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Report 2174

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WASHINGTON, D.C.

DEPARTMENT OF THE NAVY

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TESTS OF THE EFFECTS OF EXIT LENGTH AND CAMBER ON THE STATIC EFFICIENCY OF SHROUDED PROPELLERS

by

Arthur E. Johnson

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AERODYNAMICS LABORATORY
RESEARCH AND DEVELOPMENT REPORT

March 1966

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TESTS OF THE EFFECTS OF EXIT LENGTH AND CAMBER ON THE STATIC EFFICIENCY OF SHROUDED PROPELLERS

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Bureau of Naval Weapons
Problem Assignment 2-34-01

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Report 2174
Aero Report 1105

March 1966

NOTATION

c	shroud chord in feet
d_e	diameter of shroud exit in feet
d_p	propeller diameter in feet
P	power output at motor shaft, foot-pounds per second
R_C	radius of curvature of inner surface of exit section of shroud profile, in inches
T	total thrust in pounds
η_s	static efficiency, referred to diameter of shroud exit $\left(\eta_s = \frac{T^{\frac{3}{2}}}{P\sqrt{\rho \pi d_e^2}}\right)$
η_{s_p}	static efficiency, referred to propeller diameter $\left(\eta_{s_p} = \frac{T^{\frac{3}{2}}}{P\sqrt{\rho \pi d_p^2}}\right)$
ρ	air density, slugs per cubic foot
$\tan \alpha_N$	slope of inner surface of shroud at the trailing edge, measured from shroud axis (positive if duct area is increasing toward trailing edge)

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SUMMARY

The static efficiency of a group of shrouded propellers with exits of various lengths and cambers has been measured experimentally and compared with potential theory calculations. Ratios of shroud chord to exit diameter ranged from 0.40 to 0.55. Straight exit sections and diffusing sections with radii of curvature of 77 and 40 percent of the propeller diameter were tested. The diffusing shrouds with the gentler curvature were found to be the most efficient.

INTRODUCTION

The effectiveness of a shrouded propeller in producing static thrust; that is, while at zero forward speed, is dependent on the extent to which the cross-sectional area of the propeller slipstream is expanded by the shroud. In inviscid flow, the slipstream size, and hence the thrust, may be increased without limit; but in real flow the effective slipstream is limited by the effects of friction. Too rapid an expansion of duct area results in separation, while too gradual an increase in area produces large skin friction area.

The objective of this investigation was to determine experimentally the effects of varying shroud exit geometry on static efficiency (that is, the ability of shrouds to produce static thrust with a given power input). Exit geometry was varied both in length and in rate of increase of duct cross-sectional area.

DESCRIPTION OF MODELS

Each model consisted of mahogany shroud inlet and exit sections attached to the structural ring of an existing propeller-spinner-motor assembly, which has been used in other shroud investigations at the David Taylor Model Basin. The assembly is described in Reference 1. The 16-inch-diameter (nominal), three-bladed, adjustable-pitch propeller was designed for general use in shroud tests. Details of its design may be found in Reference 2.

Figures 1a and 1b are photographs of two of the models, shown mounted on a shop stand. For the tests, the models were mounted on a sting supported by a diagonal strut attached to a pyramid-type balance.

The sting and diagonal strut were covered by a windshield supported on a wooden platform erected above the balance table. Figure 2 is a sketch of the test setup, giving principal dimensions.

The profiles of the test shrouds are shown in the sketches in Figure 3. The same mahogany inlet section and metal center section were used on all the shrouds. The function of the inlet in these tests was merely to introduce smooth, unseparated flow to the rest of the internal passage; and an inlet shape was used that had been found in previous work to be suitable for this purpose.

The mahogany exit sections of the shrouds had profiles, the inner surface of which were circular arcs tangent to the metal center section. Arcs of three different radii of curvature, R_C = 6.40 inches, 12.35 inches, and infinity, were used. The outer surface of the exit sections were straight lines. Shroud length was varied by cutting off a portion of the shroud at the trailing edge and forming a new straight-line outer surface, as shown in Figure 3. Three cuts, resulting in four different lengths, were made on each exit section.

TEST PROCEDURE

The tests were carried out in the test room of the subsonic wind-tunnel building. The balance center was situated at least 8 feet from the nearest wall. The slipstream was directed toward the largest area of the test room, with the nearest obstacle being more than 20 feet away. Recirculation and other effects of the environment are believed to be negligible.

Each model configuration was tested throughout a range of propeller blade angles and throughout a range of propeller rotational speeds from 2500 rpm to 8000 rpm. Propeller blade angle was varied in order to find the best blade angle for each combination of model configuration and propeller speed. As expected, propeller speed did not have any effect except at very low values, when the resulting low thrust readings combined with experimental inaccuracies to cause wide scatter in the data. Good measurements were obtained consistently at a propeller speed of 7000 rpm. Consequently, all results presented in this report are for this speed.

RESULTS

Static efficiency of a thrust-producing device may be defined as the ratio of power required by an ideal device of a given size to produce a given thrust to the power required by a real device of the same size to produce the same thrust. In the case of shrouded propellers, the ideal device is customarily taken to be a shrouded impulse disk with a slipstream that neither expands nor contracts after leaving the exit; and the size of the device is taken to be the area of the exit circle. The static efficiency thus defined is sometimes called the "figure of merit," although differences in definition of this term sometimes create confusion. An alternate definition of static efficiency may be more useful for some readers who wish to base the calculations upon the area of the propeller disk rather than the area of the exit circle. Therefore, the results of this investigation are presented both ways. The static efficiency, η_s , based on the area of the exit circle, plotted against the ratio of shroud chord to exit diameter is presented in Figure 4. In Figure 5, the static efficiency, η_{s_p} , based on the propeller disk area is plotted against the ratio of shroud chord to propeller diameter.

Since each curve in Figures 4 and 5 represents data for a certain radius of curvature, R_C , of the inner surface of the shroud exit section, a shroud will be referred to as "highly curved," "gently curved," or "straight" (where the radius of curvature is 6.40 inches, 12.35 inches, or infinity, respectively) regardless of its length.

When the shrouds of each of the three curvatures were cut off to their shortest length, the outer surfaces had sharp corners where the mahogany tail pieces joined the metal center section (see Figure 3). It is not clear whether these corners affected the data. Therefore, in Figures 4 and 5, the curves are faired as dashed lines in the vicinity of $c/d_e = 0.40$.

For a given value of R_C , each value of shroud length determined a unique value of the slope of the inner surface of the trailing edge. For easy reference, this slope, tan α_N , is plotted in the upper portion of Figures 4 and 5.

DISCUSSION

Figure 4 shows curves of predicted static efficiency from potential theory (Reference 3). The curve for the exit sections with R_C = 6.40 inches does not go beyond a c/d_e of 0.44 because additional values were not available from Reference 3. The predictions are actually for shrouds with parabolic-cambered exit sections, but the difference between the contours of circular-cambered sections and parabolic-cambered sections are insignificant for the values of tan α_N represented here. The theoretical static efficiency is greater than 1.0 when tan α_N is greater than zero because the slipstream continues to expand after leaving the exit.

The measured static efficiency, based on exit area, is highest for the gently curved exit sections for values of c/d_e above 0.44, as may be seen in Figure 4. The straight sections are next most efficient, and the highly curved sections are least efficient. However, based on propeller area (Figure 5), the highly curved and gently curved exit sections appear to be approximately equally efficient. This apparent disagreement may be interpreted in the following way.

Figure 4 shows that if it were desired to design a static shrouded propeller, and its diametral size (at the exit) were limited, then a gently curved exit section should be employed. A shroud with a straight exit would have a larger propeller diameter but would be somewhat less efficient. A shroud with a highly curved exit section would have a smaller propeller diameter, but would be still less efficient. Figure 5 shows that approximately the same thrust would be produced by shrouded propellers with gently curved and highly curved exit sections provided they had the same power, shroud chord, and propeller diameter.

The gently curved exit sections exhibit a slight increase in static efficiency (Figure 4) with increase in length, as would be expected from the theoretical curve. The straight exit sections showed no change in efficiency with changing length, also as expected. However, the highly curved sections showed a sharp decrease in efficiency when c/d_e exceeded 0.47, suggesting the occurrence of flow separation.

Observations of the flow in the exit sections were made by means of tufts attached to the surfaces and also by means of a hand-held tuft wand. It was not possible to detect the exact onset of separation of the flow from the inner surface by this means, but a well-developed stall was observed for the highly curved section when c/d_e was equal to 0.497. This explains the sudden downward trend of the curve for $R_C = 6.40$ inches in Figure 4. The slope of the trailing edge, $\tan \alpha_N$, for this point was 0.59. Separation was not detected in the shrouds with straight or gently curved exit sections.

CONCLUSIONS

Static tests were performed on a group of shrouded propellers to determine the effects of length and camber of the shroud exit section on static efficiency. The configurations tested included four different lengths for each of three different radii of curvature, R_C, of the inner surface of the exit sections. Analysis of the results leads to the following conclusions.

1. The gently curved shrouds ($R_C = 12.35$ inches) had the best static efficiency (based on exit area) over most of the range of the ratios of shroud chord to exit diameter.

2. Shrouded propellers with gently curved and highly curved exit sections ($R_C = 12.35$ inches and 6.40 inches, respectively) produce approximately the same static thrust per horsepower if the exit sections are of equal length and the propellers are of equal diameter. However, if the exit diameters are equal, the shrouded propeller with $R_C = 12.35$ inches produces more static thrust per horsepower.

3. Flow separated from the inner surface of the longest configuration of the exit section with $R_C = 6.40$ inches. The slope of the trailing edge, $\tan \alpha_N$, of this configuration was 0.59.

Aerodynamics Laboratory
David Taylor Model Basin
Washington, D. C.
February 1966

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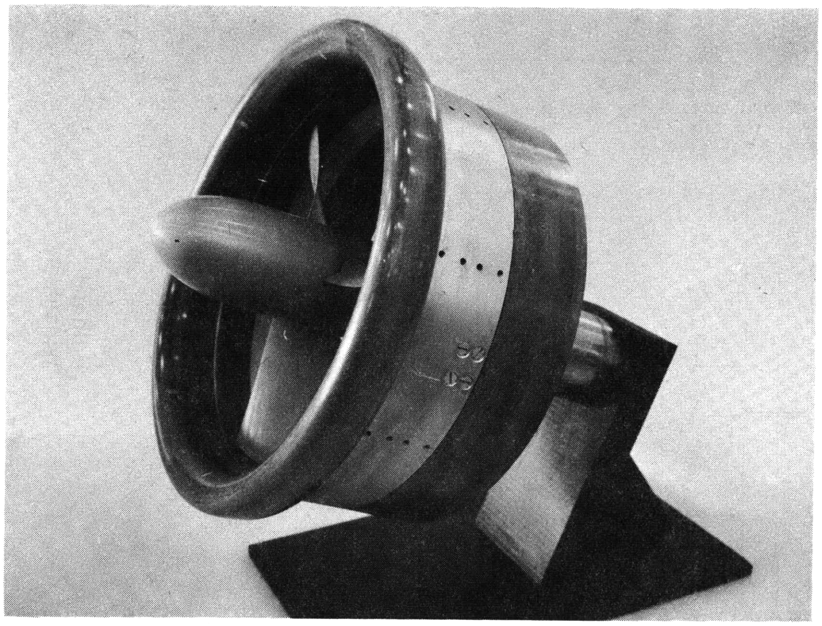

(a) Typical Long Configuration

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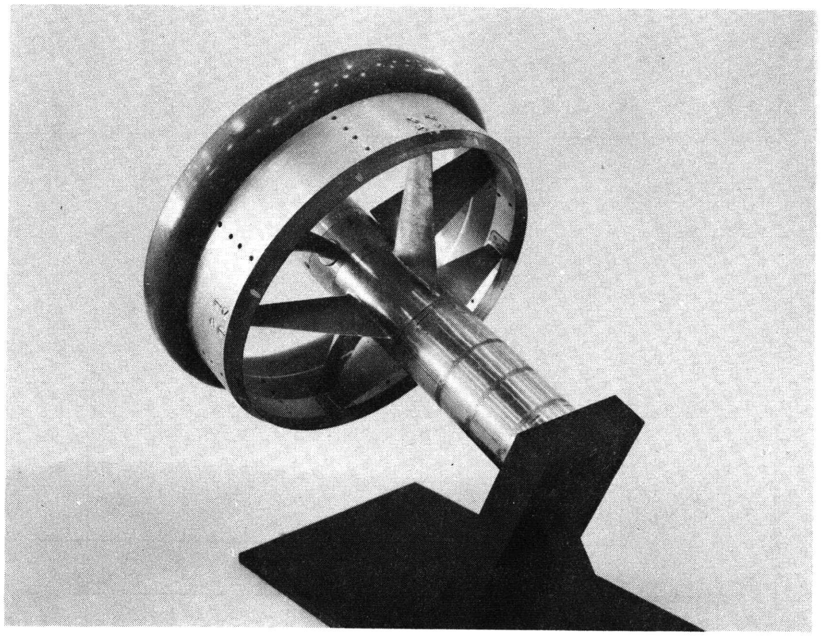

(b) Typical Short Configuration

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Figure 1 - Photographs of Models Mounted on Shop Stand

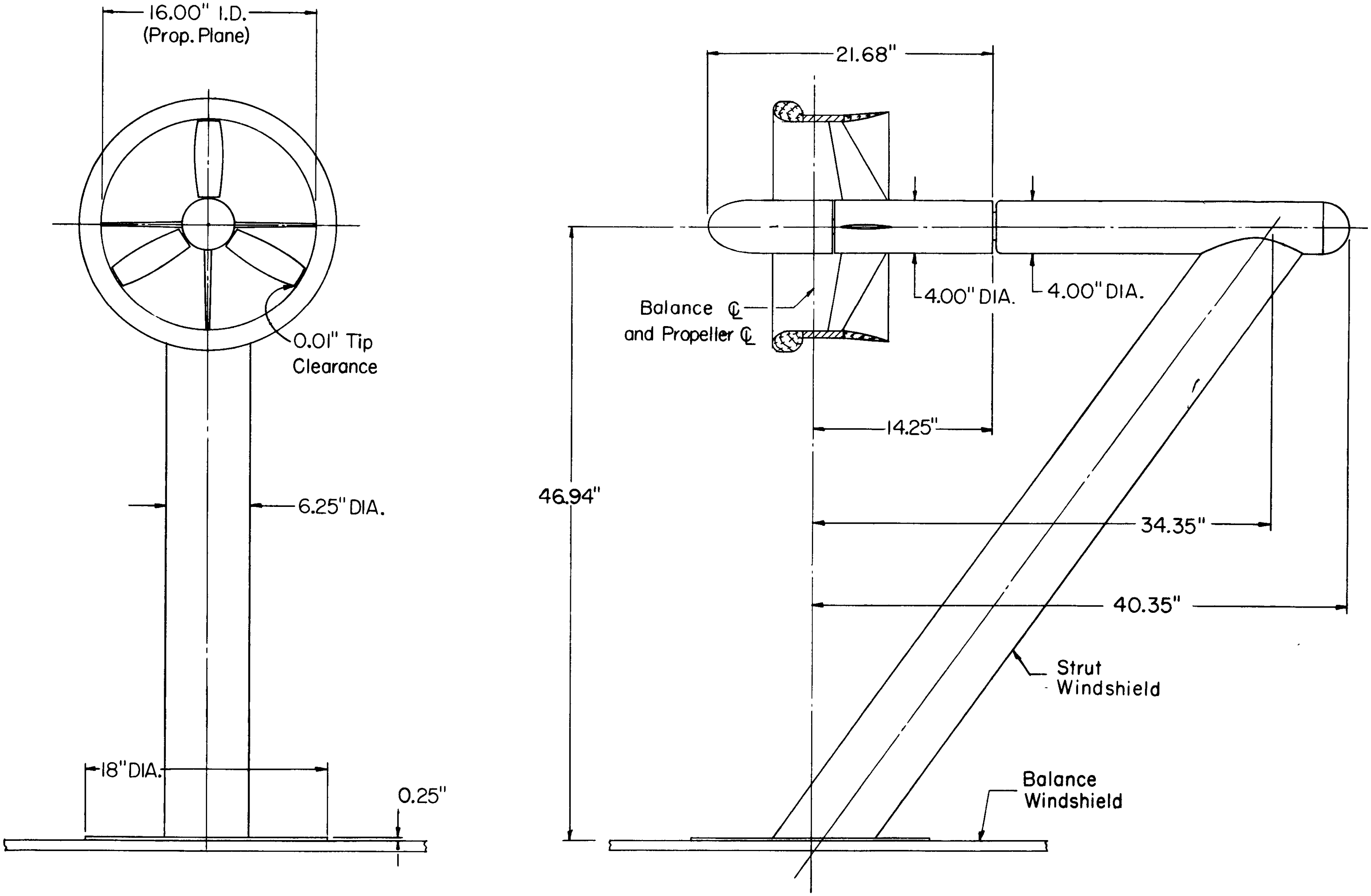
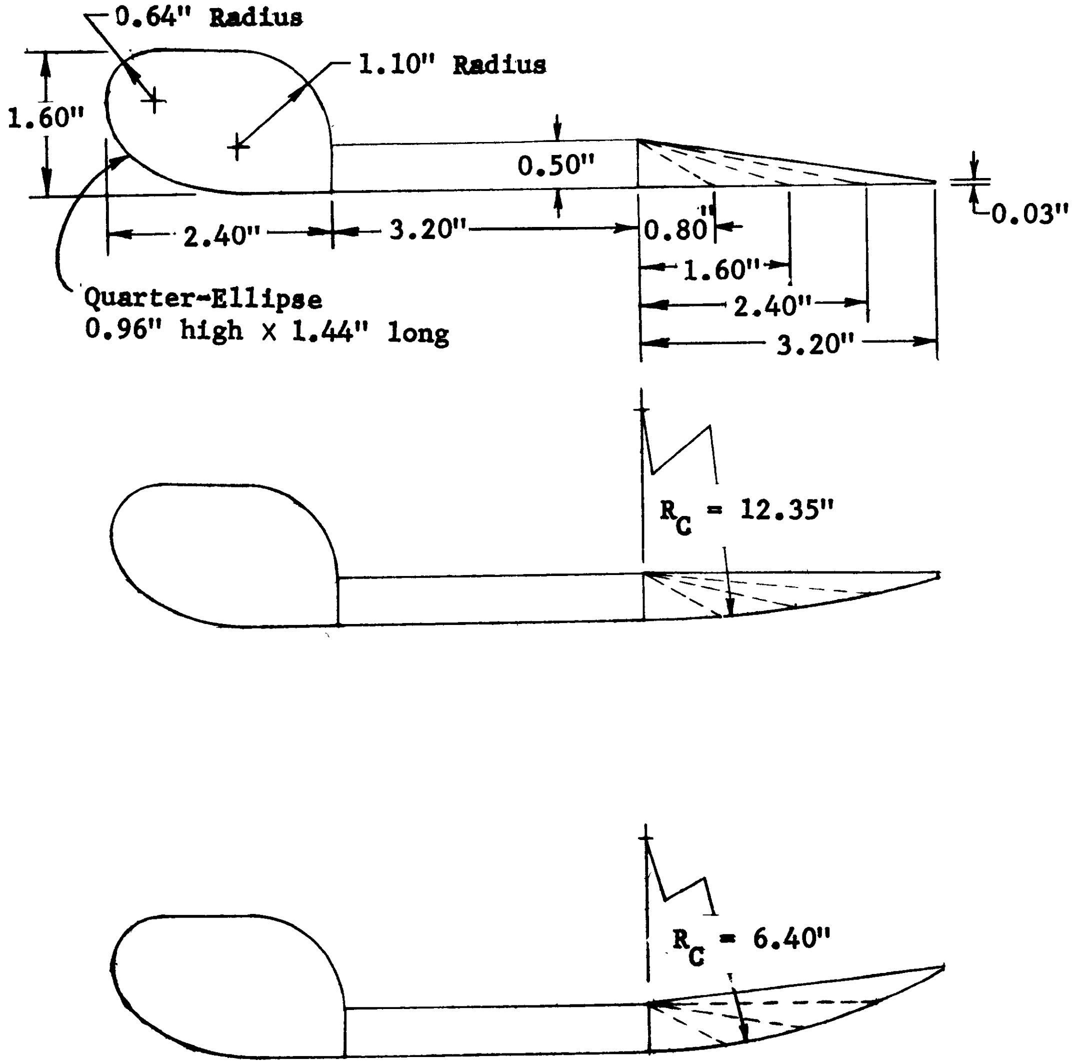


Figure 2 - Test Setup Showing General Arrangement and Principal Dimensions



Note: Dimensions are same for all three views except for exit section radius of curvature.

Figure 3 - Sketches of Shroud Profiles

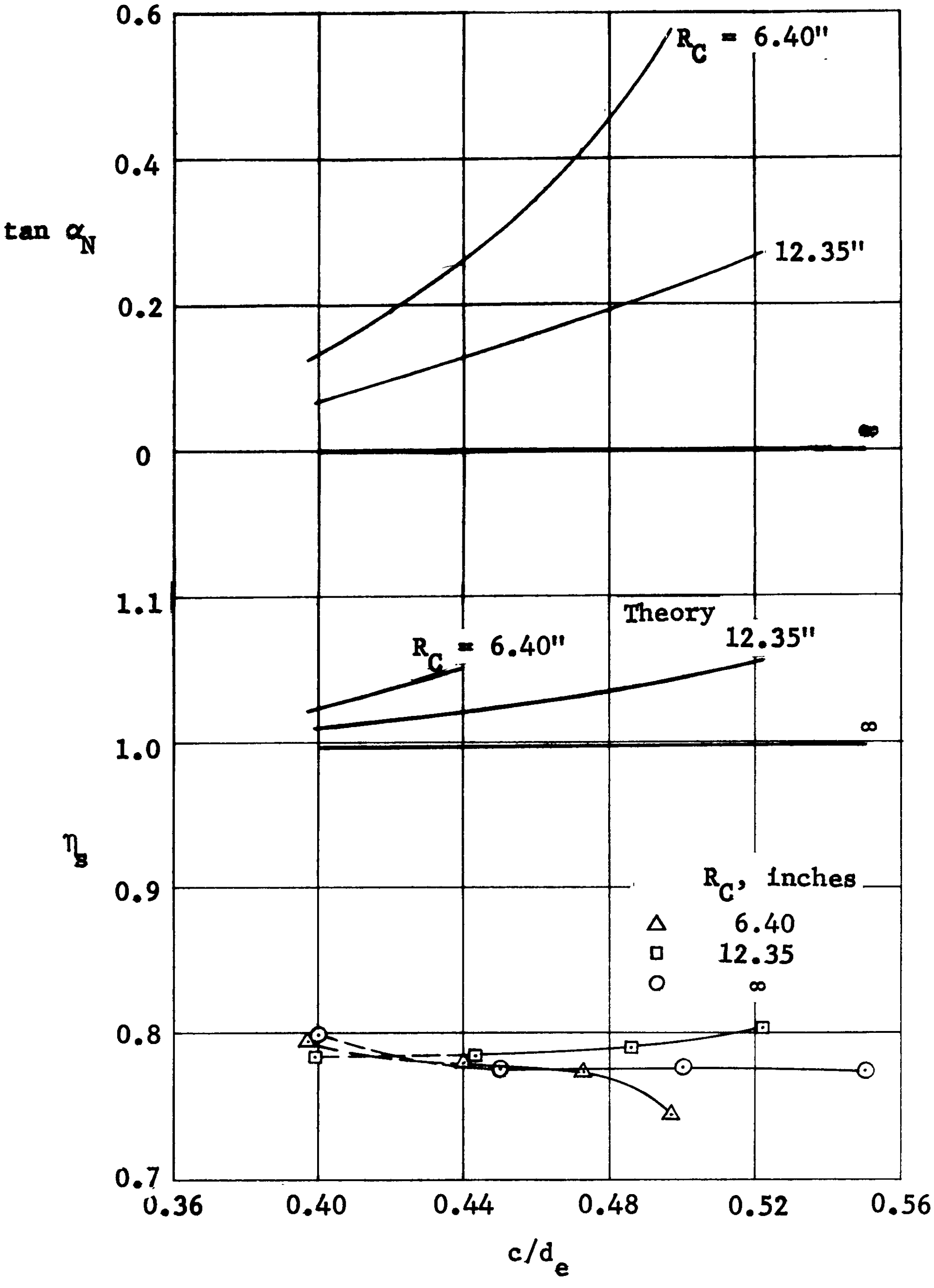


Figure 4 - Static Efficiency Based on Shroud Exit Area

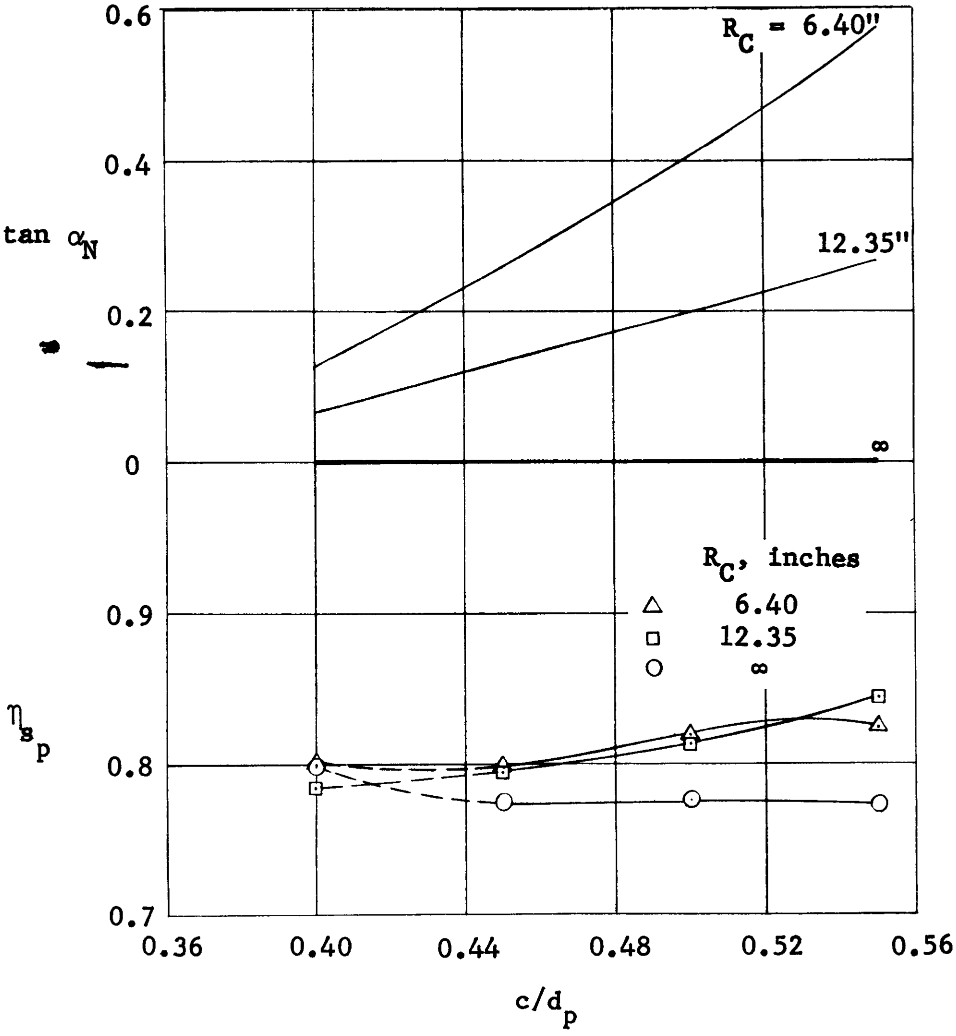


Figure 5 - Static Efficiency Based on Propeller Disk Area

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The static efficiency of a group of shrouded propellers with exits of various lengths and cambers has been measured experimentally and compared with potential theory calculations. Ratios of shroud chord to exit diameter ranged from 0.40 to 0.55. Straight exit sections and diffusing sections with radii of curvature of 77 and 40 percent of the propeller diameter were tested. The diffusing shrouds with the gentler curvature were found to be the most efficient.

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