PRINCETON UNIVERSITY

DEPARTMENT OF AERONAUTICAL ENGINEERING

U. S Army Transportation Research and Engineering Command
Fort Eustis, Virginia

Project Number: 9-38-01-000, TK902
Contract Number: DA44-177-TC-524

STUDY OF V/STOL AERODYNAMIC STATIC TEST FACILITIES

by

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Report No. 545 May 1961

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FOREWORD

The material presented in this report is the result of studies conducted by Princeton University under the sponsorship of the U. S. Army, TRECOM. This work is part of the ALART program, phase 7 of which is directed toward basic studies of V/STOL aerodynamic test facilities.

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SUMMARY

A study of the need for a new V/STOL Aerodynamic Test Facility has been conducted. Discussions with industry and research laboratory teams confirm that accurate, reliable low-speed VTOL transition data are urgently required. It is shown that existing wind tunnels are unable to provide accurate V/STOL aerodynamic data. In addition, they are largely unavailable for industry design work and basic research. A large low-turbulence wind tunnel designed specifically to obtain VTOL transition test data is the best solution for future research needs.

INTRODUCTION

This report is a preliminary study of the state of the art of obtaining reliable low-speed aerodynamic test data as required by the Army for V/STOL aircraft.

Discussions have been held with the NASA, industry design teams and non-profit research institutions in an attempt to learn the requirements for future test data and the limitations of present day facilities.

Information from the above sources and the various groups (with background of low speed static test experience) at the Forrestal Research Center is presented and analyzed to indicate whether there is a need for a large low speed aerodynamic test facility, and if so, to define its character and determine its feasibility.

The testing of powered V/STOL wind tunnel models with the attendant large free stream and wake angle distortion is considerably different from ordinary wind tunnel test work. Flow restrictions of any kind, such as walls and mounting pylons must be minimized as much as possible if one is to reproduce accurately the actual conditions under which a V/STOL aircraft would fly.

Past experience [14,26,30,31] has shown that in addition to a test facility free of aerodynamic interference, different test techniques must be adopted to gather accurate and consistent V/STOL data.

DISCUSSION

Formal talks have been held with the following groups:

1) NASA

   a) Ames 40' x 80' tunnel*

   b) Langley 30' x 60' and 17' x 17' tunnel*

2) Boeing

   a) Seattle*

   b) Philadelphia (Vertol)

3) M.I.T.

Several informal discussions have been held with these industry teams:

4) North American - Columbus

5) Curtiss Wright - Propeller Disivion

6) Ryan Aeronautical Company

7) DeHavilland - Canada

8) British Aircraft Corporation - English Electric

9) David Taylor Model Basin - Aeronautical Group

These talks are reviewed in detail in the following paragraphs.

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*Reference ALART 7 Trip Report - March 29, 1961

1a) NASA, Ames 40' x 80' tunnel.

Several difficulties were initially mentioned in testing V/STOL models in this facility.

a) Speed control in the region of $V_{tunnel} < 20$ knots becomes difficult and time to adjust the speed becomes excessively long. In addition, at speeds below 10 knots the tunnel is unable to hold a constant velocity.

b) At low speeds, the tunnel power is quite low and the $\frac{\text{MODEL POWER}}{\text{TUNNEL POWER}}$ ratio may even be greater than unity. In such a condition recirculation of slipstream wakes and the effects of the model driving the tunnel become quite large.

c) Because the tunnel was not designed for low-speed and low-turbulence, the velocity distribution and turbulence level at V/STOL transition speeds are quite poor.

d) Tunnel wall effects may be very large, and there is very little correlation with free air or flight test information. Heyson's correction theory[16] is a rough approximation for a given configuration, but cannot be expected to suffice where corrections are large. However, it does point out that the model size/tunnel size ratio must be much smaller than previously assumed in past wind tunnel test work.

This group felt quite strongly about the need for a specialized V/STOL test facility. Several years ago they had plans to build such a facility but were thwarted by lack of money and urgency.

In general, their feelings were that a very large open circuit, closed throat wind tunnel would circumvent most of the problems they were encountering in the 40' x 80' tunnel. Such difficulties as wind gusts, turbulence eddies, etc., were felt to be small and easily dealt with. Tunnel speed control should be handled by a combination of fan blade pitch and fan speed control. Heavy screening along with honeycombs in the settling chamber should create a low-turbulence level with minimum power loss.[23,24,25] This group emphasized that the low-speed range required for such a facility should not be compromised by a desire for higher speeds.

At the present time, data acquisition systems, balance systems, and model support pylons all appear to be inadequate for low-speed V/STOL test work. These were designed for large normal aircraft and cannot be expected to perform satisfactorily for the many varied VTOL configurations now being considered. The projected work load of this tunnel for full-scale test-beds, the supersonic transport and various space projects would appear to make this facility largely unavailable for basic V/STOL research.

1b) NASA, Langley 30' x 60' tunnel and 17' x 17' tunnel

Similar difficulties have been encountered here as at Ames Laboratory in testing V/STOL models. However, the 17' x 17' tunnel has an excellent velocity distribution and low turbulence level making it a very good low-speed facility. Recirculation and wall effects appear to be the only restrictions on V/STOL model testing. Unfortunately, this tunnel, also, is heavily scheduled for higher speed space and transport work in its 7' x 10' test section. This combined with the relatively small size of the 17' x 17' test section appear to limit its utility for V/STOL test work.

It was noted that a small scale model of the 17' x 17' test section was built by this group to check the flow distribution. The entrance (4' x 4') was open to the outside atmosphere, and with a honeycomb and two screens mounted in the settling chamber, no noticeable velocity variation in the test section was found due to exterior wind gusts.

The 30' x 60' open throat full scale tunnel apparently can be operated at very low air speeds down to 5 fps. However, it was said that the velocity distribution at these low speeds was quite poor. This facility, with a partial ground plane built up from the floor (making it open throat on three sides) appears to be ideal for free flight dynamic model testing but with the following difficulties:

1) Short test section length (tunnel drive fans are right at the back of the test section)
2) Partial ground plane
3) Short settling chamber with no provision for turbulence reduction

this tunnel appears to be inadequate for many types of VTOL or STOL test work. The first two features make the simulation of a large wake angle from a VTOL in transition quite impractical. The proximity of the tunnel drive fans would act to draw the wake upwards while the partial ground plane tends to deflect the wake upwards and to either side.

The work load of this tunnel already exceeds the capabilities of the present staff, so that it is largely unavailable for additional V/STOL research.

This tunnel, because of its configuration, can only offer compromised test conditions for low-speed static test work.

2a) Boeing, Seattle

This group, primarily interested in "jet risers" or jet flap STOL, posed many interesting problems for a low-speed facility to solve.

The group posed the question of what such a facility would be like and why it would be that way. How would tests be run in a V/STOL static test facility?

The latter question can be partially answered by past test work.[14,26,30,31,33] Further experience will rapidly add to knowledge of how to conduct model tests for V/STOL aircraft, but reasonably definitive techniques do already exist.

The character of a new facility is of course a principal object of this report. The Boeing group emphasized the need to define the size required and how best to simulate ground effect, ground boundary layers due to winds, gust and wind gradient effects.

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They emphasize that high speeds are not required, and they indicate a need for a specialty facility for low speed testing.

2b) Boeing, Philadelphia (Vertol)

3) M.I.T. Professor Rene Miller

In a comprehensive meeting held at Vertol's main plant in Morton, Pennsylvania, all the above questions and problem areas were examined and conclusions were drawn to the satisfaction of all concerned.

The Vertol group outlined its particular needs in relation to the future and it was concluded that it, too, is intensely interested in a new facility which would not be restricted by the compromises of current facilities.

Test procedures would follow along lines suggested by references 14, 26, 30, and 33. Model geometric similarity and full-scale angles must be preserved in tests. Reynold's numbers at .75 RADIUS in the range of $.8 - 1.0 \times 10^6$ or higher must be attained on all propellers or rotors. These requirements dictate the following:

1) Full-scale advance ratios must be preserved
2) Model disc loadings will be approximately the same as full-scale values
3) Must preserve free-stream/slipstream velocity ratio which, of course implies proper "q" ratios

Further analysis of these requirements is discussed in Part IV of this report.

With reference to the character of such a facility, Professor Miller of M.I.T. emphasized that the error involved in testing in any facility should be minimized as much as possible. With this in mind it was proposed that a detailed test program be set up to determine the wall effects on a simple propeller or rotor for thrust, power, normal fore and pitching moment. From the results of such a study, the proper $\frac{\text{MODEL SIZE}}{\text{TUNNEL SIZE}}$ ratio can then be determined. Presently available data indicates that a thrusting rotor should be at least 12-16 rotor diameters from the ground wall to avoid excessive pitching moment and normal force error. This is discussed in further detail in Part IV.

Both Boeing groups indicated that a desirable model size was in the range of a 8-10 foot wing span and at least 2 foot diameter propellers or rotors.

They would like this type of model to be tested from 10 fps to 100 fps (full scale speeds) to cover the initial transition. It was emphasized that it would be highly desirable to have in the same facility a capability of testing the same model in a smaller section at speeds from 100-250 fps. At these higher speeds the wall effects are not quite so severe and a smaller section would be permissible. All agreed that a large low-speed wind tunnel with two test sections appears to be a promising solution.

Over the past year in connection with the development of a Navy airship as a flying wind tunnel, discussions have been held with a number of companies in relation to their present and future low-speed test needs.

North American Aviation in Columbus, Ohio, has tested small 4-7 foot span models in a 16' x 14' settling chamber of its 7' x 10' wind tunnel. The wall effects at low speeds are unknown and they are very anxious to learn more of how serious the effects are. It seems probable that a correlation study will be made using an airship to check the wind tunnel. Here again, problems of driving a closed circuit wind tunnel with high model power exist in addition to being forced to use very small models.

The Curtiss-Wright people thoroughly tested their [illegible]-100 series aircraft in static and cruise configurations. Unfortunately, no facility was available to them in which they could run transition studies. They have expressed strong interest in using a large test facility for not only complete model testing, but also for propeller tests. At the present time they are using the airship test facility developed by Princeton.

Ryan Aeronautical Company has asked Princeton for methods of testing STOL's with high C_L powered wings. The lack of a suitable wind tunnel has been an unsurmountable difficulty.

Because of the lack of a sufficiently large facility, the DeHavilland Company in Toronto, Canada, has developed its DHC-4 Carbon with the aid of models mounted on a truck and above the wing of a DHC-3 Otter. They indicated that these are both unsatisfactory test methods due to the inability to control and maintain test conditions for a suitable time period. A proper test facility is urgently needed.

Mr. Ray Creasey, Director of Engineering for the English Electric Aircraft Division of British Aircraft Corporation, in a recent visit to the Forrestal Laboratory, expressed a keen interest in our pursuit of a low-speed static test installation. Similar requirements are felt in England and there has been active study of a VTOL test facility for their future needs.

The wind tunnel group of David Taylor Model Basin have shown interest in the airship flying wind tunnel and have indicated that the tunnel size restriction was quite serious. They too, feel that a new V/STOL facility would be highly desirable.

To conclude this section it might be mentioned that Forrestal personnel have, in the normal course of developing the airship as a free air test facility,[29] been in continuous contact with innumerable people from industry and private research groups who ask for only one thing: a suitable low-speed test facility to assist them in learning more about the vastly complicated flow mechanisms involved in low speed powered flight.

TECHNICAL FEASIBILITY

It has become increasingly apparent that further advances in the state of the V/STOL art will be considerably impeded by the lack of suitable experimental facilities. This section deals with what is considered suitable and why.

Static testing of V/STOL aircraft configurations for performance and stability and control data requires that the model or full-scale aircraft be in motion relative to the air around it. Also, one must require that the testing conditions shall be under complete control such that the steady state forces and moments acting on such a vehicle can be accurately measured over a range of speeds, attitudes and configurations.

Several means exist to do this by mounting the model with suitable measuring devices:

1) On a towed trailer or truck-bed
2) On an airplane which can maintain steady level flight
3) Underneath an airship
4) On a long, powered track
5) On a whirling arm
6) In a wind tunnel

Of these various methods previous work has indicated that only 3) and 6) appear to have considerable promise. For long term generation of large amounts of data encompassing many varying configurations, only 6) provides the maximum control of test conditions with the greatest convenience.

The airship, however, is invaluable in that it does provide one with a true "end point". That is, a true flight condition for a given model can be simulated with no wall effect.

Past experience has indicated that convenience and/or flexibility is of great importance for any test facility. On this basis one must select the wind tunnel as the most suitable facility and devote some considerable effort to minimize undesired wall and pylon effects.

The following problem areas will be examined in detail:

1) Tunnel wall effect (i.e., ratio of $\frac{\text{MODEL SIZE}}{\text{TUNNEL SIZE}}$)

2) Testing technique and speed range

3) Open test section vs closed test section

4) Open circuit vs closed circuit

1) Tunnel Wall Effect (i.e., ratio of $\frac{\text{MODEL SIZE}}{\text{TUNNEL SIZE}}$)

In the past, wind tunnel boundary corrections were derived for wings and bodies with the assumption that the resulting wake was negligible and undisturbed. For the simple case of the wake parallel to the tunnel stream, considerable analytical and experimental work has been done.[1-7] Wood and Durand[1] have developed a suitable correction for powered propellers mounted in a wind tunnel by taking into account the pressure and velocity changes created by a propeller at $\alpha_p = 0^o$. This correction is made to lower the advance ratio that the propeller effectively encounters.

The following equation[1] is plotted in Figure 1:

$$\frac{V'}{V} = 1 - \frac{\alpha}{2} \frac{\Upsilon}{\sqrt{1 + 2\Upsilon}}$$

where: $\Upsilon = \frac{T/A}{2q_\infty}$

$\alpha = \frac{\text{DISC AREA}}{\text{TUNNEL SECTION AREA}}$

V = tunnel velocity

V' = effective velocity

Note that the correction is dependent on DISC AREA/TUNNEL AREA and $T/A \,/\, 2q_\infty$ or the disc loading for a given free-stream velocity.

For a 2 foot propeller in a 7' x 10' tunnel developing a thrust of 120 pounds at a forward speed of 41 fps this correction would indicate a 5% error in advance ratio. i.e., $\alpha = .045$ $\Upsilon = 9.6$ thus $V'/V \approx .95$.

This correction is significant in that nearly all V/STOL aircraft configurations, because of their very nature, possess large powered wakes in low-speed flight.

At the other extreme, the case of a rotor or propeller wake perpendicular to the free stream in the hovering condition, the correction is not quite so straightforward. The true simulation of wake skew angle can no longer be ignored. Kuhn has pointed out in Reference 12 that heavily flapped wings with power are very sensitive to premature flow separation, and undesired force and moment errors due to the proximity of wind tunnel walls. Heyson's work in References 16 and 35 presents analytically determined correction factors with some experimental correlation for a limited range of conditions. He concludes that in the transition speed range where the wake is at a large angle relative to the free stream, the boundary corrections will be much larger and will change rapidly with forward velocity. In addition, these derived corrections do not consider a nonuniform disc distribution. To date, all V/STOL configurations exhibit nonuniform disc loading. In fact, a considerable pitching moment is developed on propellers, rotors, ducted fans, and fan in wings because of this nonuniform disc loading.

Additional work on the effects of the ground and/or walls on this configuration is covered in References 8-12 and 15-22. It may be safely concluded that because of the uncertainity of the large wall corrections for a hovering rotor or propeller and the undesired flow distortion created by walls, these effects must be eliminated or reduced to small values by reduction in the $\frac{\text{MODEL SIZE}}{\text{TUNNEL SIZE}}$ ratio.

Reducing model size is limited by model-building techniques and Reynold's number considerations. Increasing the tunnel size, vertical dimension in particular (Reference 35, page 18), is limited only by cost.

Figure 2 presents a qualitative picture of the effect of tunnel dimension (Z/D) and disc or power loading of the wake (q_{∞}/T/A) on the center streamline of a powered wake. The free streamline wake pattern was defined by utilizing simple momentum theory in conjunction with experimental data of the velocity decay and diameter growth of a free static jet. The wall-effect wake pattern was sketched in from smoke-flow patterns observed in Forrestal wind tunnels.

It is quite evident from Figure 2 that for the case of a high disc loading and low free stream velocity the angular distortion of the wake centerline near the disc is quite severe. This difference decreases rapidly, with a decrease in disc loading.

Preliminary experiments of the wall effect on rotors/propellers have shown that there is a possibility of considerable error due to wall effect.[29] Consider Figure 3 where the disc velocity distribution can be appreciably affected by the deflection of the wake.

In this case, the nonuniform velocity distribution causes a forward shift of the rotor/propeller thrust vector which creates a large pitching moment.[14] This pitching moment has an order of magnitude of approximately one ft.lb./lb. thrust for a 10 foot diameter propeller.[34] The effect of the wall or ground appears to be that of reducing the change in velocity distribution by decreasing the normal free-air change in wake angle, hence, reducing the measured value of the pitching moment. For this case, a negative error is introduced by the wall effect. Figure 4 is a plot of the percent error in propeller pitching moment as a function of Z/D, $q_\infty / T/A$, and propeller angle of attack to the free stream.

Work is being done to investigate the error in further detail. However, it is clear that a discrepancy does exist and that it is large and cannot be neglected. In addition, there appear to be similar errors in normal force, thrust, and power. Although apparently, not quite so large for the latter two.

It has been difficult to correlate experimental data, because of the lack of a full-scale flight-test "end point". The airship has provided a partial solution to this problem by enabling rotor/propeller tests of models that have been run in wind tunnels. Obviously, the airship provides an ideal platform to obtain an "end point" with no wall effects.

The result of the above is that for a broad range of V/STOL configurations the tunnel floor should be approximately at a Z/D of 16-20 below the model.*

The same reasoning can be applied to determine the width requirements of such a wind tunnel. Fortunately, yaw angles are usually limited to $\pm 30^\circ$ therefore easing the lateral dimension requirement. A total width of four or five wing spans would seem to be suitable.

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*Z/D refers to developed slipstream diameters, i.e., $D = .707\, D_{PROP}$. For jet flaps, the blowing slot width would be directly equal to D since there is little or no wake contraction for a free jet. However, the $q_\infty / T/A$ ratios are much lower than for a rotor by several orders of magnitude. This would require Z/D_{SLOT} clearances possibly as high as 1500. (For a 1/4" slot width this would give a $Z \sim 31$ feet.)

Although more data is needed for detailed error measurements, it appears that a test section size should be:

a) width - 4-5 wing spans

b) height - 25-30 propeller diameters

2) <u>Testing Technique and Speed Range Desired</u>

The majority of proposed VTOL configurations receive their primary lifting capability from rotating lift devices such as rotors, propellers, lift fans, and ducted propellers. From recent test work, there is evidence to show that it is possible to obtain accurate performance, i.e., power-required data from model tests. Figure 5* indicates the variation of static Figure-of-Merit (Thrust/Horsepower) with Reynold's number for a series of geometrically similar model and full-scale propellers. Reynold's number is based on the velocity and chord at the three-quarter blade radius. As is previously known from airfoil tests, it appears that by running the blade Reynold's number up to approximately one million, one can closely simulate full-scale performance conditions.

References 14, 26, 30, 33 describe test techniques which have worked well in providing V/STOL stability and control data. If Reynold's number were not important it would suffice to preserve complete geometric similarity and full-scale flow angles.

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*Work performed by W. H. Barlow of the Curtiss-Wright Propeller Division under the direction of H. V. Borst.

This would imply that one only has to maintain a given free-stream/ slipstream velocity ratio. Thus, a lower rotor disc-loading could be used with a correspondingly lower tunnel speed.

However, for accurate representation of power-required and the true simulation of slipstream wake rotation it is necessary to attain a blade Reynold's number close to 1×10^6.

With this additional consideration, the basic principle of V/STOL model testing becomes: Preserve complete geometric similarity and full-scale flow angles and maintain the Reynold's number (.75R) on the lifting elements at approximately one million.

The reason for this additional requirement is that wake rotation and shaft horsepower are dependent on the blade profile drag coefficient. At $N_R < 1 \times 10^6$ this drag coefficient will increase by as much as 200%-300% at a $N_R = 100,000$.

With the above criterion in mind, an examination of propeller or rotor sizes and their corresponding rate of rotation for a given N_R and tip Mach number will be instructive.

Table I indicates that a suitable Reynold's number is governed by:

$$N_{R_{.75R}} = 3/4 \cdot 6380 \cdot a \cdot M_{TIP} \cdot \bar{c}_{.75R}$$

where:

$a \sim$ speed of sound (fps)

$\bar{c}_{.75R} \sim$ chord at three-quarter radius (ft.)

TABLE I

DIAMETER	M_{TIP}	N_R	RPM	$\bar{c}_{.75R} = 2.5$ in.
1.00'	.9	1×10^6	19,160	$M_{TIP} = .90$
2.00'	.9	1×10^6	9,580	
4.00'	.9	1×10^6	4,790	

Fixing $N_{R_{.75R}}$ at 1×10^6 and $M_{TIP} = .9$ will specify the minimum usable rotor/propeller blade chord at approximately 2.5 inches.

Present day model techniques have indicated that a two-foot diameter propeller is the smallest desirable size when considering the effect of rpm on data acquisition and safety procedures. Slower turning rotors usually range from 4 to 8 feet in diameter.

However, the present range of operation is satisfactory and it is evident that full-scale advance ratios can be easily obtained through transition (V/nD = constant).

Propeller or rotor disc loading is primarily a function of thrust coefficient and blade velocity (or tip Mach number).

$$\frac{T}{A} \sim C_T \, \rho \, M^2_{TIP} \, a^2$$

Therefore, by maintaining full-scale tip Mach number and blade angle (this determines C_T), model disc-loadings will be equal to full-scale values.

In summary, the data of Figure 5 and the requirements of industry have resulted in the following model testing criterion:

1) Full-scale advance ratios must be preserved

2) Full-scale tip Mach number must be preserved

3) Therefore tunnel velocities must be approximately full-scale values

4) Full-scale flow angles will approximately be preserved

5) Full-scale disc loadings will approximately be preserved

6) Geometric similarity must be preserved

For the speed range of such a facility, there are two conflicting requirements:

a) A wide speed range down to 5 fps

b) Low-turbulence level, even velocity distribution over the whole range

Most VTOL vehicles have a transition speed range from 0 to 150 kts. Therefore, to satisfy 1)-6), the tunnel velocity must also be 0 - 150 kts. Past work[23,24,25] has indicated that it is difficult to maintain a good low-turbulence velocity distribution over such a wide speed range in one test section.

Figure 2 indicates that a smaller test section is perfectly acceptable for higher values of $q_{\infty}/T/A$, thus a dual test section wind tunnel appears to be a logical solution. The large test section would be designed for initial transition studies, 0 - 50 kts. While the smaller second section would cover the speed range from 50 - 150 kts.

Such an arrangement would permit a wide range of test work to be accomplished in a single facility with ease and flexibility. Test work from 150 kts and higher should be easily handled by the smaller higher speed wind tunnels already in existence.

3) Open Test Section vs Closed Test Section

Heyson has reported in Reference 35 that for small skew angles (hover or low speed flight) large errors will be incurred if the lower boundary of an open jet tunnel is free. This same error can be extended to the case of a yawed wake in the horizontal plane, where open sides of the jet would cause the same error.

In effect, an open test section is undesirable for V/STOL static test work because of the nonuniformity of the test section boundaries. A powerful slipstream would blow completely out of the jet boundary, whereas a lower-powered slipstream might impinge on the diffuser bell-mouth and bob in or out of the tunnel. Such oscillations and nonuniformities are very undesirable and would only lead to erratic and unsuitable test conditions.

One of the most difficult facets of V/STOL static test work is the problem of being able to completely control all test conditions.

An open throat adds another variable which is difficult to control. Therefore, a completely closed-large test section would seem to be a better choice.

4) Open-Circuit vs Closed-Circuit Wind Tunnel

As it was shown in Part III of this report, slipstream recirculation and attendant velocity instability are unfavorable characteristics of closed circuit tunnel configurations, so that open circuit would be preferable.

There are two difficulties with such an arrangement:

1) Sensitivity to atmospheric gusts

2) Power wastage

The latter becomes quite small with proper diffuser design, less than 10% of the total tunnel power. For such a low speed tunnel requiring no more than 5-6000 hp such losses are quite small.

Although there are several large open return tunnels in Europe which appear to work quite well, the gust sensitivity problem, particularly for a large low-speed tunnel might be quite severe. However, the tools for obtaining turbulence reduction and uniform velocity distributions, specifically, screens, honeycombs, and large contraction ratios are very useful in damping out wind gusts and other atmospheric disturbances.

Nearly all successful smoke tunnels are of the open return variety, and some even are open to the atmosphere.[23,24,25] Long experience with these facilities has shown no serious difficulties due to gust sensitivity.

Experiments at Princeton with a small 1/40 scale model of a proposed V/STOL facility have shown that, indeed, the gust sensitivity is quite low.

In addition, as mentioned earlier, the NASA 17' x 17' pilot tunnel worked quite well with the proper addition of a honeycomb and damping screens.

Either method of tunnel construction could be made to work, but it appears that an open-circuit tunnel would be the simplest and most flexible design.

CONCLUSION

From this study of the V/STOL industry's needs and future requirements for low-speed aerodynamic static test data the following results have been obtained:

1) A large low-speed test facility is in urgent demand to further the state of the art in VTOL performance and stability and control.

2) This facility should be a low-speed wind tunnel designed specifically for V/STOL transition testing. It should be large enough and of such a nature to minimize to a negligible degree all wall effects and flow distortions.

3) Adequate VTOL test techniques have been developed to use such a facility to best advantage. In addition, the following requirements should be met:

   a) Preserve full-scale flow angles and advance ratio.

   b) Operate rotating lift systems at a Reynold's number of approximately one million which implies

   c) Approximately full-scale disc loadings.

4) Sufficient data is available to determine an approximate tunnel size and speed range.

   a) Low-speed section 40' x 50', 0-85 fps

      High-speed section 20' x 30', 0-250 fps

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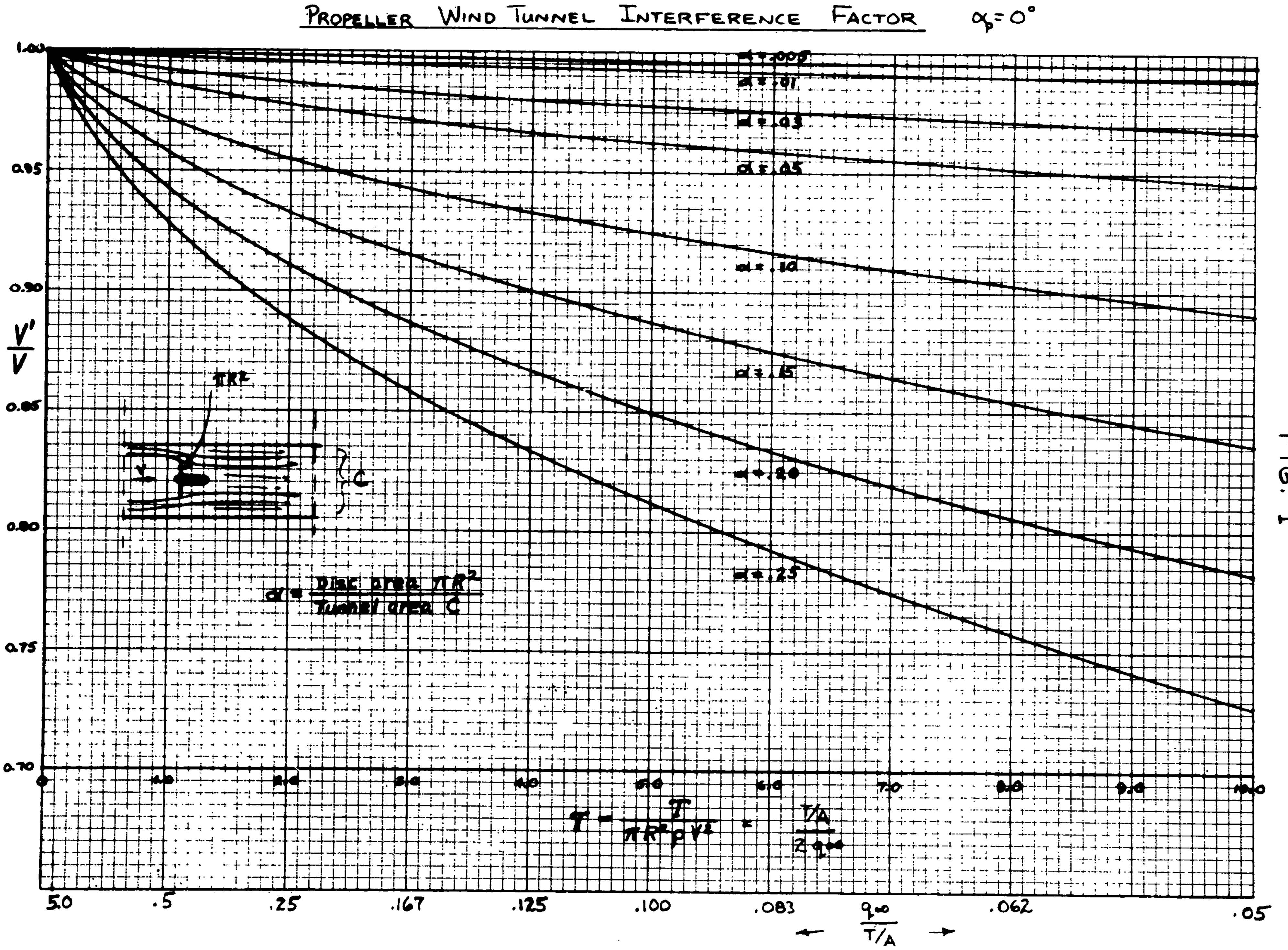
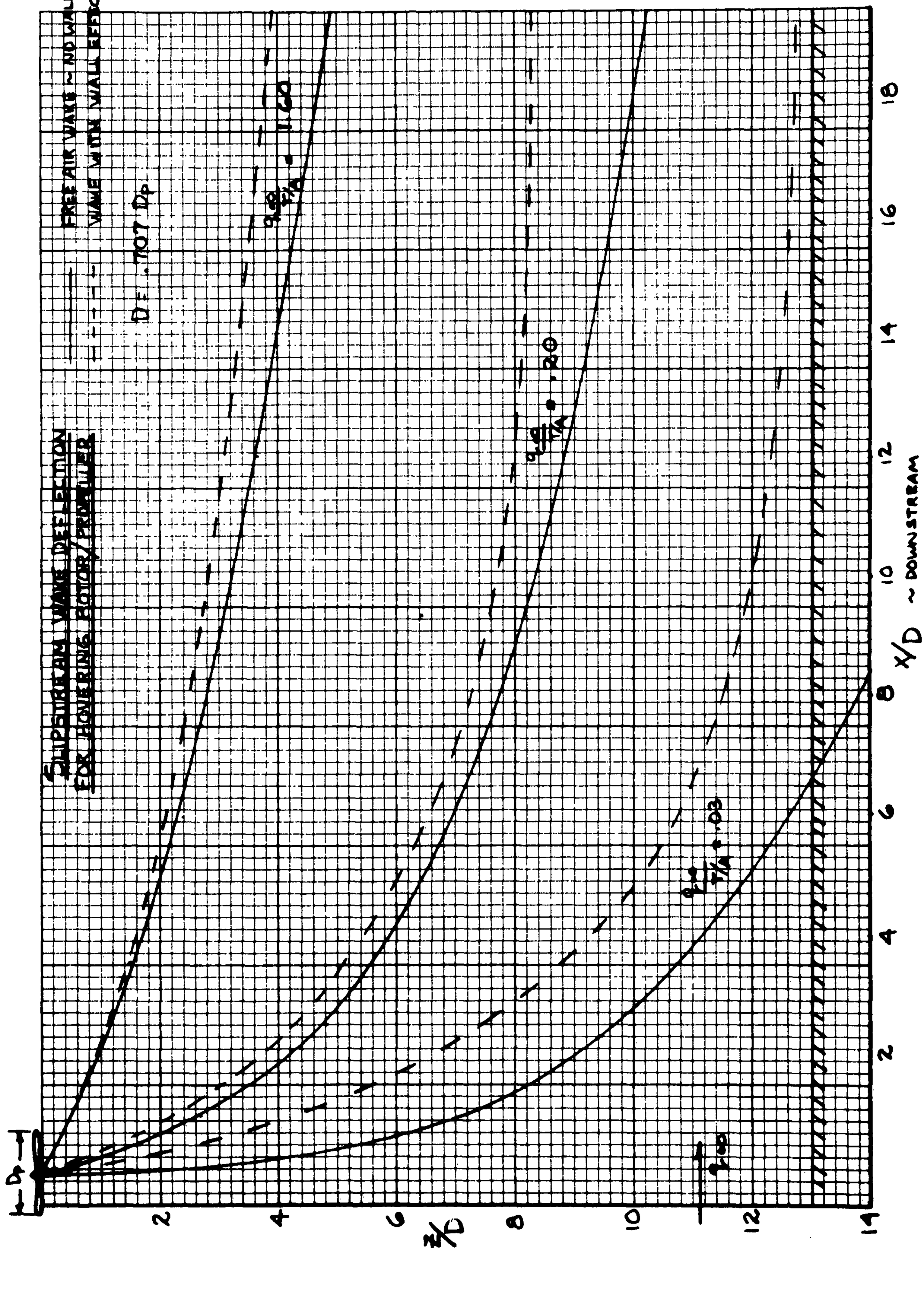


PROPELLER WIND TUNNEL INTERFERENCE FACTOR $\alpha_p = 0°$
$\frac{V'}{V}$
1.00
0.95
0.90
0.85
0.80
0.75
0.70
α = .005
α = .01
α = .03
α = .05
α = .10
α = .15
α = .20
α = .25
πR²
C
$\alpha = \frac{\text{Disc area } \pi R^2}{\text{Tunnel area } C}$
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
$\tau = \frac{T}{\pi R^2 \rho V^2} = \frac{T/A}{2 q_\infty}$
5.0
.5
.25
.167
.125
.100
.083
.062
.05
$\frac{q_\infty}{T/A}$

FIG. 1

FIG. 2



SLIPSTREAM WAKE DEFLECTION
FOR HOVERING ROTOR/PROPELLER
FREE AIR WAKE ~ NO WALLS
WAKE WITH WALL EFFECT
D = .707 Dp
Dp
q∞/(T/A) = 1.60
q∞/(T/A) = .20
q∞/(T/A) = .03
x/D ~ DOWNSTREAM
z/D

FIG. 3

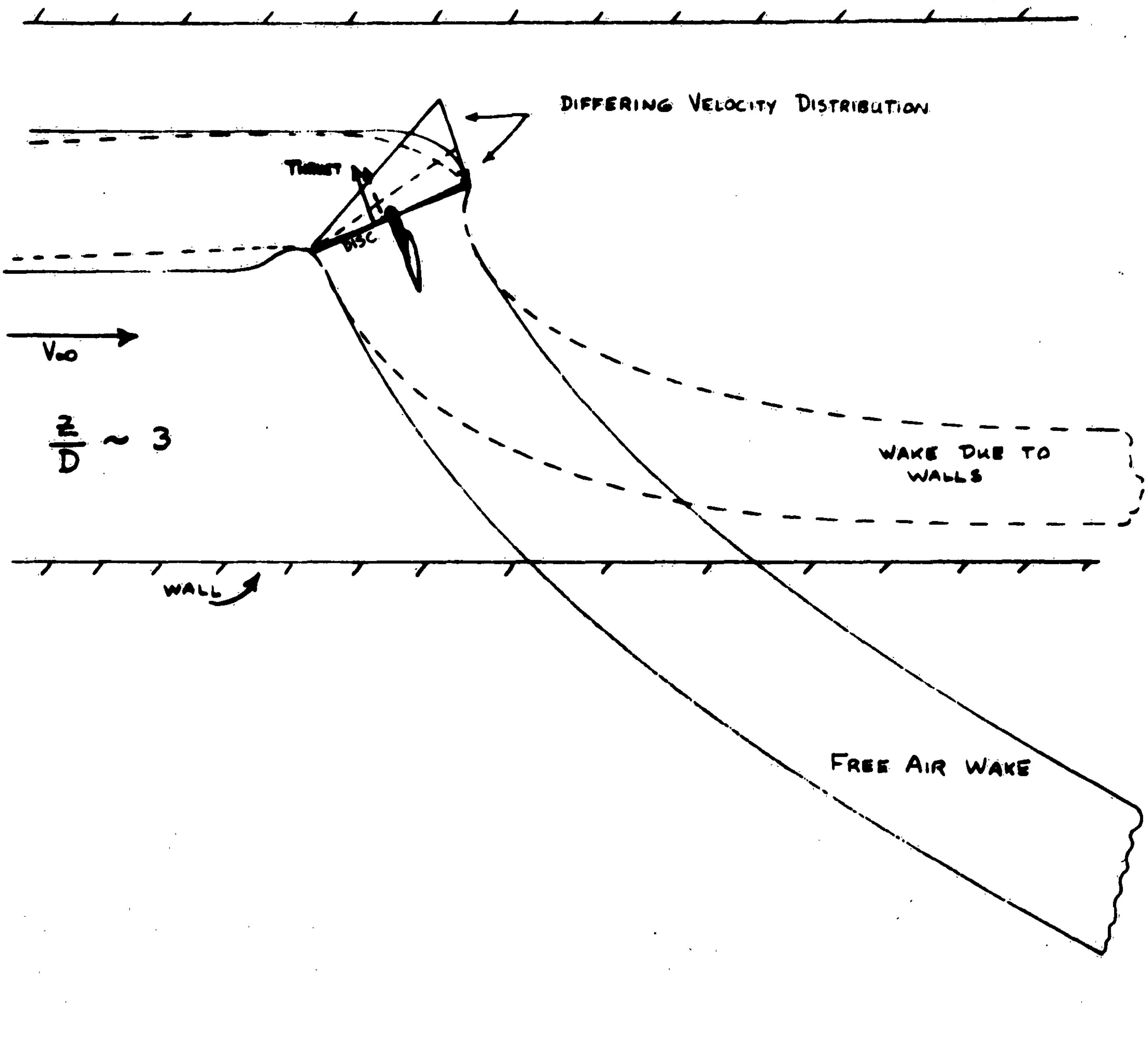
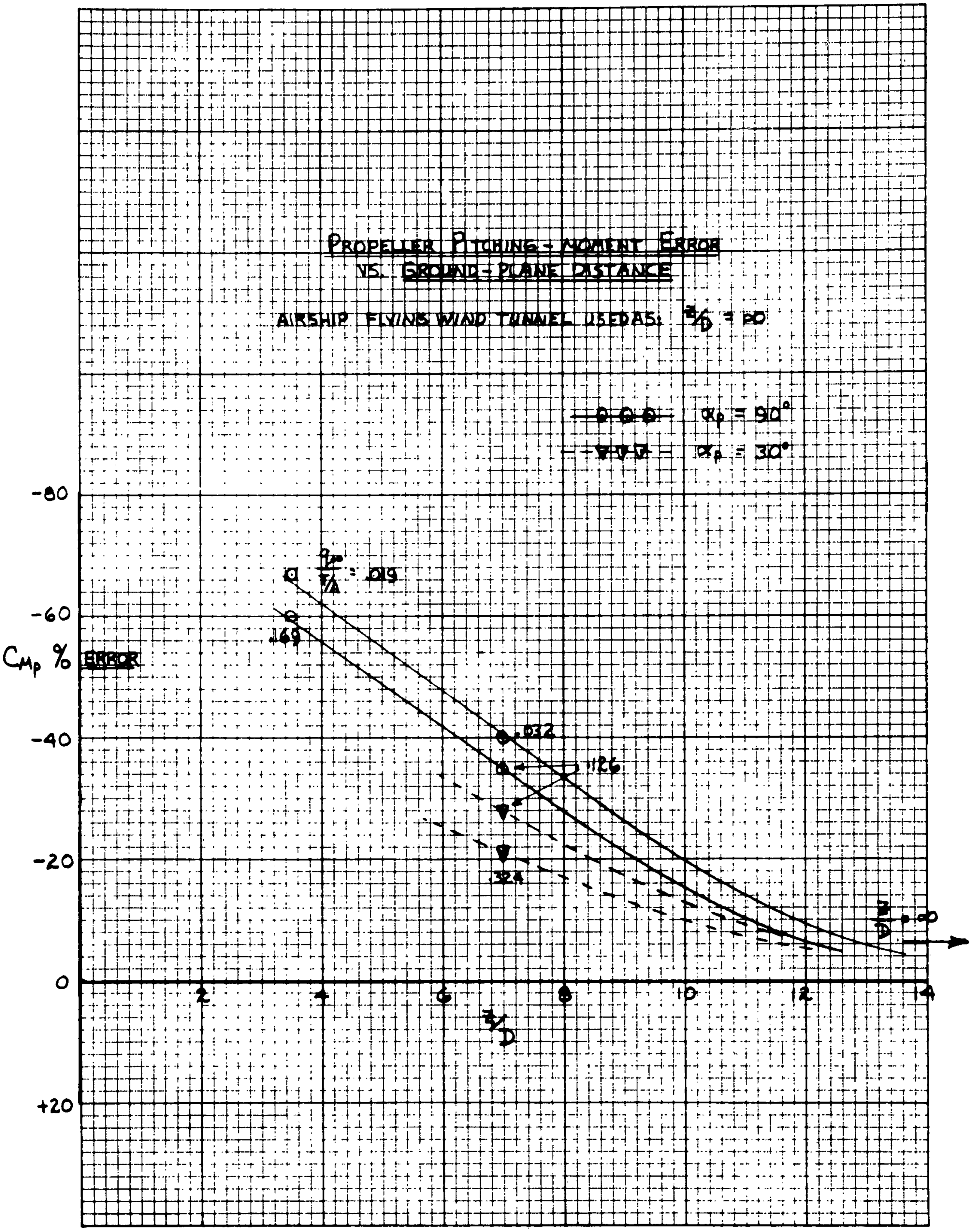


FIG. 3 CHANGE OF DISC LOAD DISTRIBUTION DUE TO WALL/GROUND EFFECT

FIG. 4



PROPELLER PITCHING-MOMENT ERROR
VS. GROUND-PLANE DISTANCE
AIRSHIP FLYING WIND TUNNEL USED AS: Z/D = ∞
αp = 90°
αp = 30°
-80
-60
-40
-20
0
+20
CMp % ERROR
.019
.169
.032
.126
.324
2
4
6
8
10
12
14
Z/D
Z/D = ∞

FIG. 4

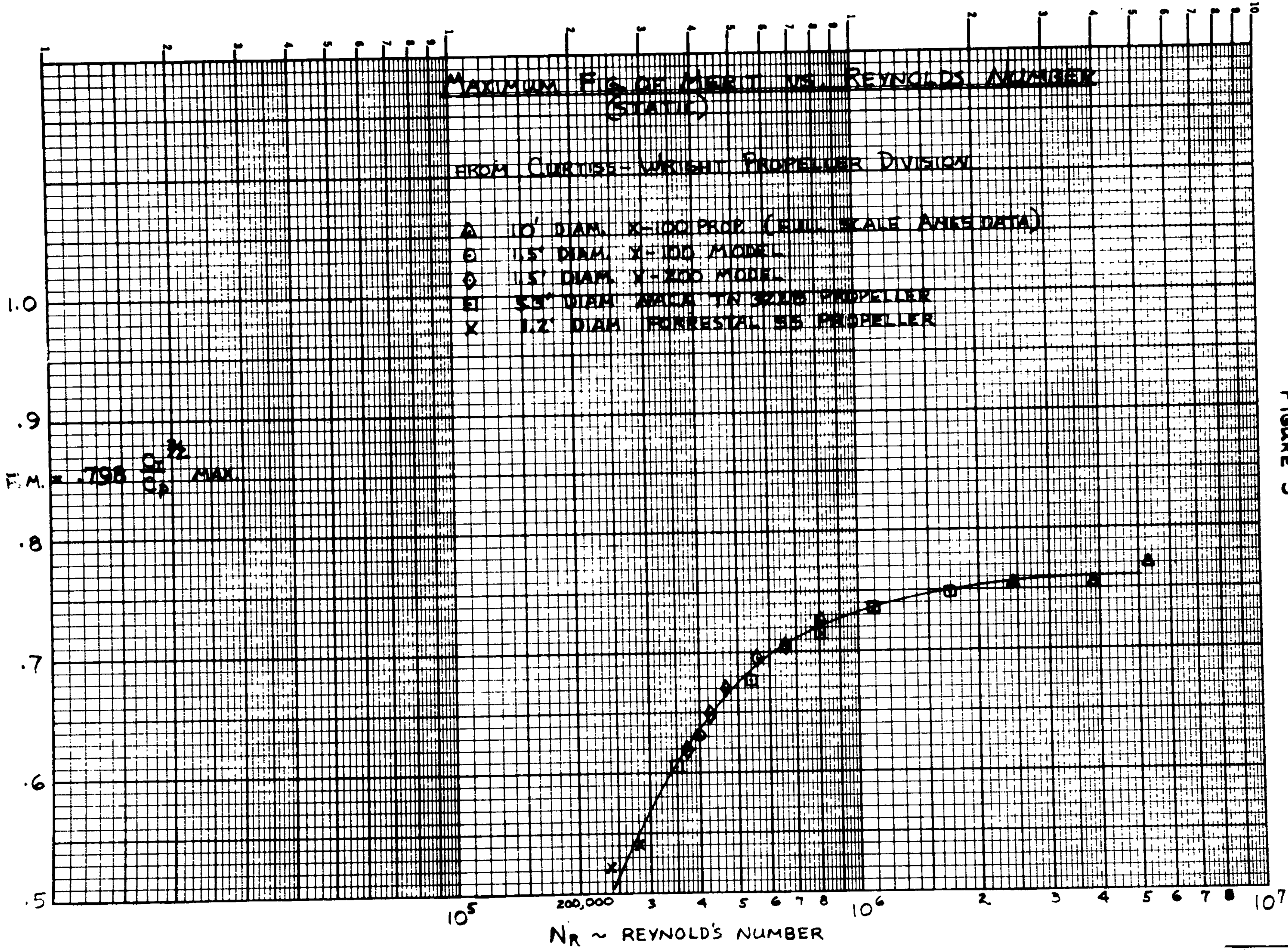

MAXIMUM FIG. OF MERIT VS. REYNOLDS NUMBER
(STATIC)
FROM CURTISS-WRIGHT PROPELLER DIVISION
△ 10' DIAM. X-100 PROP. (FULL SCALE AMES DATA)
⊙ 1.5' DIAM. X-100 MODEL
◇ 1.5' DIAM. X-200 MODEL
⊡ 5.5' DIAM NACA TN
X 1.2' DIAM FORRESTAL PROPELLER
F.M. = .798 $\frac{C_T^{3/2}}{C_P}$ MAX
1.0
.9
.8
.7
.6
.5
10^5
200,000
10^6
10^7
N_R ~ REYNOLD'S NUMBER

FIGURE 5

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- H. E. Payne, III

Report No. 545, May 1961
25 pages

Contract No. DA44-177-TC-524
Project No. 9-38-01-000, TK902
Unclassified Report

UNCLASSIFIED

1. VTOL-STOL
2. Wind Tunnel Design
3. Wind Tunnel Wall Effects
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