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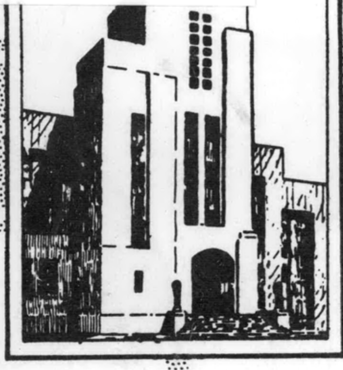

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DEPARTMENT OF THE NAVY

DAVID TAYLOR MODEL BASIN

HYDROMECHANICS

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APPLIED MATHEMATICS

THE EFFECT OF AXIAL SPACING AND DIAMETER ON THE POWERING PERFORMANCE OF COUNTERROTATING PROPELLERS

by

Richard Hecker and Neil A. McDonald

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HYDROMECHANICS LABORATORY

RESEARCH AND DEVELOPMENT REPORT

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Report 1342

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LIST OF ILLUSTRATIONS

NOTATION

a=0.8	- NACA meanline designation
c	- Clearance between blades
C_{T_S}	- Loading coefficient $\left(\frac{T}{\rho/2 \frac{\pi}{4} D^2 V_s^2}\right)$
d	- Distance between blade centerline
D	- Diameter
EAR	- Expanded area ratio $\left(\frac{4Z}{\pi}\int_{x_h}^{1.0} \frac{l}{D} dx\right)$
e	- Efficiency
h	- Clearance between blade edges
J	- Speed Coefficient $\left(\frac{V}{nD}\right)$
K_q	- Torque coefficient $\left(\frac{Q}{\rho n^2 D^5}\right)$
K_t	- Thrust coefficient $\left(\frac{T}{\rho n^2 D^4}\right)$
l	- Chord length (expanded)
$l_{0.7}$	- Chord length (expanded) at 0.7R
l_L	- Longitudinal chord length
n	- Rotational speed of propeller
P	- Pitch
P/D	- Pitch ratio
Q	- Torque
R	- Propeller radius
R_e	- Reynolds number $\left(l_{0.7}\sqrt{\frac{V^2+(0.7\pi nD)^2}{\nu}}\right)$
T	- Thrust
t	- Thrust deduction
V_S	- Ship speed
w	- Wake fraction

x	-	Nondimensional radius r/R
Z	-	Number of blades
λ	-	Advance coefficient $\left(\frac{V}{\pi n D}\right)$
ν	-	Kinematic viscosity of water
ρ	-	Mass density of water

ABSTRACT

An investigation of counterrotating (CR) propellers was conducted at the David Taylor Model Basin. For this investigation a series of counterrotating propellers was designed and tested in open water. Part of this series was used to investigate the effect of axial spacing on efficiency while another part was used to study the effect of the forward propeller diameter on efficiency. Two methods, one theoretical and one empirical, were used to predict the optimum forward diameter.

The results show that axial spacing has a negligible effect on efficiency as long as the propellers are operating at their design spacing. The effect of forward propeller diameter on efficiency is shown to be essentially the same as for single propellers. The results further indicate that either of the two methods used to determine the optimum forward diameter is adequate.

Due to limitations imposed by the test equipment the propellers were run at Reynolds numbers lower than usually considered acceptable. The experimental results, however, compare well with theory.

INTRODUCTION

Counterrotating propellers, which consist of two propellers mounted on coaxial shafts and rotating in opposite directions, offer several advantages over single propellers. The most obvious advantage is the gain in efficiency due to the recovery, by the aft propeller, of some of the rotational energy imparted to the water by the forward propeller. The ability to obtain torque balance between the propellers and thereby eliminate contra-torque devices while still maintaining stability is most desirable. Of equal importance are the advantages resulting from lower blade loading and the accompanying delay of the inception of cavitation. This lower blade loading also allows higher horsepower for the same diameter.

Amongst the disadvantages of counterrotating propellers are the mechanical complications necessary to transmit the power through a coaxial counterrotating shaft. Also, the design of the propellers themselves is rather involved, and there is presently little published data available, which the designer may use as a basis for checking his design. Finally, it must be noted that the torque balance, although desirable, is extremely sensitive to pitch. Therefore, small errors in the design or manufacture of the propellers can cause wide variations in the torque balance.[1]

Bourne, in his treatise on the screw propeller[2], discusses several types of counterrotating propellers developed in the early 1800's such as those of Dollman and Perkins. Bourne also recounts model tests and full-scale trials conducted by Ericsson during the period of 1836-1839. These trials were conducted to show the improvement of the screw propeller over the paddle wheel, but during his earlier experiments Ericsson used counterrotating propellers. Rota[3,4] was among the first to show that the efficiency of counterrotating propellers behind a ship is greater than that of a single propeller. The gain realized is due to the partial recovery of the rotational energy imparted to the water by the forward propeller.

Schaffran[5] investigated the effect of axial spacing on narrow two-bladed air screws. The propellers used by Schaffran were not designed as counterrotating propellers but were single propellers merely placed at various distances behind one another on co-axial shafts. Durand[6] and others[7,8] did experimental work on counterrotating airscrew performance but axial spacing was not included in their investigations.

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[1] References are given on page 4[illegible]

The development of counterrotating propeller theory has logically followed that of single propeller theory. As in single propeller theory somewhat separate approaches have been utilized. One approach (used at TMB) employs Lerbs' induction factors[9,10] while other investigators[11,12,13,14,15,16] use more classical methods. The subsequent programming and use of high-speed computers have reduced calculating time of Lerbs' method from four weeks to forty minutes for the same calculations,[17] thereby making feasible a systematic study of counterrotating propellers.

A program was therefore initiated at the David Taylor Model Basin to apply Lerbs' theory of counterrotating propellers and to obtain experimental verification of the theory. The first parameters investigated were axial spacing and optimum diameter as it affects the powering performance of non-cavitating propellers. The results show that propellers designed by this method meet the design conditions and that axial spacing has little effect on propeller efficiency. It is further shown that an empirical method, utilizing single propeller series, can be used to determine the optimum diameter of the forward propeller.

GENERAL CONSIDERATIONS AND DESCRIPTION OF PROPELLERS

Among the many factors that affect the powering performance of CR propellers are axial spacing, forward propeller diameter, number of blades on each propeller, expanded area ratio, scale effect, and relative rpm. Since axial spacing and forward propeller diameter are unique to CR propellers and are considered the most important parameters of CR propellers they were studied first. Thus, all the propeller sets evaluated in this investigation were designed for the same conditions of thrust, rpm, and speed. In addition all the propellers in this series were designed for Lerbs' optimum pitch distribution.[9] The full-scale design conditions are given in Table 1.

TABLE 1

Full-Scale Design Conditions of Propellers

Thrust (total)	80,150 pounds
Propeller Revolutions	130 rpm
Ship Speed	21 knots
Wake Fraction	0.15 (assumed constant radially)
Thrust Deduction	0.15
Number of Blades per Propeller	4
Type of Blade Section	TMB modified NACA 66 Section, NACA a=0.8 meanline
Cavitation Criteria	No cavitation at design conditions

For practical reasons, the range of axial spacing between counter-rotating propellers is limited. Hence, a range of axial spacing (d/R) of 0.2 to 0.8 was chosen for the present investigation. Each set of propellers was designed for a specific axial spacing and all the propeller tests reported herein were performed at the designed axial spacing.*

The optimum propeller diameter for the given design conditions was calculated theoretically using Lerbs' method.[9] Figure 1 shows the results of these calculations for four-bladed propellers with expanded area ratios (EAR) of 0.30 and 0.45. As seen from the figure the optimum diameter varies with EAR. However, a diameter of 13.5 feet is very close to optimum for both EAR's.

In addition to the theoretical calculations an alternate method, utilizing Troost curves[18] for single propellers was employed to determine the optimum diameter. When using this method the Troost propeller is assumed to develop one-half the total thrust. The results of this empirical method are shown in Figure 2.

Using a diameter of 13.5 feet, several sets of propellers were designed and built at various axial spacings. These are propellers 3682-3 (d/R=0.8), 3684-5 (d/R=0.5), and 3686-7 (d/R=0.223).** The value of d/R=0.223 was used because it was impossible to maintain blade clearance at any closer spacing while considering optimum pitch distribution. Figure 3 shows the minimum spacing, (d/R), that can be used with CR propellers designed by this method. Details of the derivation are given in the appendix.

Propellers 3690-91 (d/R=0.5) are identical in design to propellers 3684-5 except that the model diameter has been increased 33%. These propellers were used to detect scale effect on the CR propellers. Drawings of these propellers are given in Figures 4 through 12.

As a means of verifying the methods of determining the optimum forward diameter three more sets of model propellers representing three different full-scale diameters (i.e.,11.875 ft, 13.5 ft, 15.125 ft) were designed and built. These are propellers 3714-15, 3718-19, and 3720-21 which were designed for d/R=0.5 and EAR=0.45. Drawings of these propellers are given as Figures 13 through 18.

Propellers 3714-15 have the same ship diameter (13.5 ft.) and (d/R = 0.5) as 3684-85. These two sets of propellers differ in that 3714-15 have a smaller model diameter (10 inches) and a larger

* The effect of operating CR propellers at spacings other than design is the subject of another current investigation.

** Propeller 3687A is an alternate aft propeller used with 3686 and designed to alter the torque balance by a change in pitch.

Table 2
Summary of Propeller Data

PROPELLER	POSITION	ROTATION	PROPELLER DIAMETER (FEET)	MODEL DIAMETER (INCHES)	$(P/D)_{0.7}$	EAR	C_{T_S}	λ_S	K_{T/J^2}	d/R	AXIAL CLEARANCE AT 0.7R (INCHES)
3682	FWD	LH	13.50	12.017	1.255	0.305	0.4589	0.3858	0.2494	0.800	3.700
3683	AFT	RH	12.96	11.536	1.413	0.327					
3684	FWD	LH	13.50	12.017	1.272	0.304	0.4589	0.3858	0.2494	0.500	1.888
3685	AFT	RH	13.06	11.625	1.380	0.315					
3686	FWD	LH	13.50	12.017	1.291	0.303	0.4589	0.3858	0.2494	0.223	0.220
3687	AFT	RH	13.23	11.776	1.320	0.322					
3687A	AFT	RH	13.23	11.776	1.326	0.324					
3690	FWD	LH	13.50	16.001	1.272	0.304	0.4589	0.3858	0.2494	0.500	2.514
3691	AFT	RH	13.06	15.479	1.380	0.315					
3714	FWD	LH	13.50	10.000	1.262	0.450	0.4589	0.3858	0.2494	0.500	1.179
3715	AFT	RH	13.06	9.674	1.365	0.450					
3718	FWD	LH	11.875	10.000	1.564	0.454	0.5931	0.4386	0.3224	0.568	1.311
3719	AFT	RH	11.390	9.592	1.692	0.451					
3720	FWD	LH	15.125	10.000	1.074	0.456	0.3657	0.3443	0.1987	0.446	0.915
3721	AFT	RH	14.730	9.739	1.151	0.453					

expanded area ratio (0.45). This change was made in order to obtain realistic lift coefficients for the propellers and resulted in slightly higher Reynolds numbers during the tests. Propellers 3718-19 were designed with a forward (ship) diameter of 11.875-ft, whereas propellers 3720-21 were designed for 15.125 ft. This covered the practical range for the given full-scale design conditions. A summary of the propeller characteristics is given in Table 2.

The propellers used in this investigation were manufactured from a solid block of 14T6 aluminum. Previously nearly all propellers at DTMB were made from castings. The propeller castings require extensive hand finishing and in addition aluminum castings are often non-homogeneous. When using solid aluminum the material is, of course, homogeneous and in addition a substantial savings in time and money is realized. Briefly the procedure is first to cut a rough projected outline (Figure 11). This blank is then mounted on a Keller machine and finished to within 0.010 inches. A Keller machine is a contour miller which in the case of propellers has a follower on a pattern blade. The follower controls the motion of the cutting head. After machining the propellers are hand finished to within 0.003 inches.

APPARATUS AND PROCEDURE

The instruments used to test the propellers consisted of a hollow shaft transmission dynamometer which had previously been designed and built for use with one of the existing solid shaft transmission dynamometers. A transmission type dynamometer measures thrust and torque but doesn't absorb any of the torque load. These dynamometers are described in Reference 19. Figure 20 shows the dynamometer arrangement used for testing and, as can be seen, both propellers are geared to rotate at the same RPM. A light duty shunt motor, designed to operate at 5400 rpm, was used through a 3.2:1 reduction gear to drive the dynamometers. Two 2-channel Minneapolis-Honeywell (Brown) graphic recorders were used to record the thrust and torque of each propeller. A TMB Revolution-Speed-Time unit was used to record propeller RPM and speed of advance.

The TMB aluminum propeller boat was used for the tests of these propellers. The shunt motor, dynamometers and the dynamometer shafting were mounted in the propeller boat, and the boat was attached rigidly to the basin towing carriage. Figures 21 through 25 show the propellers mounted on the counterrotating shafts of the propeller boat, and the range of axial spacing may be noted by comparing these figures.

Since no method has been developed for simultaneously calibrating a pair of counterrotating dynamometers, they were calibrated individually with each dynamometer loaded simultaneously in thrust and torque. Figure 26 shows the calibration set-up. The driving motor is a gravity type dynamometer and the load is absorbed by a 1/2 horsepower d-c motor driven through a thrustless coupling. The Brown recorder and the recorder control units are visible at the end of the dynamometer table. Once a consistent method of operation was established, the repeatability of calibration and test results was quite good.

Before beginning each test, the thrust and torque recording instruments were checked to insure that thrust and torque were being recorded through their proper calibrated channels. All testing equipment was operated for a minimum of 15 minutes in order to stabilize the heating effect which is characteristic of these dynamometers.

The tests were run in open water over the range of J equal zero to thrust equal zero. These tests were originally intended to be run at constant propeller rpm, beginning at a low towing carriage speed and working up to the maximum desired speed. However, the actual test procedure was somewhat altered due to the low allowable loads of the dynamometers. At the lower carriage speeds the rpm was reduced in order to stay within the maximum dynamometer limits. Once the desired rpm was reached it was held constant while the carriage speed was further increased to the point where zero thrust was obtained. This procedure gave the highest obtainable Reynolds number over the entire test range. The Reynolds numbers obtained, however, were always lower than the minimum desired.

RESULTS

The test data were reduced to the usual non-dimensional coefficients of J, K_t, K_q, and e by the UNIVAC high-speed computer. It should be noted that all coefficients including those of the after propeller are based on the diameter of the forward propeller. The equations used for data reduction are:

Thrust Coefficients

Fwd: $$K_{T_F} = \frac{T_F}{\rho n^2 D_F^4}$$

Aft: $$K_{T_A} = \frac{T_A}{\rho n^2 D_F^4}$$

Total: $$K_T = \frac{T_F + T_A}{\rho n^2 D_F^4}$$

Torque Coefficients

Fwd: $$K_{Q_F} = \frac{Q_F}{\rho n^2 D_F^5}$$

Aft: $$K_{Q_A} = \frac{Q_A}{\rho n^2 D_F^5}$$

Total: $$K_Q = \frac{Q_F + Q_A}{\rho n^2 D_F^5}$$

Speed Coefficient $J = \frac{V}{nD}$

Efficiency $e = \frac{(T_F + T_A)V}{2\pi(Q_F + Q_A)n}$

Torque Unbalance $\frac{\Delta Q}{Q} = \frac{K_{QA} - K_{QF}}{K_Q}$

where

T_F - Fwd thrust

T_A - Aft thrust

Q_F - Fwd torque

Q_A - Aft torque

V - Speed of advance

n - rps of each propeller

D_F - Fwd diameter

ρ - Density of water

Figures 27 through 34 are the results of the open water tests of the eight sets of counterrotating propellers. Coefficients of thrust (K_{tF}, K_{tA}) and torque (K_{qF}, K_{qA}) are shown for the forward and after propellers as well as the coefficients of total thrust (K_t) and total torque (K_q) for the counterrotating system. The operating point for each set is indicated by the crossing of the total K_t curve by the contour of K_T/J^2. The design values of K_T/J^2 for each propeller set are given in Table 2. Table 3 shows the design J, operating J, efficiency, and torque balance of the propellers. As can be seen by comparing the operating and design J's all the propellers appear to be slightly overpitched.

TABLE 3

OPEN WATER TEST RESULTS

Propeller Set	Design J	Operating J	Efficiency	K_{q_F}	K_{Q_A}	Torque Unbalance
3682-3	1.030	1.082	0.795	0.0298	0.0339	6.4%
3684-5	1.030	1.078	0.764	0.0316	0.0337	3.2%
3686-7	1.030	1.070	0.778	0.0308	0.0323	3.4%
3686-7A	1.030	1.082	0.772	0.0322	0.0328	1.0%
3690-91	1.030	1.072	0.760	0.0312	0.0318	1.0%
3714-15	1.030	1.057	0.768	0.0307	0.0310	0.4%
3718-19	1.171	1.246	0.747	0.0643	0.0689	3.5%
3720-21	0.919	0.939	0.718	0.0170	0.0193	6.4%

Figure 35 shows the effect of axial spacing on the efficiency of propellers 3682 through 3691, as determined by theory and from test results. ORL, Penn. State[20] tested these propellers for cavitation inception. Their test results show that in all cases no cavitation occurs at the design condition. The non-cavitating ORL data at operating J is shown on Figure 35 for comparison. The theoretical curve shows essentially no change in efficiency with axial spacing for the range investigated. The scatter of the test spots is within the accuracy of the test equipment and the agreement with theory is quite good. It is, therefore, concluded that no change in efficiency arises from a change in axial spacing when the propellers are operated at their design spacing.

The test results of the propellers designed for various diameters are compared to theory in Figure 36. The test spots were taken from the open water curves at the operating J given in Table 2. Although a discrepancy of about two percent exists around 13.5-ft. between theory and test results, the general agreement is such that either of the two methods used to predict optimum diameter should be considered acceptable. The agreement between the test results and the curve from Troost is especially important since no known series of counterrotating propellers is available.

In an attempt to investigate the effect of the model propeller size on performance, propellers 3690-91 (16 inch model diameter) were tested and compared with propellers 3684-5 (12 inch model diameter). A comparison of the results of the open water tests is given in Figure 37. Due to the limitations of the test equipment both sets of propellers were tested at essentially the same Reynolds number. For this reason no conclusions can be drawn concerning the scale effect of CR propellers. The results are included in this report for information. The Reynolds numbers achieved during the above tests was lower than the 4×10^5 recommended by Roundy.[21]

CONCLUSIONS

DESIGN PROCEDURE

The series of counterrotating (CR) propellers reported herein are, as far as it is known, among the first CR propellers designed by Lerbs' theory. The three-way agreement between theory, TMB tests, and ORL tests lead to the conclusion that CR propellers designed by this method will perform as predicted. The torque balance of propellers designed by this method is generally within five percent. The propellers have an open water efficiency slightly higher than can be expected with single propellers. The reduced loading of counterrotating propellers over single propellers makes the cavitation problem less severe. Although some refinements to the theory are necessary the only difficulty thus far encountered is an overpitching of the order of three to five percent.

OPTIMUM DIAMETER

Although the optimum diameter of counterrotating propellers can always be determined by calculating several propellers at various diameters, a shorter method is of great value. The results of this investigation show that Troost curves can be used to determine the optimum diameter of CR propellers provided the Troost propeller is calculated for one-half the desired thrust. The diameter so determined should not be reduced five percent as is the usual practice for single propellers. In this connection it should be noted that the optimum diameter of CR propellers is usually less than that of a single propeller, so that optimum CR propellers can often be used where optimum single propellers are too large.

AXIAL SPACING

The axial spacing of counterrotating propellers is most often dictated by the shape of the body or ship to be propelled as well as by mechanical considerations. The test results and theory both confirm that axial spacing has little effect upon the efficiency of CR propellers. It is stressed, however, that this conclusion applies only to CR propellers operated at their design spacing.

FUTURE INVESTIGATIONS

Future investigations should include the determination on the overall performance of the effect of different number of blades on each propeller, the effect of expanded area ratio, different number of rpm for each propellers, and scale effect.

Further refinement of the pitch correction as applied to counterrotating propellers is necessary in order to eliminate the overpitching thus far encountered. It is expected that a lifting surface correction, currently being developed, will alleviate this dificiency.

APPENDIX A

CALCULATION OF MINIMUM SPACING

One of the conditions which must be chosen prior to designing counterrotating propellers is the axial spacing (d/R). Very often due to the limited space available for the propellers the clearance between the propellers must be kept to a minimum. A method of estimating the closest axial spacing possible during preliminary design is therefore very useful.

There are two general methods of obtaining counterrotating blade outlines in use. One method frequently used for more lightly loaded propellers is to obtain a blade shape such that the longitudinal outline is straight from the hub to perhaps 0.7R. This is done where cavitation is no problem and where the loading is such that blade outline has little effect upon efficiency. When this method can be used, blade clearance can be determined quite accurately early in the design.

The second method of determining the blade outline is the usual method in which the chord length is based on cavitation and strength. This second method was used on the propellers reported herein.

Since the chord length as determined by the second method changes only slightly with different mean lines and thicknesses a minimum spacing can be determined as a function of EAR and P/D. Experience has shown that the minimum clearance of counterrotating propellers most often occurs between 0.4R and 0.5R so that this derivation assumes minimum spacing at 0.45R.

The method outlined in this appendix will include the following simplifying assumptions:

(a) The minimum clearance is assumed to occur at 0.45R.

(b) The chord is assumed to be a true helix.

(c) The chord lengths of the forward and aft propellers are equal.

(d) The clearance (h) is small enough so that multiples of h, h^2 and dh can be ignored. *

* Although it is easier to remove multiples of h from the equations, a solution can easily be obtained without this linearization. Since the entire purpose of these calculations is to determine a minimum value for h, the multiples will always be small enough to ignore. In fact, (h) minimum should be as close to zero as is mechanically possible.

Considering the chord as part of a helix the non-dimensional longitudinal chord length is calculated by

$$\frac{l_L}{D} = \sqrt{\frac{(l/D)^2 (P/D)^2}{(\pi x)^2 + (P/D)^2}}$$

where

l_L - Longitudinal chord length

l - Expanded chord length

P - Propeller pitch

x - Non-dimensional radius

Referring to Figure 39, the axial spacing parameter d/R can be expressed in terms of l_L assuming $l_{L_F} = l_{L_A}$ (assumption c).

$$d = l_L - h$$

$$d/R = \frac{2 l_L}{D} - \frac{h}{R}$$

where

h - Clearance between blade edges

By substitution, squaring the equation, and dropping the small terms h^2 and d•h we write:

$$\left(\frac{d}{R}\right)^2 = \frac{(l/D)^2 (P/D)^2}{(\pi x)^2 + (P/D)^2}$$

The four-bladed counterrotating propellers in this series had an average $(\frac{l}{D})$@0.45R = 0.2199. Expressing this $\frac{l}{D}$ in terms of EAR:

$$l/D = \frac{0.2199}{0.45} EAR$$

$$= 0.4887 EAR$$

Substituting and taking the square root leads to:

$$d/R \doteq \frac{(0.4887 EAR)^2 (P/D)^2}{1.9986 + (P/D)^2} \quad \text{for } x = 0.45$$

This equation will give the approximate value of d/R which can be obtained for a particular set of counterrotating propellers. In practice, this equation has been found to be about 10 percent high. Since in the preliminary stages of a design (P/D 0.45) and EAR can only be approximated. The accuracy is considered sufficient for a first estimate.

Figure 3 is based on a four-bladed propeller but it can be used for propellers with other than four blades. If a propeller has Z blades the figure can be used by multiplying the expanded area ratio by Z/4 and using the value obtained as the ordinate of the figure. It should be noted that as the number of blades increases the radius at which the minimum spacing occurs moves toward the tip and assumption (a) becomes less valid.

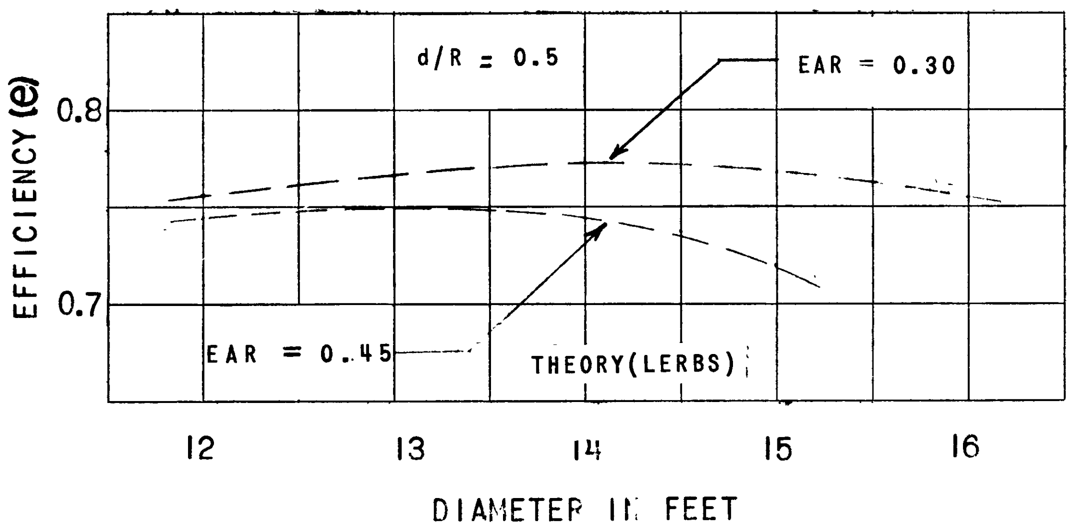

Figure 1 - Effect of Forward Propeller Diameter on Efficiency

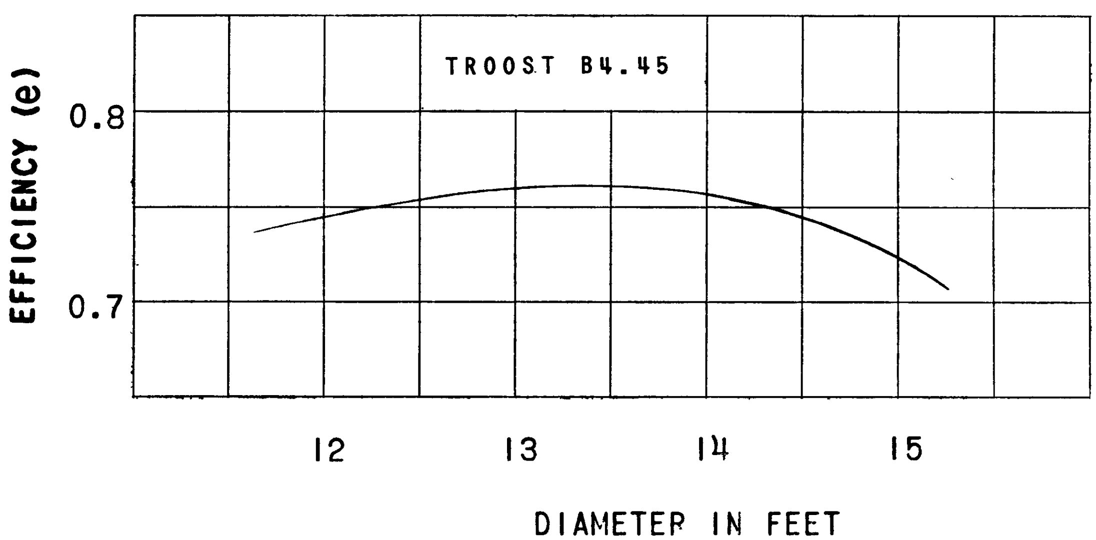

Figure 2 - Effect of Propeller Diameter on Efficiency as Determined from Troost Curves

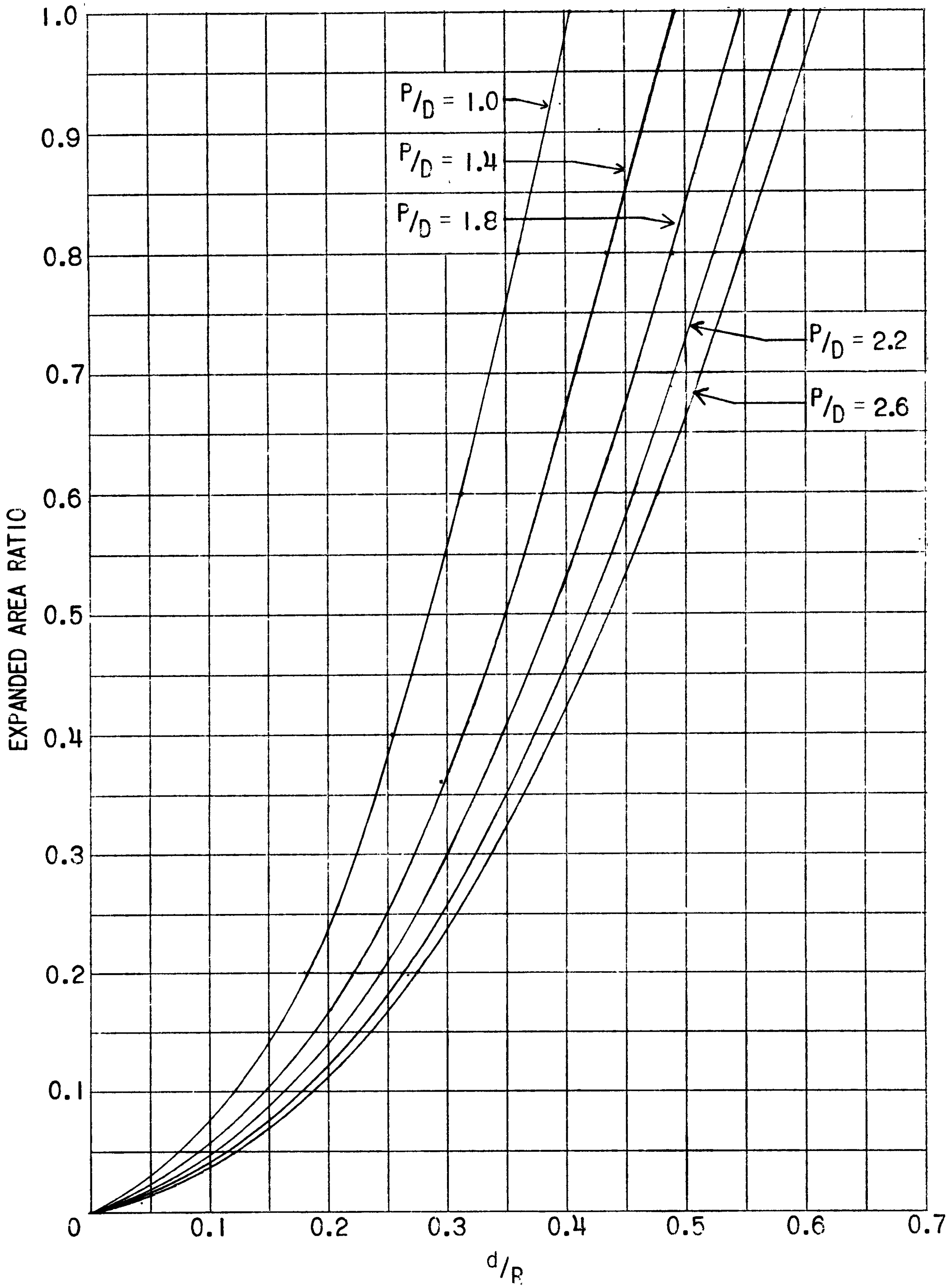

Figure 3 - Minimum Axial Spacing for Four-Bladed Counterrotating Propellers at 0.45R

PROPELLER 3682
FORWARD

NUMBER OF BLADES............ 4
EXP. AREA RATIO.............. 0.305
MWR.......................... 0.150
BTF.......................... 0.031
P/D (AT 0.7R)............... 1.255
DIAMETER.................... 12.017 ins.
PITCH (AT 0.7R)............. 15.081 ins.
ROTATION.................... L. H.
TEST n.................. 6.0 to 8.5 rps
TEST V_a.................3.0 to 11.0 fps

TESTED FOR....... DTMB
DESIGNED BY...... DTMB
DRAWING NO. P-3682

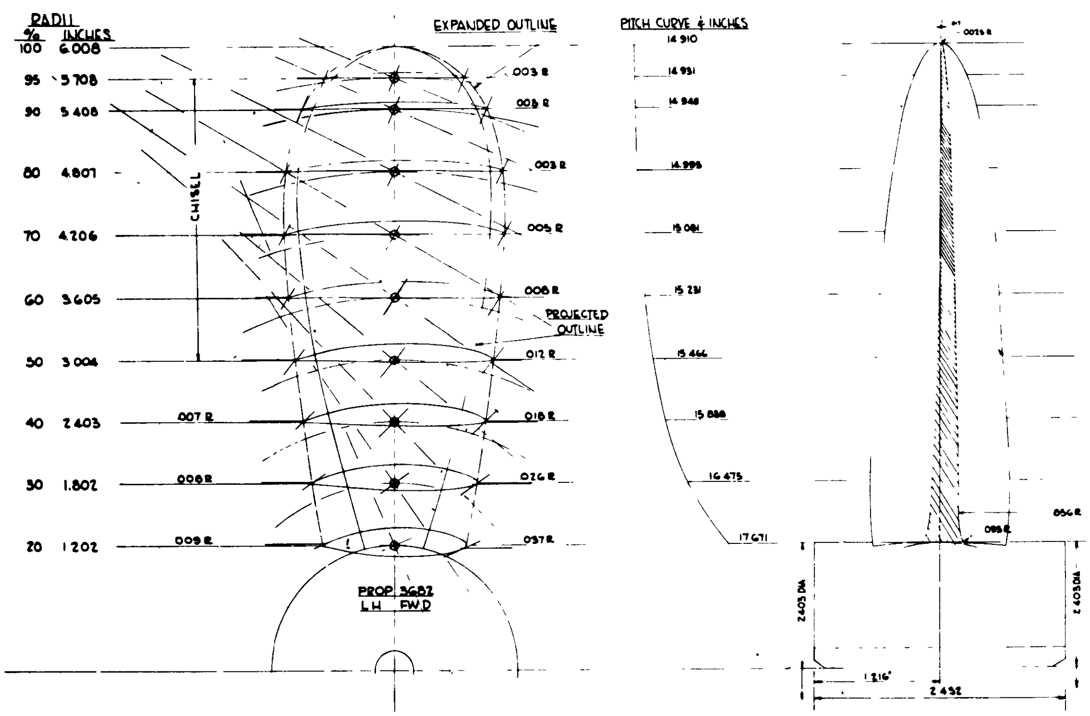

Figure 4 - Drawing of Propeller 3682

PROPELLER 3683
AFTER

NUMBER OF BLADES............ 4
EXP. AREA RATIO............. 0.327
MWR......................... 0.161
BTF......................... 0.031
P/D (AT 0.7R)............... 1.413
DIAMETER....................11.536 ins.
PITCH (AT 0.7R).............16.296 ins.
ROTATION.................... R. H.
TEST n..................6.0 to 8.5 rps
TEST V_a..................3.0 to 11.0 fps

TESTED FOR....... DTMB
DESIGNED BY...... DTMB
DRAWING NO P-3683

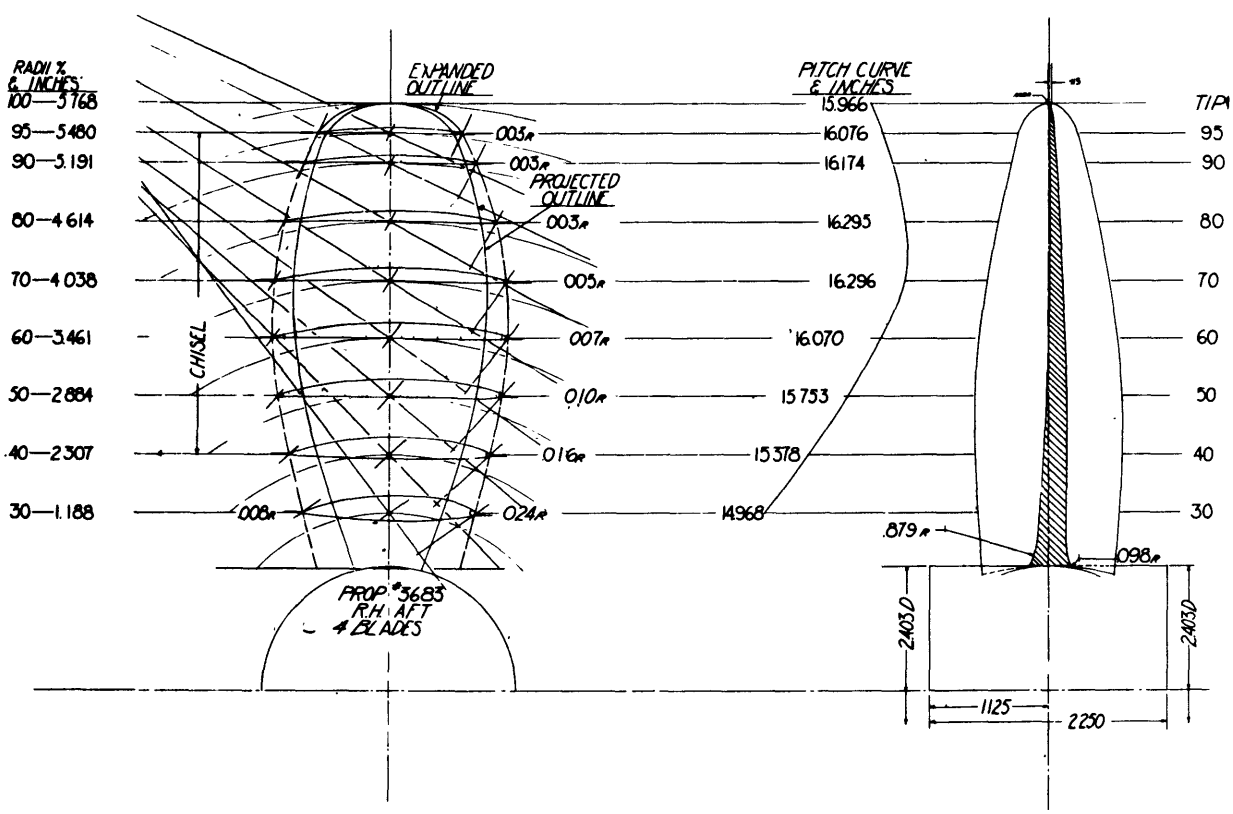

Figure 5 - Drawing of Propeller 3683

PROPELLER 3684
FORWARD

NUMBER OF BLADES............ 4
EXP.AREA RATIO.............. 0.304
MWR......................... 0.149
BTF......................... 0.029
P/D (AT 0.7R)............... 1.272
DIAMETER.................... 12.017 ins.
PITCH (AT 0.7R)............. 15.289 ins
ROTATION.................... L. H.
TEST n.................. 5.8 to 7.2 rps
TEST V_a................ 3.0 to 10.0 fps

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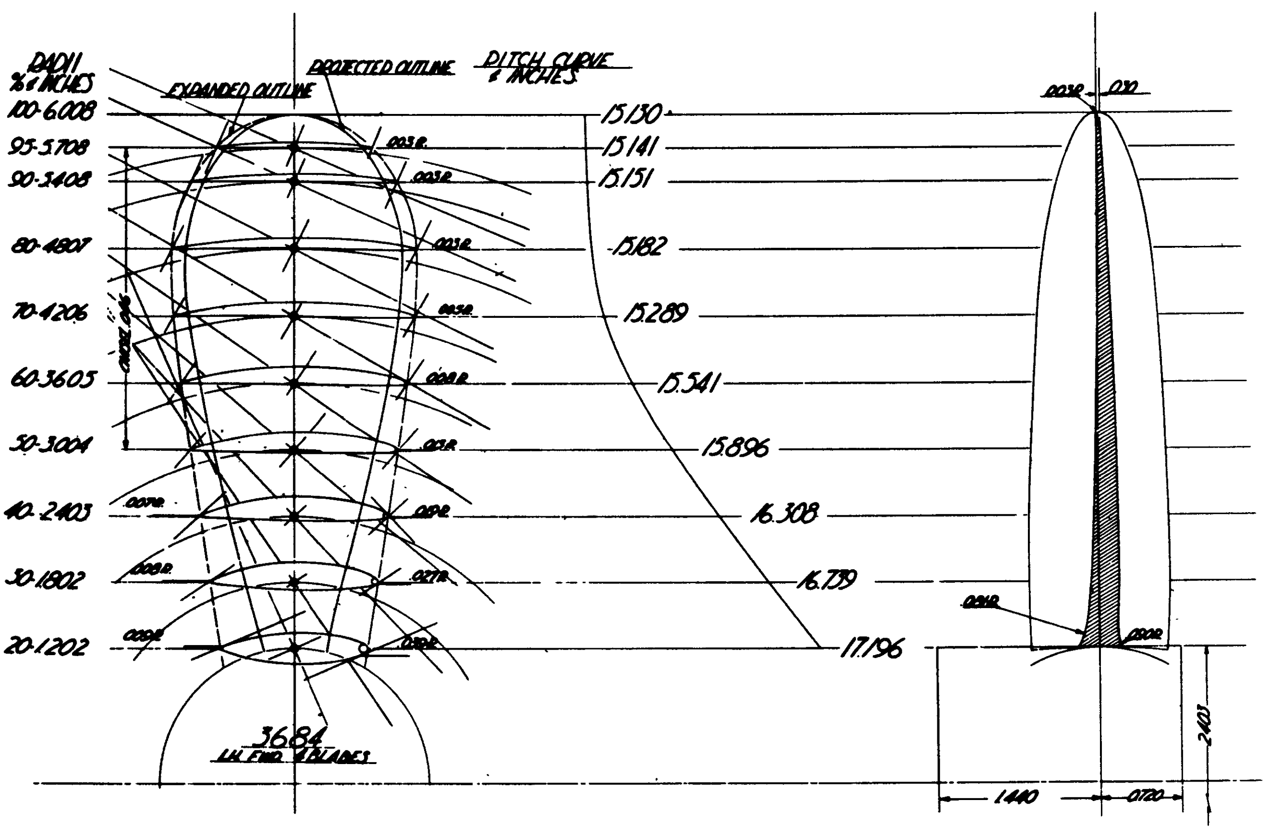

Figure 6 - Drawing of Propeller 3684

PROPELLER 3685
AFTER

NUMBER OF BLADES............ 4
EXP. AREA RATIO............. 0.315
MWR......................... 0.156
BTF......................... 0.029
P/D (AT 0.7R)............... 1.380
DIAMETER....................11.625 ins.
PITCH (AT 0.7R).............16.043 ins.
ROTATION.................... R. H.
TEST n.................5.8 to 7.2 rps
TEST V_a...............3.0 to 10.0 fps

TESTED FOR....... DTMB
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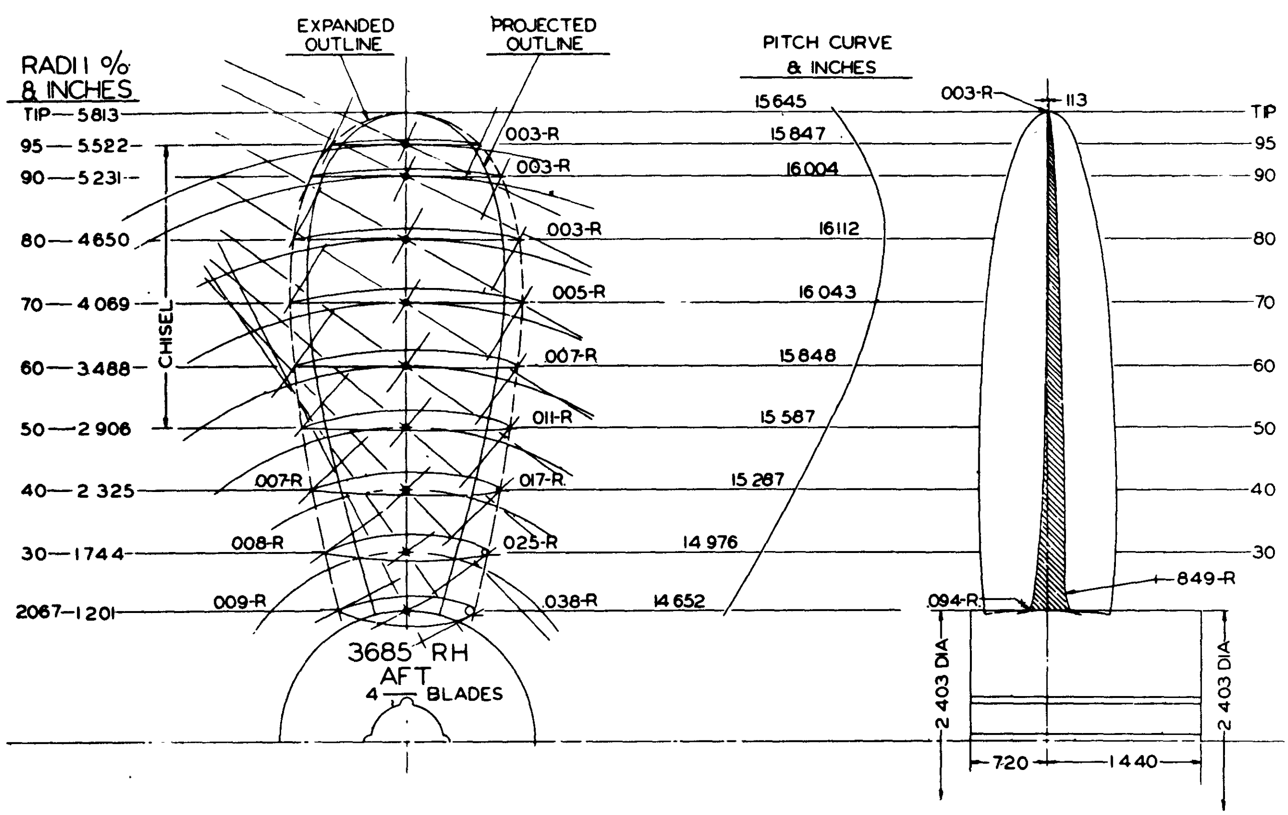

Figure 7 - Drawing of Propeller 3685

PROPELLER 3686
FORWARD

NUMBER OF BLADES............	4
EXP.AREA RATIO..............	0.303
MWR.........................	0.149
BTF.........................	0.028
P/D (AT 0.7R)...............	1.291
DIAMETER....................	12.017 ins.
PITCH (AT 0.7R).............	15.510 ins.
ROTATION....................	L.H.
TEST n......................	5.9 to 8.2 rps
TEST V_a..................	3.0 to 12.0 fps

TESTED FOR....... DTMB
DESIGNED BY...... DTMB
DRAWING NO. P-3686

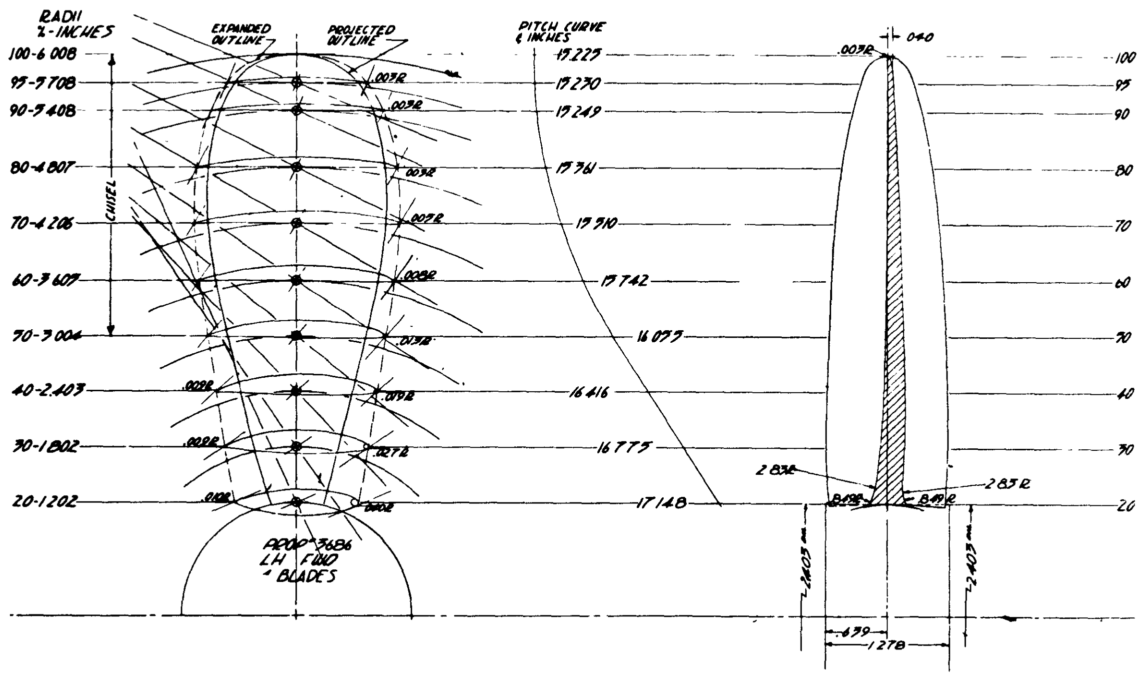

Figure 8 - Drawing of Propeller 3686

PROPELLER 3687
AFTER

NUMBER OF BLADES............	4
EXP. AREA RATIO............	0.322
MWR........................	0.159
BTF........................	0.030
P/D (AT 0.7R)..............	1.320
DIAMETER...................	11.776 ins.
PITCH (AT 0.7R)............	15.543 ins.
ROTATION...................	R.H.
TEST n.....................	6.0 to 8.2 rps
TEST V_a.................	3.0 to 11.6 fps

TESTED FOR....... DTMB
DESIGNED BY...... DTMB
DRAWING NO. P-3687

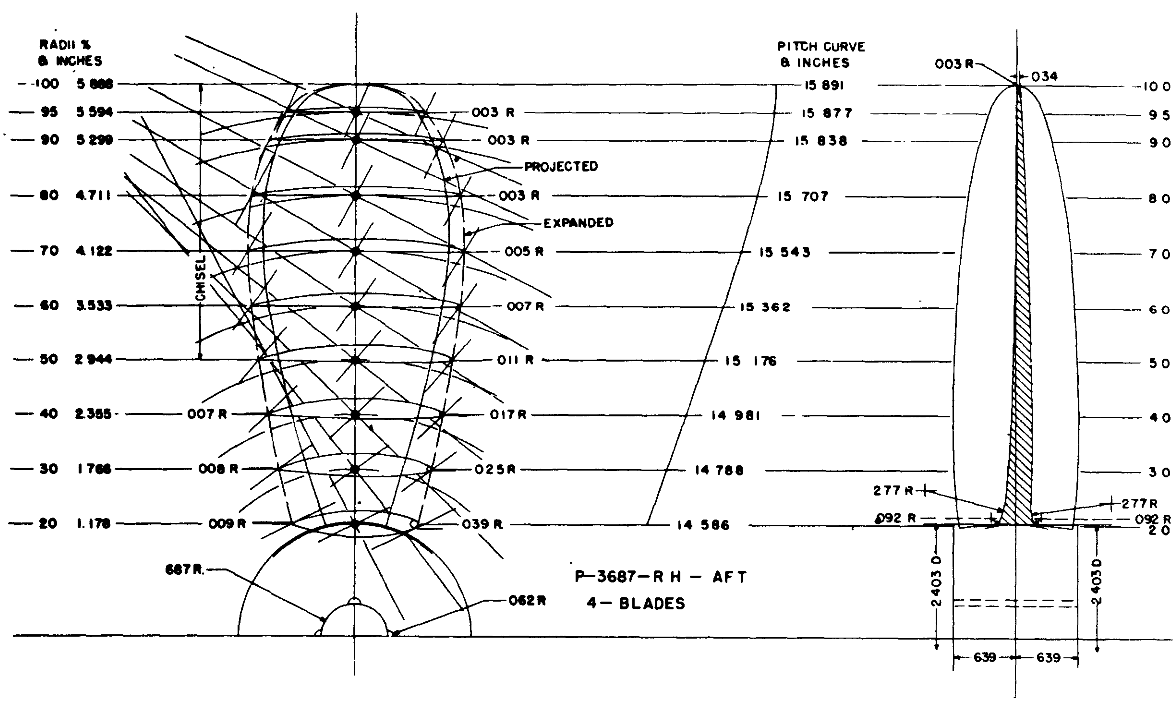

Figure 9 - Drawing of Propeller 3687

PROPELLER 3690
FORWARD

NUMBER OF BLADES............ 4
EXP. AREA RATIO............. 0.304
MWR......................... 0.149
BTF......................... 0.029
P/D (AT 0.7R)............... 1.272
DIAMETER....................16.001 ins.
PITCH (AT 0.7R).............20.358 ins
ROTATION.................... L. H.
TEST n................. 2.8 to 6.1 rps
TEST V_a................1.0 to 11.8 fps

TESTED FOR....... DTMB
DESIGNED BY...... DTMB
DRAWING NO P-3690

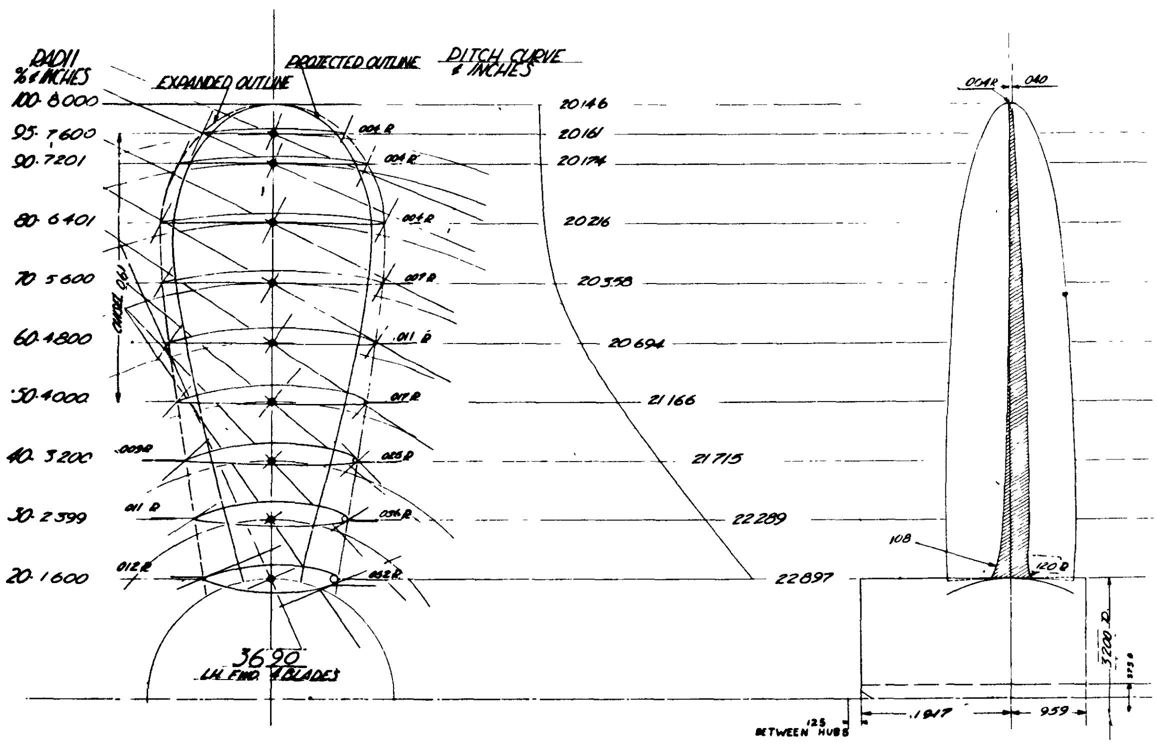

Figure 10 – Drawing of Propeller 3690

PROPELLER 3691
AFTER

NUMBER OF BLADES............ 4
EXP.AREA RATIO.............. 0.315
MWR......................... 0.156
BTF......................... 0.029
P/D (AT 0.7R)............... 1.380
DIAMETER.................... 15.479 ins.
PITCH (AT 0.7R)............. 21.362 ins.
ROTATION.................... R. H.
TEST n.................... 2.8 to 6.1 rps
TEST V_a.................. 1.0 to 11.8 fps

TESTED FOR....... DTMB
DESIGNED BY...... DTMB
DRAWING NO P-3691

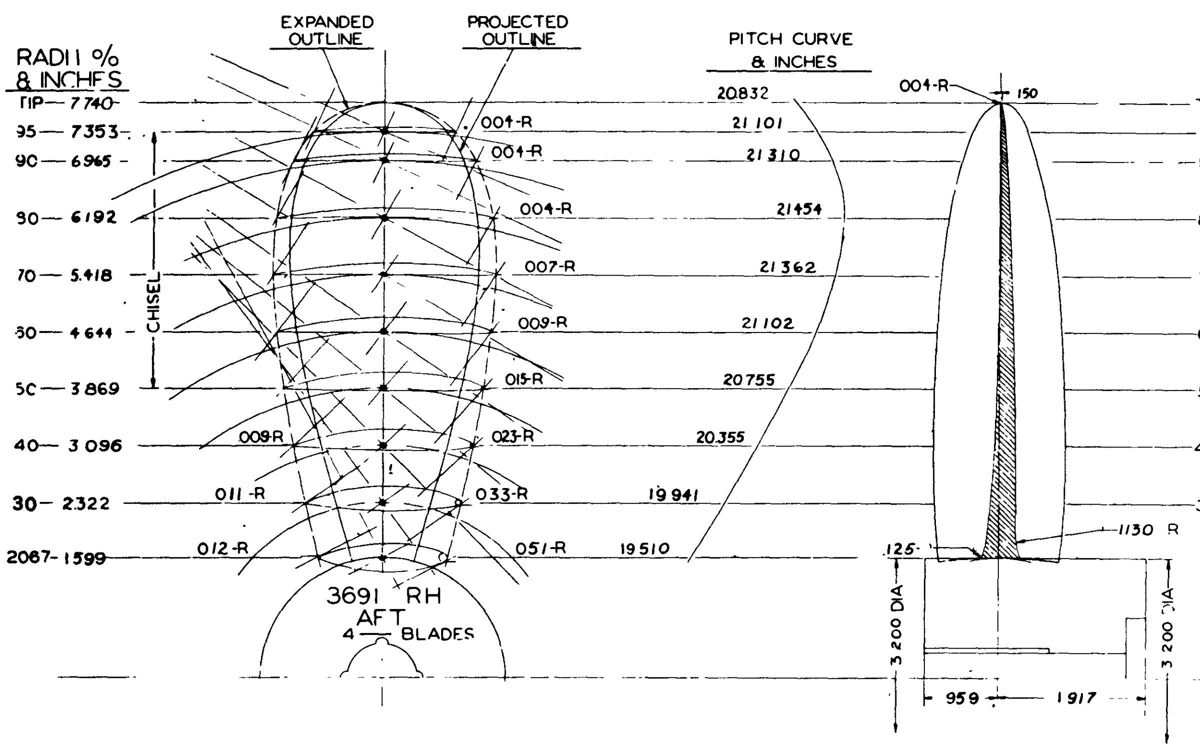

Figure 11 - Drawing of Propeller 3691

PROPELLER 3687A
AFTER

NUMBER OF BLADES............ 4
EXP.AREA RATIO.............. 0.324
MWR......................... 0.159
BTF......................... 0.030
P/D (AT 0.7R)............... 1.326
DIAMETER....................11.776 ins
PITCH (AT 0.7R).............15.622 ins.
ROTATION.................... R.H.
TEST n................. 5.9 to 8.2 rps
TEST V_a................3.0 to 12.0 fps

TESTED FOR....... DTMB
DESIGNED BY...... DTMB
DRAWING NO P-3687A

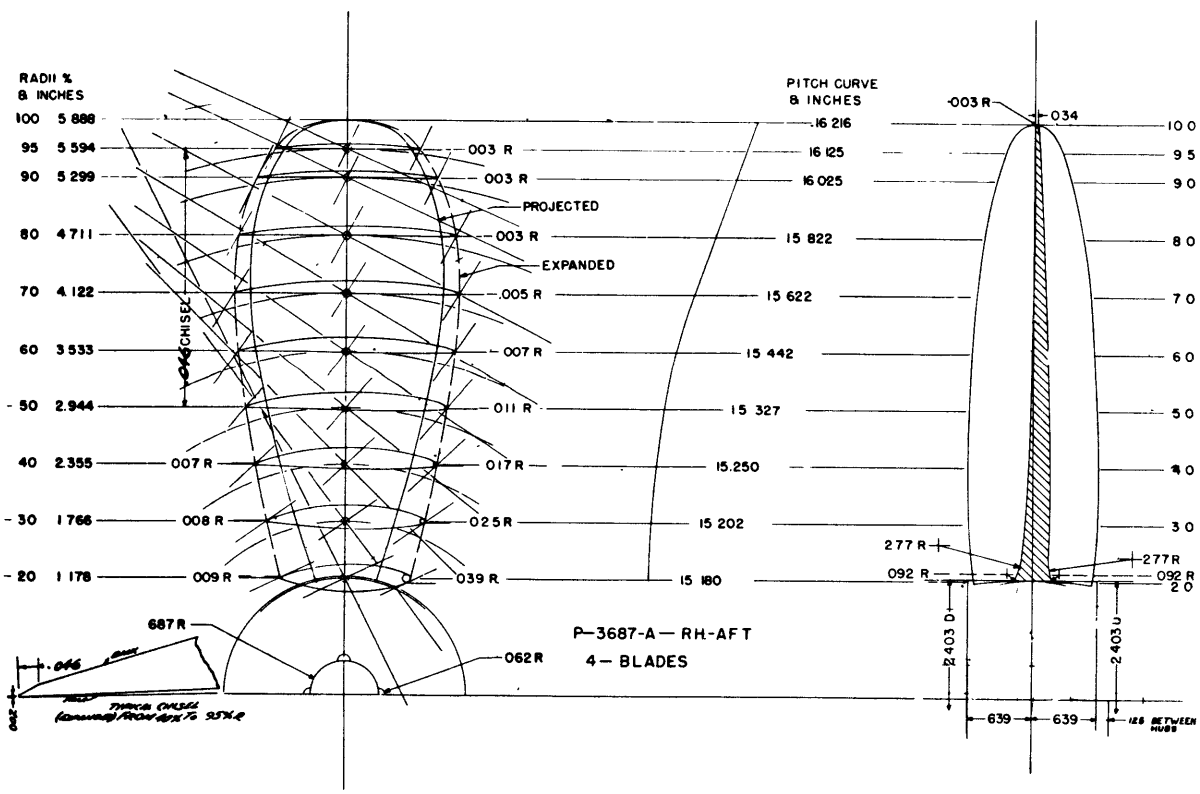

Figure 12 - Drawing of Propeller 3687A

PROPELLER 3714
FORWARD

NUMBER OF BLADES............	4
EXP.AREA RATIO..............	0.450
MWR.........................	0.221
BTF.........................	0.029
P/D (AT 0.7R)...............	1.262
DIAMETER....................	10.000 ins.
PITCH (AT 0.7R).............	12.620 ins.
ROTATION....................	L. H.
TEST n......................	9.1 rps
TEST V_a..............	3.0 to 11.0 fps

TESTED FOR....... DTMB
DESIGNED BY...... DTMB
DRAWING P-3714

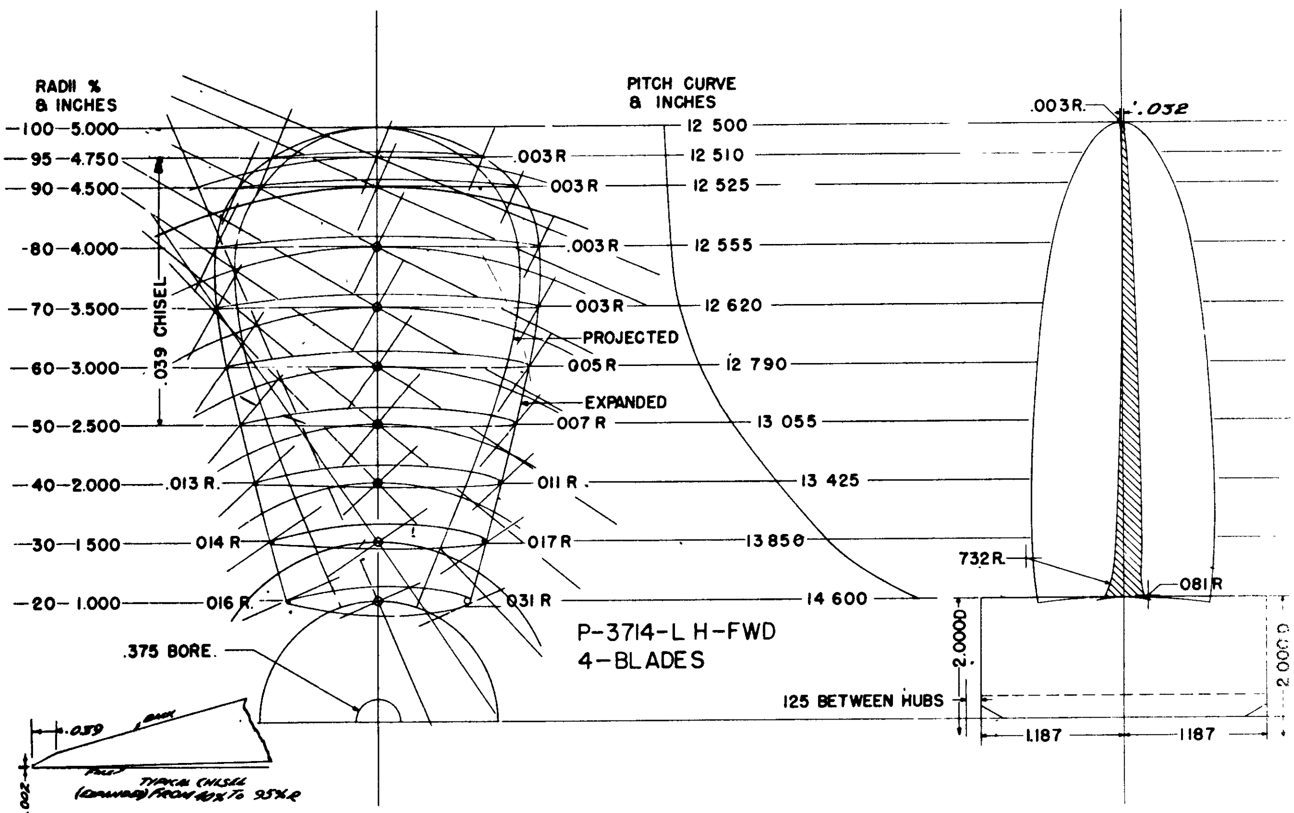

Figure 13 - Drawing of Propeller 3714

PROPELLER 3715

AFTER

NUMBER OF BLADES............ 4
EXP. AREA RATIO............. 0.450
MWR......................... 0.223
BTF......................... 0.029
P/D (AT 0.7R)............... 1.365
DIAMETER.................... 9.674 ins.
PITCH (AT 0.7R).............13.200 ins.
ROTATION.................... R. H.
TEST n...................... 9.1 rps
TEST V_a.............3.0 to 11.0 fps

TESTED FOR....... DTMB
DESIGNED BY...... DTMB
DRAWING NO. P-3715

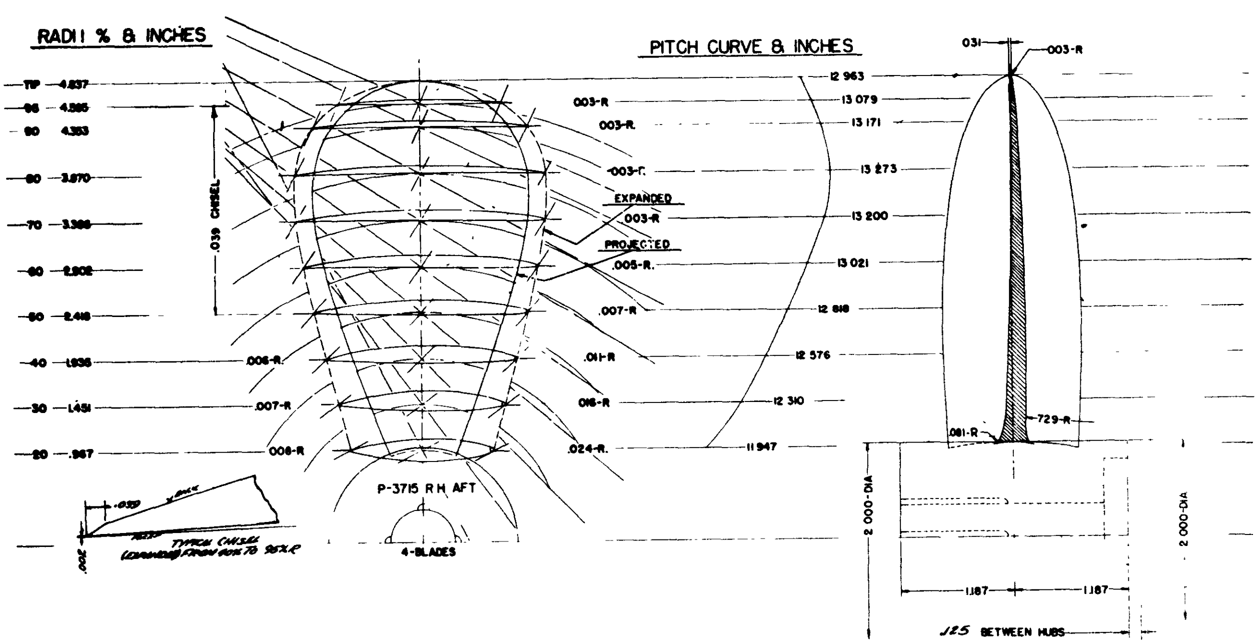

Figure 14 - Drawing of Propeller 3715

PROPELLER 3718

FORWARD

NUMBER OF BLADES............ 4
EXP.AREA RATIO.............. 0.454
MWR......................... 0.223
BTF......................... 0.029
P/D (AT 0.7R)............... 1.564
DIAMETER....................10.000 ins.
PITCH (AT 0.7R).............15.640 ins.
ROTATION.................... L.H.
TEST n...................6.7 to 8.3 rps
TEST V_a................ 3.0 to 13.0 fps

TESTED FOR....... DTMB
DESIGNED BY...... DTMB
DRAWING NO. P-3718

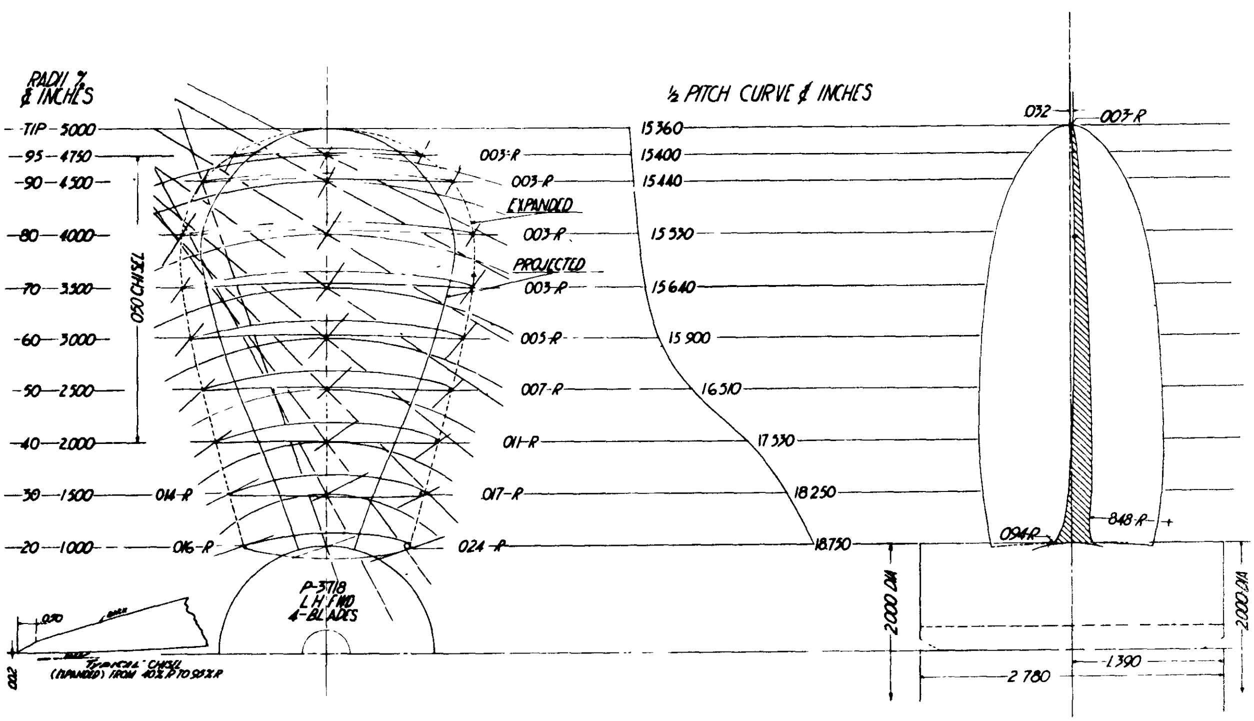

Figure 15 - Drawing of Propeller 3718

PROPELLER 3719
AFTER

NUMBER OF BLADES............ 4
EXP. AREA RATIO............. 0.451
MWR......................... 0.226
BTF......................... 0.029
P/D (AT 0.7R)............... 1.692
DIAMETER.................... 9.592 ins.
PITCH (AT 0.7R)............. 16.233 ins.
ROTATION.................... R.H.
TEST n.................. 6.7 to 8.3 rps
TEST V_a.................3.0 to 13.0 fps

TESTED FOR....... DTMB
DESIGNED BY...... DTMB
DRAWING NO.. P-3719

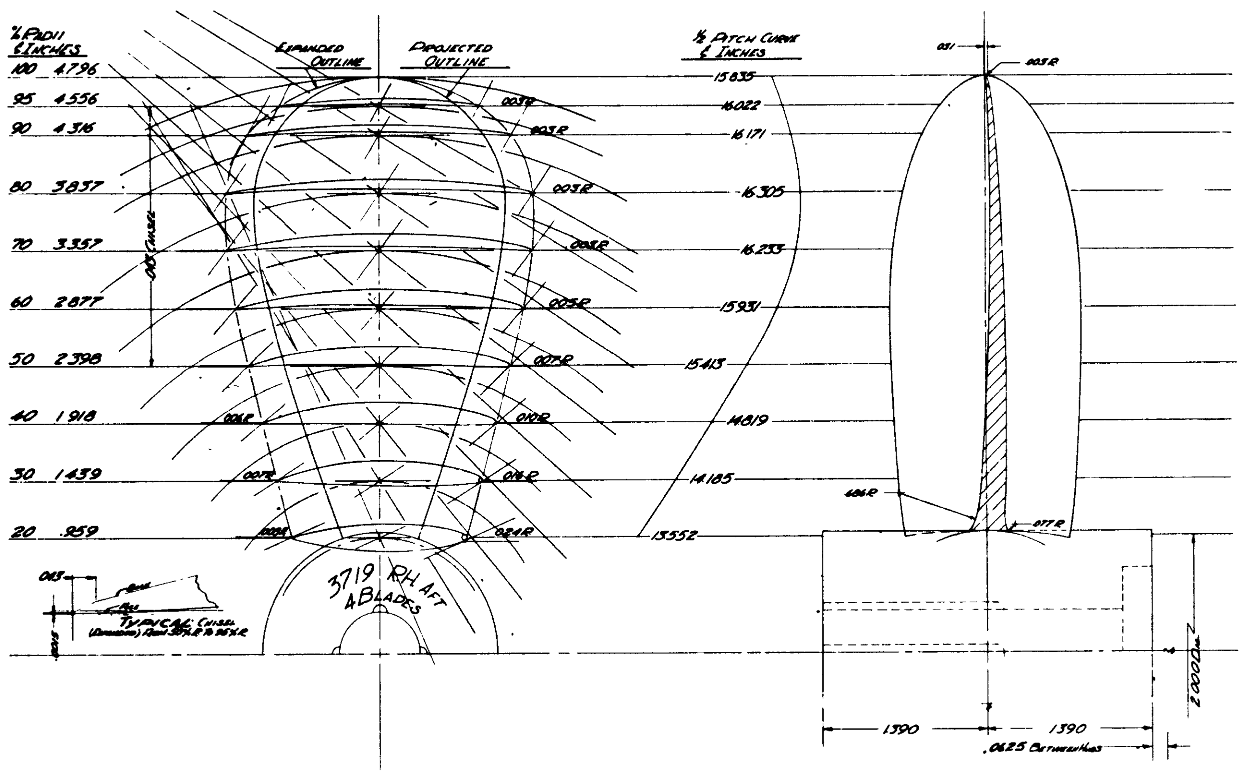

Figure 16 - Drawing of Propeller 3719

PROPELLER 3720
FORWARD

NUMBER OF BLADES............	4
EXP.AREA RATIO..............	0.456
MWR..........................	0.224
BTF..........................	0.029
P/D (AT 0.7R)...............	1.074
DIAMETER....................	10.000 ins.
PITCH (AT 0.7R).............	10.740 ins
ROTATION....................	L.H.
TEST n......................	9.9 rps
TEST V_a.................	3.0 to 10.0 fps

TESTED FOR....... DTMB
DESIGNED BY...... DTMB
DRAWING NO. P-3720

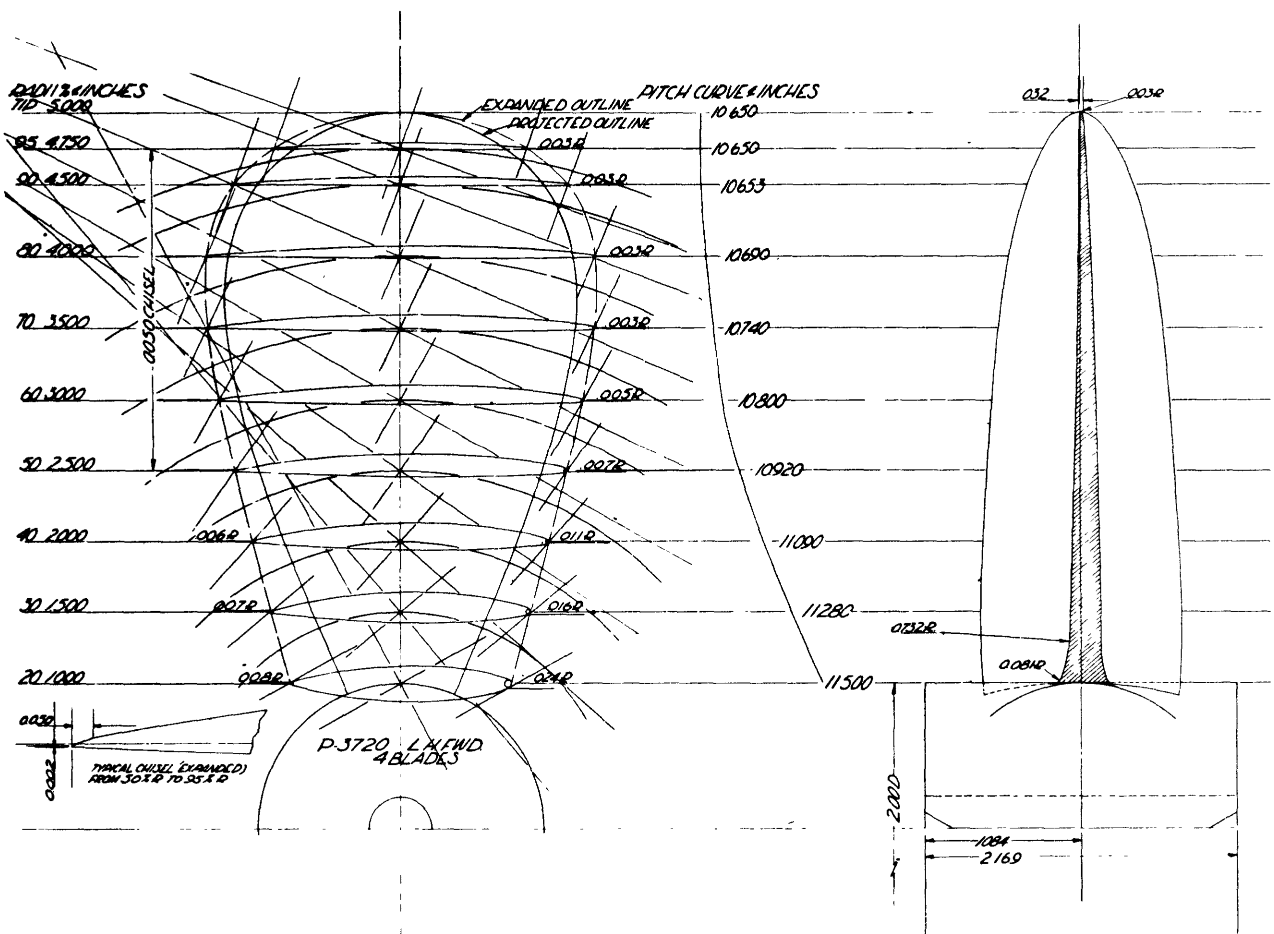

Figure 17 - Drawing of Propeller 3720

PROPELLER 3721
AFTER

NUMBER OF BLADES............	4
EXP. AREA RATIO.............	0.453
MWR.........................	0.224
BTF.........................	0.029
P/D (AT 0.7R)...............	1.151
DIAMETER....................	9.739 ins.
PITCH (AT 0.7R).............	11.209 ins
ROTATION....................	R.H.
TEST n......................	9.9 rps
TEST V_a..............	3.0 to 10.0 fps

TESTED FOR....... DTMB
DESIGNED BY...... DTMB
DRAWING NO. P-3721

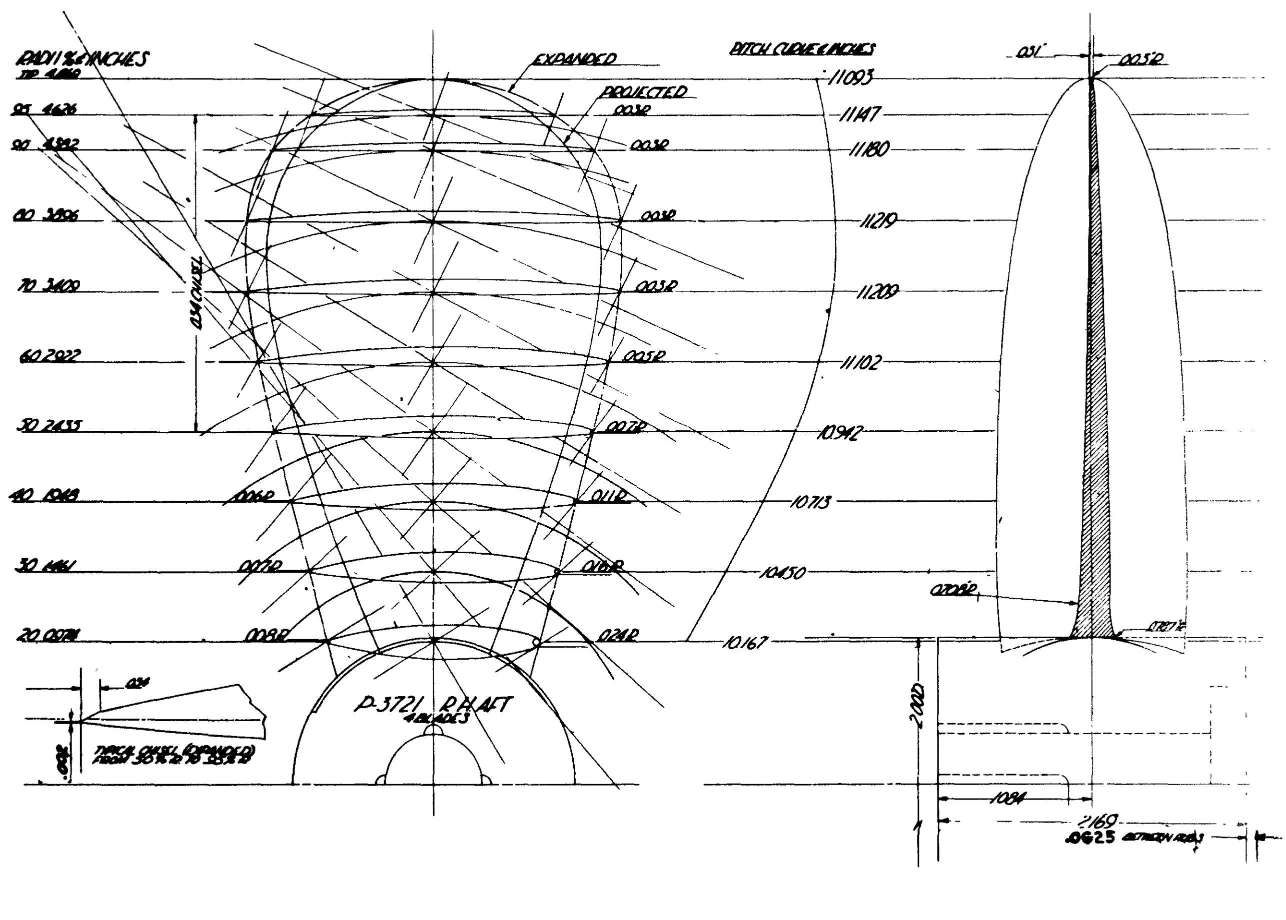

Figure 18 - Drawing of Propeller 3721

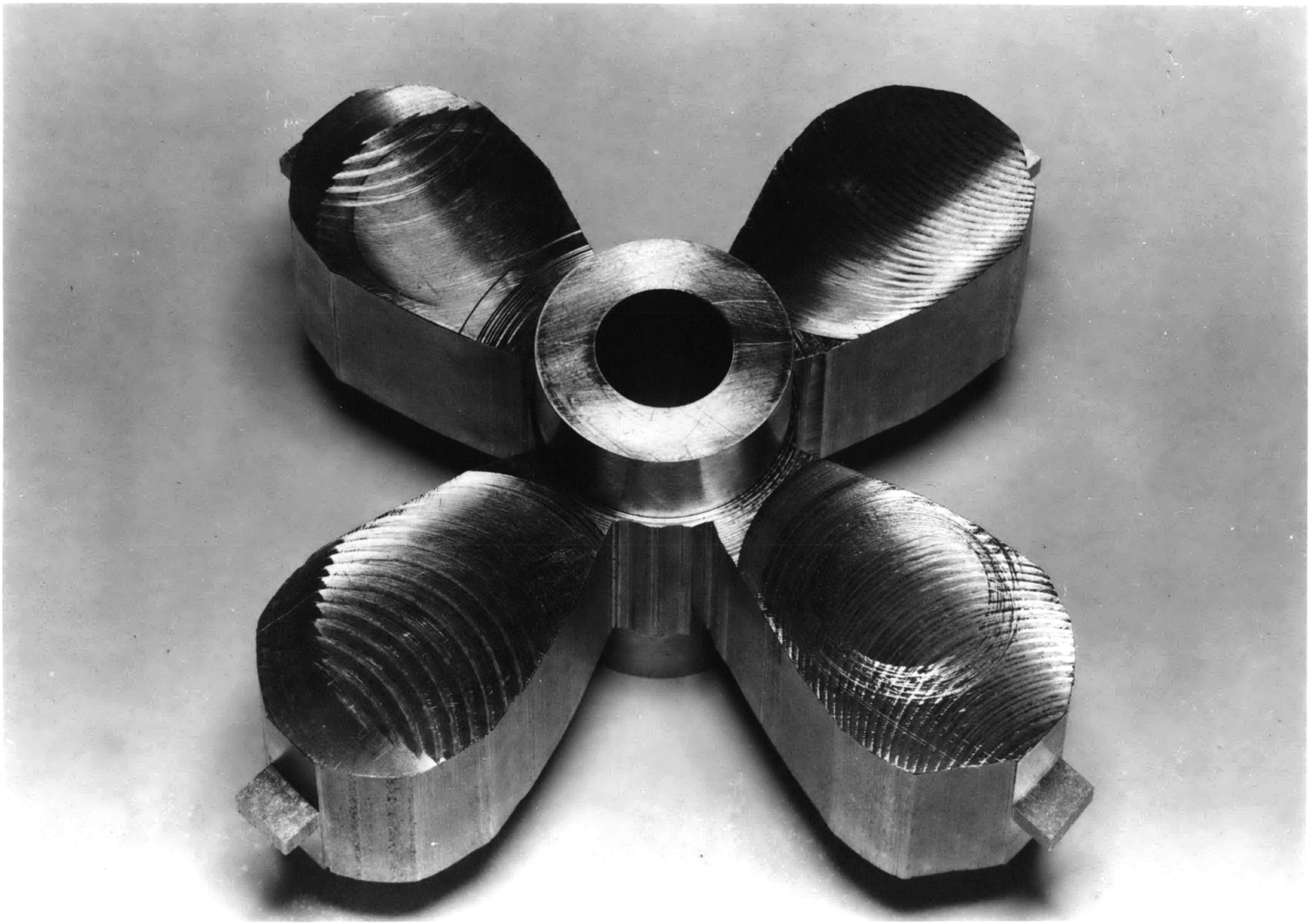

Figure 19 - Propeller Blank Ready for Keller Machine

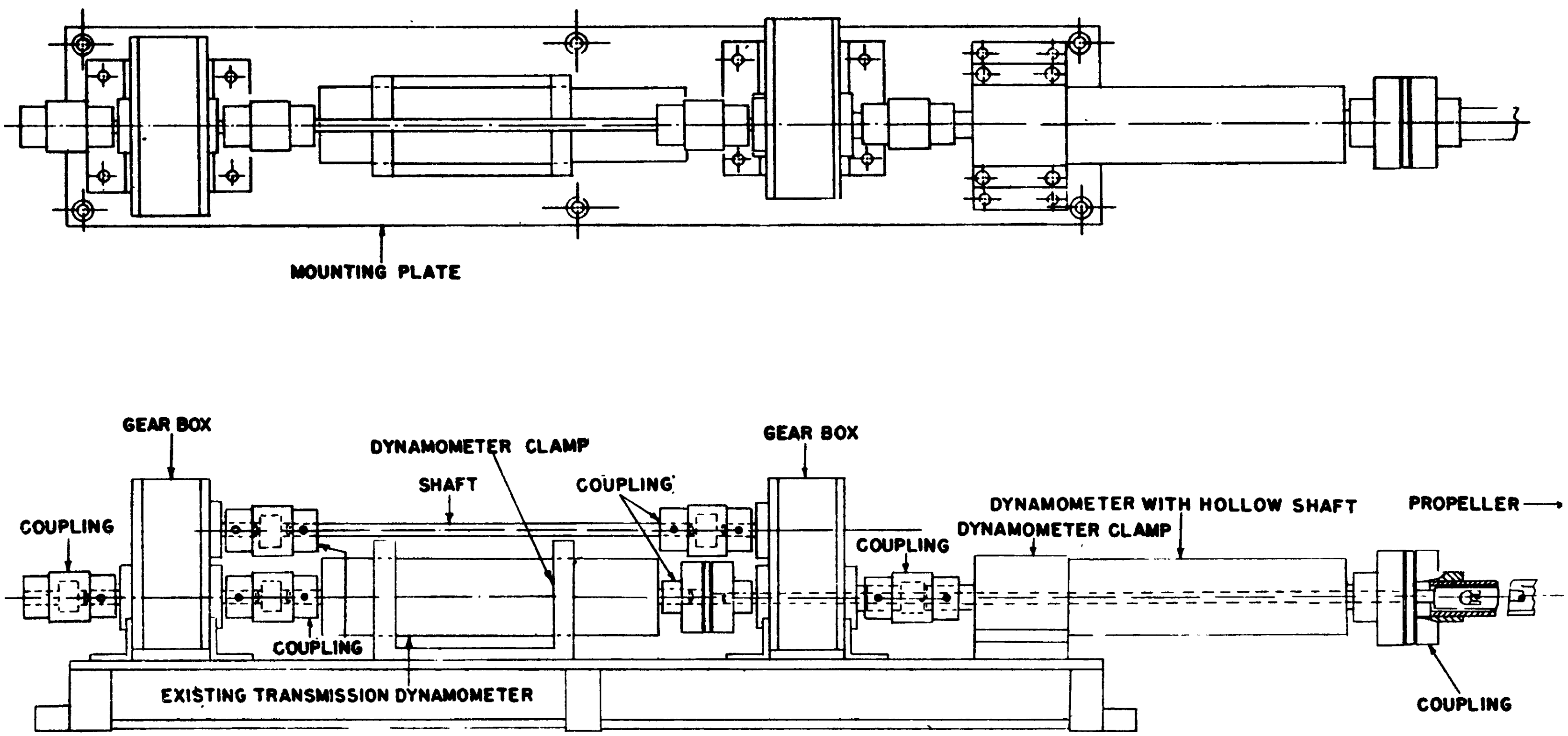

Figure 20 - Counterrotating Propeller Dynamometer Arrangement

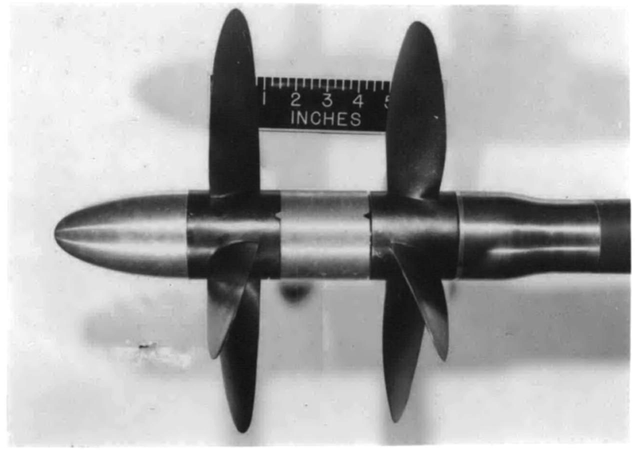

Figure 21 - Propellers 3682-83 Installed on Propeller Boat

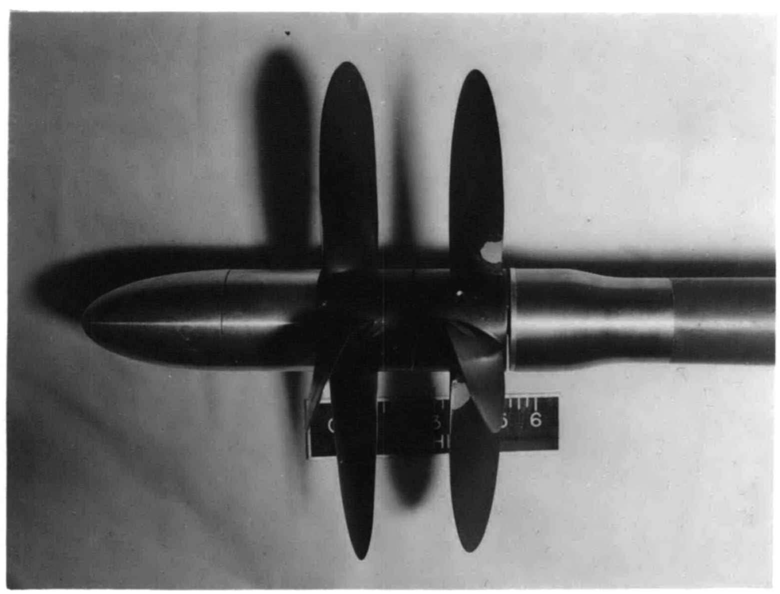

Figure 22 - Propellers 3684-85 Installed on Propeller Boat

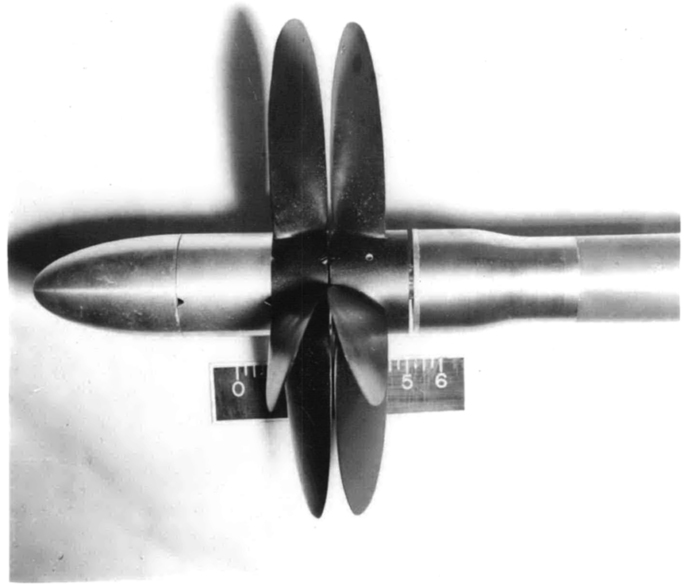

Figure 23 - Propellers 3686-87 Installed on Propeller Boat

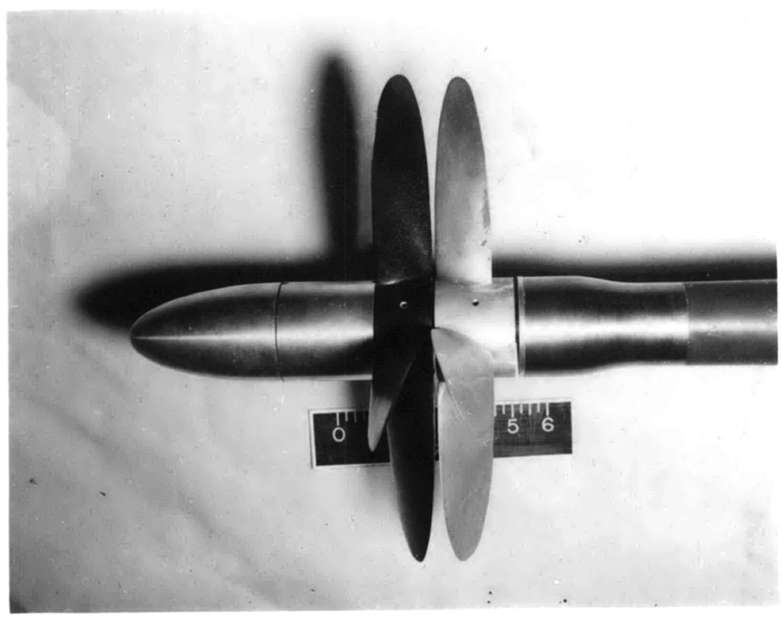

Figure 24 - Propellers 3686-87A Installed on Propeller Boat

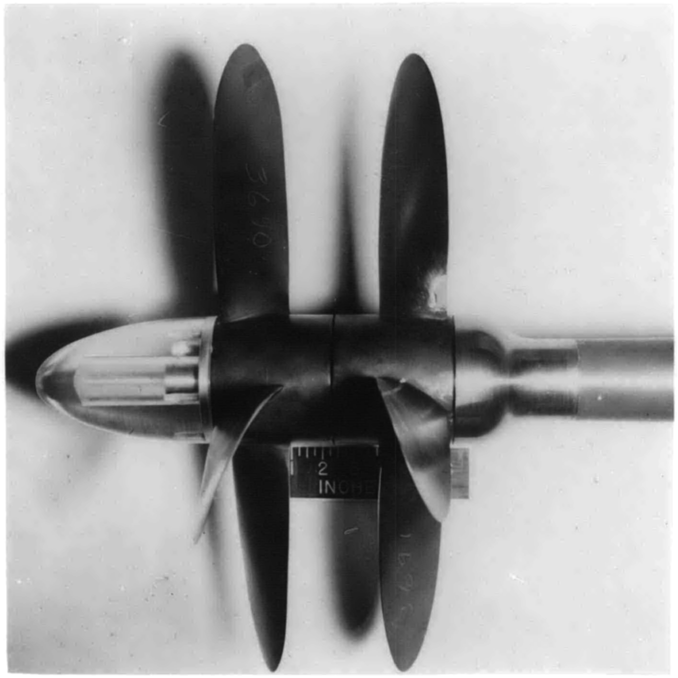

Figure 25 - Propellers 3690-91 Installed on Propeller Boat

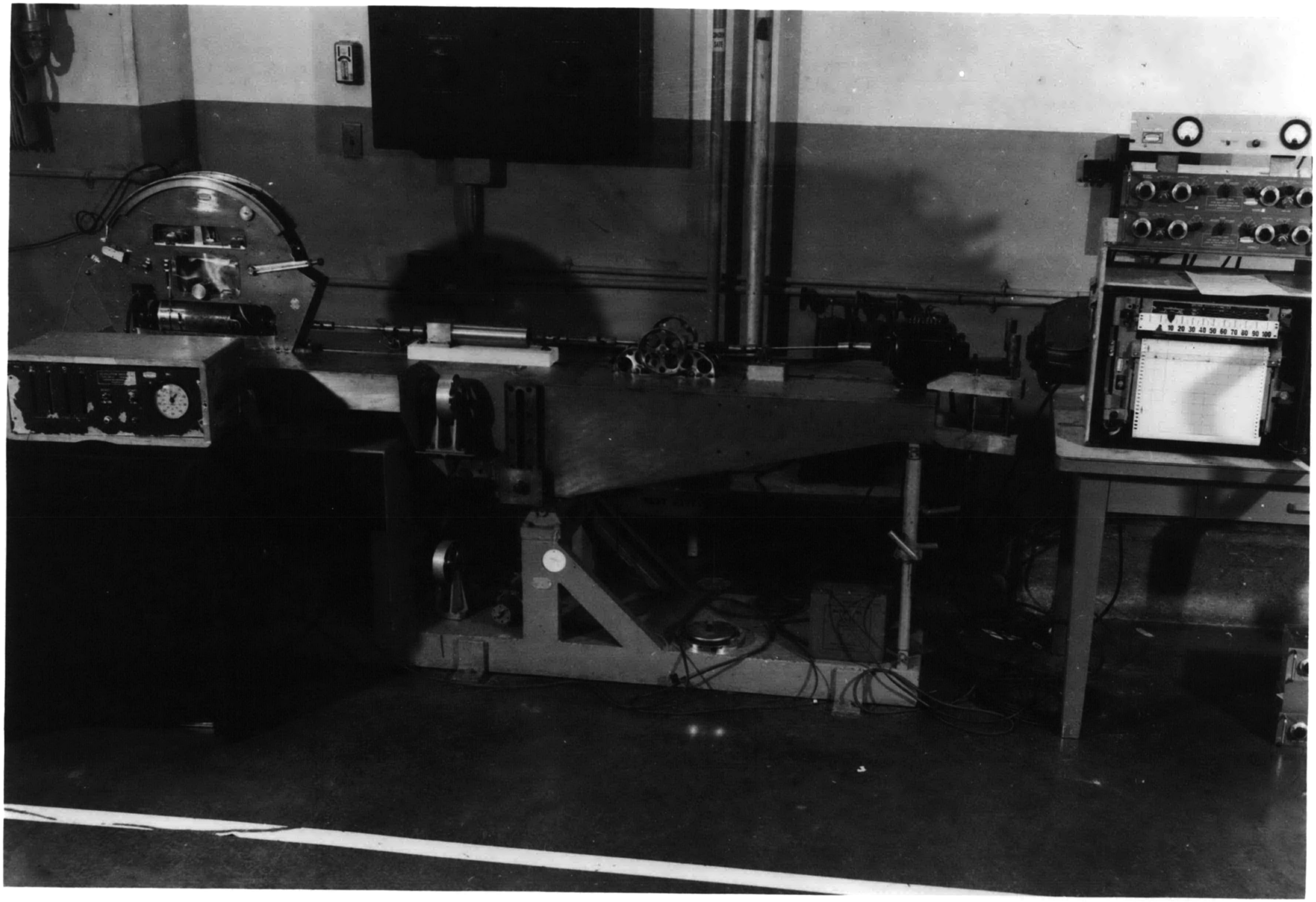

Figure 26 - Calibration Set-Up for Transmission Dynamometer

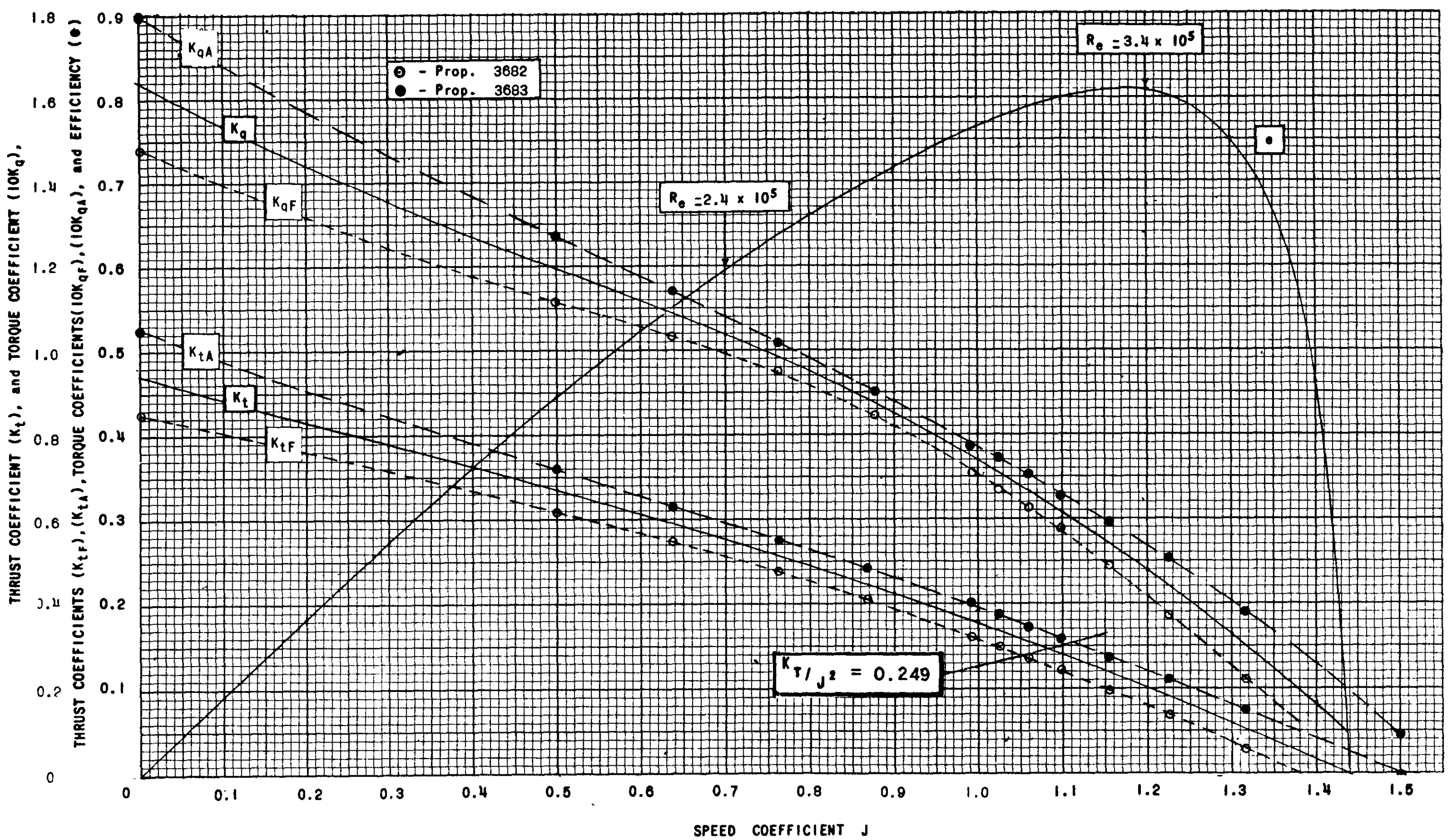

Figure 27 – Open Water Characteristics of Propellers 3682-83

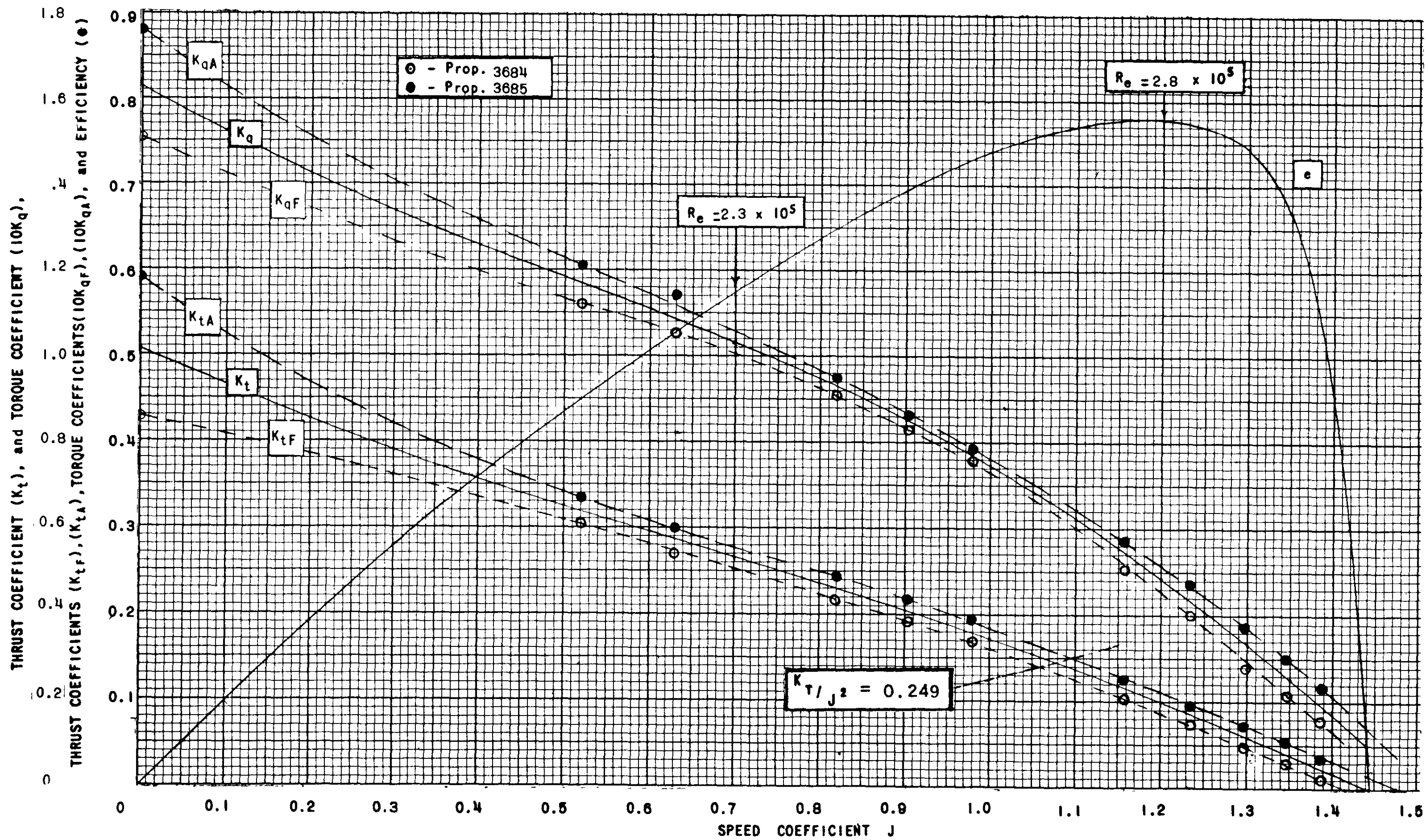

Figure 28 - Open Water Characteristics of Propellers 3684-85

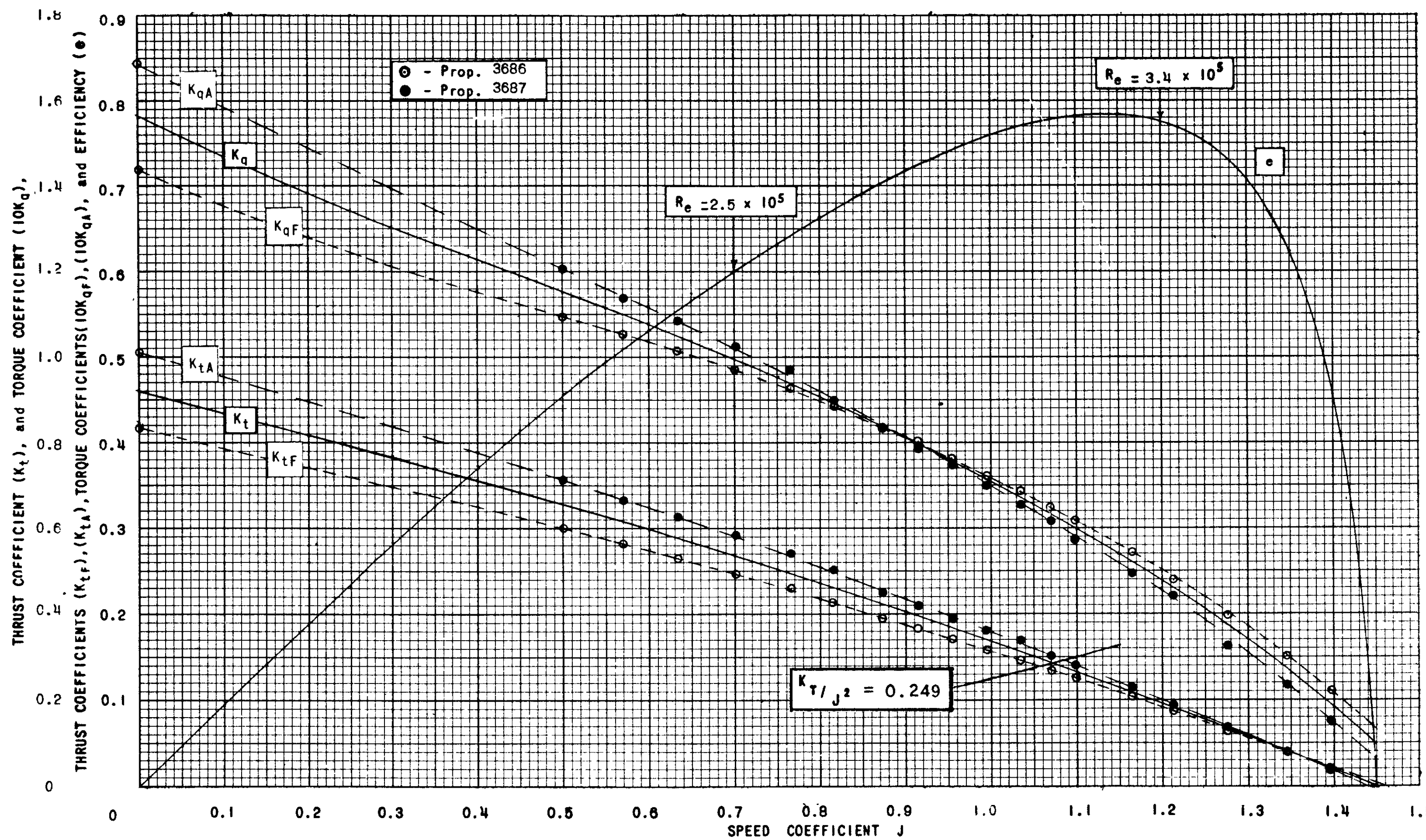

Figure 29 - Open Water Characteristics of Propellers 3636-87

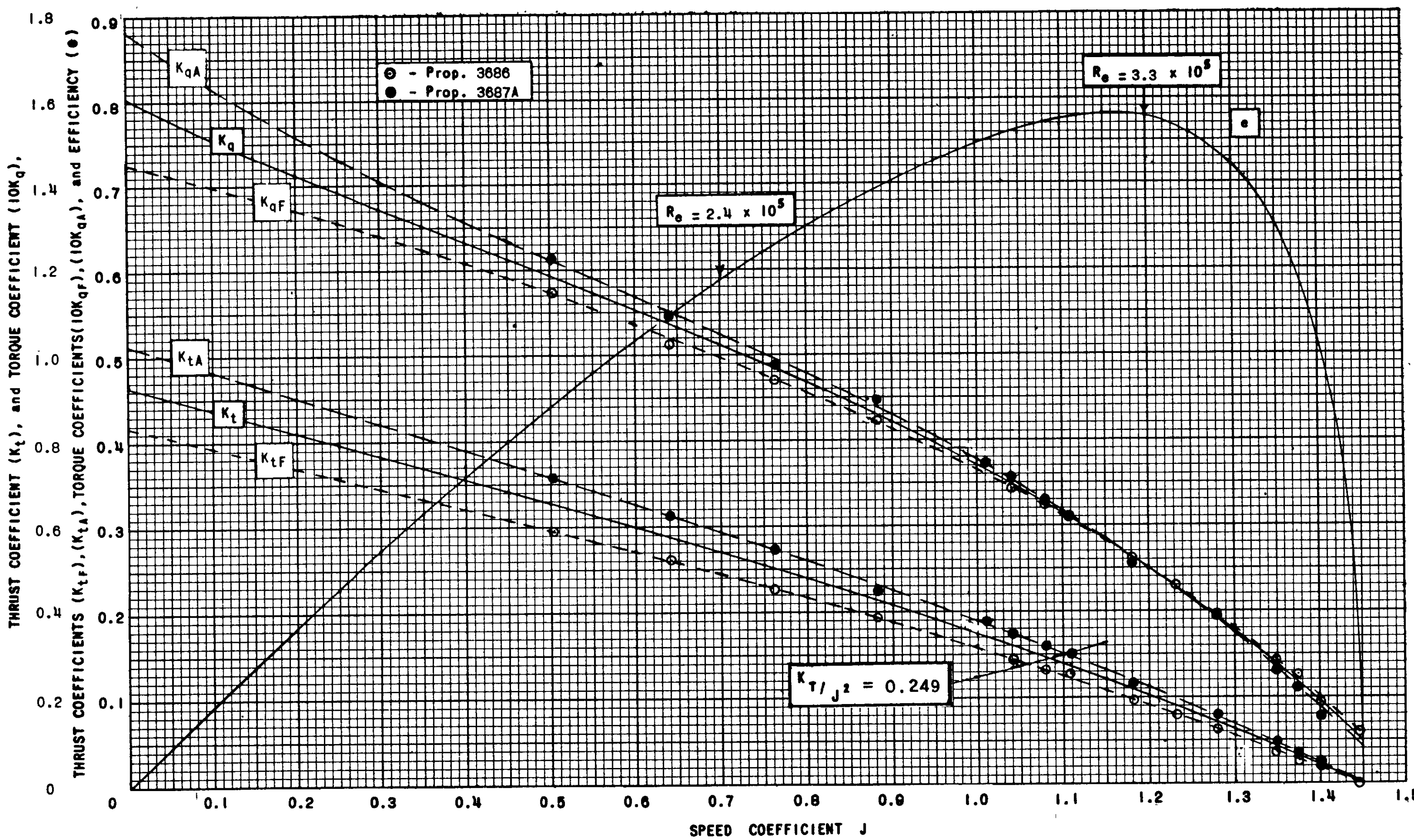

Figure 30 - Open Water Characteristics of Propellers 3686-87A

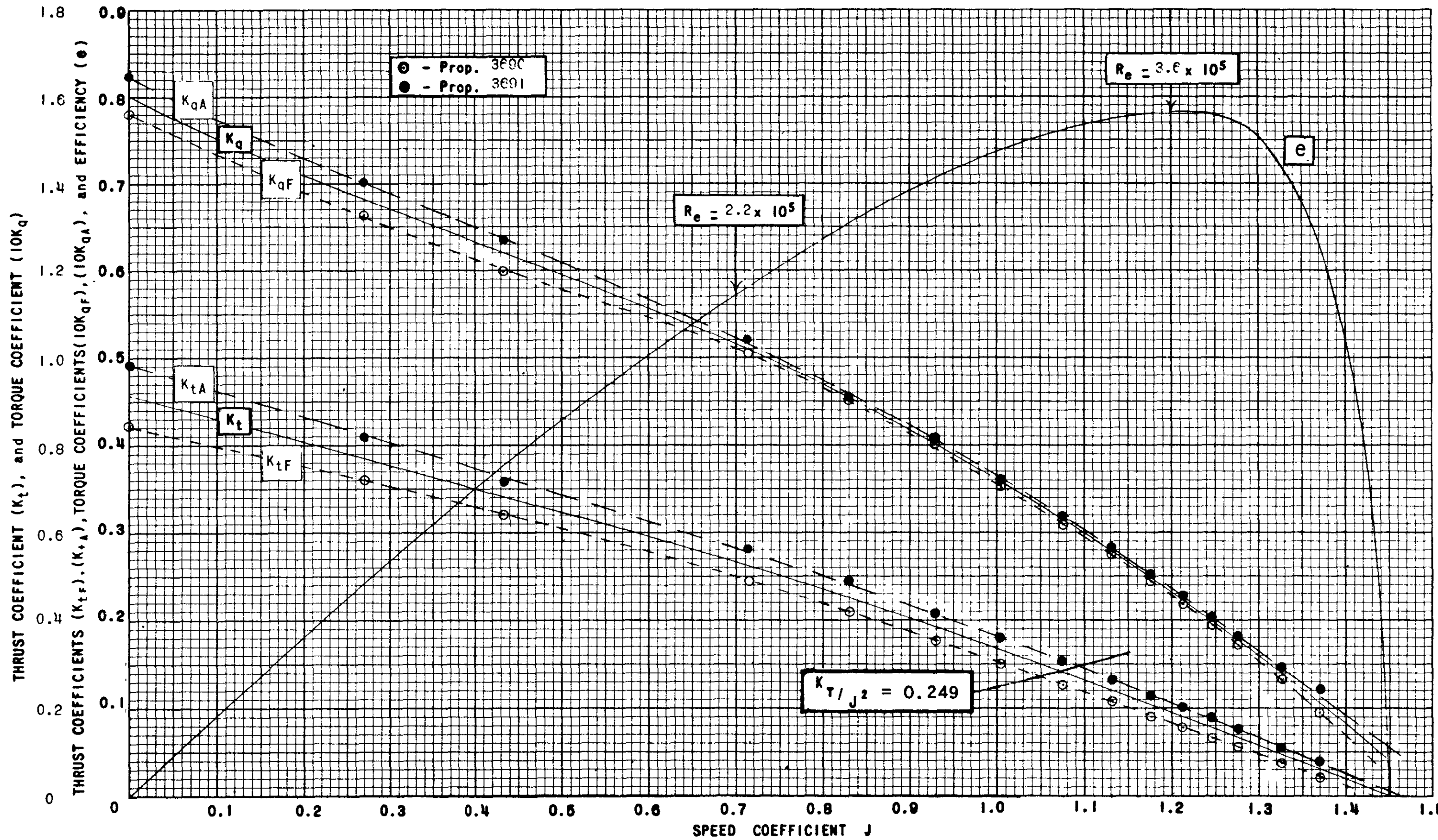

Figure 31 - Open Water Characteristics of Propellers 3690-91

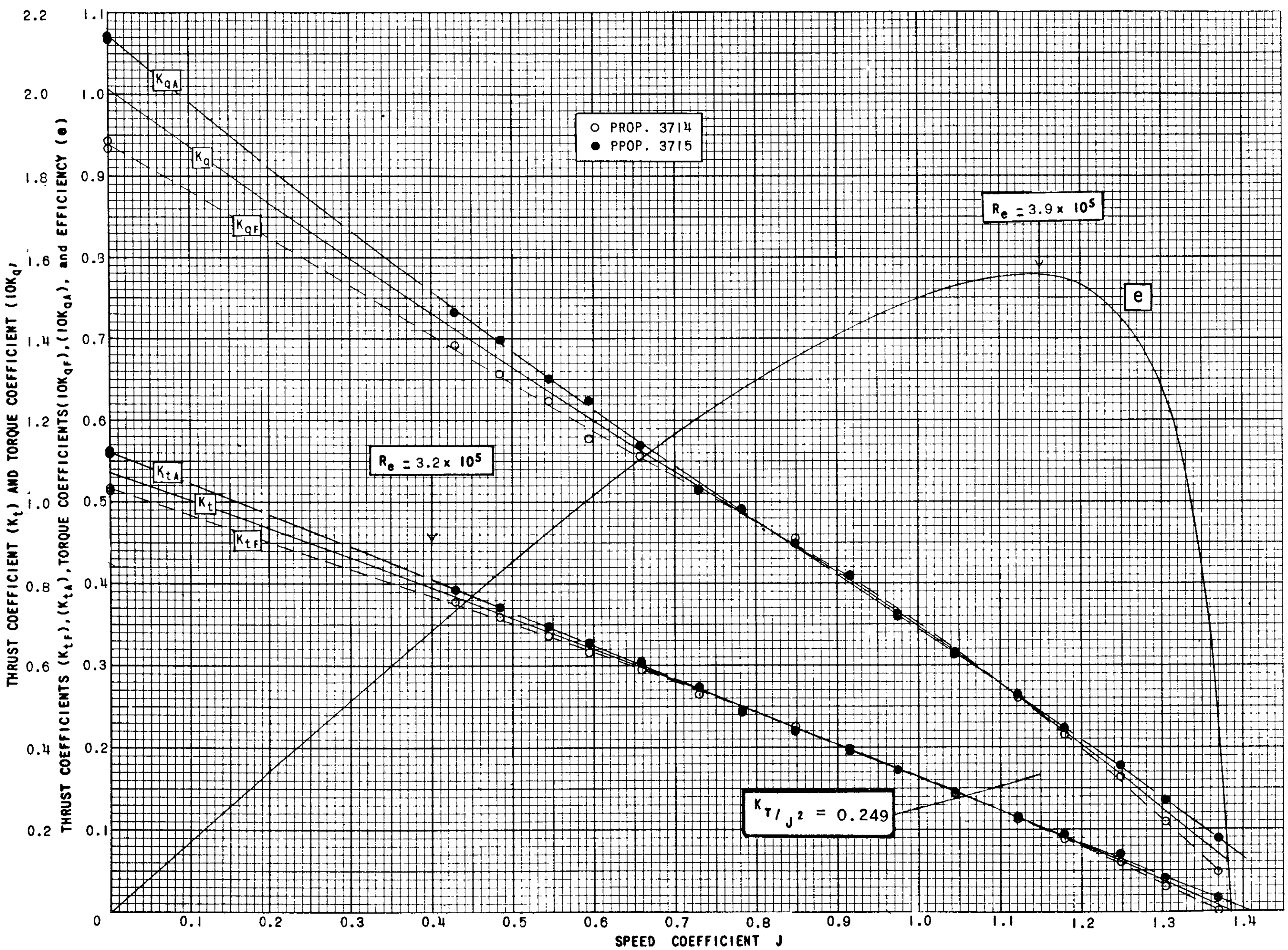

Figure 32 - Open Water Characteristics of Propellers 3714-15

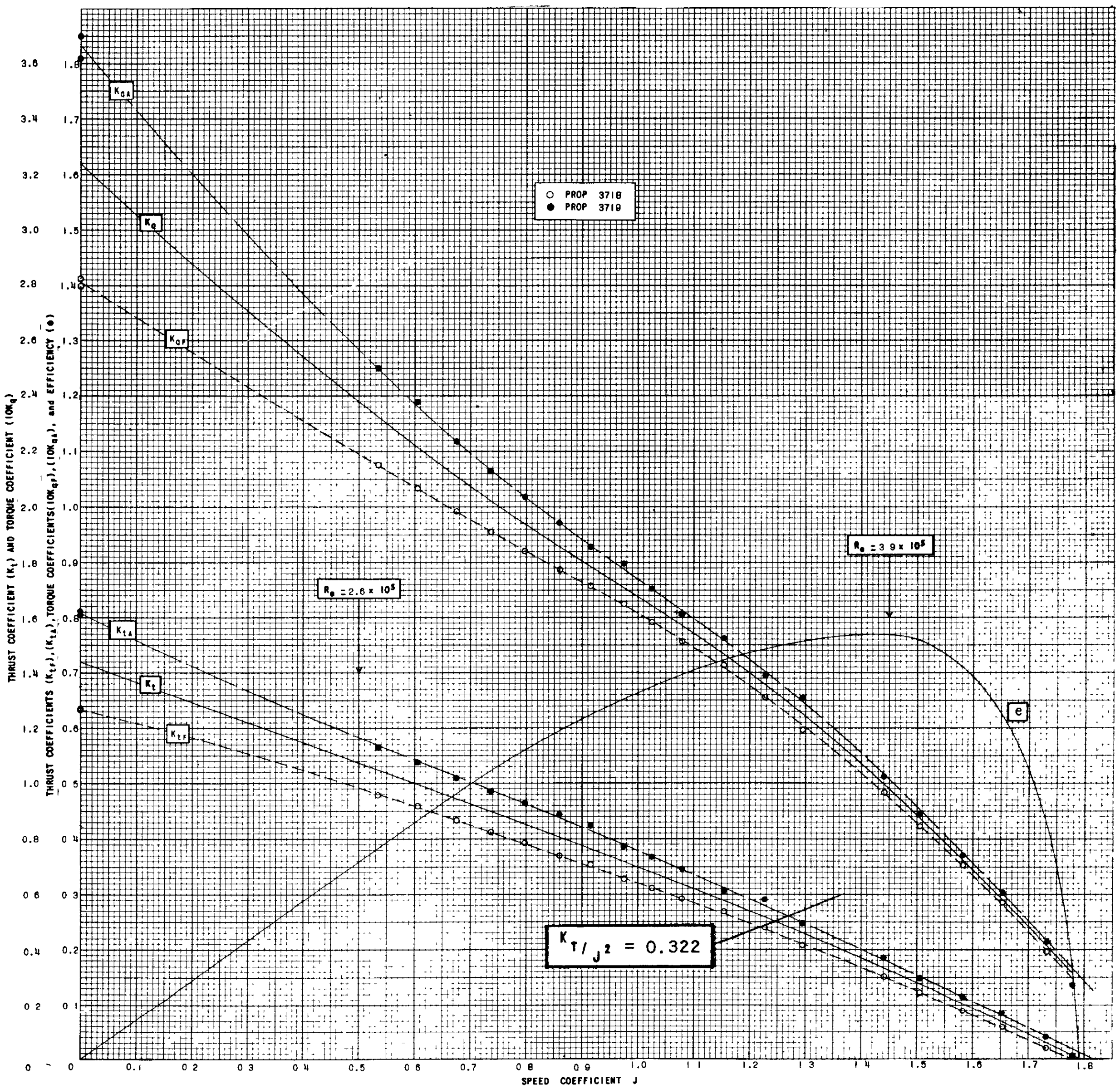

Figure 33 – Open Water Characteristics of Propellers 3718-19

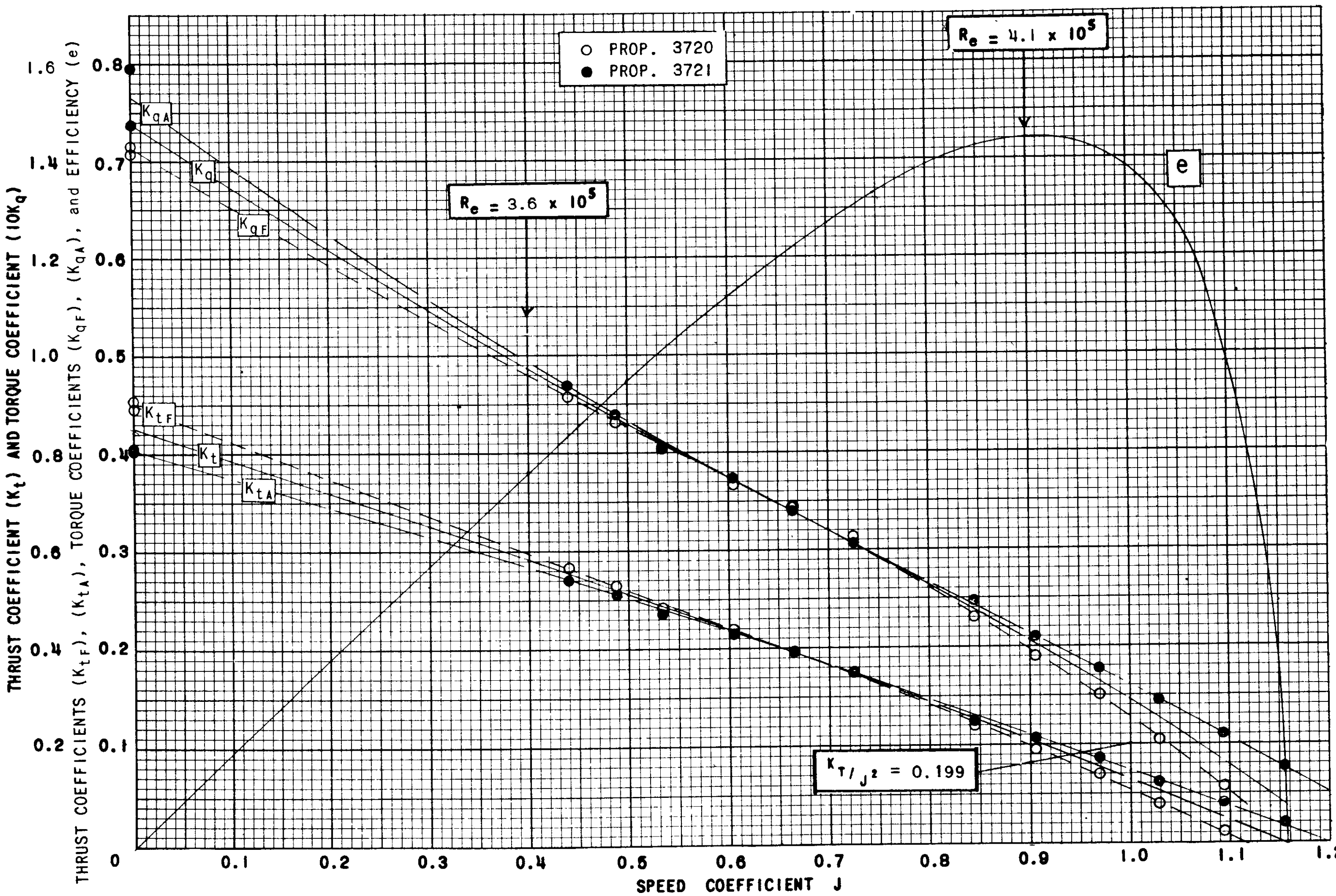

Figure 34 - Open Water Characteristics of Propellers 3720-21

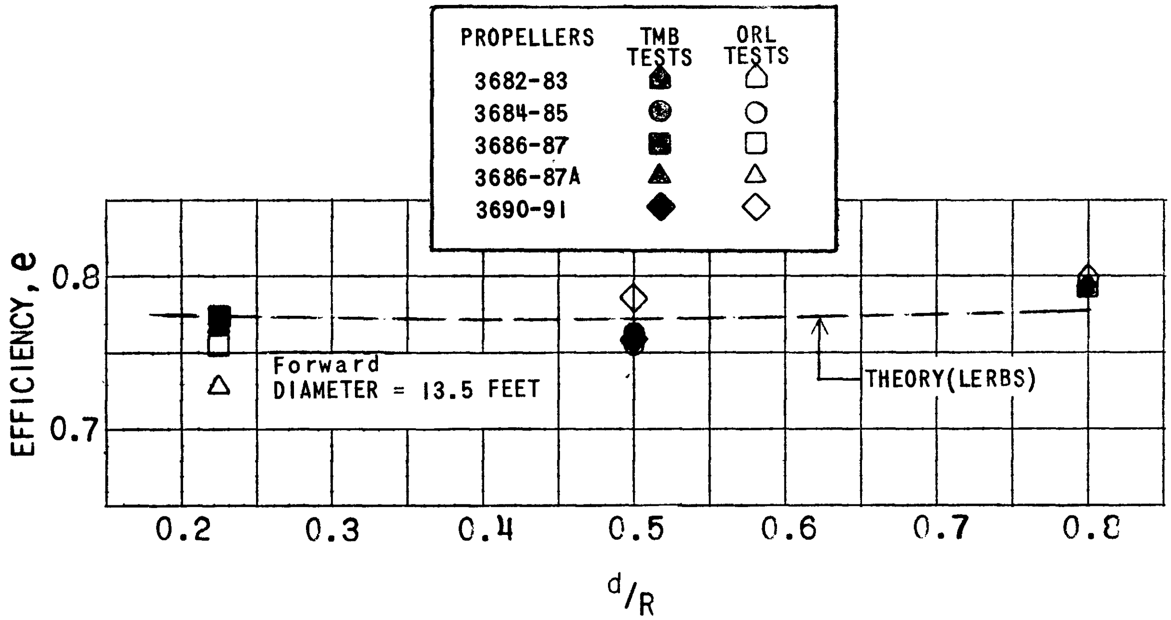

Figure 35 - Effect of Axial Spacing on Efficiency

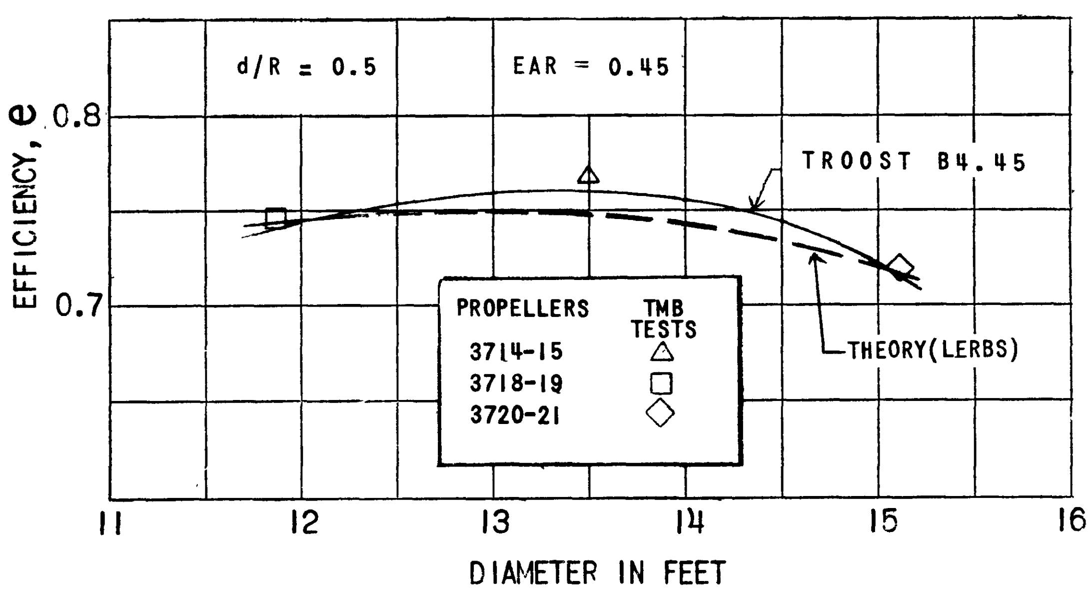

Figure 36 - Effect of Forward Propeller Diameter on Efficiency

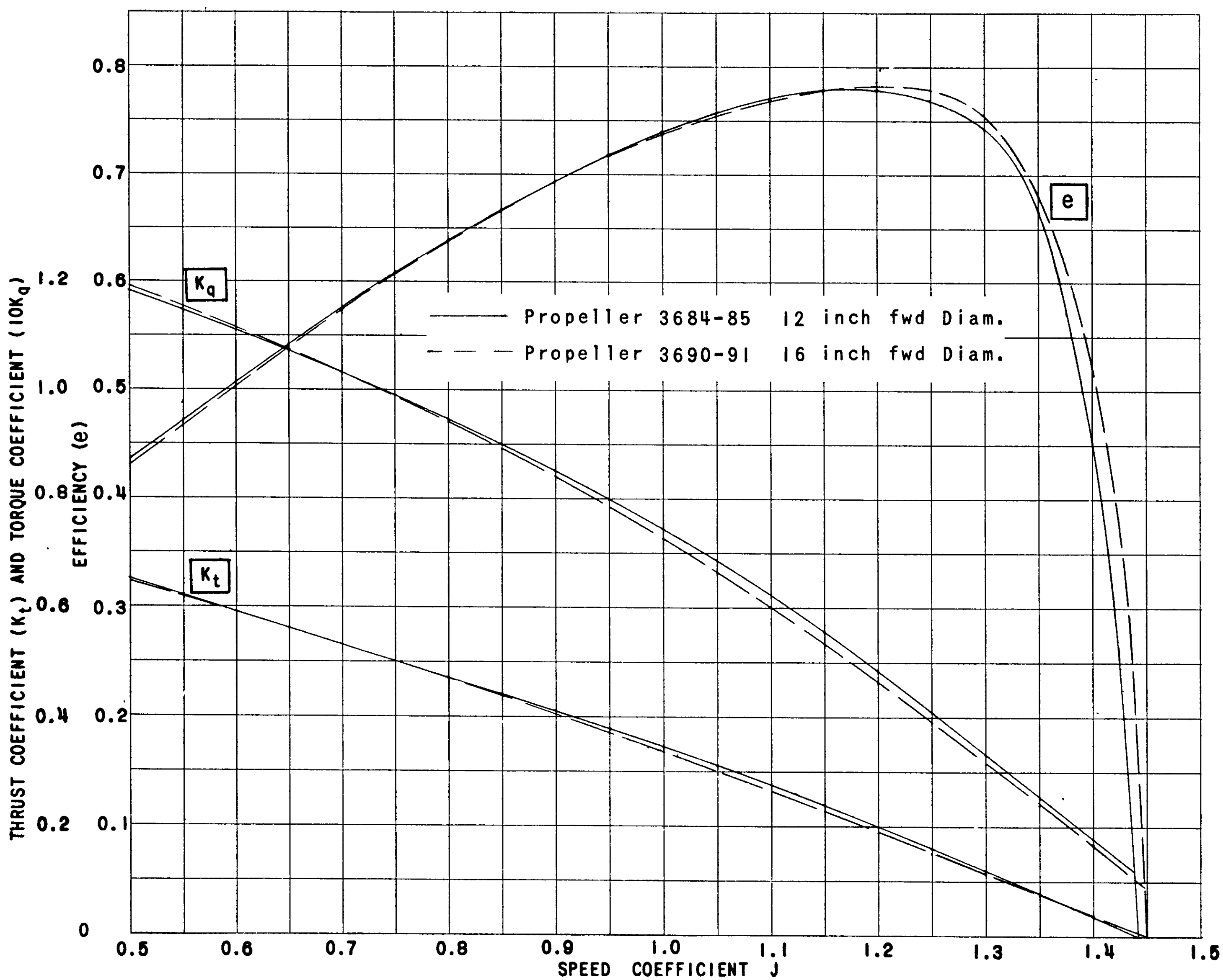

Figure 37 - Effect of Model Propeller Size on Performance of Propeller Set

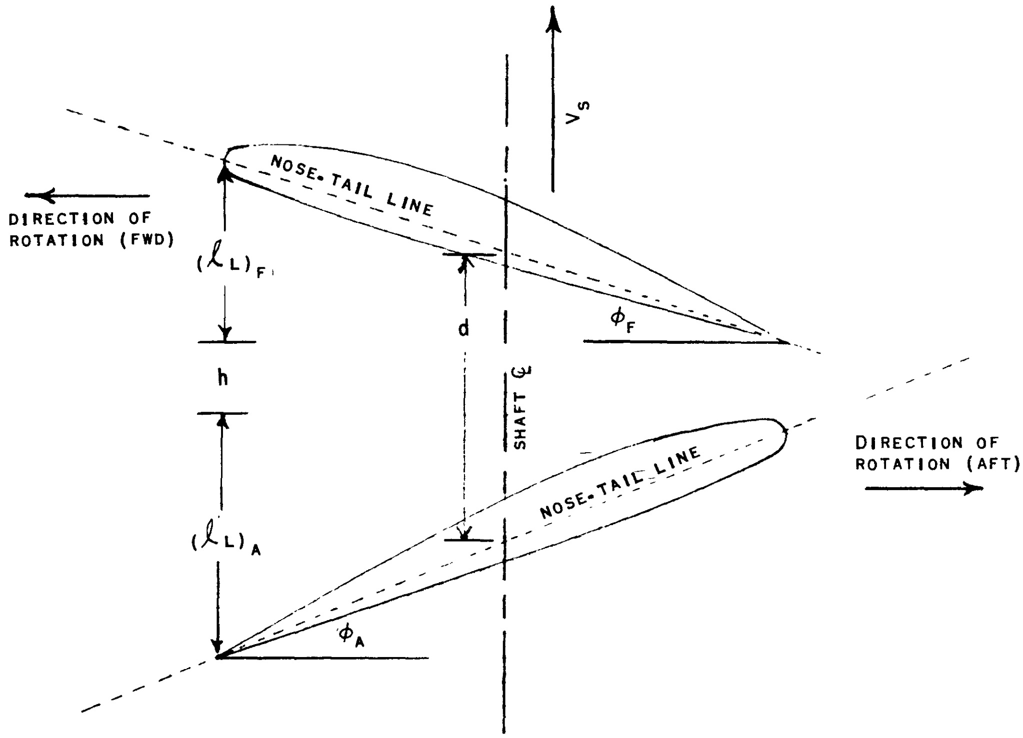

Figure 38 - Diagram of Axial Spacing of Counterrotating Propellers

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Investigation of counterrotating (CR) propellers was conducted at the David Taylor Model Basin. For this investigation a series of counterrotating propellers was designed and tested in open water. Part of this series was used to investigate the effect of axial spacing on efficiency while another part was used to study the effect of the forward propeller diameter on efficiency. Two methods, one theoretical and one empirical, were used to predict the optimum forward diameter.

Results show that axial spacing has a negligible effect on efficiency as long as the propellers are operating at their design

1. Counterrotating propellers (Marine) – Design – Mathematical analysis
2. Counterrotating propellers (Marine) – Efficiency – Model tests
3. Propeller models – Model TMB 3682-87A; 3690-91; 3714-15; 3718-21

I. Hecker, Richard
II. McDonald, Neil A.
III. S-R009 01 01

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Results show that axial spacing has a negligible effect on efficiency as long as the propellers are operating at their design

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