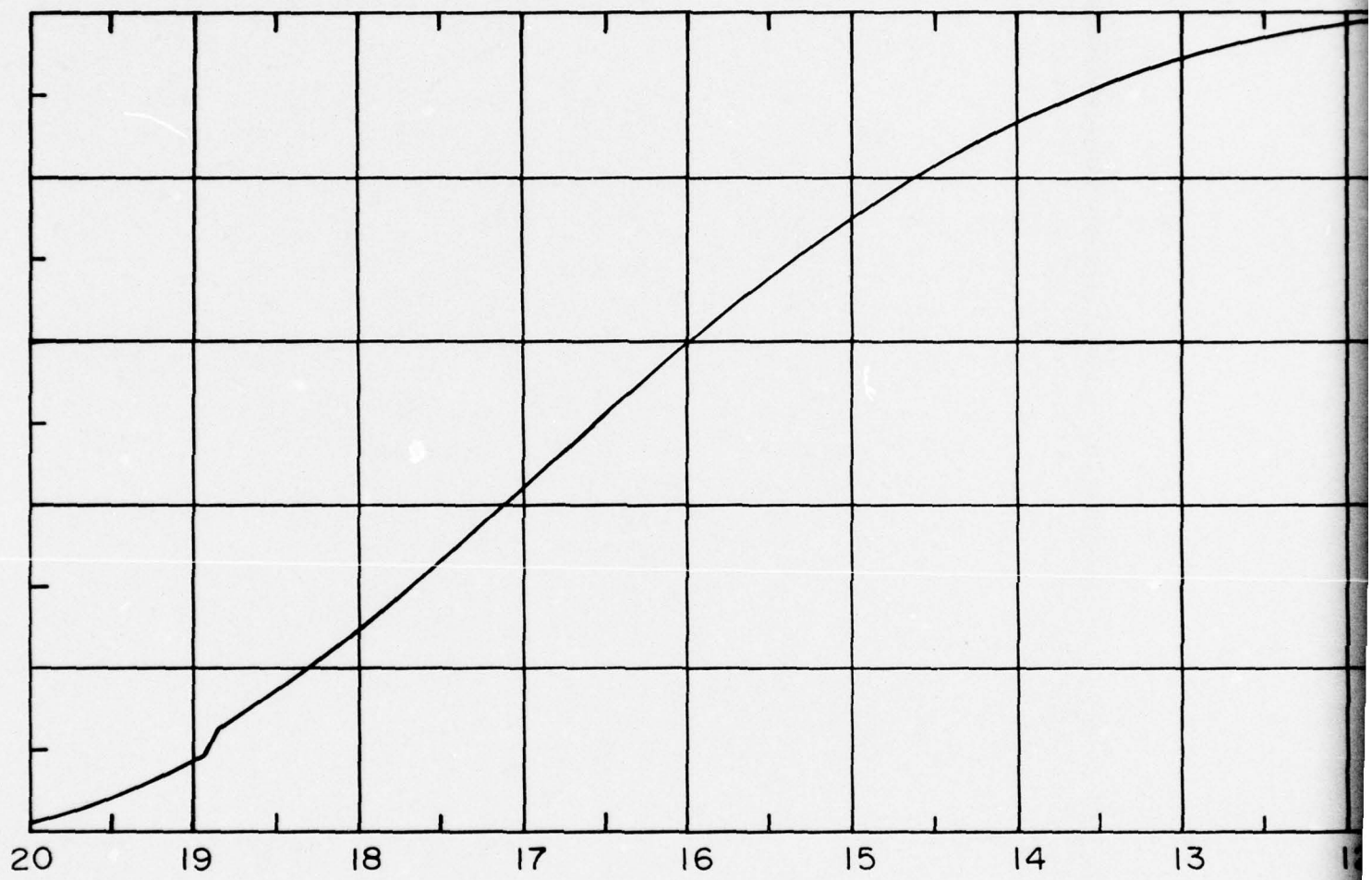
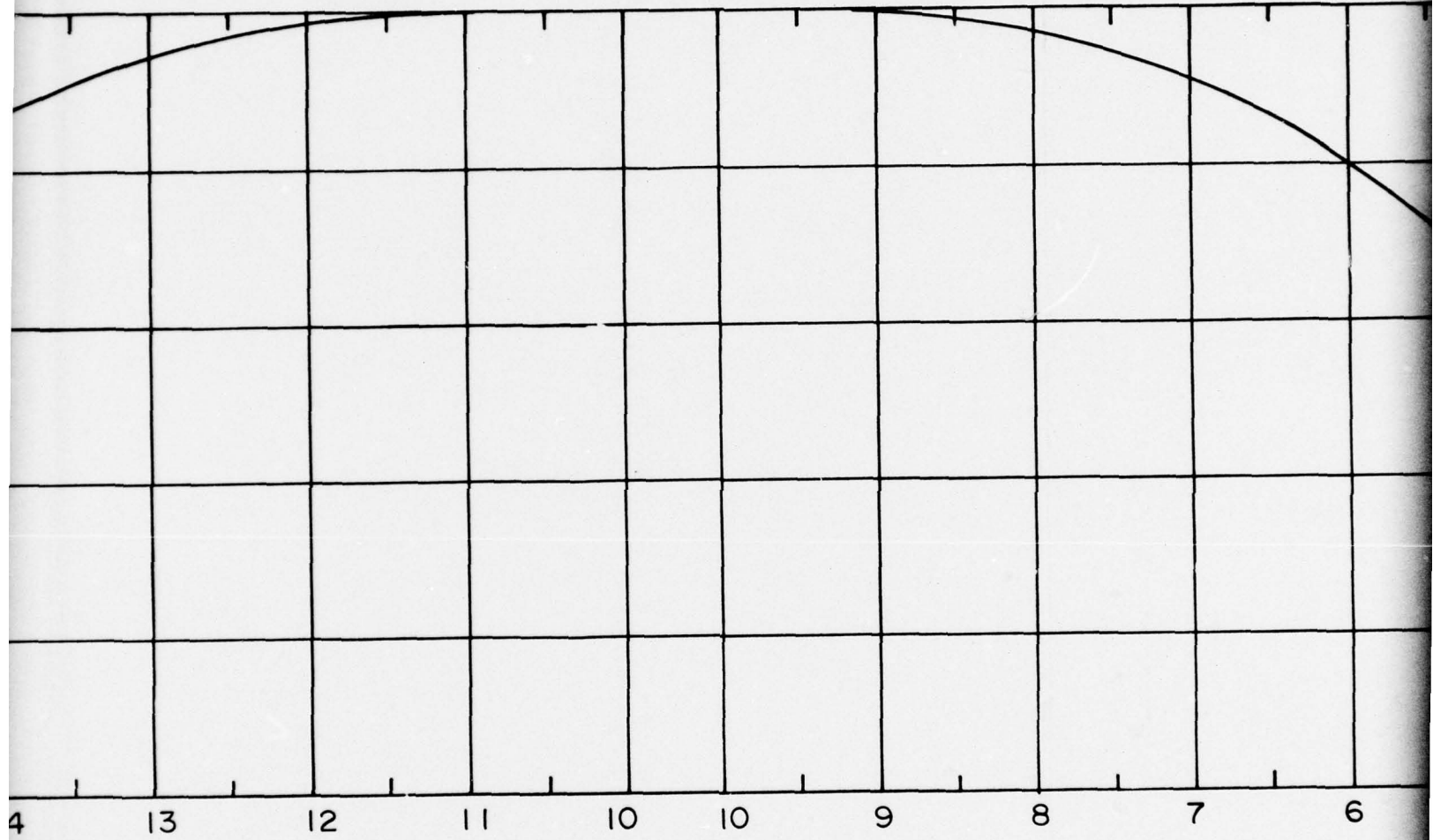


FIGURE 2.

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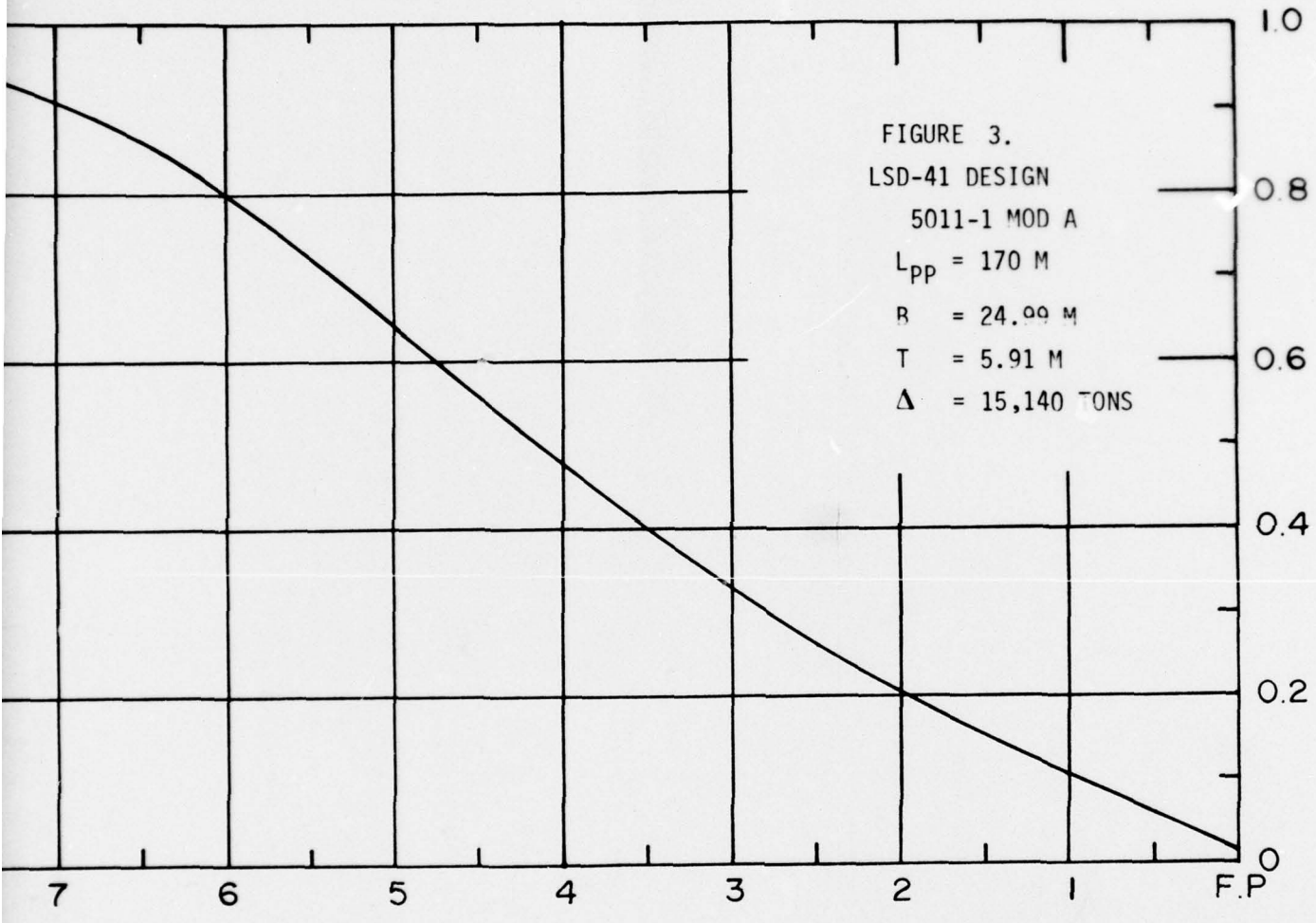


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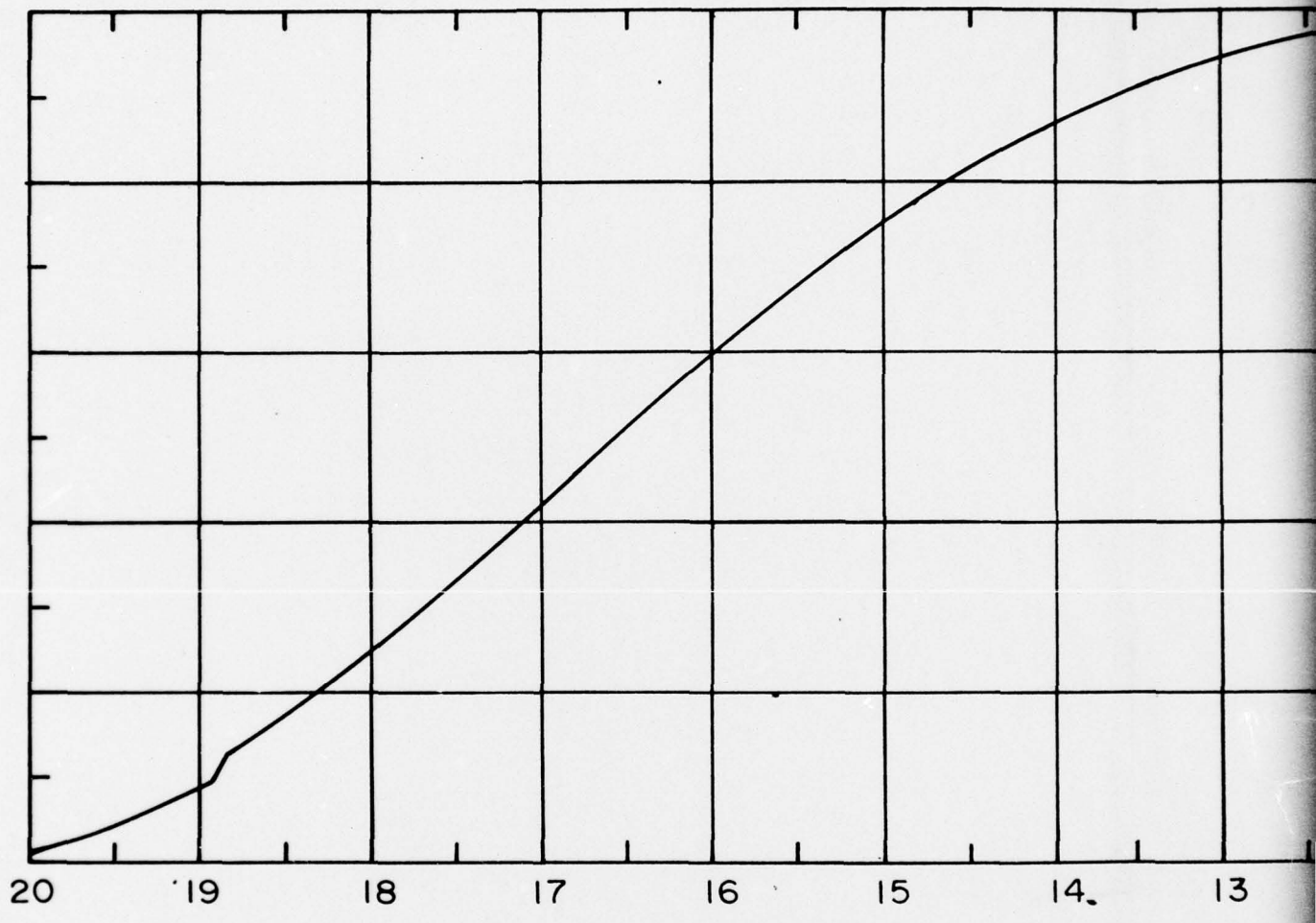


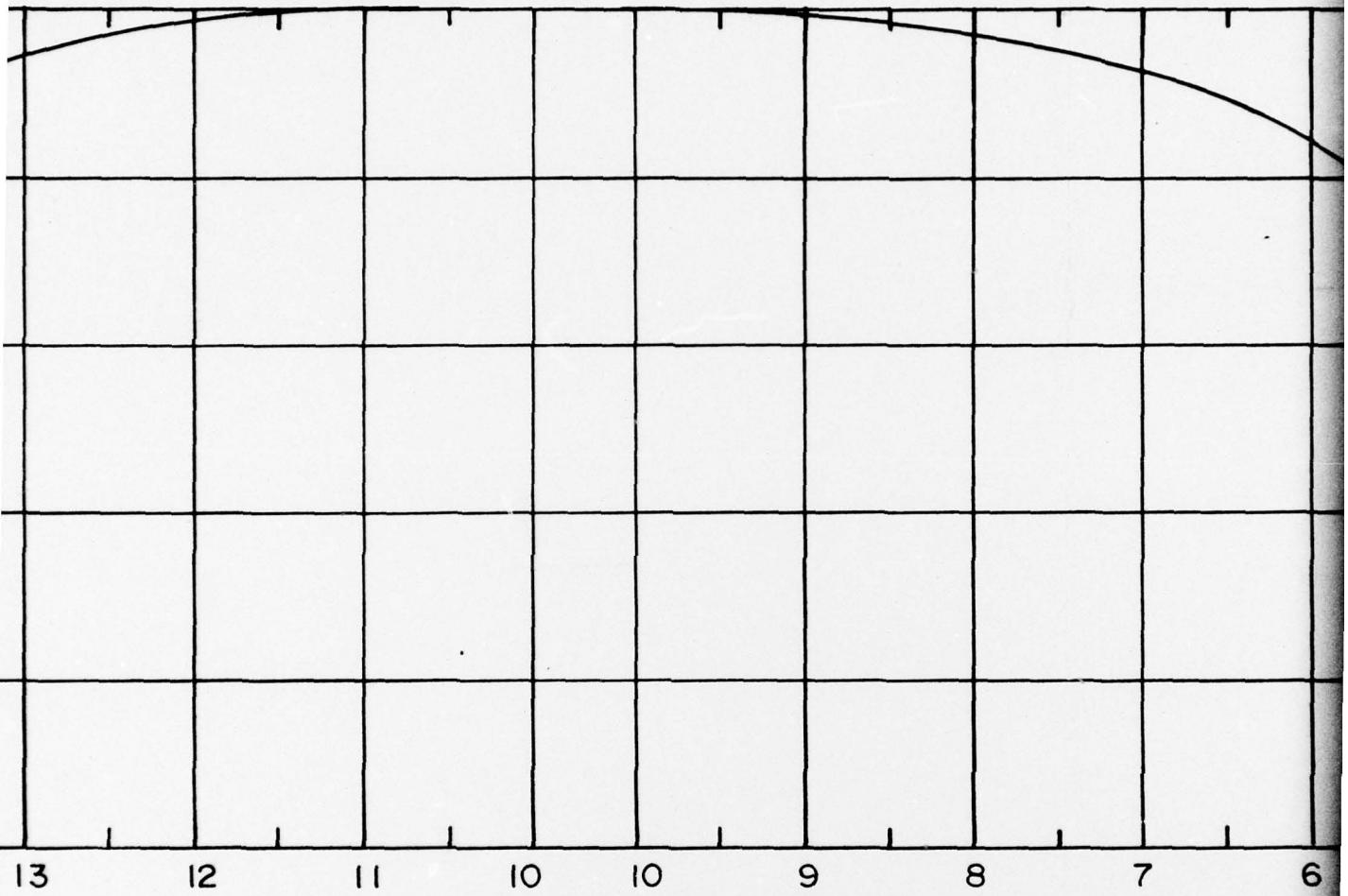
$A/A_x$  (WITH SKEG)

FIGURE 3.  
LSD-41 DESIGN  
5011-1 MOD A  
 $L_{pp} = 170$  M  
 $B = 24.99$  M  
 $T = 5.91$  M  
 $\Delta = 15,140$  TONS

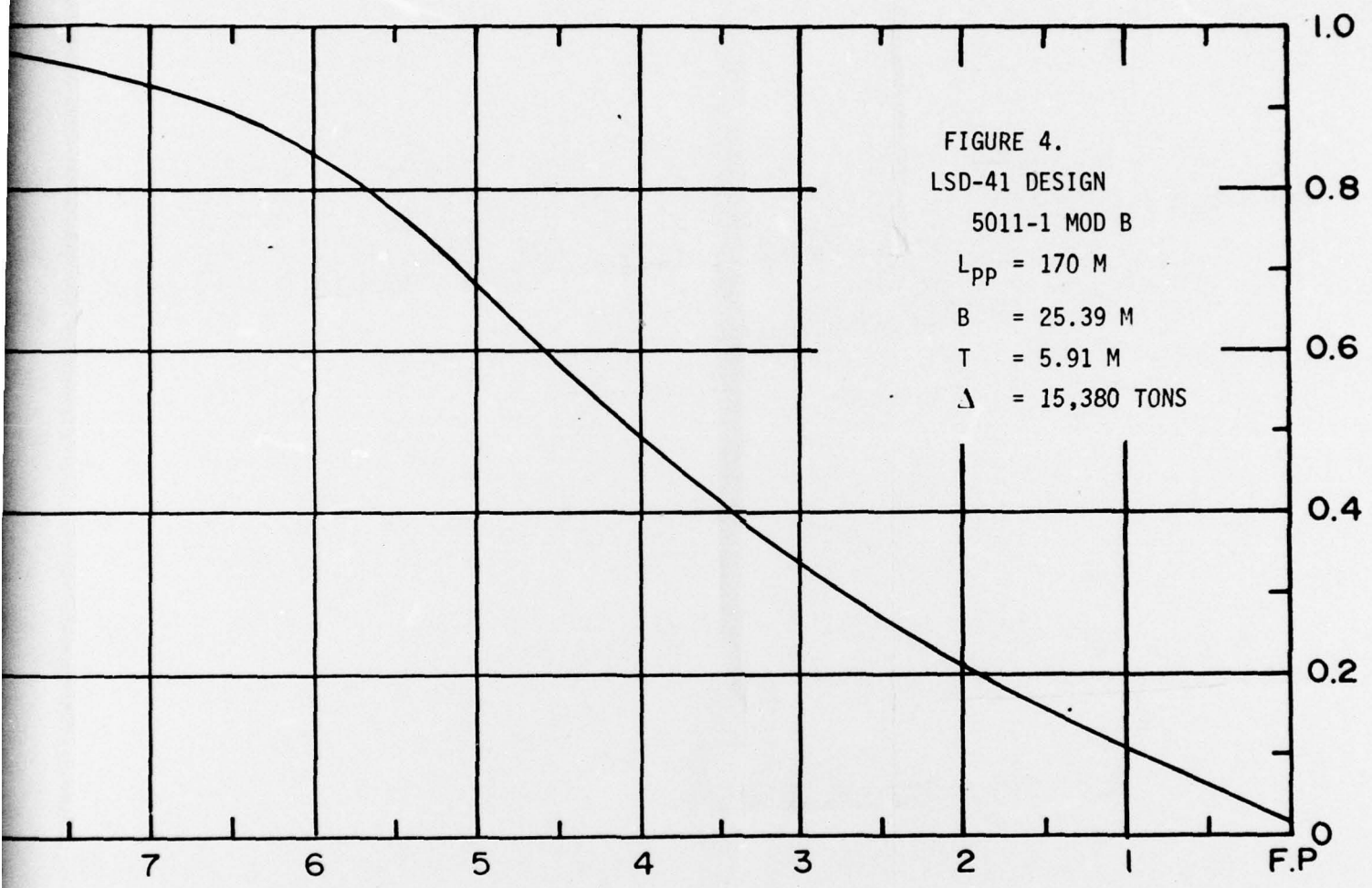


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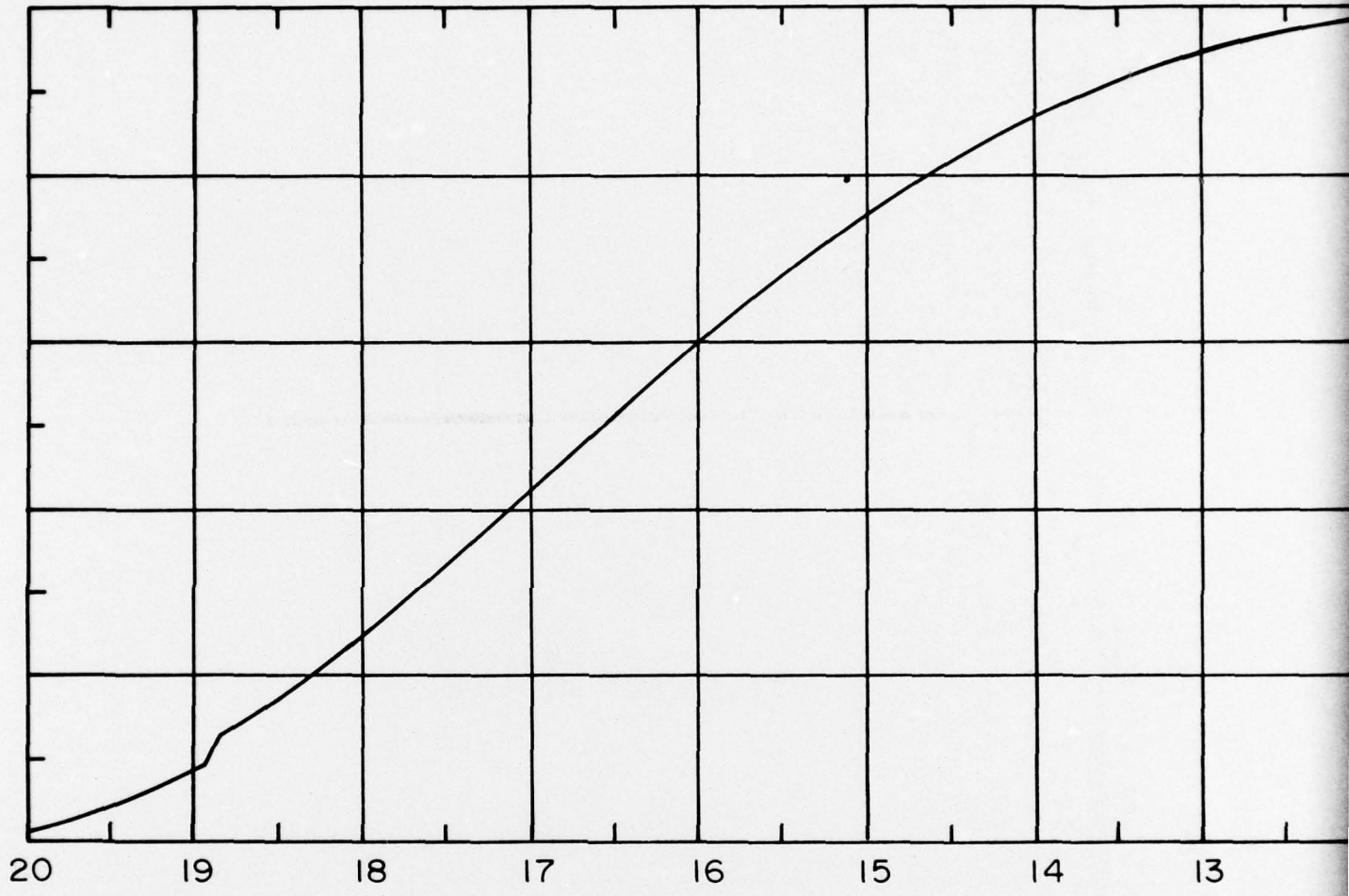




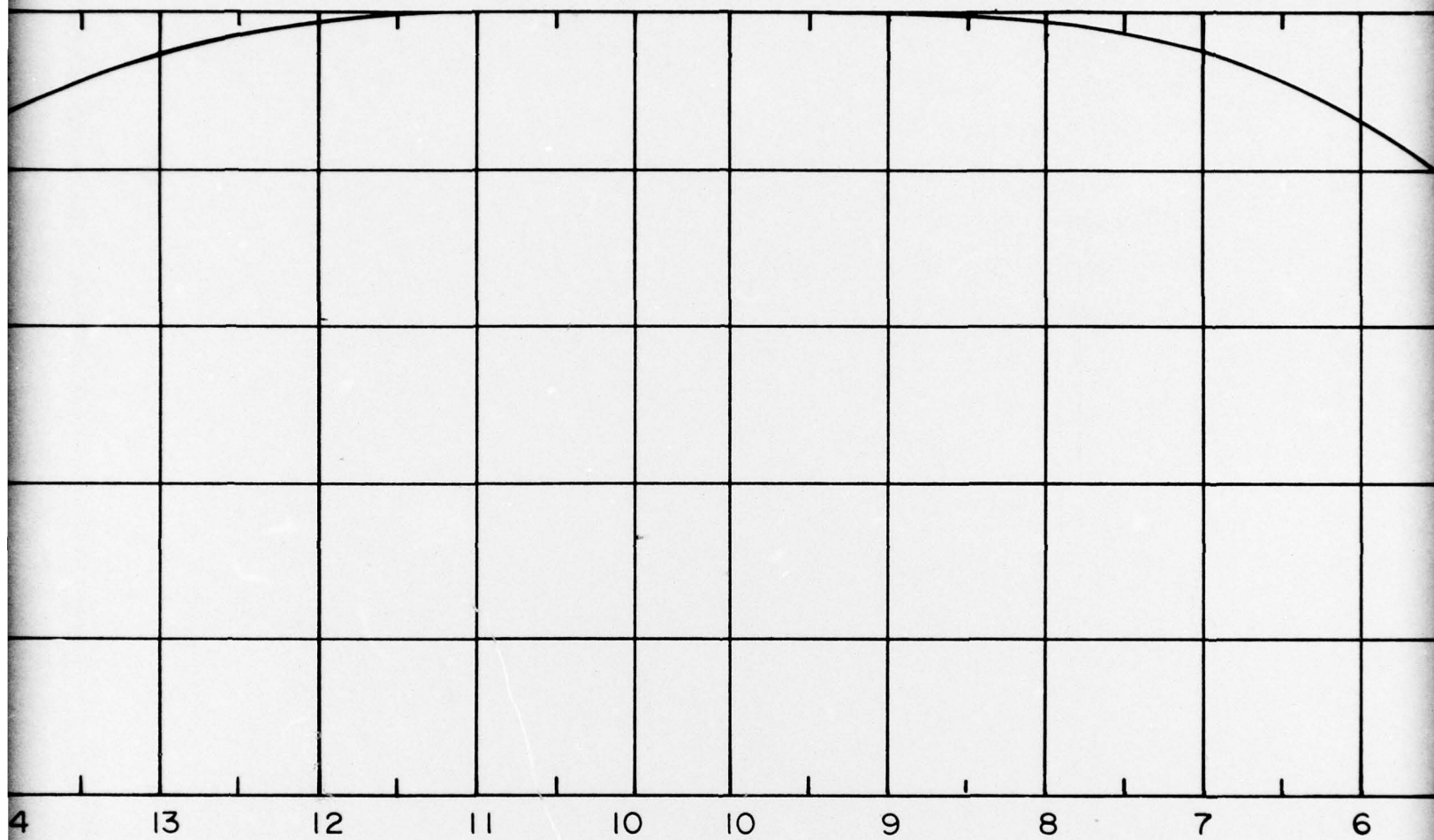
$A/A_x$  (WITH SKEG)



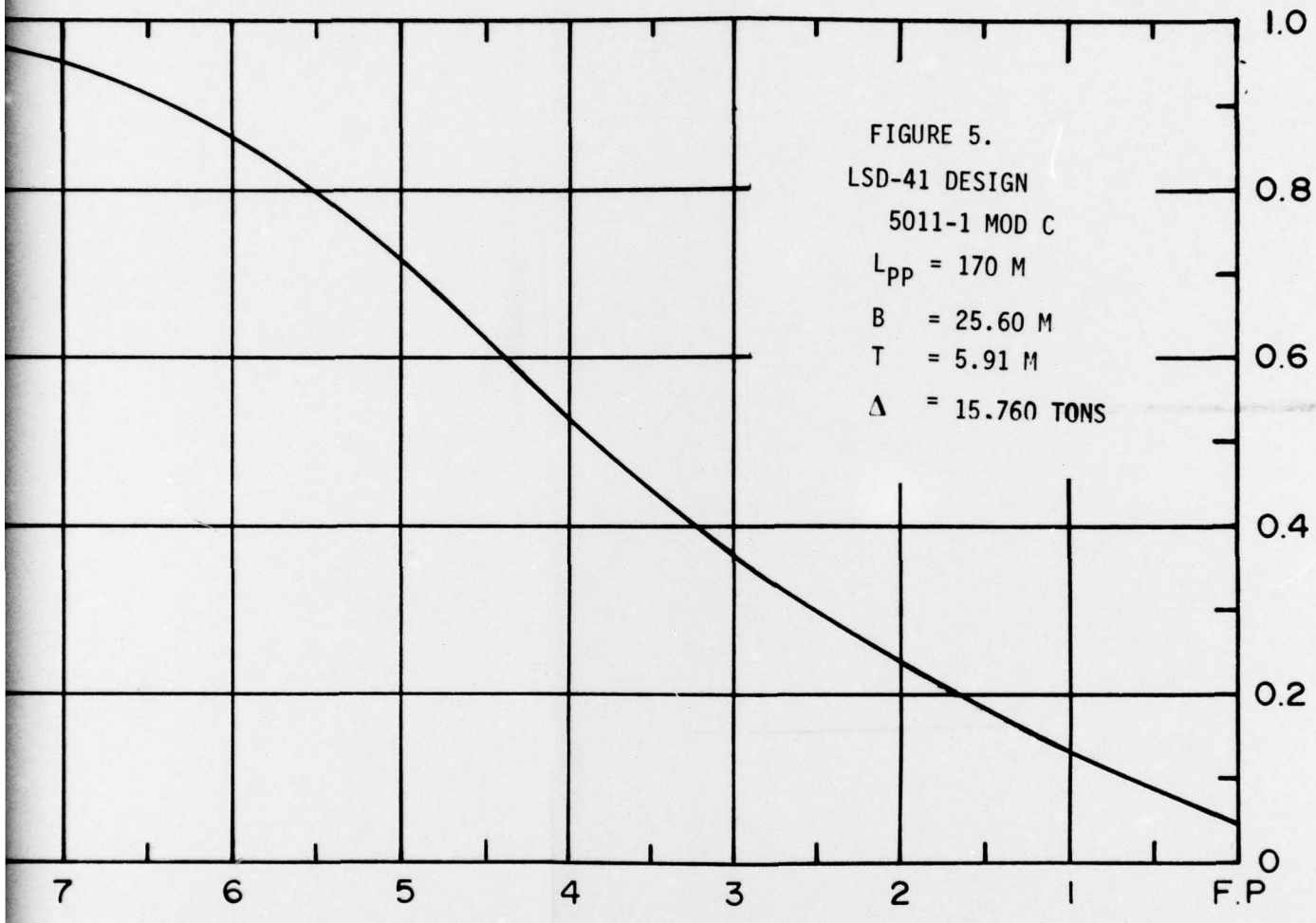
1



2



$A/A_x$  (WITH SKEG)



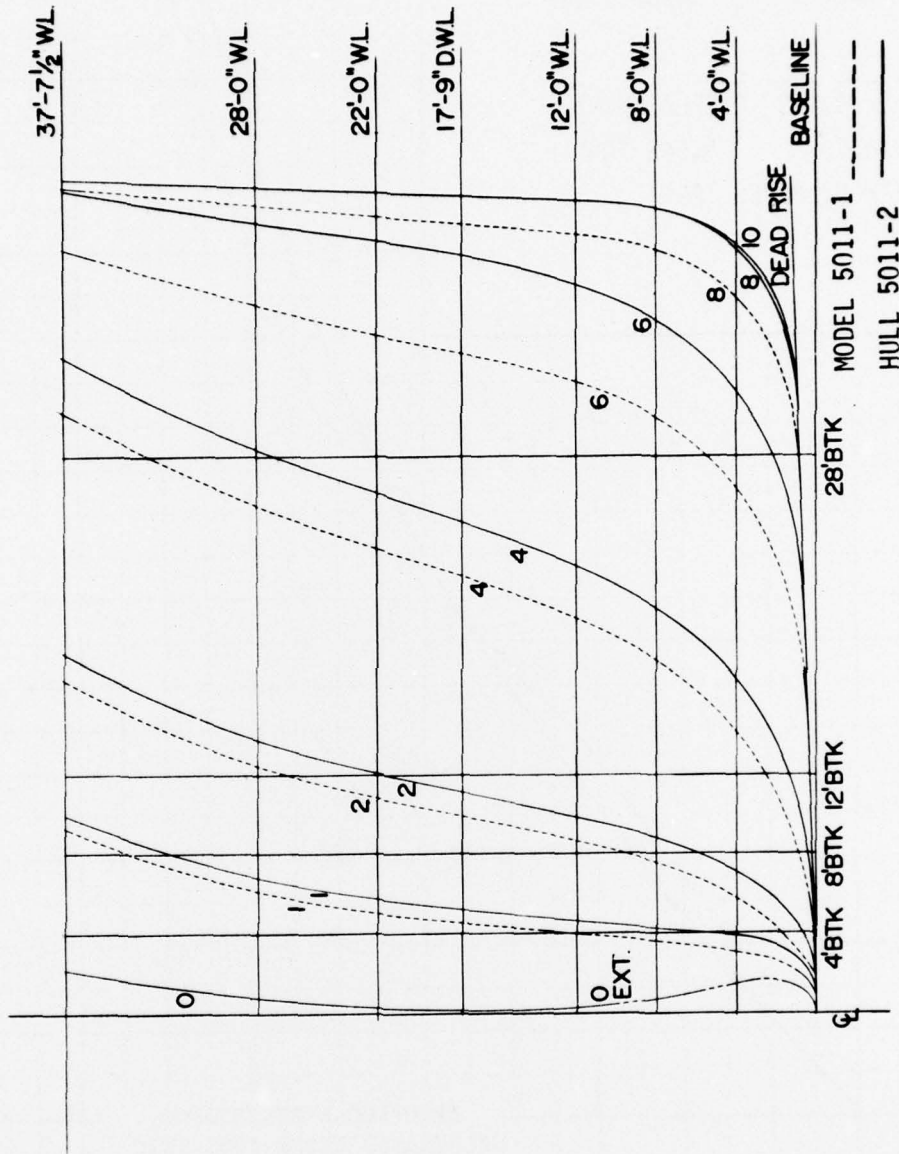


FIGURE 6.

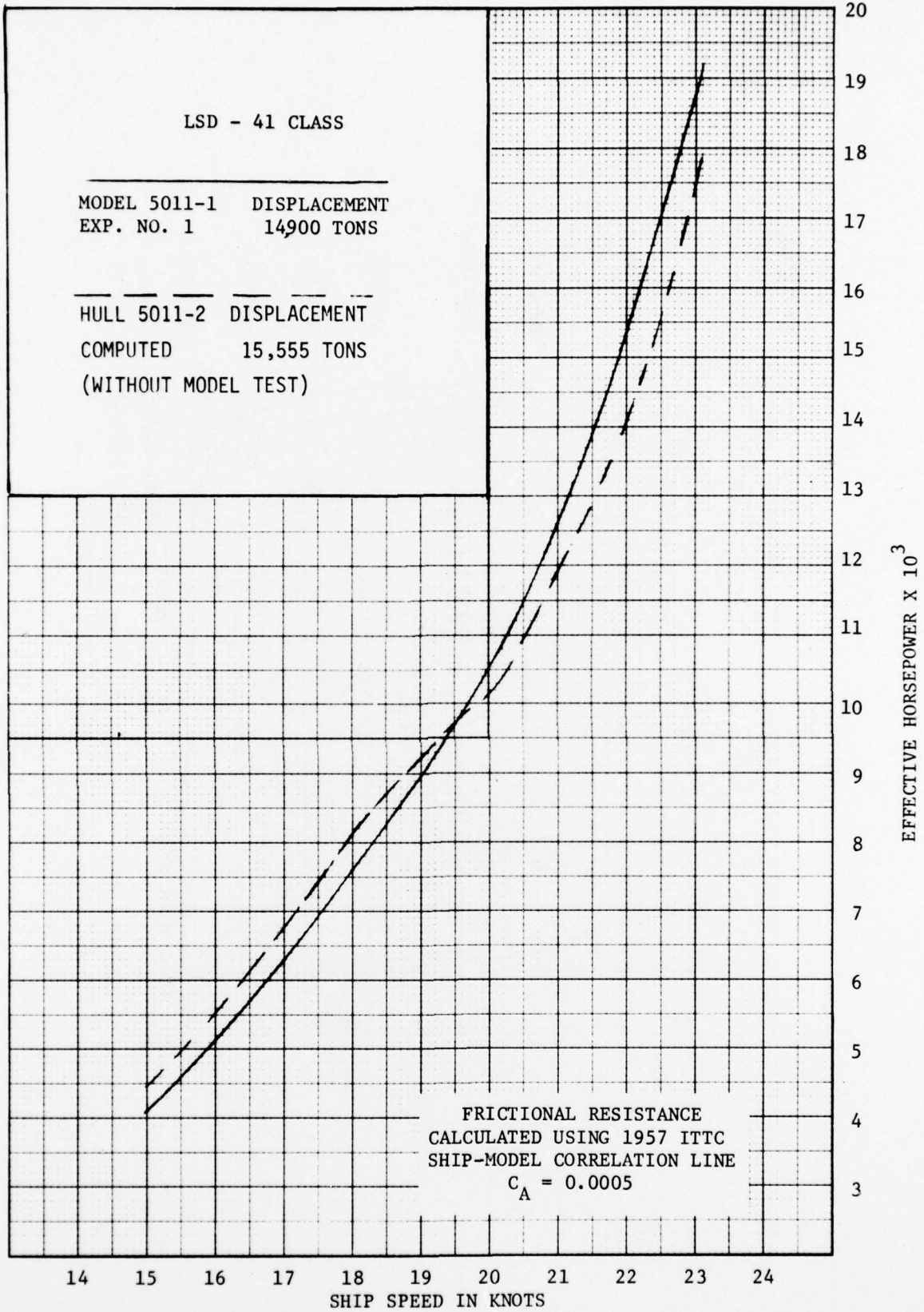
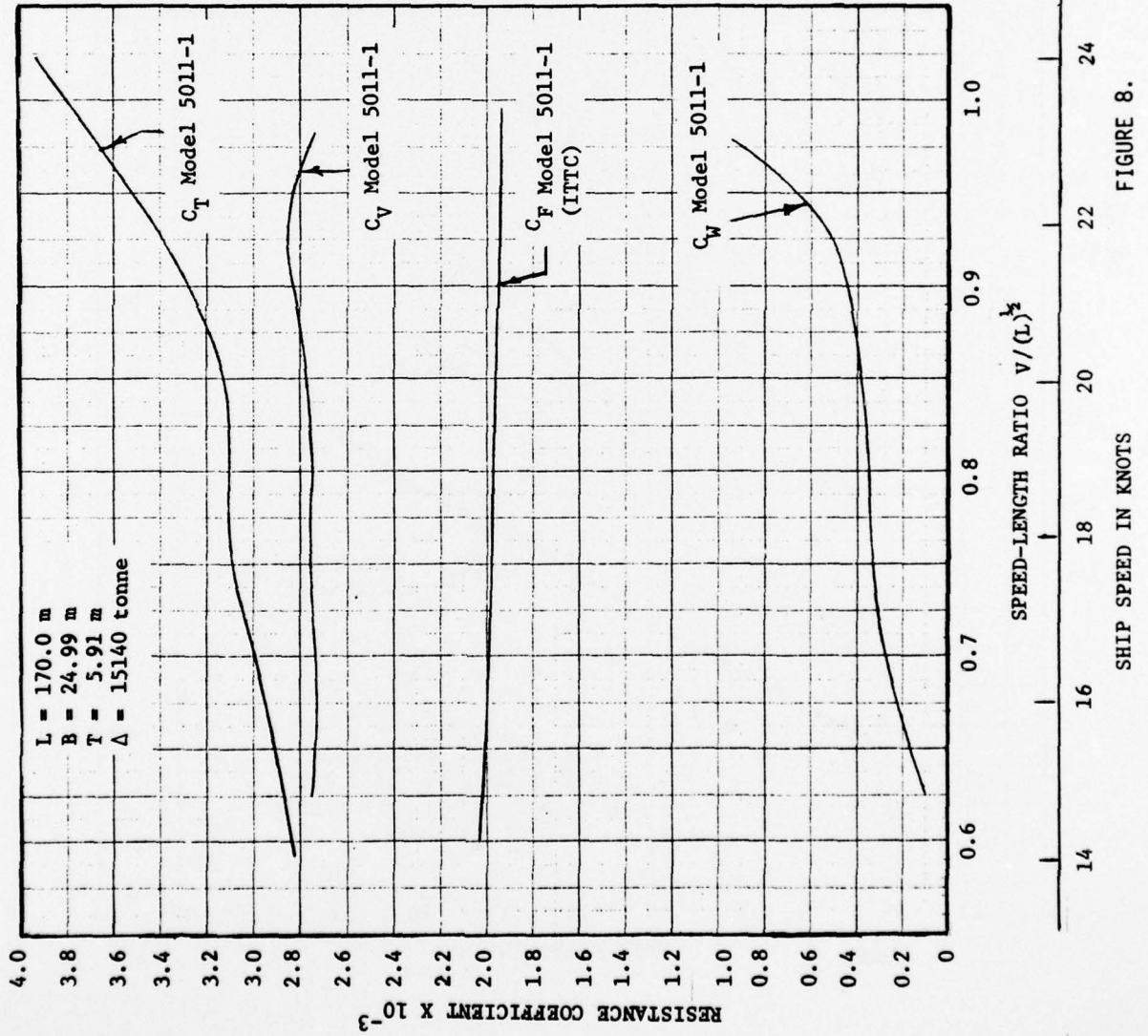


FIGURE 7.

RESISTANCE CURVES FOR LSD-41 DESIGN REPRESENTED BY MODEL 5011-1



NOMENCLATURE

$C_T$	= Total Resistance Coefficient
$C_T$	= $R_{T, \frac{1}{2} \rho S V^2}$
$C_V$	= "Viscous" Resistance Coefficient
$C_V$	= $C_T - C_W$
$C_F$	= 1957 I.T.T.C. Ship-Model Correlation Line
$C_F$	= $0.075 / (\log Re - 2)^2$
$C_W$	= "Wave" Resistance Coefficient (derived from longitudinal wave cut)

FIGURE 8.

HORSEPOWER AND RPM CURVES  
FOR  
INCREASED DISPLACEMENT LSD-41  
ESTIMATED FROM PROPULSION TESTS OF  
MODEL 5011-2  
PROPELLER 3662-63

SHIP		PROPELLER	
LENGTH (LWL)	557.7 FT.	NUMBER	3662-63
BEAM	82.0 FT.	DIAMETER	12.50 FT.
DRAFT	19.4 FT.	PITCH	11.89 FT.
DISPL.	15550 TONS	NO. OF BLADES	5
TRIM	Even Keel	MEAN WIDTH RATIO	0.330
W S	50050 SQ. FT.	EXP. AREA : DISC AREA	
APPENDAGES	Shafts	B.T.F.	0.060
	Struts, Rudders,	DIRECTION OF ROTATION	Outward
	Skeg & Bilge Keels	TIPS BELOW SURFACE	
		TIP CLEARANCE	

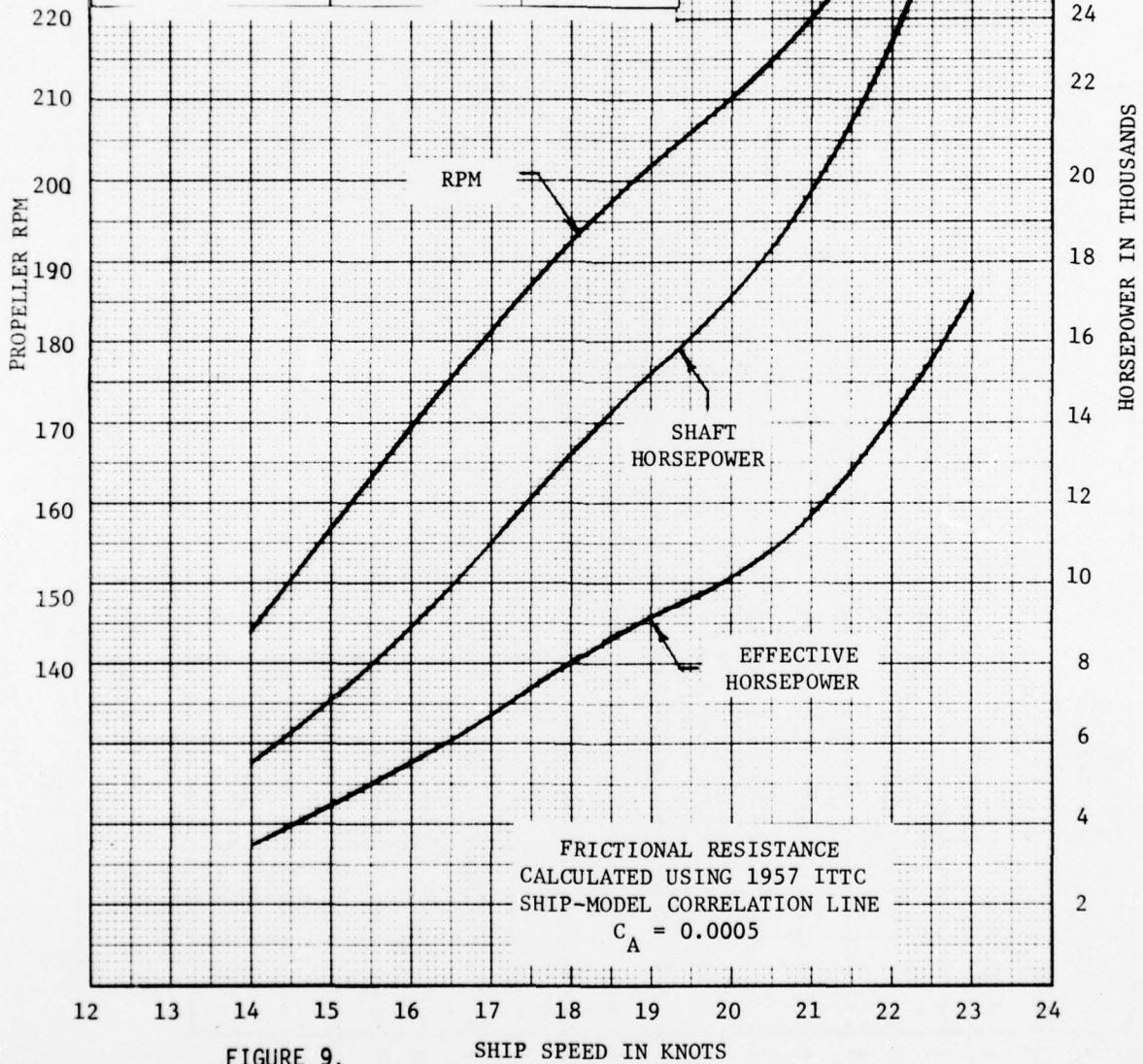


FIGURE 9.

TABLE 1

SUMMARY OF LSD-41 HULL FORM MODIFICATION

MODEL	BEAM	DISPLACEMENT at 19.4 FT	LONG. CENT. BUOY.	$C_W \times 10^{-3}$ at 22 KTS	$C_R \times 10^{-3}$ at 22 KTS
5011-1 (Test 1)	82 Ft	14,900 Tons	1.5% A	0.496	1.475
A	82	15,140 (1.016)	1.1% A	0.232	-
B	83.3	15,380 (1.021)	0.7% A	0.219	-
C	84	15,760 (1.058)	0.04% A	0.204	-
D	86	16,390 (1.100)	1.1% F	0.238	-

$C_F$  at 22 Kts =  $1.443 \times 10^{-3}$

$C_A$  at 22 Kts =  $0.5 \times 10^{-3}$



TABLE 3  
THIN SHIP STATION AREAS IN SQUARE METERS

STATION	OPTIMUM THIN SHIP	MODIFIED THIN SHIP
FP	0	0
1	0.00148	0.00148
2	0.00515	0.00515
3	0.00920	0.00920
4	0.01205	0.01205
5	0.01336	0.01336
6	0.01434	0.01434
7	0.01689	0.01689
8	0.02206	0.02206
9	0.02908	0.02908
10	0.03549	0.03549
11	0.03863	0.03863
12	0.03738	0.03738
13	0.03283	0.02830
14	0.02701	0.02575
15	0.02070	0.01710
16	0.01296	0.01170
17	0.00500	0.00650
18	0.00540	0.00180
19	0.02139	0.00100
AP	0.0	0.0

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