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By Hugh L. Dryden and Ira H. Abbott

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THE DESIGN OF LOW-TURBULENCE WIND TUNNELS[1]

By Hugh L. Dryden and Ira H. Abbott

SUMMARY

Within the past 10 years there have been placed in operation in the United States four low-turbulence wind tunnels of moderate cross-sectional area and speed, one at the National Bureau of Standards, two at the NACA Langley Laboratory, and one at the NACA Ames Laboratory. In these wind tunnels the magnitude of the turbulent velocity fluctuations is of the order of 0.0001 to 0.001 times the mean velocity. The existence of these wind tunnels has made possible the development of low-drag wing sections and the experimental demonstration of the unstable laminar boundary-layer oscillations predicted many years ago by a theory formulated by Tollmien and Schlichting.

The development of the low-turbulence wind tunnels was greatly dependent on the development of the hot-wire anemometer for turbulence measurements, measurements of the decay of turbulence behind screens, measurements of the effect of damping screens on wind-tunnel turbulence, measurements of the flow near a flat plate in air streams of varying turbulence, and measurements of the drag of specially designed low-drag airfoils. These investigations were conducted in collaboration with Schubauer, Skramstad, Jacobs, Von Doenhoff and other members of the staff of the National Bureau of Standards and the National Advisory Committee for Aeronautics, Von Kármán and Liepmann of the California Institute of Technology, and G. I. Taylor and his colleagues at Cambridge University.

This paper reviews briefly the state of knowledge in these various fields and those features of the results which make possible the attainment of low turbulence in wind tunnels. Specific applications to two wind tunnels are described.

INTRODUCTION

One of the important tools of airplane design is the wind tunnel, a tool older than the airplane itself. The increasing complexity of the airplane-design problem during the last 20 years has stimulated the continued improvement of wind tunnels and wind-tunnel techniques to provide data of increasing accuracy and applicability.

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The first essential requirement of wind tunnels, that of obtaining a reasonably steady air stream approximately uniform in speed and direction of flow across the test section, was met as long ago as 1909 in the wind tunnels of Prandtl and Eiffel, which produced a great wealth of scientific data to be applied to aircraft design. The presence of "scale effect," or influence of size of model and speed of test, was recognized at an early date and model tests were placed on a sound theoretical basis through use of the principles of dimensional analysis. The Reynolds number became the key measure of the applicability of wind-tunnel data. The desire to approach flight conditions of scale and speed as measured by the flight Reynolds number resulted in the obvious trend to wind tunnels of large size and high speed. Important advances in techniques included improved balances and other measuring equipment; new methods for supporting models, especially at high speeds; more accurate corrections for the effects of the limited size of the air stream; and the inclusion of the effects of power and of some dynamic flight conditions. These trends have continued to the present time.

One solution of the problem of scale effect was reached in 1923 with the construction of the variable-density wind tunnel by the National Advisory Committee for Aeronautics, in which the Reynolds number was increased by operating the wind tunnel at a pressure of 20 atmospheres, thus increasing the air density and the Reynolds number by a factor of 20. A second solution was reached with the construction of the full-scale wind tunnels in 1931 at the NACA Langley Laboratory and in 1944 at the NACA Ames Laboratory. These tunnels are large enough to test full-size small airplanes at moderate speeds.

As airplane speeds have increased, the principles of variable density and large size have been applied to high-speed wind tunnels with necessary compromises because of high power requirements. The goal is to approach full-scale Reynolds numbers and Mach numbers as closely as possible.

Less obvious, but equally important advances have been made in improving wind tunnels with regard to uniformity and steadiness in speed and direction of the air stream. The wind-tunnel air stream is characterized by the presence of small eddies of varying size and intensity which are collectively known as turbulence. Many aerodynamic measurements are greatly influenced by the values of the intensity and scale of these eddies even though the turbulent fluctuations may be very small as compared with the mean speed. Flight investigations have not indicated the presence of atmospheric disturbances of sufficiently small scale to cause appreciable aerodynamic effects.

The use of wind-tunnel data for predicting the flight performance of aircraft has always been hampered by the presence of turbulence in the air stream. Comparison of results obtained on spheres in the wind tunnels of Prandtl and Eiffel in 1912 showed that turbulence could have gross effects on aerodynamic measurements comparable with the effects of Reynolds number. Such results led to the establishment of international programs of tests of standard airfoil and airship models and to

numerous comparative tests of spheres in wind tunnels of different turbulence. It is now known that the drag of a sphere may vary by a factor as large as 4, the minimum drag of an airship or airfoil model by a factor of at least 2, and the maximum lift of an airfoil by a factor of as much as 1.3 in air streams of different wind tunnels at the same Reynolds and Mach numbers (references 1 to 5).

Improved simulation of flight conditions in wind-tunnel testing through the reduction of air-stream turbulence was slow in realization. Considerable confusion existed at one time about the desirability of reducing the turbulence. The effect of increased turbulence on some aerodynamic characteristics is qualitatively similar to increased scale, which was greatly desired. The apparent success in some applications of the concept of an "effective" Reynolds number led many investigators to believe that turbulence was desirable. Moreover, the wind-tunnel designer was faced with the practical situation that, although it was easy to increase turbulence, it was not known to what extent it would have to be reduced to simulate flight conditions and no effective method of reducing turbulence to small values was then known. The result was that the turbulence of the usual wind tunnel of about 10 years ago was of the order of 1/2 to 1.0 percent of the mean speed.

The reduction in turbulence of more recently constructed wind tunnels is largely the result of a better, though still incomplete, understanding of the effects of turbulence on the boundary layer and of the character of turbulence itself, especially the laws of decay and the effect of damping screens. This understanding was greatly dependent on the development of the hot-wire anemometer for quantitative turbulence measurements. Comparative drag measurements on low-drag airfoils in various wind tunnels and in flight showed the sensitivity of their characteristics to very low levels of turbulence and stimulated further work. These investigations were conducted in collaboration with Schubauer, Skramstad, Jacobs, Von Doenhoff, and other members of the staff of the National Bureau of Standards and the National Advisory Committee for Aeronautics, Von Kármán and Liepmann of the California Institute of Technology, and G. I. Taylor and his colleagues at Cambridge University.

It seems appropriate, because of the great importance of turbulence effects in fluid mechanics, to outline the principles of design of modern wind tunnels of low turbulence and to illustrate their application to two specific wind tunnels, the $4\frac{1}{2}$-foot wind tunnel of the National Bureau of Standards and the Langley two-dimensional low-turbulence pressure tunnel of the NACA.

SYMBOLS

A	cross-sectional area of wind stream or duct
C	constant
D	diameter of a sphere
L	scale of turbulence
P	pressure coefficient $\left(\frac{p - p_o}{\frac{1}{2}\rho U^2}\right)$
R	Reynolds number
R_e	"effective" Reynolds number
R_δ	Reynolds number based on thickness of boundary layer
R_y	correlation coefficient $\left(\frac{\overline{u_1 u_2}}{u_1 u_2}\right)$
U	mean speed
U'	mean turbulence intensity
c	contraction ratio of a wind tunnel $\left(\frac{A_s}{A_t}\right)$
c_d	section drag coefficient
f	turbulence reduction factor
k	pressure-drop coefficient for a screen $\left(\frac{p_u - p_d}{\frac{1}{2}\rho U^2}\right)$
n	number of screens
p	static pressure
p_o	static pressure of free stream
u	component of velocity fluctuations produced by turbulence, parallel to mean flow, measured with respect to mean speed

v, w	mutually perpendicular components of velocity fluctuations produced by turbulence, normal to mean flow and measured with respect to mean speed
u', v', w'	root-mean-square values of u, v, and w
$\overline{uv}$	mean value of product of u and v
x	distance measured parallel to mean flow
y	distance measured normal to mean flow
α	frequency parameter $\left(\frac{2\pi}{\lambda}\right)$
δ	boundary-layer thickness
δ^*	boundary-layer displacement thickness
λ	wave length
μ	viscosity of air
ν	kinematic viscosity (μ/ρ)
ρ	mass density of air

Subscripts:

0	conditions at a particular time or place
1, 2	values at neighboring points
s	settling chamber of a wind tunnel
t	test section of a wind tunnel
u, d	values at points upstream and downstream of a screen, respectively, in a duct of constant cross-sectional area

MEASUREMENT OF TURBULENCE

The understanding of turbulent flow and the development of methods for reducing the turbulence level are dependent on the existence of methods for measuring turbulence. The hot-wire anemometer has become the standard instrument for this purpose (references 6 to 9). Techniques have been developed for measuring the root-mean-square of the component u

of the velocity fluctuations in the direction of flow u' and corresponding root-mean-square values v' and w' for the components v and w in two directions perpendicular to the flow and to each other. Techniques have also been developed for measuring the mean value $\overline{uv}$ which is proportional to the turbulent shearing stress, and for measuring the correlation coefficients of the type $\frac{\overline{u_1 u_2}}{u_1' u_2'}$, where u_1 and u_2 are values of u at two neighboring points. From such measurements the average dimensions and shape of the eddies present in the air flow may be determined.

The turbulence in a wind-tunnel air stream not too close to a source of turbulence is a random motion with no periodic components present and is often, though not always, isotropic. In isotropic turbulence, $u' = v' = w'$ and $\overline{uv} = 0$. The magnitude of the fluctuations may then be specified by u'. The quantity u'/U, where U is the mean speed, is termed the intensity of the turbulence.

The scale of isotropic turbulence, which in effect specifies the average size of the eddies, is defined in terms of the correlation coefficient $R_y = \frac{\overline{u_1 u_2}}{u_1' u_2'}$ at two neighboring points separated by a distance y normal to the stream. The scale L is defined as

$$L = \int_0^\infty R_y \, dy$$

A more complete discussion of the intensity and scale of isotropic turbulence is given in reference 10.

The hot-wire anemometer is being continuously improved in ruggedness, convenience, and accuracy but it remains an instrument of considerable complexity and cost. The services of expert technicians are required for its successful maintenance and use. Consequently, there remains considerable interest in other methods for the qualitative determination of the general turbulence level of an air stream using only the measuring equipment normally available in any wind tunnel. Such methods must depend on the effect of turbulence in some aerodynamic measurement which can be calibrated in terms of u'/U and L.

Measurements of the drag coefficient of a sphere as proposed by Prandtl (reference 11) have been used with considerable success to indicate the turbulence level of the older wind tunnels (references 2, 4, and 10). The critical Reynolds number at which the drag coefficient of a sphere of diameter D decreased rapidly was found to be a function

of $\left(\frac{u'}{U}\right)\left(\frac{D}{L}\right)^{1/5}$, decreasing with increasing values of the turbulence parameter. The critical Reynolds number was stated either as that for which the drag coefficient of the sphere was 0.3 (reference 2) or that for which the pressure coefficient from an orifice in the rear portion of the sphere was 1.22 (references 4 and 10). The value of the critical Reynolds number for turbulence-free air is of the order of 385,000 (reference 4).

Although such sphere tests provide reliable indications of the general turbulence level in low-speed wind tunnels with high levels of turbulence (>0.5 percent), they are not suitable for tests in high-speed wind tunnels or in wind tunnels of very low turbulence. Thus, as a result of sphere tests in the Langley 8-foot high-speed tunnel, Robinson (reference 12) shows that spheres could not be used to determine the turbulence level at speeds above about 270 miles per hour because compressibility effects completely masked the effects of Reynolds number and turbulence. The sphere is also insensitive to the effects of low levels of turbulence. Thus, Robinson measured critical Reynolds numbers at low speeds in the 8-foot tunnel that were essentially the same as those for free air. Subsequent measurements of the turbulence in this wind tunnel with a hot-wire anemometer showed the intensity of the longitudinal fluctuations to be about 0.15 percent and the horizontal normal component about 0.5 percent of the speed corresponding to the sphere measurement. This turbulence level is now known to be sufficiently high to affect considerably the Reynolds number of transition of a laminar boundary layer in a region of zero or small falling pressure gradient.

The drag characteristics of smooth and fair NACA low-drag airfoils were known to be sensitive to turbulence. Jacobs proposed that this characteristic might be used to indicate the relative turbulence level of wind tunnels for which the turbulence could not be evaluated by sphere tests. Even small increases of the turbulence level reduced the Reynolds number at which the transition point moved upstream from the location of minimum pressure with a corresponding increase of drag.

A special symmetrical airfoil was designed for this purpose. The section (fig. 1 and table I) was 15 percent thick and had a very low, slightly favorable pressure gradient selected to increase the sensitivity of the laminar boundary layer to low turbulence levels as compared with the sensitivity of the usual NACA low-drag airfoils. A steel model of this section was constructed with a span of $91\frac{1}{4}$ inches and a chord of 60 inches. The model was constructed in three sections to permit tests to be made in either the narrow test sections of the Langley two-dimensional tunnels or in the large conventional wind tunnels. The central portion of the model was built of a $\frac{3}{16}$-inch-thick stainless-steel skin on cold-rolled-steel ribs. Comparative tests of other models of the same section showed that no surface irregularities were present that would affect transition in the Langley two-dimensional low-turbulence pressure tunnel.

Drag tests of the model at zero angle of attack using the wake-survey method were made in several NACA wind tunnels.

Results of drag tests of the model in four low-speed NACA wind tunnels are shown in figure 2. The turbulence level of the Langley two-dimensional low-turbulence pressure tunnel (TDT) is a few hundredths of 1 percent (reference 13) according to hot-wire measurements. Similar measurements in the Langley 19-foot pressure tunnel showed the turbulence level of this tunnel to be about 0.3 percent based on the longitudinal component. The NACA 7- by 10-foot wind tunnels are indicated to have an intermediate turbulence level, while the Ames 12-foot low-turbulence pressure wind tunnel appears to have the lowest.

A comparison of the drag measurements for the model in the Langley 8-foot and Ames 16-foot high-speed tunnels is given in figure 3, together with the data from the low-turbulence tunnel for comparison. The drag data from the high-speed tunnels differ from those obtained in the low-speed tunnels in that, following the original drag rise, the drag curve levels out and even decreases with increased Reynolds numbers. This result is thought to be associated with compressibility effects, and the data should not be interpreted to indicate a very low turbulence level at high speed. Even though the data were obtained at speeds below the critical, compressibility effects may be expected to increase the favorable pressure gradients along the airfoil surfaces and thus to increase the stability of the laminar layer at the high speeds. The stagnation pressures of both the high-speed tunnels are substantially atmospheric and, consequently, equal Reynolds numbers indicate approximately equal Mach numbers. It may, therefore, be concluded that the Ames 16-foot tunnel has a lower level of turbulence than the Langley 8-foot tunnel.

It may be concluded that drag measurements on a smooth, fair model of a sensitive low-drag airfoil are useful for the qualitative determination of the relative levels of turbulence of wind tunnels having turbulence levels of the order of a few hundredths to a few tenths of 1 percent, provided the measurements are made at low Mach numbers. Considerable research will be necessary to develop similar methods suitable for high Mach numbers.

ORIGIN AND DECAY OF TURBULENCE

Recent progress in the reduction of turbulence in wind tunnels is dependent on the knowledge which has been gained of the origin and decay of turbulent motion. The presence of turbulence in a flow may be traced to the existence of a discontinuity in temperature, density, or velocity in the flow. Such a surface of discontinuity may arise in the flow around or near a solid body as a result of flow separation, as a result of an incoming jet of air, or in various other ways. As a consequence of a dynamic instability, such a surface of discontinuity rolls up into

discrete vortices; because of the viscosity the localized vorticity then diffuses to form the fully developed turbulent motion. Even in the case of frictional flow along a surface, an instability develops which finally leads to turbulent motion.

Much of the information about the origin and decay of turbulence has been derived from experiments on circular cylinders or on screens made up of woven wire. No turbulence will be generated if the Reynolds number is sufficiently low. Dr. Schubauer in his report on damping screens (reference 14) shows that no turbulence is shed by a screen if the Reynolds number is less than about 30 to 60, the value depending on the mesh and wire diameter of the screen. Thus, for any reasonable speed and size of object, any obstruction in a wind-tunnel air stream will generate turbulence.

At some distance from the source the turbulence will tend to become isotropic. The laws of decay of isotropic turbulence have been investigated both experimentally and theoretically but are not yet finally established. Taylor (reference 15) gave the relation

$$\frac{1}{u'} - \frac{1}{u_0'} = C \int_0^x \frac{dx}{UL} \tag{1}$$

where u_0' is the intensity of the turbulence at the point from which x is measured, u' is the intensity of the turbulence at the point x, U is the mean speed at x, and L is the scale of the turbulence at the point x. The value of the constant C has been found to be about 0.22 for wire screens with wire diameter equal to about one-fifth the mesh distance (reference 10). There is reason to believe that the value of the constant does not vary greatly with the shape of the turbulence-producing obstacle.

When the turbulence is produced by screens, the value of L increases with increasing x. Little information is available as to the variation of L with the shape of the turbulence-producing obstacle or as to changes in L during flow through a passage of changing cross section, as in the entrance section of a wind tunnel. However, the scale of the turbulence at a distance of about 200 diameters behind a wire is of the order of the diameter of the wire.

Very near the source of turbulence, that is, at values of x less than about 100 times the wire diameter, the turbulence is not isotropic and there is appreciable variation of mean speed in the wake of the obstacle. The test section of a wind tunnel should in no case be so close to a turbulence-producing obstacle.

Many experiments have been made of the variation of u' and L behind screens in a stream of uniform speed and cross section. In the present state of knowledge the following relations are suggested for design purposes

$$\left(\frac{u_0'}{u'}\right)^2 = 1 + 0.58\,\frac{u_0'}{U}\,\frac{x - x_0}{L_0} \tag{2}$$

$$\left(\frac{L}{L_0}\right)^2 = 1 + 0.58\,\frac{u_0'}{U}\,\frac{x - x_0}{L_0} \tag{3}$$

where u' and L are the intensity and scale at x, and u_0' and L_0 are the intensity and scale at x_0. These relations are believed to be conservative. Theoretical considerations suggest that in many cases as the intensity decreases to low values the rate of decrease is greater than indicated by the formulas (references 16 and 17). Even though these equations may not be rigorously accurate over a wide range, they are a sufficient guide to methods of reducing the turbulence in wind tunnels.

SOURCES OF WIND-TUNNEL TURBULENCE

In a satisfactory wind tunnel, the speed and direction of the flow at any point are free of long-period fluctuations; and the short-period fluctuations, collectively classed as turbulence, are statistically constant. In other words, the flow must be free of large eddies or speed changes associated with such effects as unsteady separations of the boundary layer on the tunnel wall. The flow in the diffuser and return passages should be checked and all permanent or unsteady flow separation eliminated. Sometimes this can be done by airfoil deflectors to deflect high-speed air into a separating region, by screens to promote filling of the diffuser, or by boundary-layer suction. At any rate, large-scale slow fluctuations must be eliminated.

The turbulence in the test section of a wind tunnel may not be identified with that normally present in pipe flow at Reynolds numbers above the critical value. The contraction and acceleration of the air stream entering the test section produce a stream with a core of nearly uniform speed with a thin boundary layer at the walls. The growth of the boundary layer through the short test section is small compared with the dimensions of the air stream, and fully developed turbulent pipe flow does not result.

While the turbulent boundary layer flowing against the increasing pressure in the diffuser and return passage thickens rapidly, this source of turbulence appears to be much less important than the wakes of objects in the stream in various parts of the circuit. Such objects are the propeller with its associated mountings, spinner, and antiswirl vanes and the essential guide vanes at the corners of the circuit. Honeycombs are seldom used in large modern wind tunnels. Guide vanes, like honeycombs, are fairly effective in reducing large-scale turbulence originating upstream. Consequently, the set of guide vanes immediately upstream from the test section is usually the most important source of turbulence.

Recent experiments and theoretical analyses (references 18 to 20) have shown that the noise of the propeller and other sound sources may place a lower limit on the turbulence level since sound waves cause air motions which produce an effect similar to that of turbulence.

METHODS OF REDUCING TURBULENCE

The form of equations (1), (2), and (3) suggests certain methods of reducing turbulence – namely, (a) reducing u_0', the initial intensity of the turbulence; (b) making the distance x from the source of the turbulence to the test section as great as possible; (c) making the scale of the turbulence as small as possible; and (d) keeping the mean speed U small for the greatest possible part of the distance x. These considerations lead to the design of a wind tunnel with a large contraction ratio; individually small, closely spaced, and well-designed guide vanes at the corner directly upstream from the test section; and a long settling chamber between this corner and the start of the contraction of the entrance cone. With such measures it has been possible to obtain turbulence levels of 0.25 percent with a contraction ratio of 7. These design features are also favorable for the introduction of damping screens which have permitted a further reduction of turbulence by a factor of 6 or more.

The aerodynamic characteristics of damping screens are presented by Dr. Schubauer in considerable detail (reference 14). It is sufficient for the present purpose to note that damping screens reduce the intensity of the oncoming turbulence and, unless their Reynolds number is very low, generally introduce a small-scale turbulence.

As shown by Schubauer, the effectiveness of one screen in damping the oncoming turbulence is well approximated by the formula

$$f = \frac{1}{\sqrt{1 + k}} \tag{4}$$

or, in the case of n screens (reference 19)

$$f = \frac{1}{(1 + k)^{n/2}} \tag{5}$$

where f is the reduction factor and k is the pressure-drop coefficient for the screen. It is obviously more efficient to obtain a desired reduction factor by the use of several screens with small pressure-loss coefficients rather than by the use of a single dense screen.

If the damping screens are operated above their critical Reynolds number, turbulence is caused by the screens themselves with the result that the intensity immediately downstream from a screen may be considerably higher than that upstream. The utility of the screens in reducing turbulence results from the rapid decay of the fine-grain turbulence resulting from the screen. These effects are shown in detail in the paper by Schubauer.

In the course of work associated with the design of screens for the NACA low-turbulence wind tunnels in 1939, it was noted from tests of screens in a smoke tunnel that no turbulence was produced if the screens were operated at sufficiently low Reynolds numbers (reference 13). This effect has been studied by Schubauer who found that every screen has a well-defined Reynolds number, which depends on solidity, below which eddies are not shed. Although the screens of the NACA low-turbulence wind tunnels are designed to operate below the critical Reynolds number, the practical necessity for so doing has not been proved. It appears that the decay of the fine-grain turbulence from a screen of small mesh size permits a very low turbulence level to be obtained at ordinary distances from the screen.

An important consideration in the application of damping screens is the abnormal behavior of certain screens reported by Schubauer. Although not understood, the production of abnormally high, slowly decaying longitudinal fluctuations by certain screens is thought to be associated with imperfections of these screens. It appears important, especially in the case of large screens, to select a mesh and wire size capable of being woven with accuracy and to handle the screen in such a manner as to avoid distortion of the mesh in installation.

EFFECTS OF CONTRACTION

A large contraction or area ratio between the settling chamber and test section has several advantages. A large contraction ratio results in a low airspeed in the settling chamber, thus permitting the installation of a number of damping screens without excessive penalty for

the power absorption and also permitting greater decay of turbulence in a given length of settling chamber. Furthermore, unless the contraction has the effect of greatly increasing the turbulent energy of the stream, the ratio of the turbulent intensity to the mean speed will decrease through the entrance cone as the mean speed increases.

The effects of contraction have been studied theoretically by Prandtl (reference 21) and Taylor (reference 22). These studies were limited by consideration of only regular types of disturbance and neglect of decay. Taylor's results depend on the type of disturbance assumed and indicate that contraction may result in either an increase or a decrease of the turbulent energy. Prandtl predicts a decrease of u' in the ratio $1/c$ and an increase of v' and w' in the ratio $\sqrt{c}$, where c is the contraction ratio. If a turbulent intensity U' is defined as

$$U' = \sqrt{\frac{1}{3}\left(u'^2 + v'^2 + w'^2\right)}$$

then, according to Prandtl, U' would vary as

$$\sqrt{\left(\frac{2c}{3}\right) + \left(\frac{1}{3c^2}\right)}$$

This formula would predict an increase of U' of approximately 2 for a contraction ratio of 6 and of 3.5 for a ratio of 18 and result in a net reduction of the ratio U'/U of 0.33 and 0.19, respectively.

Such calculations should be used cautiously because of limitations of the theory. Experimental observations show that contraction, by exerting a selective effect on the components of velocity fluctuations, decreases u' and increases v' and w'. It is not known that decay in the contracting region can be predicted quantitatively by linear considerations of the velocity and distance traveled or that the results can then be superposed on the estimated effect of contraction. Measurements at the National Bureau of Standards in the $4\frac{1}{2}$-foot tunnel, behind the screens in the settling chamber and in the test chamber, indicate (reference 19) for this particular case that the effects of contraction and decay on the turbulent energy substantially cancel each other. This result should not be generalized, however, without further study.

APPLICATION OF PRINCIPLES TO SPECIFIC WIND-TUNNEL DESIGNS

The $4\frac{1}{2}$-Foot Tunnel of the National Bureau of Standards

The application of the methods of reducing wind-tunnel turbulence is illustrated by the modernization of the $4\frac{1}{2}$-foot wind tunnel of the National Bureau of Standards. Figure 4 is a photograph of the wind tunnel and figure 5 is a longitudinal section through the center line. The design of the tunnel was begun in November 1937, and construction was completed in September 1938.

The over-all length of the tunnel is 80 feet and the height is 25 feet, these dimensions being fixed by the requirement that the tunnel be housed in the existing building. The structure above the ground line, except for the entrance section, consists of tongued and grooved pine boards fastened to angle-iron framing. The entrance section is made of galvanized iron fastened to joined wooden stringers. The structure below ground level is of reinforced concrete.

The test section is 19 feet long. Its cross section is a regular octagon, $4\frac{1}{2}$ feet between opposite faces. The expanding exit cone provides a transition from the octagonal cross section at the test section to the 7-foot circular cross section at the fan. The eight-blade fan is driven by a 75-horsepower, direct-current motor. The return duct is rectangular in cross section throughout its length. The straight section or settling chamber upstream of the entrance section is octagonal in cross section, 12 feet across the flats, and 7 feet long. The contraction ratio is 7.1:1.

Commercial guide vanes are used at the four corners as indicated in figures 4 and 5. The guide vanes in the first turn upstream from the test chamber are of $2\frac{7}{8}$-inch chord and are spaced $1\frac{1}{2}$ inches on centers. The guide vanes in the other turns are of $6\frac{1}{2}$-inch chord and are spaced $3\frac{3}{8}$ inches on centers. Damping screens are installed in the settling chamber.

The turbulence levels in the test section of the tunnel with various single screens and combinations of two, three, and six screens installed in the settling chamber are summarized in table II. The turbulence level expressed as the ratio U'/U_t is seen to vary from 0.265 percent with no damping screens to 0.043 percent with six screens. The predicted values of the turbulence level with screens based on a damping factor of

$$\frac{1}{(1 + k)^{n/2}}$$

are also given in table II. It will be seen that the agreement of predicted and measured turbulence levels is excellent, considering the limitations of the theory, except at the lower levels where the measured values are higher. This discrepancy is thought to be associated with noise as previously mentioned.

It is apparent that the use of damping screens is the most important feature in obtaining a very low level of the turbulence. It should be noted, however, that the turbulence level without damping screens is relatively low, especially for a wind tunnel of this size. This relatively low initial turbulence level undoubtedly simplifies the screen installation required and is obtained by the use of small, closely spaced guide vanes and a long settling chamber.

Langley Two-Dimensional Low-Turbulence Pressure Tunnel

The Langley two-dimensional low-turbulence pressure tunnel (reference 13) was designed especially for research on wing sections. A low-turbulence air stream was desired in which systematic investigations of large numbers of airfoils could be made at flight values of the Reynolds numbers. It was also considered desirable to test the wing sections in two-dimensional flow to obviate the difficulties that had been encountered in the NACA variable-density tunnel in obtaining section data from tests of finite-span wings and in correcting adequately for support interference.

Preliminary design of such a wind tunnel was started in 1937, and a full-scale model of the tunnel was completed in 1938. This model, which differs in detail from the final design, was constructed cheaply to operate at atmospheric pressure and is known as the Langley two-dimensional low-turbulence tunnel. The final tunnel (figs. 6 and 7) was placed in operation early in 1941. It is of welded steel construction to permit operation at pressures up to 10 atmospheres. The test section is 3 feet wide, $7\frac{1}{2}$ feet high, and $7\frac{1}{2}$ feet long. The contraction ratio is 17.6:1. The tunnel is powered by a 2000-horsepower motor driving a 20-blade fan 13 feet in diameter.

Structural requirements of the pressure shell imposed compromises on the design of the tunnel. The principles of use of damping screens were inadequately understood at the time construction of the tunnel was started. The results of research at the National Bureau of Standards and of experience with the model of the tunnel required complete revision of the planned screen installation. The screen installation was consequently made in an air passage and structure not designed for its accommodation. The final arrangement is not considered to be optimum.

An unusual feature of the tunnel is the torus-like bends with six corners at the large end and eight corners at the small end to accomplish

each 180° turn. Eight sets of guide vanes are provided at the small end and three "splitter" vanes at the large end. These features of the tunnel were dictated by cost and strength requirements and are not believed to be aerodynamically desirable.

Cooling coils supported on a coarse honeycomb are mounted in the large end of the tunnel upstream of the entrance section. A screen with 60 meshes to the inch is fastened to the downstream face of the honeycomb. A series of 11 damping screens is mounted between the dense screen and the entrance section. Each screen has 30 meshes per inch with 0.0065-inch-diameter wire. The screens are installed 3 inches apart. Each damping screen has a pressure coefficient of approximately 1.0. The last damping screen is located at the beginning of the contracting section.

It will be noted that, in contrast with the NBS $4\frac{1}{2}$-foot tunnel, reliance is placed on the cooling-coil damping-screen installation to reduce the high turbulence resulting from the aerodynamically unfavorable turns of the air passage.

Great care was taken with the screen installation (reference 13) because it was not known exactly what imperfections could be tolerated and because of the difficulty of inspection, repair, or replacement once the installation was made. The phosphor-bronze screen was specially woven in 7-foot-wide strips with special selvages. The strips were fastened together by sewing with 0.0065-inch-diameter wire with a stitch that preserved equal density of the screen across the seam. The resulting screens were installed so that any wakes from the seams would pass above and below the model. Each screen was tensioned along its periphery to a stress corresponding to about one-half the yield value to reduce sagging under load. Care was taken to make and install the screens without touching them by hand in order to avoid possible future corrosion that would eventually cause local changes in the pressure-drop coefficient. It is not known to what extent these precautions are required, but it is now thought that considerable relaxation of these specifications would result in a satisfactory installation.

Only limited measurements of the tunnel turbulence have been made with a hot-wire anemometer. The results of some of the measurements are presented in figure 8 for a pressure of 4 atmospheres. (See reference 13.) The turbulence levels presented are values of u'/U. It will be seen that, at this tunnel pressure, the turbulence level increases from about 0.02 percent at low speed to a value of about 0.05 percent at a speed corresponding to a Reynolds number of about 4.5×10^6 per foot of model chord. At higher speeds, the turbulence rises more rapidly. Spot checks of the turbulence level at other pressures indicate that increasing pressure is favorable for obtaining a low level of turbulence at a given value of the model Reynolds number. No wakes from the seams in the screens have been detected.

It is interesting to note that the more rapid rise of the turbulence shown in figure 8 occurs at roughly the Reynolds number where the damping screens begin to produce turbulence themselves. It is not thought, however, that this result is significant even with the comparatively small distance for decay provided in this installation. The existence of lower turbulence levels at the same Reynolds number at higher tunnel pressures also tends to discount such an explanation for the increase of turbulence with speed. Qualitatively, it has been noted that there is a tendency for the intensity of the turbulence to correlate with the power input to the tunnel and with the noise level. It is thought that vibration and noise are factors limiting the turbulence of this tunnel.

Many features of the two-dimensional low-turbulence pressure tunnel were not used in the design of the Ames 12-foot pressure tunnel, although compromises with the requirements of the pressure shell were still necessary. In particular, six sets of guide vanes were used instead of splitter vanes in the 180° turn upstream of the entrance section. The cooling coil was eliminated and a settling chamber was provided in which a simplified screen installation was mounted. As indicated by figure 2, this newer tunnel is believed to have a lower turbulence level than the two-dimensional wind tunnel.

CONTRIBUTION OF LOW-TURBULENCE WIND TUNNELS TO AERONAUTICAL SCIENCE

The two low-turbulence wind tunnels which have been described have been essential tools in two major contributions to aeronautical science: The experimental confirmation of the Tollmien-Schlichting theory of the stability of laminar flow and the development of low-drag airfoils.

Stability of Laminar Boundary Layer

The effects of turbulence on aerodynamic measurements have long been known to be intimately connected with transition from laminar to turbulent flow in the boundary layer. Until recently the mechanism of transition was a subject of considerable discussion and controversy. A theoretical treatment of the related problem of the stability of laminar flow in a boundary layer had been given by Tollmien and Schlichting (references 23 and 24). Their computations indicated instability of the two-dimensional laminar layer with Blasius velocity distribution to small sinusoidal disturbances if the Reynolds number exceeded a value which was a function of the wave length of the disturbance. Tollmien (reference 25) extended this work to investigate the effects of pressure gradients, showing especially that the distortion of the Blasius profile associated with rising pressures in the direction of the flow was unfavorable to laminar stability.

The Tollmien-Schlichting theory was not accepted immediately as a satisfactory explanation of the mechanics of transition. For the mathematical reason of obtaining a linear differential equation, a very small disturbance was assumed although it was known that the usual disturbances were not small. The theory did not predict transition in the sense of the change from laminar to eddying flow but rather predicted the conditions for damping or amplification of the very small disturbances. The theory showed that laminar stability was a critical function of the wave length or frequency of the disturbances, whereas all experimental results appeared to indicate that the point of transition was little affected by the frequency if the amplitude was fixed.

Experimental work at the National Bureau of Standards (reference 26) established the existence of comparatively large fluctuations of speed in the laminar boundary layer over a flat plate well upstream of the point of transition. These measurements were made by means of hot-wire apparatus with different pressure gradients along the plate and with different levels of turbulence of the air stream. It was shown that the fluctuations did not cause the average velocity distribution to depart from the Blasius velocity profile and, consequently, that turbulent shearing stresses were not associated with these fluctuations. Transition caused a departure from the Blasius distribution to the characteristic turbulent velocity profile, but the laminar and turbulent boundary layers could not be distinguished on the basis of the magnitude of the speed fluctuations alone. It was not apparent from these data, however, whether the observed fluctuations were "free" oscillations of the Tollmien-Schlichting type or whether they were "forced" oscillations produced by the turbulence of the air stream.

Later, during the investigations of low-drag airfoils at the NACA in air streams of very low turbulence, it was observed that small three-dimensional protuberances on the airfoil surfaces either caused transition to occur almost immediately at the protuberance or did not affect transition at all. Small two-dimensional protuberances or waves, however, often caused transition to occur sooner than on the smooth surface, but still a long distance downstream from the protuberance. The velocity distribution, as measured by pressure probes, in the laminar layer between the protuberance and the point of transition was not affected by these small protuberances. It was apparent that some transition-producing mechanism existed that was not associated with the shape of the average velocity distribution. The Tollmien-Schlichting concept of amplified disturbances provided a qualitative explanation of such phenomena.

Schubauer and Skramstad (reference 18) extended the work at the National Bureau of Standards to the lowest attainable level of the free-stream turbulence. By an ingenious method of introducing disturbances of known frequency by a small vibrating ribbon, they confirmed the Tollmien-Schlichting theory both with respect to the concept of amplification of small disturbances and quantitatively as regards the calculation of the stability boundaries. The experimental results are shown in figure 9, together with the stability boundaries as calculated by Lin (reference 27).

The mechanism of the instability of the laminar boundary layer is now well understood. Whatever small disturbances are initially present are selectively amplified until large sinusoidal oscillations occur. These regular waves grow in amplitude, become distorted, and burst into high-frequency fluctuations. The nonlinear problems of the amplification of the large oscillations and of the mechanism of conversion to turbulent flow remain problems for future research.

It should be noted that the theory of Tollmien and Schlichting has been extended to compressible flows over flat plates by Lees and Lin (references 28 and 29) and that Liepmann (reference 30) investigated the effects of convex and concave surfaces. Liepmann showed that the effects of convexity were small but that the mechanism of transition on concave surfaces was different, being three-dimensional in nature.

It is significant that the work of Schubauer and Skramstad required the use of an air stream of very low turbulence (about 0.02 percent). The earlier work in an air stream with a turbulence level of about 0.5 to 1.0 percent had been confused by transition associated with momentary separation resulting from finite disturbances in the free stream as proposed by G. I. Taylor in reference 31. The fundamental difference in the mechanism of transition in a turbulent air stream and in a stream of very low or zero turbulence makes it imperative that aerodynamic measurements be made in a low-turbulence air stream if they are to be accurately applicable to free flight.

Low-Drag Airfoils

The Langley two-dimensional low-turbulence pressure tunnel has permitted the systematic investigations required for the development of useful low-drag airfoils. It had become apparent in 1937 that any further pronounced reduction of the profile drag of wings must be obtained by a reduction of the skin friction through increasing the relative extent of the laminar boundary layer. The attainment of extensive laminar boundary layers at large Reynolds numbers was an unsolved experimental problem. Although the mechanism of transition was not understood, it was known that low turbulence and the avoidance of increasing pressures in the direction of flow were requirements for extensive laminar flow.

The requirement of low turbulence could best be met by flight tests, and numerous investigations have been made in flight following the pioneer work of Jones (reference 32) who demonstrated the possibility of obtaining extensive laminar layers at fairly high Reynolds numbers. Flight investigations do not, however, provide a practical method for the systematic tests required to obtain a useful family of airfoils. Only in a wind tunnel is it practical to make the extensive airfoil investigations required by our inadequate understanding of the turbulent boundary layer and our consequent inability to predict airfoil characteristics except to a limited extent at low lift coefficients.

The completion of the model two-dimensional tunnel in 1938 provided a facility for exploratory investigations even though the initial turbulence level was not satisfactory. The first test in this tunnel in June 1938 of an airfoil designed to permit laminar flow indicated a minimum drag coefficient of 0.0033, or about one-half of the lowest drag coefficient ever before measured for an airfoil of comparable thickness. Figure 10 shows comparative drag data for an early low-drag airfoil as obtained in the low-turbulence tunnel (LTT) and in the variable-density tunnel (VDT). (See reference 5.) The minimum drag coefficient measured in the low-turbulence tunnel is less than one-half that from the highly turbulent variable-density tunnel. The small range of lift coefficient over which low drag is obtained results partly from the now obsolete shape of the airfoil and partly from the unsatisfactory turbulence level of the tunnel as initially constructed (about 0.1 percent). The turbulence level of the model tunnel was later lowered (u'/U about 0.02 percent) by a screen installation generally similar to that previously described for the pressure tunnel (reference 13).

Exploratory investigations were continued in the modified model tunnel until the pressure tunnel was completed in 1941. These investigations were invaluable in showing the limits within which compromises had to be made between low drag and desirable lift and moment characteristics. Satisfactory theoretical methods were also found during this period for designing the airfoils to produce the desired types of pressure distribution. Systematic investigations in the pressure tunnel then led to the evolution of the NACA 6-series airfoils, data for which are summarized in reference 33. This family of airfoils combines desirable lift characteristics with the possibility of low drag if the wing surfaces are smooth and fair. If the surfaces are not smooth and fair, the characteristics of this family are no worse than those of the older sections under the same conditions.

The requirement for fair and smooth surfaces was early found to present the greatest obstacle to the practical attainment of extensive laminar flow. The roughness and unfairness associated with usual methods of construction always resulted in premature transition at flight values of the Reynolds number. Difficulty was experienced in flight in obtaining low drag even with specially constructed and faired surfaces because of small waves and specks of dust or insects. Moreover, the turbulent boundary layer spreads downstream from each speck so that even a comparatively few imperfections result in predominantly turbulent flow. It is uncertain whether extensive laminar flow can be realized under conditions of field maintenance, although some modern high-speed airplanes, if carefully maintained, have sufficiently smooth and fair wings to permit low drag.

The problem of stabilizing the laminar boundary layer to disturbances associated with surface imperfections has attracted much attention. Investigations of the effectiveness of suction slots in stabilizing the laminar boundary layer were made in the model tunnel and in flight

from 1938 to 1940. Although some extensions of the laminar layer were obtained by this method, no apparent increase of stability was obtained for disturbances arising from surface imperfections. Such investigations have now been resumed to include the study of effects of suction through porous surfaces. Although no results of practical significance have been obtained, it appears that suction through porous surfaces does have a stabilizing effect. The theoretical work of Lees (reference 29) indicates that heat transfer to the surface may stabilize the laminar layer at high supersonic speeds.

Comparisons of results obtained from tests of low-drag airfoils in the wind tunnel and in flight are difficult because uncertainties with regard to the surface conditions appear to have greater effects than the residual wind-tunnel turbulence. The highest value of the boundary-layer Reynolds number R measured in flight just before transition is about 9000 (reference 34) where

$$R = \frac{\rho U \delta}{\mu}$$

In this equation, U is the velocity just outside the boundary layer and δ is the distance from the surface to the point where the dynamic pressure in the boundary layer is one-half that outside the layer. This value of the boundary-layer Reynolds number corresponds approximately to a value of 20,000 for a Blasius profile, with δ defined as the thickness corresponding to a local speed 0.995 that of the free-stream velocity. The drags of smooth and fair models measured in the two-dimensional low-turbulence pressure tunnel may be predicted by assuming a Reynolds number at transition equal to that measured in flight (fig. 11). It thus appears that the wind-tunnel results are comparable with those that would be obtained in flight with unusual care devoted to obtaining smooth fair surfaces.

Low-turbulence wind tunnels have been essential to the research on low-drag airfoils. The extensive investigations necessary to determine the proper compromises between the conflicting requirements of airfoil design would not have been possible without these wind tunnels.

NACA Headquarters
Washington, D. C., October 13, 1948

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TABLE I

ORDINATES OF

NACA 66,1-015 AIRFOIL SECTION

[Stations and ordinates given in percent of airfoil chord]

Station	Ordinate
0	0
.5	1.191
.75	1.433
1.25	1.798
2.5	2.440
5.0	3.344
7.5	4.028
10	4.585
15	5.468
20	6.137
25	6.647
30	7.019
35	7.289
40	7.448
45	7.500
50	7.436
55	7.237
60	6.898
65	6.362
70	5.572
75	4.645
80	3.631
85	2.568
90	1.504
95	.582
100	0
L.E. radius: 1.61	

TABLE II

COMPARISON OF OBSERVED AND PREDICTED REDUCTION OF TURBULENCE BY USE OF DAMPING SCREENS

IN NATIONAL BUREAU OF STANDARDS $4\frac{1}{2}$-FOOT WIND TUNNEL

$\left[U_t = 109 \text{ ft/sec}\right]$

Screen	nk	$\frac{1}{(1 + k)^{n/2}}$	u'/U_t (percent)	v'/U_t (percent)	w'/U_t (percent)	U'/U_t (percent)	
						Observed	Predicted
None	------	------	0.089	0.301	0.335	0.265	-----
18-mesh, 0.011-in. wire	0.895	0.726	.052	.199	.239	.182	0.192
20-mesh, 0.017-in. wire	2.18	.561	.041	.163	.199	.150	.149
24-mesh, 0.0075-in. wire	.730	.760	.053	.228	.244	.195	.201
60-mesh, 0.007-in. wire	4.20	.438	.038	.141	.133	.114	.116
Two 18-mesh, 0.011-in. wire	1.790	.527	.041	.166	.155	.133	.140
Three 18-mesh, 0.011-in. wire	2.685	.383	.037	.114	.123	.099	.102
Six screens (three 20-mesh, 0.017-in. wire; three 24-mesh, 0.0075-in. wire)	[a]8.7	[b].0776	.039	.044	.044	.043	.021

[a]$3k_{20} + 3k_{24}$, where k_{20} and k_{24} are the pressure-drop coefficients for the 20-mesh and the 24-mesh screens, respectively.

[b]$\frac{1}{(1 + k_{20})^{3/2} (1 + k_{24})^{3/2}}$.

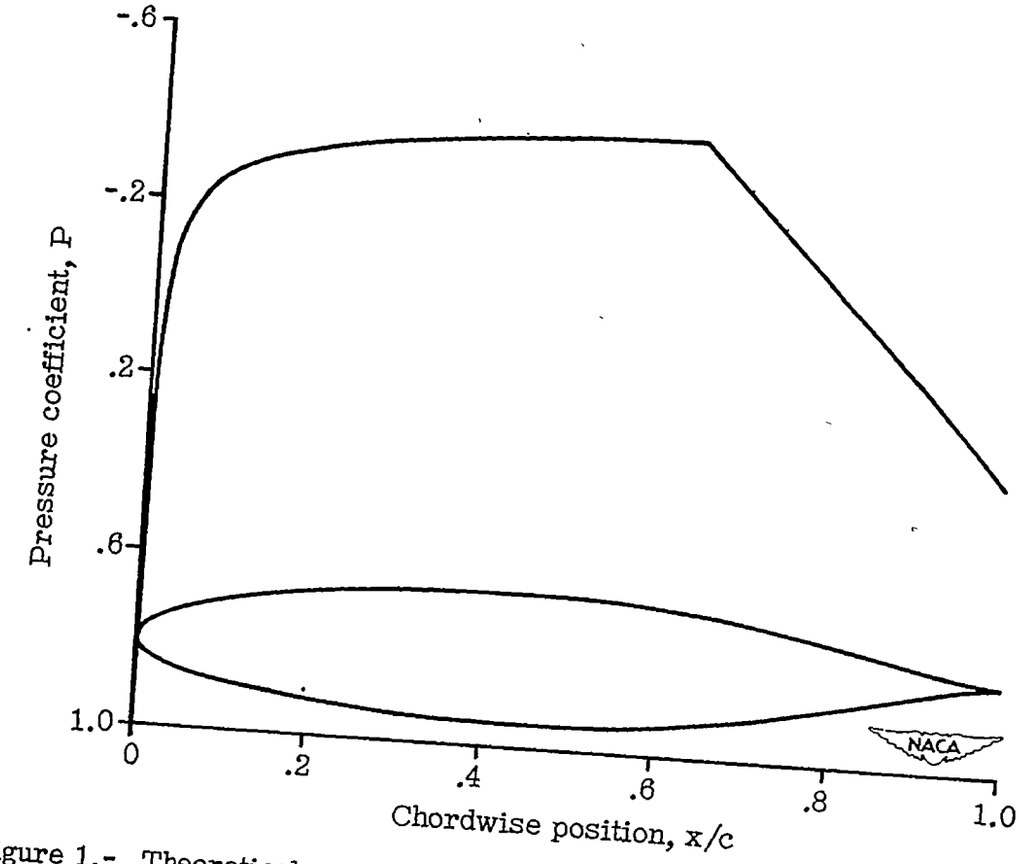

Figure 1.- Theoretical pressure distribution for NACA 66,1-015 airfoil section at zero lift.

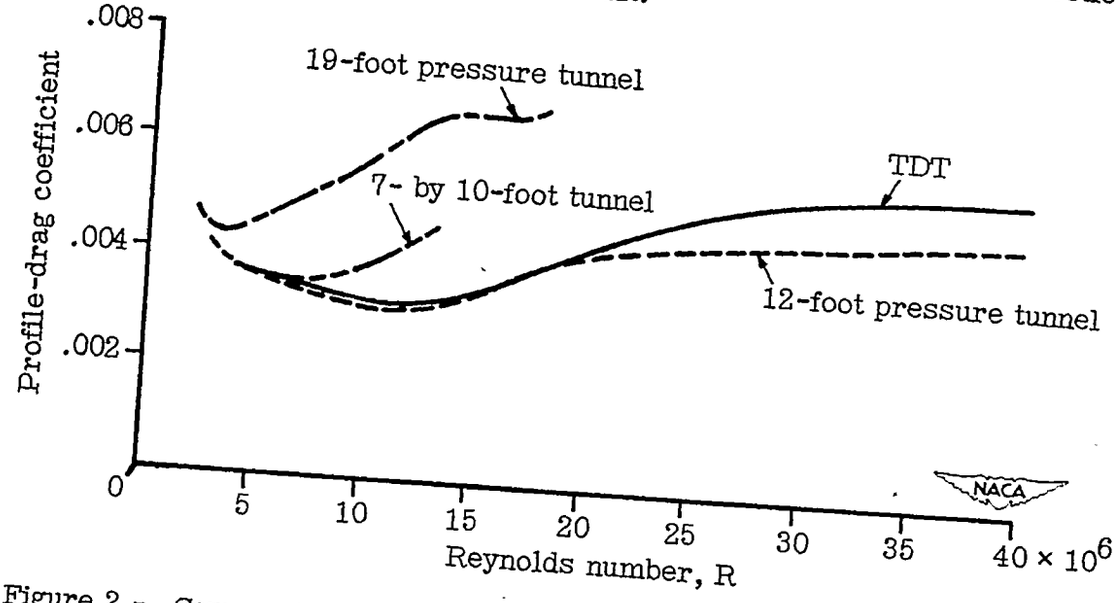

Figure 2.- Comparative drag measurements of NACA 66,1-015 airfoil in four NACA low-speed wind tunnels.

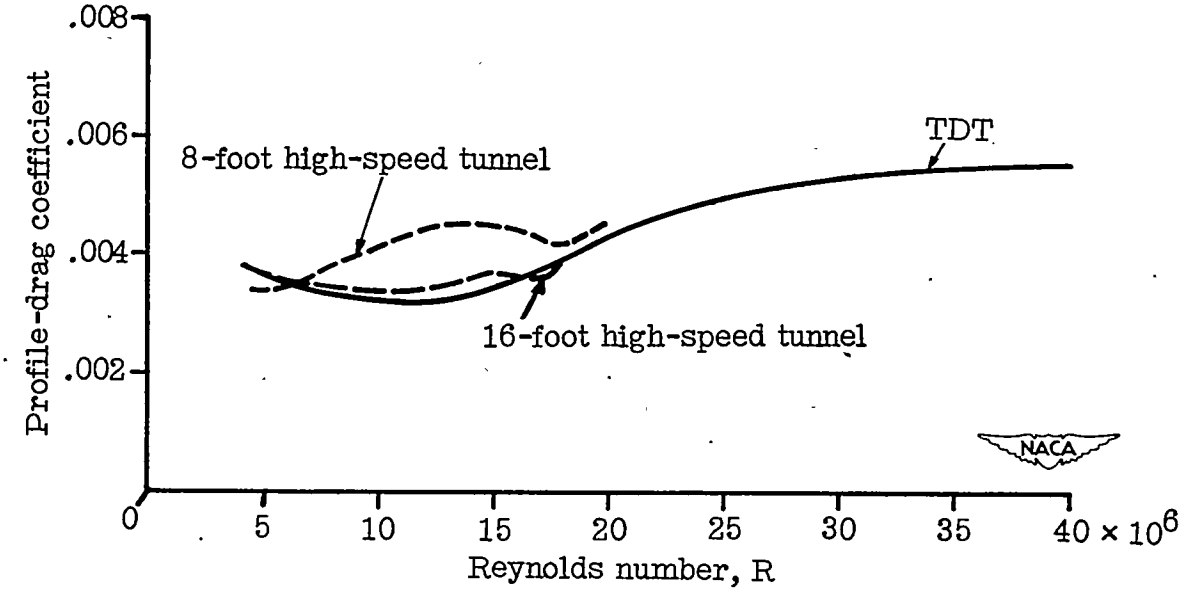

Figure 3.- Comparative drag measurements of NACA 66,1-015 airfoil in three NACA wind tunnels.

Figure 4.- The $4\frac{1}{2}$-foot wind tunnel of the National Bureau of Standards.

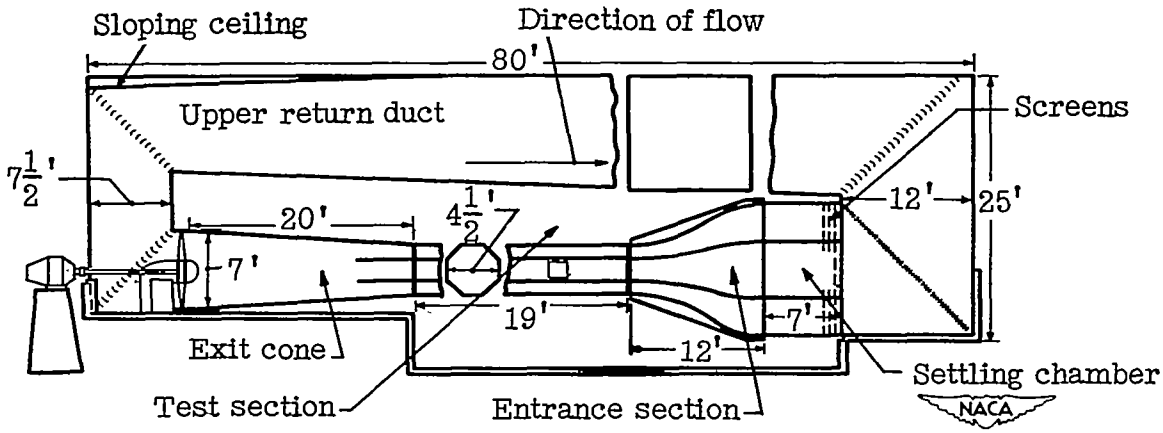

Figure 5.- Longitudinal cross section of the $4\frac{1}{2}$-foot wind tunnel of the National Bureau of Standards.

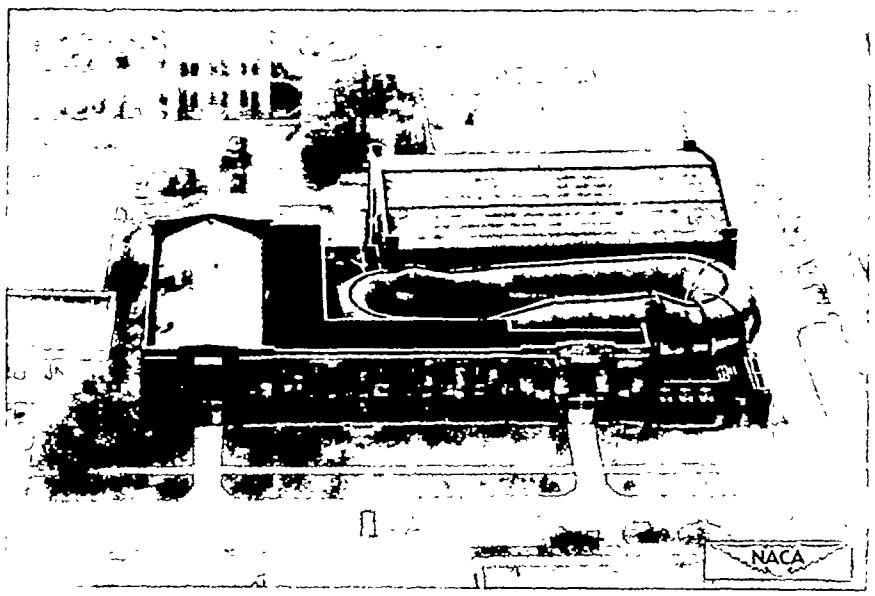

Figure 6.- The Langley two-dimensional low-turbulence pressure tunnel.

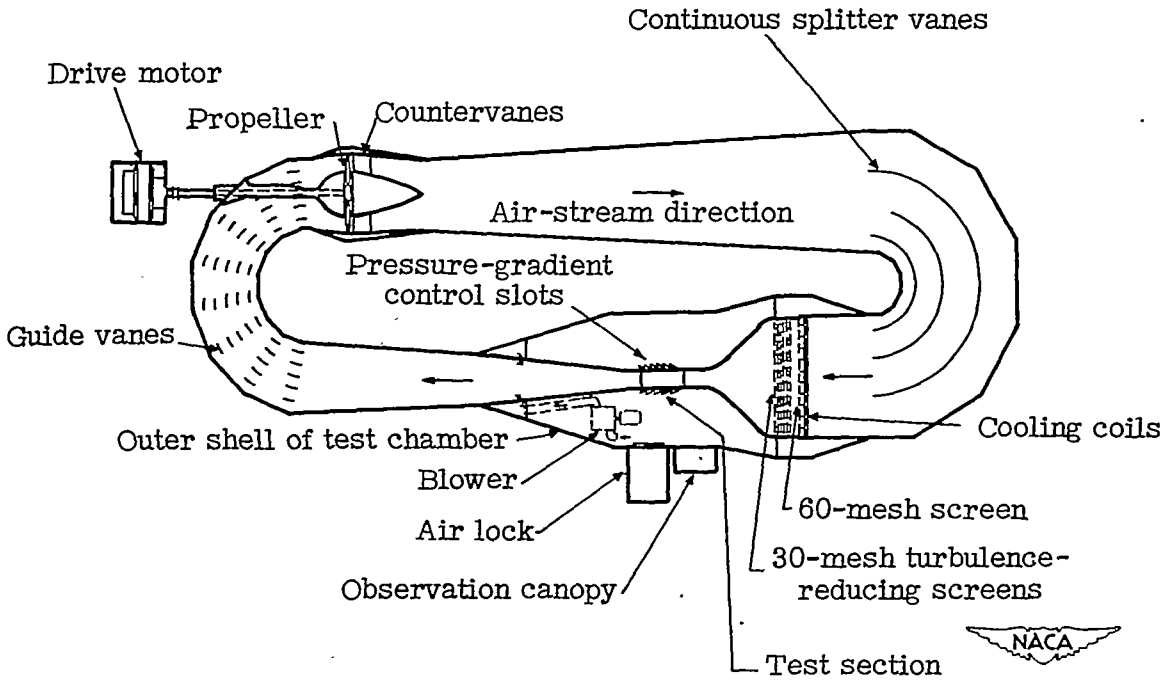

Figure 7.- The Langley two-dimensional low-turbulence pressure tunnel.

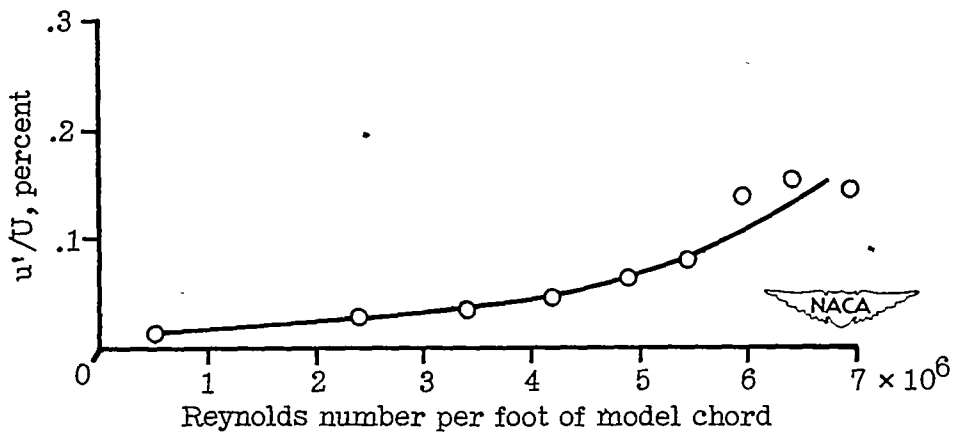

Figure 8.- Turbulence level u'/U of the Langley two-dimensional low-turbulence pressure tunnel at a pressure of 4 atmospheres. (Data from reference 13.)

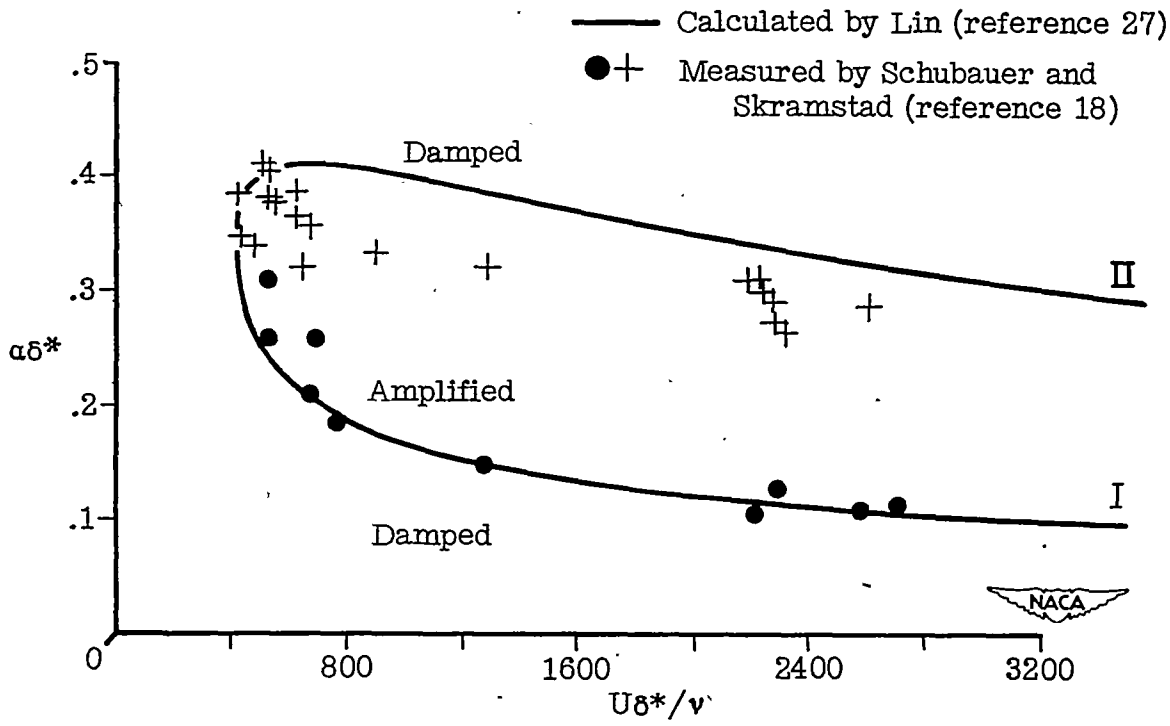

Figure 9.- Curve of neutral stability for Blasius profile.

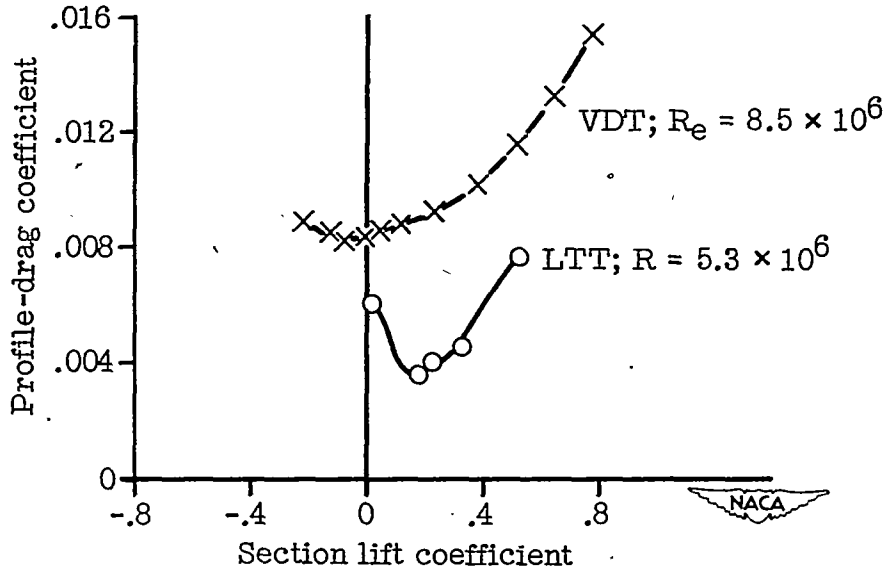

Figure 10.- Profile-drag characteristics of NACA 27-215 airfoil section. (Data from reference 5.)

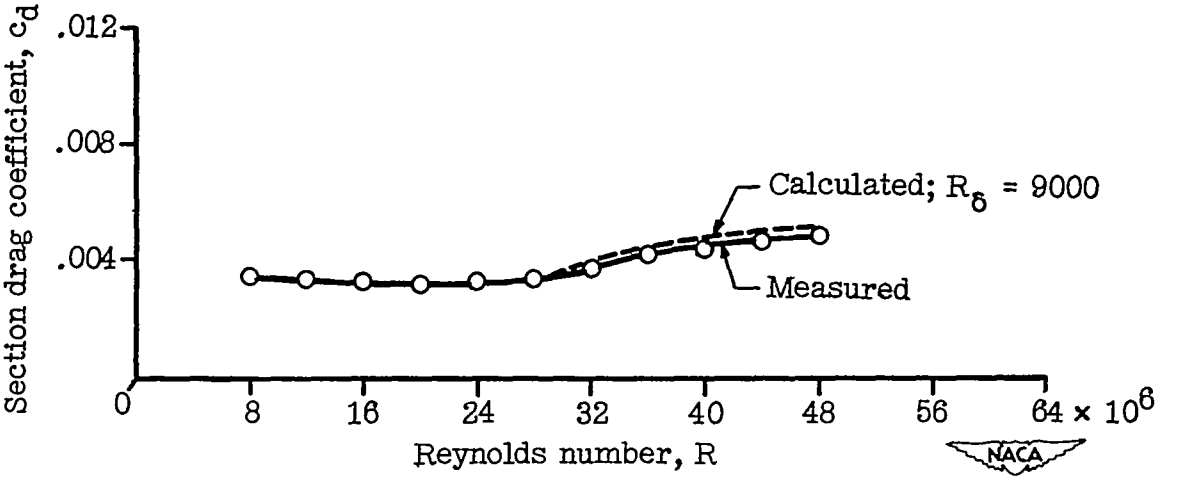

Figure 11.- Measured and calculated drag coefficients for a low-drag airfoil tested in the Langley two-dimensional low-turbulence pressure tunnel.