REPORT OF THE PANEL ON THEORETICAL AERODYNAMICS

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INTRODUCTION

There is little doubt that the main use of the NTF, at least in its early years, will be to provide data on configurations which are intended to fly at Reynolds numbers beyond those that the present production-oriented wind tunnels can attain. This utilization is reasonable since elimination of uncertainties related to Reynolds number scaling can have enormous benefits. Adverse scaling effects can be identified in "early time," various cures examined, and the unpleasant surprises minimized or eliminated. If more accurate Reynolds number scaling provides an unexpected "plus," then the possibilities of exploiting it are greatly enhanced.

Clearly, the near-term payoff of the NTF will be in terms of more efficient aircraft (that is, in range, speed, economy, and maneuverability) than those arrived at by using the age-old procedure of design, test, and then redesign. The difference with the advent of the NTF is that redesign will be done on the basis of data taken at full- rather than sub-scale Reynolds numbers. It is equally clear that the more important long-range benefits will be the improvement in the design tools and a better understanding of how to utilize the present wind tunnels to obtain more meaningful data.

TUNNEL ENVIRONMENT

The NTF is nearing its final stages of design; therefore, large changes in its primary components are not likely. Still it behooves those in a position to effect design changes or additions to keep an open mind toward suggestions aimed at making the data to be obtained in the facility more accurate and more representative of the free-air environment. Hence, the members of the Applied Theoretical Aerodynamics Panel concluded that in view of the strong general concern expressed by a number of panels at the workshop, the NTF design team should examine closely the suggestions made herein with respect to flow quality. Since the panel was clearly not cognizant of all the flow quality studies which have been made, these suggestions will have to be examined in light of past considerations.

With the high Reynolds number capability of the NTF, designers and theoreticians are most anxious to determine the ability of their design tools and computational techniques to predict high Reynolds number phenomena as well as to simply scale up low Reynolds number data. This presupposes in some minds that the NTF will provide an absolute result, one identical to that obtainable in free air. Free-air flow quality can never be achieved; however, it can be approximated dependant upon the effort expended to obtain as low turbulence and low noise environment as possible (or needed). In addition, errors brought about by nonuniform flow and tunnel-wall interference must be understood to the point where corrections can be made for them or minimization of them is possible through limitations on model size and tunnel test conditions.

Flow Quality

The flow-quality goals for the NTF are given in figure 1. Also shown for comparison are numbers indicative of the environments of the Langley 8-foot transonic pressure tunnel and the Langley 16-foot tunnel. Clearly, the turbulence-intensity and fluctuating-static-pressure levels proposed for the NTF are substantially lower than the existing levels of the other two facilities.

In the case of turbulence intensity Tu it would appear on the basis of the data shown in figure 2 (taken from ref. 1) that a turbulence intensity goal of 0.001 is sufficiently low to insure that further reductions would not yield any further increases in transition Reynolds number. However, figure 2 also shows a variation in transition Reynolds number from one data source to another at turbulence levels below 0.002. This variation in transition Reynolds number could be due to noise.

The proposed noise level of the NTF in terms of fluctuating static pressure is $\Delta C_p = 0.002$, which corresponds to 131 dB and 150 dB at total pressures of 101.3 kN/m^2 (1 atm) and 911.9 kN/m^2 (9 atm), respectively. This level is very low; in fact, it is sufficiently low to permit the tunnel to be used to establish buffet boundaries according to reference 2. Unfortunately, there is no certainty that this goal can be achieved by NTF. Since the measured ΔC_p levels in the Langley 8-foot transonic pressure tunnel and 16-foot tunnel are about six times greater than that proposed for the NTF, it is evident that special design and acoustic treatments will be required for the NTF to attain the design noise level.

For example, the design of the plenum, slots, and ejectors should be implemented with acoustic materials and the use of finite edge radii where possible. Another area where noise treatment could be beneficial where none is now planned is in the corners and on the turning vanes. Unnecessary turbulence and noise can be generated by the turning vanes if they are not designed by using the best methods now available. Also, the vanes will extract more energy from the flow than necessary (requiring more power) if they are not as efficient as can be produced. The panel recommends that a review of the turning-vane design procedures be reviewed with NASA and industry experts to determine whether the best procedures have been used.

Tunnel-Wall Interference

The walls of the NTF, like every subsonic/transonic tunnel, will cause errors in the measured pressures, forces, and moments. At subsonic speeds, wall-interference correction procedures based on linear theory do an adequate job; at transonic speeds, the phenomenon is nonlinear and present understanding of it is incomplete. A number of activities are in progress which will ameliorate the situation, but they will not get to the point by the startup of the NTF where corrections can be applied without experimental verification of their applicability.

In order to achieve the required confidence in NTF data, it is necessary to be assured that the measured Reynolds number effects are not affected by wall interference effects. This is a difficult job in conventional tunnels; it becomes even more complex for the NTF. The performance of the slots in providing blockage relief is dependent to some degree on the thickness of the incoming boundary layer. When the Reynolds number can change by an order of magnitude as in the NTF, one can expect the slot performance to change also. This effect is shown schematically in figure 3. Hence, the anxiety over the ability to separate Reynolds number and wall interference effects is real.

To aid in making more intelligent tunnel wall corrections for the NTF, the panel proposes that as a part of the tunnel calibration, two simple wing-body models of different size be tested. Pressures on the model and near the wall should be measured as well as the model lift, drag, and pitching moment. Correction techniques using "wall" pressures should then be applied to assess and correct for wall interference. Corrected forces and moments for the large model will be compared with those for the small model which are assumed to be "interference-free" data. The big problem here is that the interference-correction techniques are not now available. Hopefully, current research efforts will yield such a tool.

PROBLEMS IN THEORETICAL AERODYNAMICS

In recent years significant progress (see refs. 3 to 5) has been made in the development of computational techniques for the prediction of complicated flow fields. Considerable effort is currently being expended to develop both viscous-inviscid interaction techniques and numerical procedures for solving the time-averaged Navier-Stokes equations for flows containing separated regions. In addition, inviscid computations have reached a point where calculations can now be made over a wide Mach number range for practical shapes of significant complexity. In time, as more confidence is gained in these procedures, they will become a more integral part of the design process and replace many of those in current use. In order to gain greater confidence, experimental verification is required and the NTF facility will provide an excellent opportunity because of its large Reynolds number range.

In many cases the aerodynamic quantity of interest may be only a weak function of Reynolds number and can be predicted with good accuracy without accounting for viscous effects. The lift force on a wing body at low speeds and angles of attack sometimes falls in this category. At transonic speeds almost everything, including lift, becomes very sensitive to Reynolds number variation. In the following paragraphs a number of viscous-flow topic areas of concern to the theoretician will be discussed.

BOUNDARY-LAYER FLOWS

Two-Dimensional Data

Figure 4 illustrates graphically the strong role that viscous effects play at transonic speeds. Pressure distributions on a two-dimensional supercritical airfoil at M = 0.73 for the three Reynolds numbers (6×10^6, 40×10^6 and 400×10^6) shown in this figure give the following lift and drag results:

Reynolds number	C_L	C_D
6×10^6	0.305	0.0101
40×10^6	.372	.0074
400×10^6	.425	.0057

Note that the lift and drag coefficients for a Reynolds number of 6×10^6, typical of many of the present tunnels, are substantially different from the results for 40×10^6 which, in turn, are very different from the values for 400×10^6. The calculations depicted were made by using the Korn-Garabedian transonic analysis program (ref. 6) which includes the boundary-layer displacement effect and skin-friction drag determined by the method of Nash and MacDonald for turbulent flows. Note that the computed displacement thickness has been added to the airfoils shown in figure 4. Various empiricisms are used to simulate the strong viscous-inviscid interaction at the trailing edge, primarily to achieve more accurate pressure distributions. Drag variations and relative results, (that is, one airfoil's drag compared with a second one) are well predicted but absolute levels may be substantially in error. Shown in figures 5 and 6 are the theoretical results for another two-dimensional, supercritical airfoil obtained by Bavitz. (See ref. 7.) The Reynolds number range in this instance extends from 2×10^6 to 200×10^6 and the Mach number (0.759) is sufficiently high to cause a shock. Changes in the pressure distribution with increasing Reynolds number are evident in figure 5, the most noticeable change occurring in shock position between Reynolds numbers of 2×10^6 and 10×10^6. The variation of shock position over the complete Reynolds number range is given in figure 6 along with the change in lift, the boundary-layer form factor, and displacement thickness at $x/c = 0.95$. It is very evident that most of the changes in the quantities plotted (drag was not given) occur at Reynolds numbers below 40×10^6. Empiricisms similar to those used in the Korn-Garabedian program are also employed in the Bavitz method at the trailing edge to obtain more accurate pressures. No special technique is employed to account for the shock — boundary-layer interaction.

Figure 7 shows a high-lift system proposed for the energy efficient transport (EET). Figure 8 gives a typical pressure distribution on each of the four elements computed by the Lockheed multielement two-dimensional, airfoil program (ref. 8) which includes viscous interaction. Figure 9 shows an interesting result; that is, the total drag coefficient as computed by this program continues to decrease as the Reynolds number increases from the present wind-tunnel levels to a Reynolds number of 100×10^6. Verification of this prediction could be made by the NTF facility.

Research is underway to put the trailing-edge-interaction calculation on a firmer theoretical base, and it appears it will come to fruition in the next 3 to 4 years. Parallel research in the interaction of a shock with a boundary layer at transonic speeds is underway and should start paying off at about the same time as the trailing-edge research. The need for high Reynolds number data is clear in order to evaluate these predictive techniques and to gain confidence in their flight Reynolds number capability. It is likely that the NTF will provide some of the needed two-dimensional data; however, most of its contributions will come in the three-dimensional flow field studies.

Three-Dimensional Data

The airfoil calculations discussed so far and the problems attendant thereto have their counterpart in three-dimensional flows. With the extra dimension the viscous flow phenomena are naturally more complex, and consequently, the state of the art of 3-D theory lags behind that of 2-D. There are several 3-D boundary-layer computer codes (for example, see refs. 9 and 10) that have emerged during the past few years, but 3-D shock and trailing-edge interactions have not even been attempted. Results from one of these 3-D boundary-layer codes (ref. 9) are plotted in figure 10. Chordwise variations of the chordwise and spanwise components of the skin-friction coefficient for the F-8 supercritical wing at the 52 percent semispan station are shown. This type of 3-D boundary-layer codes requires validation at both high and low Reynolds numbers. This validation requires measurements of boundary-layer quantities such as skin-friction, velocity profiles, etc.

New methods for treating viscous flow in the juncture region of intersecting surfaces and near wing tips will also require experimental checks. Hopefully, much of this work which is diagnostic in nature can be done in existing facilities with only a few high Reynolds number spot checks in the NTF.

Transition

There are other basic problems in 3-D boundary-layer theory which require diagnostic measurements in order to be properly evaluated. The prediction of transition, with and without suction, and of separation are crucial to the ultimate success of any comprehensive boundary-layer or Navier-Stokes program. Hopefully, the NTF can attain a flow quality high enough to aid in the formulation and validation of improved transition criteria for incorporation into the viscous codes.

There are transition criteria based on stability analyses and test data which have had mixed success. For some configurations and/or flow regimes, the lack of accuracy is not critical. For supercritical airfoils (wings) at transonic speeds, this is not true. Figure 11 shows for a Reynolds number of 6×10^6 the changes in pressure distribution, lift, and drag for the airfoil of figure 4 that occur when the transition location is changed from the leading edge to 0.3 chord. Note that when transition is fixed at the 0.3 chord location, the lift (0.381) and drag (0.0072) coefficients are very nearly the values obtained at the 40 x 10^6 Reynolds number in figure 4 with transition at the leading edge. Theoretical calculations can be used in this way to set transition locations (trip strips) in low Reynolds number facilities so as to simulate the flow at a higher Reynolds number. This technique implies that forced and natural transition will yield the same downstream boundary layer. Even when transition can be fixed to give a good approximation of the high Reynolds number displacement thickness and consequently lift, there is no assurance that the velocity profiles and, hence, the skin-friction drag are equally well approximated. The questions regarding the use of transition strips should be looked at in the NTF where both simulation and full-scale experiments can be conducted. This problem will be discussed in more detail in the "Experiments" section.

Turbulence Model

One final and perhaps the most important element in the boundary-layer and Navier-Stokes codes is the turbulence model. At the present time, turbulence modeling is the pacing item in the further development of these codes for flow fields involving separation. In addition, for 3-D attached boundary-layer flows, it is not clear how to model the component of Reynolds stress involving the cross-flow velocity. It is recognized that the NTF facility is a difficult environment in which to make hot-wire measurements. In addition, special considerations will have to be given to the difficulties incurred due to the thin boundary layer which exists at large Reynolds numbers. Detailed velocity-profile measurements in the boundary layer with a pitot probe coupled with skin-friction measurements at flight Reynolds numbers could contribute immeasurably to the data base required for turbulence model evaluation. Configurations yielding pressure gradients and separation are required.

FLOW SEPARATION

Flow separation appears in varying degrees and at a variety of locations on an aircraft. The conditions under which flow separation will occur, and the extent of the separated region when there is reattachment, are dependent on Reynolds number. The prediction of these flow phenomena has been attempted by using a variety of techniques and governing equations, but they are generally without substantiation at high Reynolds numbers. The NTF could be most useful in establishing the Reynolds number dependence of the separation point (line) location for some well chosen 2-D (or 3-D) configurations.

Two-Dimensional Data

Airfoil separation can occur at the leading edge, at the foot of a shock if the flow is transonic, and at the trailing edge. Each of these separation phenomena is sensitive to Reynolds number, particularly the first since the shape of the leading-edge separation bubble is strongly influenced by the transition from laminar to turbulent flow. A phenomena which is not well understood and not yet satisfactorily analyzed is that of leading-edge bubble bursting. Flow separation can also start at the trailing edge and work its way forward with increasing angle of attack until the entire top side of the wing is separated. The result of an approximate analysis of such a flow field by an inviscid analysis of Barnwell (ref. 11) is shown in figures 12 and 13. In these calculations the separation point is prescribed; more realistically one would like to perform the computations free of such empiricisms. Again the corroboration of such a theory would be aided by the wide Reynolds range capability of the NTF in establishing a correlation of separation point and Reynolds number.

Axisymmetric Flow

Two important areas of flow separation research are the understanding and successful prediction of the flow at the aft end of a fuselage and the boattail — jet-plume interaction. Many questions remain unanswered. For example, how is the boattail — jet-plume interaction region affected by the change from current wind-tunnel Reynolds numbers to those at flight conditions? With an increase in Reynolds number the jet entrainment is altered which in turn alters the boattail flow field and, hence, the separation point location. Hopefully, the NTF facility can be used to simulate such a flow field by injecting room-temperature nitrogen through a jet nozzle and measuring the resulting boattail pressure distribution.

Three-Dimensional Data

Computations of 3-D viscous, separated flow fields is beyond the current state of the art. Typical of the current efforts in computing 3-D flows with leading-edge separation is the inviscid technique of Weber, Brune, Johnson, Lu, and Ruppert given in reference 12. In this procedure, the separated leading-edge vortex is represented by vortex paneling; the panel positions and singularity strengths are solved for iteratively. Unfortunately, one cannot expect complete success of an inviscid theory in describing the separated flow over a low-aspect-ratio wing as evidenced by the large Reynolds number sensitivity depicted in figure 14, which was taken from reference 13. Clearly, this phenomena is a viscous one and, in time, after viscous codes are developed to analyze such flows, the NTF could serve to verify such procedures over a wide Reynolds number range.

NTF ROLE IN THEORY DEVELOPMENT

Most of the current subsonic and transonic tunnels spend a part of their test time obtaining data required by the aerodynamicist to check the accuracy of his theoretical methods. This testing can take many forms and can vary considerably in complexity. In the early development stage of a theoretical method, tests on a simple idealized configuration may be required; for a mature technique a very complex, "realistic" geometry may be tested for validation purposes. If one is just starting out to develop a method or if large discrepancies occur between prediction and experiment by using an existing method, the need for detailed diagnostic measurements in the flow field and/or surface pressures can be paramount. Thus the tunnel is used not only to validate predictive methods but also to improve mathematical models of various flow phenomena.

The panel envisions the role of the NTF in theory development as similar to that just described for the conventional tunnel. Implementation, however, will be much more difficult than in the past. The low temperatures and high dynamic pressures associated with the highest Reynolds numbers present unique environmental problems for the diagnostic instrumentation. In addition, the thinness of the boundary layer at high Reynolds numbers presents resolution problems much more severe than those encountered now on comparably sized models at lower Reynolds numbers. The panel suggests that an increased effort in cryogenic tunnel instrumentation be made to include diagnostic instrumentation such as surface hot-wire gages, hot-wire probes, floating C_f gages, Preston tubes, razor-blade and thin-flim gages, and laser velocimeters. Rake support requirements is another area which requires attention.

EXPERIMENTS

In this section seven experiments are proposed for the NTF facility by the panel. These proposed experiments are based on the unique capabilities of the proposed NTF facility to aid in better understanding of the problems in theoretical aerodynamics discussed previously.

EXPERIMENT 1: THEORY VALIDATION FOR HIGH-ASPECT RATIO WING-BODY COMBINATION

Objective: Code verification for configurations typical of subsonic/transonic transport aircraft

Background:

(1) Lack of validated scaling laws

(a) Little confidence in turbulent attached-flow scaling

(b) No guidelines where separated flows present - including vortex flows

(2) Methodology requires checks and calibration at high Reynolds number

(3) Lack of fundamental aerodynamic modeling data

(a) Little at low Reynolds numbers

(b) Nonexistent at high Reynolds numbers

(4) 3-D design codes require validation

Justification:

(1) More efficient flight vehicles

(2) Increased level of confidence in design

(3) Reduce flight test time

(4) Understanding of flow mechanisms at high Reynolds number

Special considerations:

(1) Instrumentation

(a) Skin friction gages

(b) Thin-film and razor-blade gages

(c) Laser doppler velocimeter

(2) Measurements

(a) Boundary-layer profiles

(b) Wakes (rake measurements)

(c) Turbulence

(d) Flow visualization:

Shear flows

Limiting streamlines

Transition location

Precursor work desired:

(1) All instrumentation development completed in 0.3-m transonic cryogenic tunnel prior to NTF on line

(2) Continued theoretical and experimental research for code development in available facilities to as high Reynolds number as possible

(3) Configuration selection

(a) Wing body - typical of 1984 transport optimized for high Reynolds number

(b) Test in low Reynolds number facility with trip strips

Joint effort NASA/Industry:

(1) Research ideas

(2) Cost sharing of computer code verification

Priority:

First priority

EXPERIMENT 2: THEORY VALIDATION FOR LOW-ASPECT-RATIO MODERATELY SWEPT WING

Objective: Validate 1982 wing-body viscous-inviscid codes

Background:

(a) Superior transonic maneuvering

(b) Advanced aerodynamic concepts; e.g., variable camber, L.E. and T.E. devices

Approach:

(a) 3-D wing-body-tail model, no nacelles

(b) Component build up

(c) 2 wings: low camber/high camber

(d) $R_{\bar{C}} = 50 \times 10^6$

(e) Angles of attack through stall

(f) Forces, moments, pressures

Special considerations:

(a) If possible, visualization; skin-friction

(b) Strain gages for loads

(c) Buffet instrumentation

Precursor:

(a) Complete validation (boundary-layer details) of 2-D methods: $R_C = 5 \times 10^6 \rightarrow 20 \times 10^6$

(b) Complete validation (boundary-layer details) of 3-D wing theory; $R_{\bar{C}} = 5 \times 10^6$

(c) Test projected NTF model at $R_{\bar{C}} = 5 \times 10^6$ and correlate with theories (if correlation indicates problems, test only isolated wing in NTF for R effects)

(d) Use theories to predict NTF results

NTF test:

Joint effort with theory developers

Priority:

First priority

EXPERIMENT 3: THEORY VALIDATION FOR LOW-ASPECT-RATIO HIGHLY-SWEPT WING

Objective: Code verification for configurations typical of supersonic cruise aircraft

Background:

(a) Flows over wing upper surface dominated by leading-edge vortex at design conditions

(b) Primary vortex induces secondary vortex - position and strength of vortices sensitive to R at low R; high R sensitivity unknown

(c) Only low Reynolds number data available to check inviscid models of wing flow fields

(d) Need for theoretical and empirical scaling law for highly swept wings

(e) High Reynolds number effect on control-surface effectiveness unknown

Approach:

(a) Use existing arrow-wing models

(b) Modify as required for cryogenic environment

(c) Flat, twisted, and cambered wings will be available with leading edge and trailing edge control surfaces

Special considerations:

Flow visualization if possible for high and low Reynolds number leading-edge vortex studies

Precursor:

Continued development of viscous and inviscid codes for highly-swept wing using available facilities

Priority:

Second priority

EXPERIMENT 4: THEORY VALIDATION FOR HIGH-LIFT SYSTEMS ON HIGH-ASPECT RATIO WINGS

Objective: Validation of existing 2-D and 3-D computational techniques for pressure distribution, forces and moments

Background:

(a) Design and wind-tunnel validation at low R has historically produced more complex flap systems than needed at flight R

(b) New analysis/design techniques available

Types of measurements:

(a) Total forces and moments

(b) C_p on wing and flap

(c) Confluent boundary-layer properties

(d) Separated flow location and flow-field properties

(e) Flow-field details of wing/flap tip vortex rollup

Special considerations:

(a) Small flap elements to instrument

(b) Separated flow measurements

(c) Thin boundary layers on flap elements

Precursor tests:

2-D tests of high-lift systems in Langley LTPT facility

Priority:

Second priority

EXPERIMENT 5: REYNOLDS NUMBER SCALING

Objective: Use NTF as a facility for developing and validating Reynolds number scaling techniques, so as to render conventional wind tunnels more reliable for configuration development work

Justification: Operational environment of NTF precludes heavy use as a configuration development facility, since rapid tunnel entry and quick, on-line model tailoring are required in a configuration development and refinement program. NTF can establish the limits within which conventional tunnels can be effectively and reliably used.

Special considerations:

(a) Probably configuration oriented. Test series organized about specific categories of configuration shapes, flow phenomena, etc.

(b) Requires detailed flow diagnostic measurements.

- Forces
- Moments
- Detailed boundary-layer measurements
- Shock structure and positions
- Surface shear stress directions
- Trailing-edge boundary-layer measurements

(c) NTF must be validated as providing truthful full-scale R data with free transition that is representative of atmospheric flight.

(d) Program may have to be duplicated in several conventional tunnels because of differences among them (i.e., turbulence level, etc.).

Precursor work required:

(a) Flow diagnostic technique development:

- Boundary-layer and near-wake surveys
- Wall flow visualization (e.g. oil flow)
- Shock-wave visualization
- Identify test configuration(s)

(b) Explore concept of "Reynolds Number Incremented Geometry;" i.e., design to maximum performance at low R , and apply a "data base (or theory) generated" geometry change to arrive at a near-optimum high R shape for a one-shot validation test.

(c) Joint NASA/Industry effort:

Scaling techniques must be validated for the conventional developmental tunnels in use by Industry.

Priority:

First priority. This endeavor will enable NTF to have a near-term impact on real airplane designs configurated for optimal performance at flight Reynolds numbers.

EXPERIMENT 6: DYNAMIC SHOCK - BOUNDARY-LAYER INTERACTION

Objective: Definition of the effect of free boundary-layer transition on shock - boundary-layer interaction under dynamic (and static) flow conditions.

Background:

(a) Dynamic shock - boundary-layer interaction is a problem of fundamental importance with great impact on structural design and performance of advanced aircrafts.

(b) The effect of upstream free transition on shock location is well known. It is also well documented that there is a strong coupling between free transition and the airfoil motion.

Approach:

(a) Static tests can define shock dependence on α at different R (and q) with and without tripping devices. Dynamic tests can define the motion dependence of the shock for the above parameters.

(b) Static test with pressure instrumentation and flow visualization. Dynamic test, forced oscillations, and α-ramps using fluctuating pressure transducers.

Percursor work required:

(a) Tests in tunnels with less instrumentation difficulties could provide definition of the tests needed in NTF to extend information to high R in both 2-D and 3-D tests.

(b) Select moderate aspect-ratio-wing geometry.

Priority:

Second priority.

EXPERIMENT 7: EFFECT OF R and M_∞ ON DYNAMIC STALL

Objective: The NTF facility can provide the separation of variables needed to define the individual effects of R and M_∞.

Background:

(a) The negative aerodynamic damping and associated stall flutter is dependent upon static characteristics from which unsteady perturbation is made.

(b) Both $C_{L\ MAX}$ and the deep stall characteristics are sensitive to M_∞.

(c) All present static and dynamic stall data are contaminated by undefined compressibility effects and are only at low R.

(d) The large R-range possible in NTF at various levels of dynamic pressure could also help resolve the sidewall or side-plate interference problem in 2-D tests.

Approach:

(a) Static tests with balance and/or pressure instrumentation.

(b) Dynamic tests with forced oscillations and α-ramps using dynamic balance and/or fluctuating pressure transducers.

Precursor:

Select moderate aspect-ratio-wing geometry.

Priority:

Second priority.

REFERENCES

1. Michel, R.: Effects of Flow Turbulence and Noise on Aerodynamic Phenomena and Wind Tunnel Results. AGARD-R-615, June 1974.

2. Mabey, Dennis G.: Some Remarks on the Design of Transonic Tunnels With Low Levels of Flow Unsteadiness. NASA CR-2722, Aug. 1976.

3. Aerodynamic Analyses Requiring Advanced Computers. NASA SP-347, Parts I and II, Conference Held at Langley Research Center, Hampton, Virginia, Mar. 4-6, 1975.

4. Taylor, T. D.: Numerical Methods for Predicting Subsonic, Transonic, and Supersonic Flow. AGARDograph No. 187, Jan. 1974.

5. Peyret, R.; and Viviand, H.: Computation of Viscous Compressible Flows Based on the Navier-Stokes Equations. AGARDograph No. 212, Sept. 1975.

6. Bauer, Frances; Garabedian, Paul; Korn, David; and Jameson, Antony. Supercritical Wing Sections II. Lecture Notes in Economics and Mathematical Systems, Springer Verlag, New York, 1975.

7. Bavitz, P.: Analysis Method for Two Dimensional Transonic Viscous Flow. NASA TN D-7718, 1974.

8. Stevens, W. A.; Goradia, S. H.; and Braden, J. A.: Mathematical Model for Two-Dimensional Multi-Component Airfoils in Viscous Flow. NASA CR-1843, 1971.

9. Cebeci, Tuncer; Kaups, Kalle; and Ramsey, Judy A.: A General Method for Calculating Three-Dimensional Compressible Laminar and Turbulent Boundary Layers on Arbitrary Wings. NASA CR-2777, 1977.

10. McLean, J. Douglas: Three-Dimensional Boundary Layer Calculations for Swept Wings. AIAA Paper 77-3, 1977.

11. Barnwell, R. W.: Two Inviscid Computational Simulations of Separated Flow About Airfoils. AIAA Paper No. 76-379, 1976.

12. Weber, James A.; Brune, Guenter W.; Johnson, Forrester, T.; Lu, Paul; and Rubbert, Paul E.: A Three-Dimensional Solution of Flows Over Wings With Leading Edge Vortex Separation. Aerodynamic Analyses Requiring Advanced Computers, NASA SP-347, 1975, pp. 1013-1032.

13. Smith, J. H. B.: Improved Calculations of Leading-Edge Separation From Slender Delta Wings. RAE Tech. Rep. No. 66070, Mar. 1966.

	National transonic facility	Langley 8-foot transonic pressure tunnel	Langley 16-foot tunnel
Flow uniformity, $\frac{\Delta q}{q}$	±0.001	- -	- -
Turbulence intensity, Tu	0.001	0.008	0.007
Fluctuating static pressure, ΔC_p	0.002	0.014	0.012
Noise (SPL) p_t = 101.3 kN/m^2(1 atm) p_t = 911.7 kN/m^2(9 atm)	131 dB 150 dB	- -	143 dB

Figure 1.- Flow quality indicators.

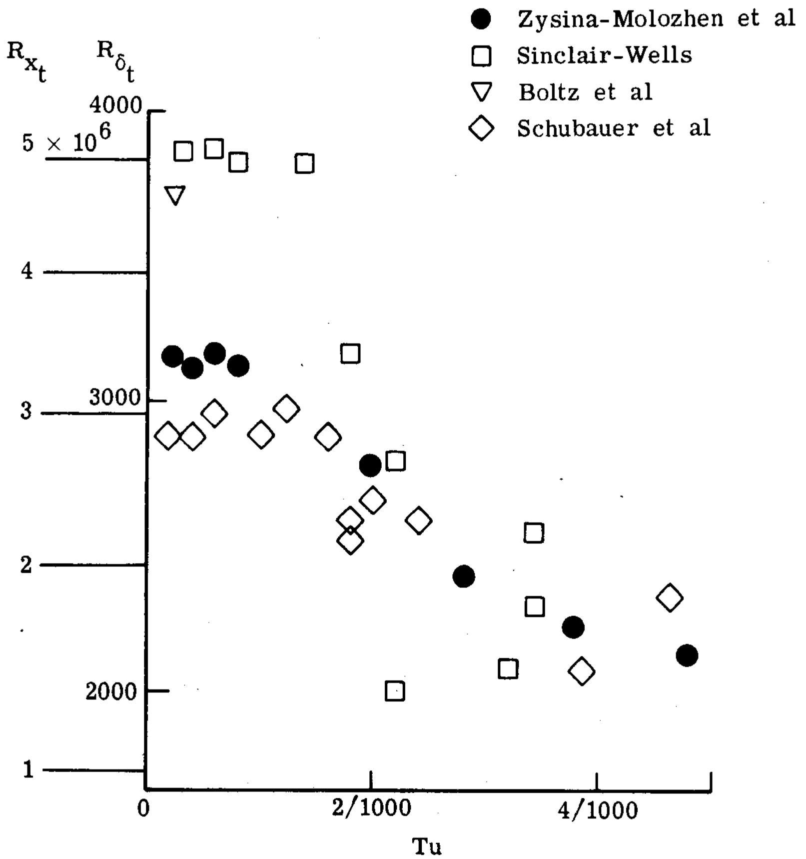


Figure 2.- Insufficiency of turbulence intensity as parameter for transition at low free-stream turbulence. Acoustic phenomena? (Flat-plate incompressible flow.)

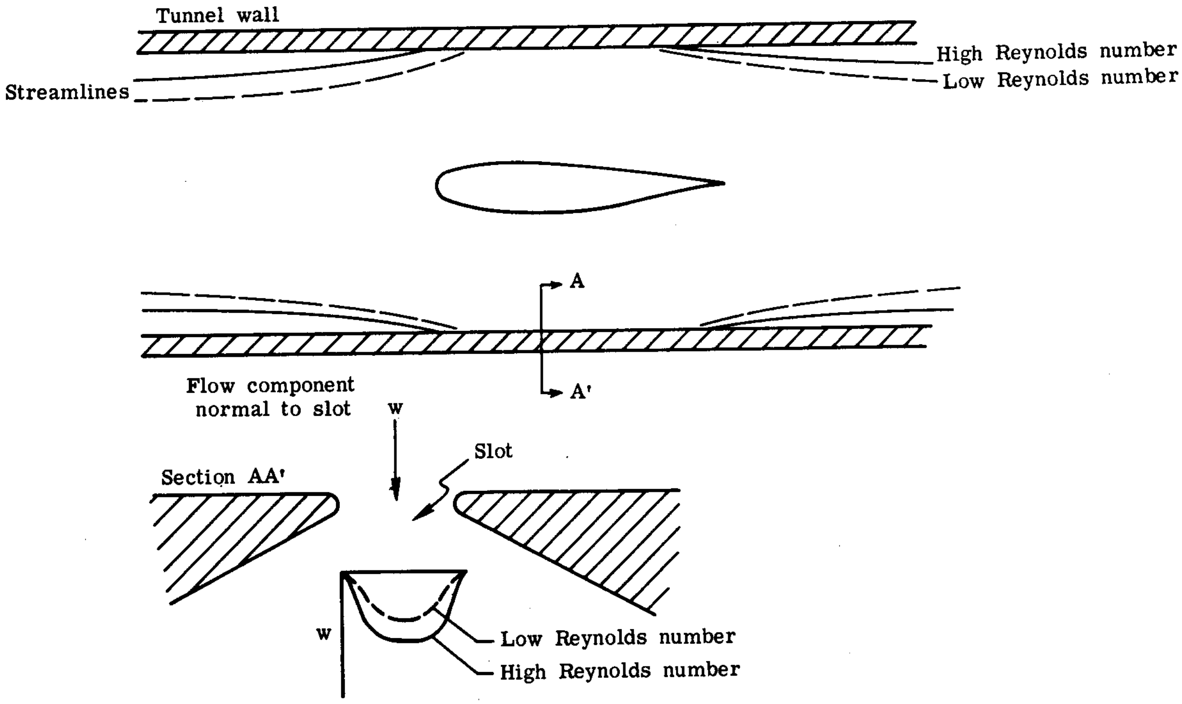


Figure 3.- Effect of Reynolds number on wind-tunnel wall interference.

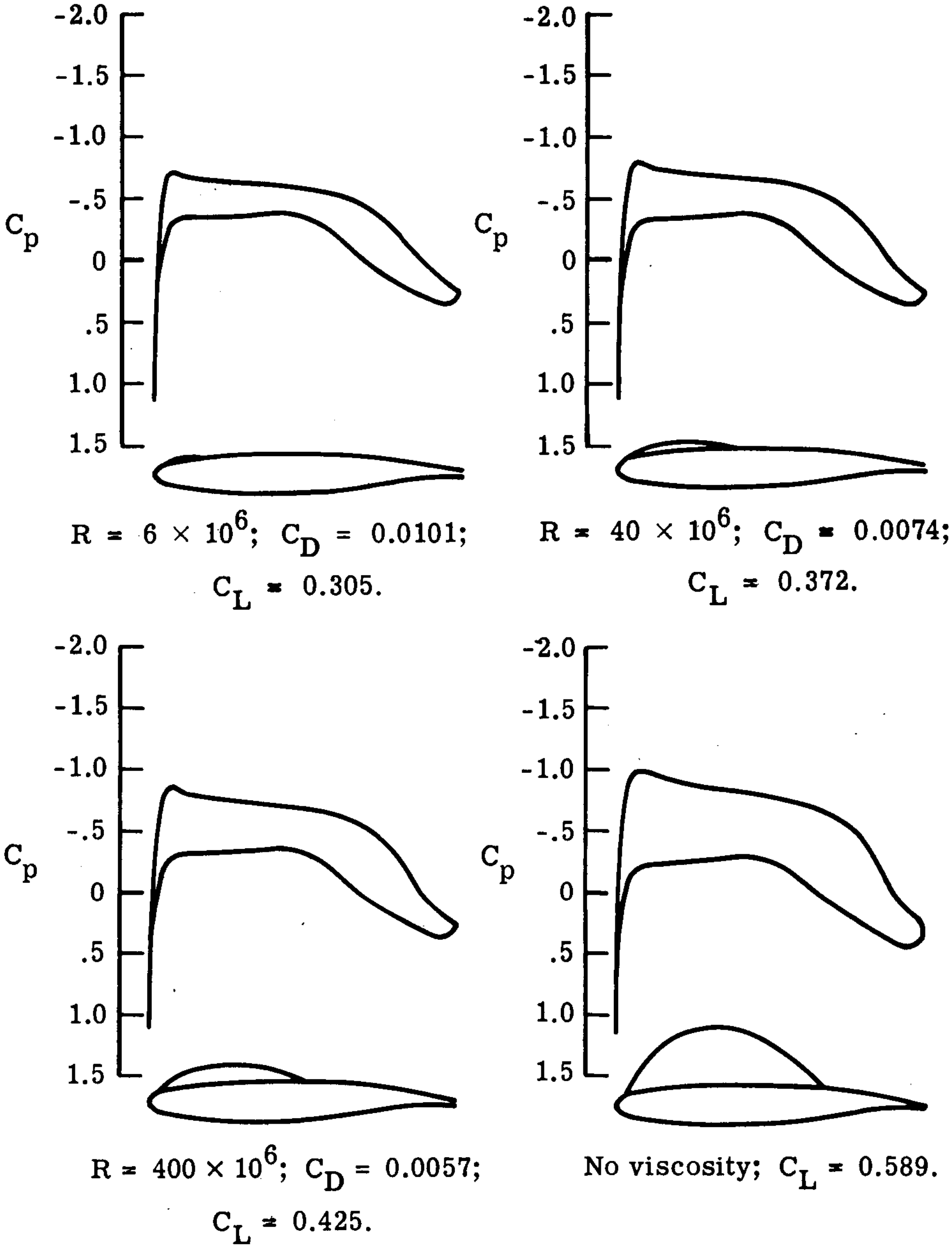


Figure 4.- Effect of Reynolds number on lift and drag of a supercritical airfoil at $M_\infty = 0.730$.

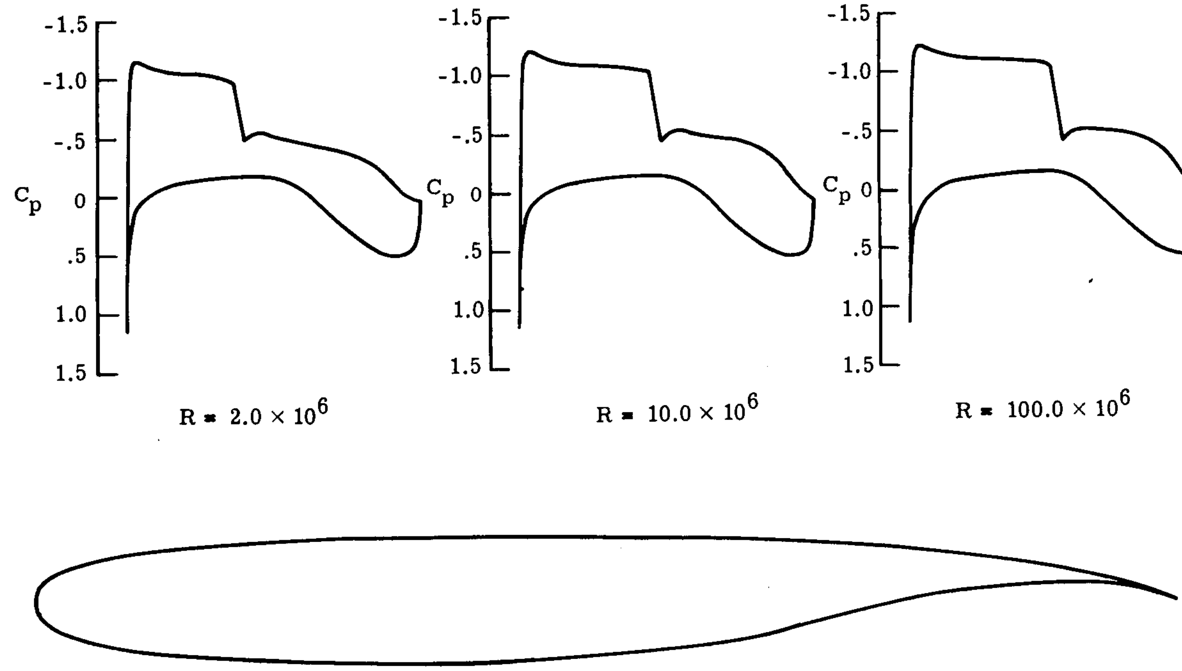
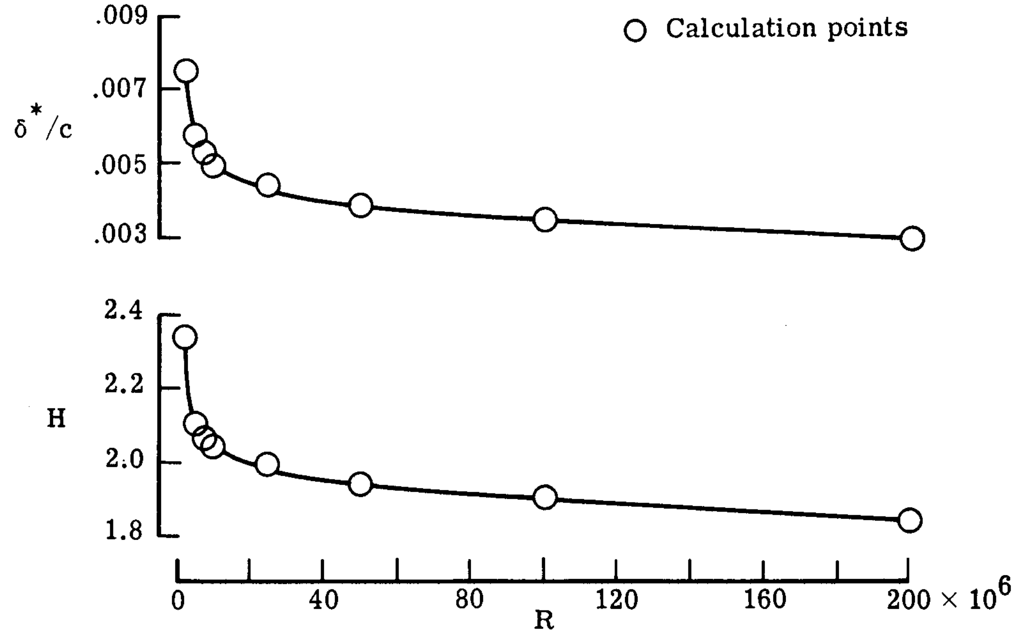
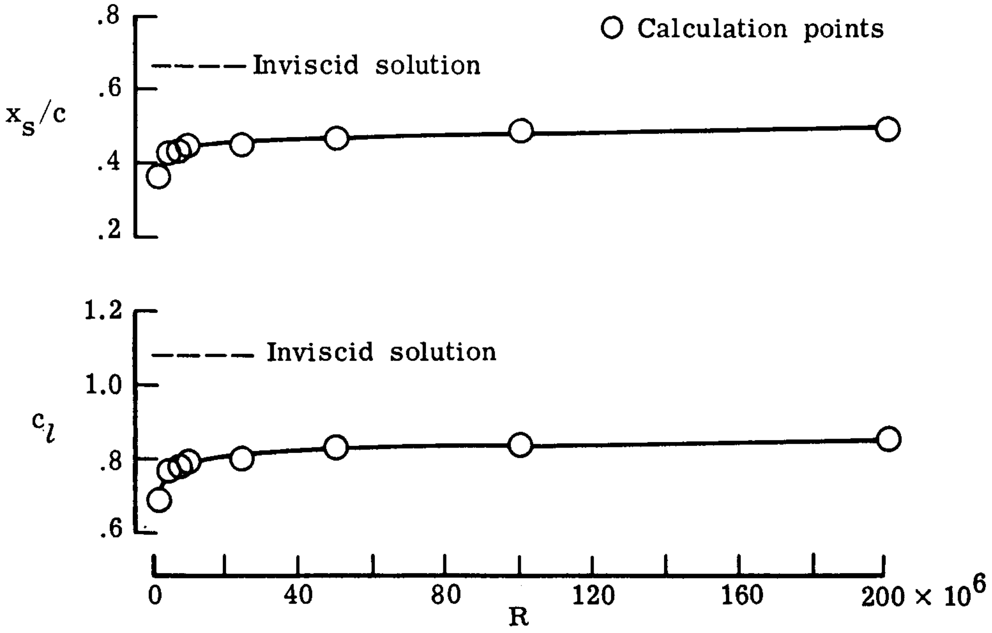


Figure 5.- Pressure distributions for a typical supercritical airfoil at $M_\infty = 0.759$ and $\alpha = 0.95^\circ$.



Boundary-layer characteristics; upper surface; x/c = 0.95.



External flow characteristics

Figure 6.- Variation of selected quantities with Reynolds number at $M_\infty = 0.759$ and $\alpha = 0.95^\circ$.

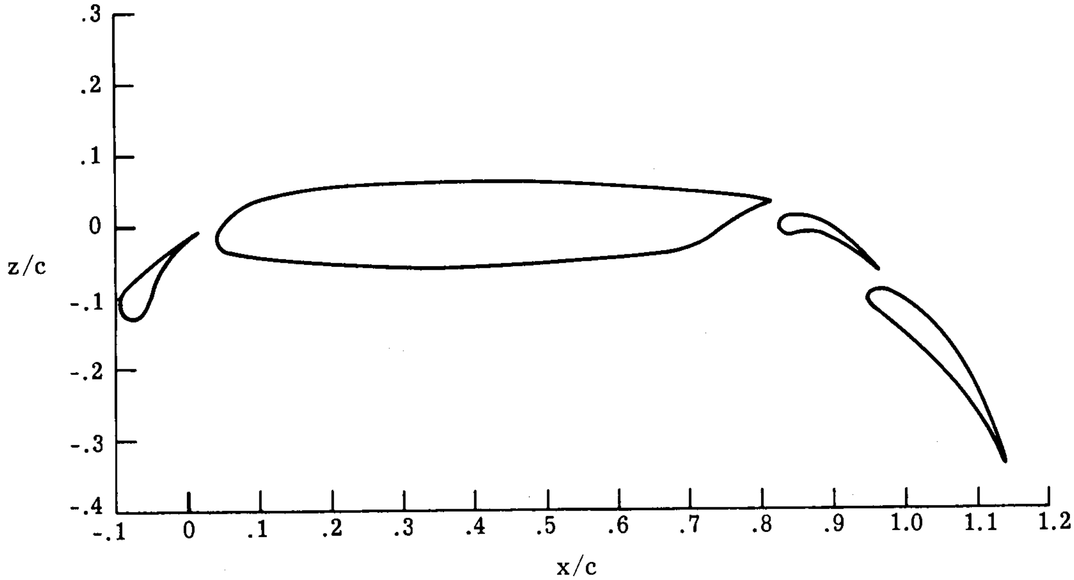


Figure 7.- Sketch of energy efficient transport medium-vane, double-slotted flap.

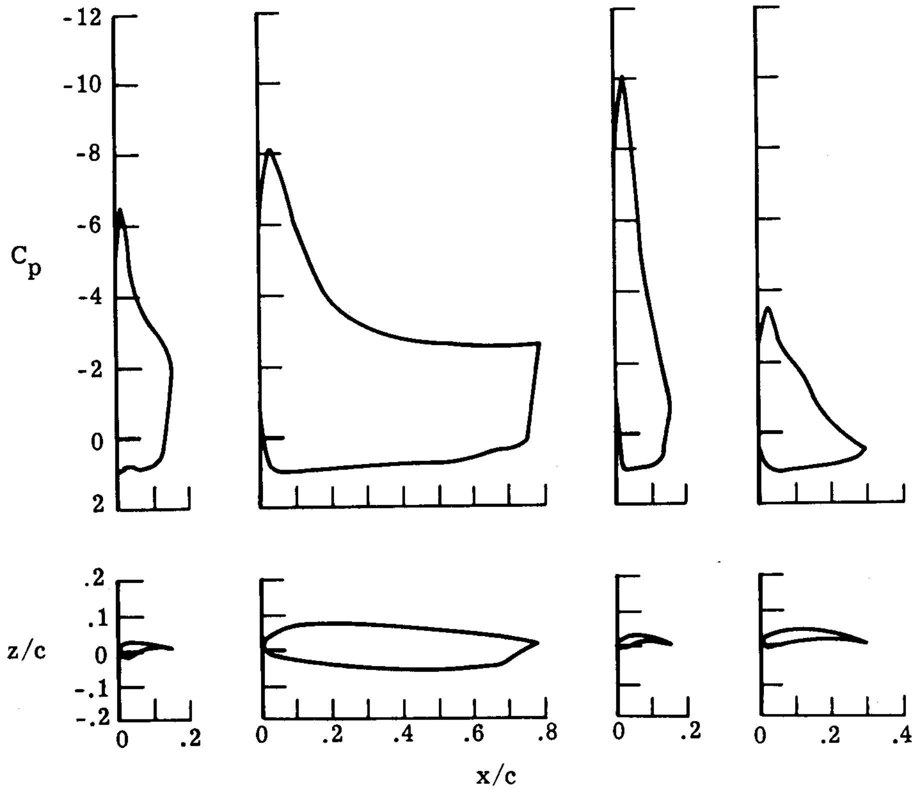


Figure 8.- Pressure distribution on EET medium vane, double-slotted flap. $M_\infty = 0.2$; $\alpha = 5.0°$.

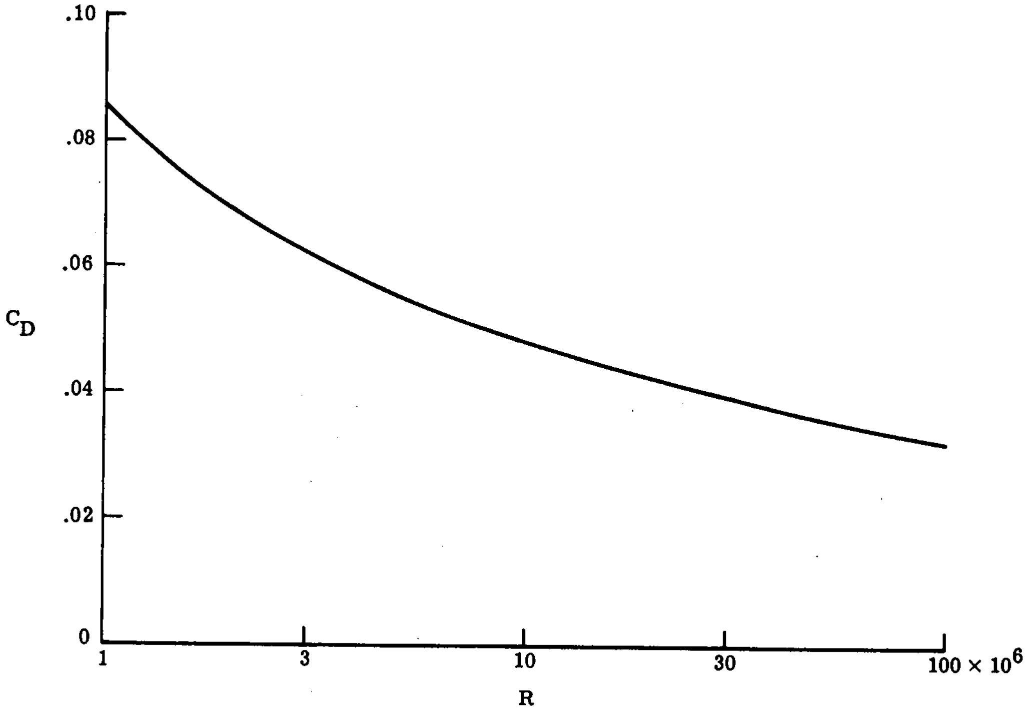


Figure 9.- Drag coefficient versus Reynolds number for energy efficient transport (EET) medium vane, double-slotted flap. $M_\infty = 0.2$; $\alpha = 5.0^\circ$.

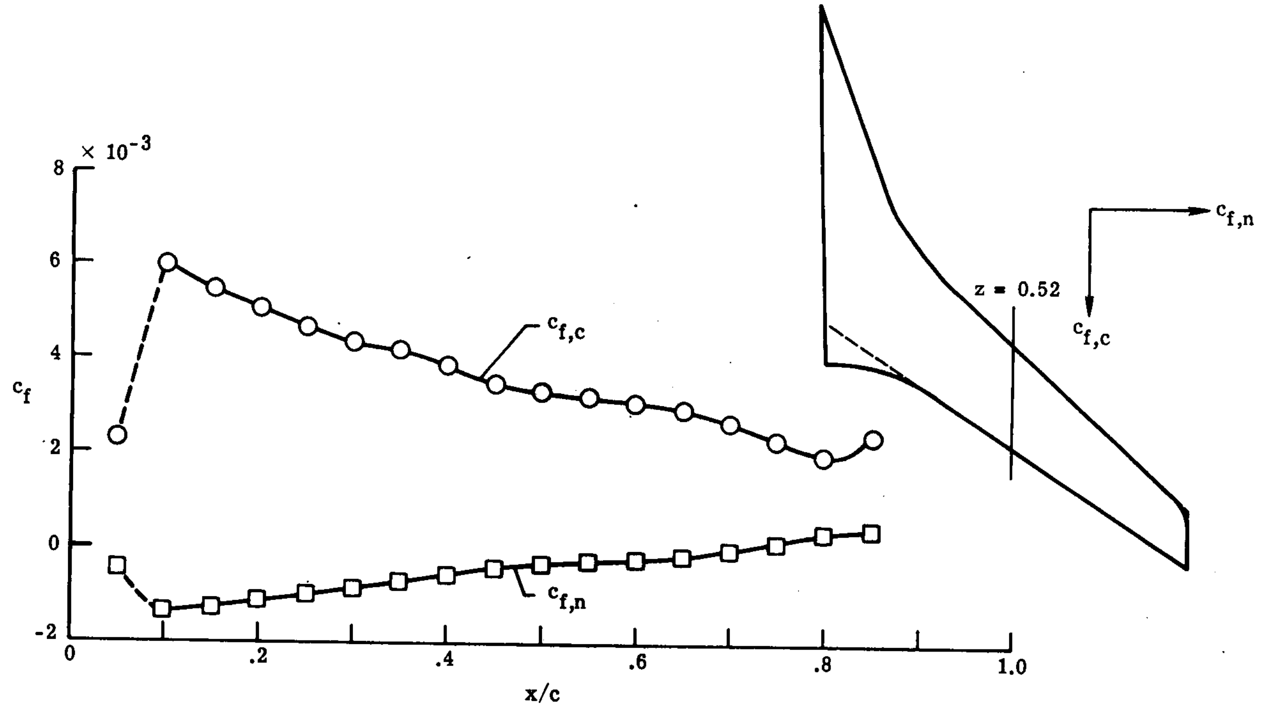


Figure 10.- Results from Cebeci 3-D boundary-layer program; chordwise variation of local skin friction coefficients. $M_\infty = 0.99$; $z = 0.52$; $R = 4.9 \times 10^6$.

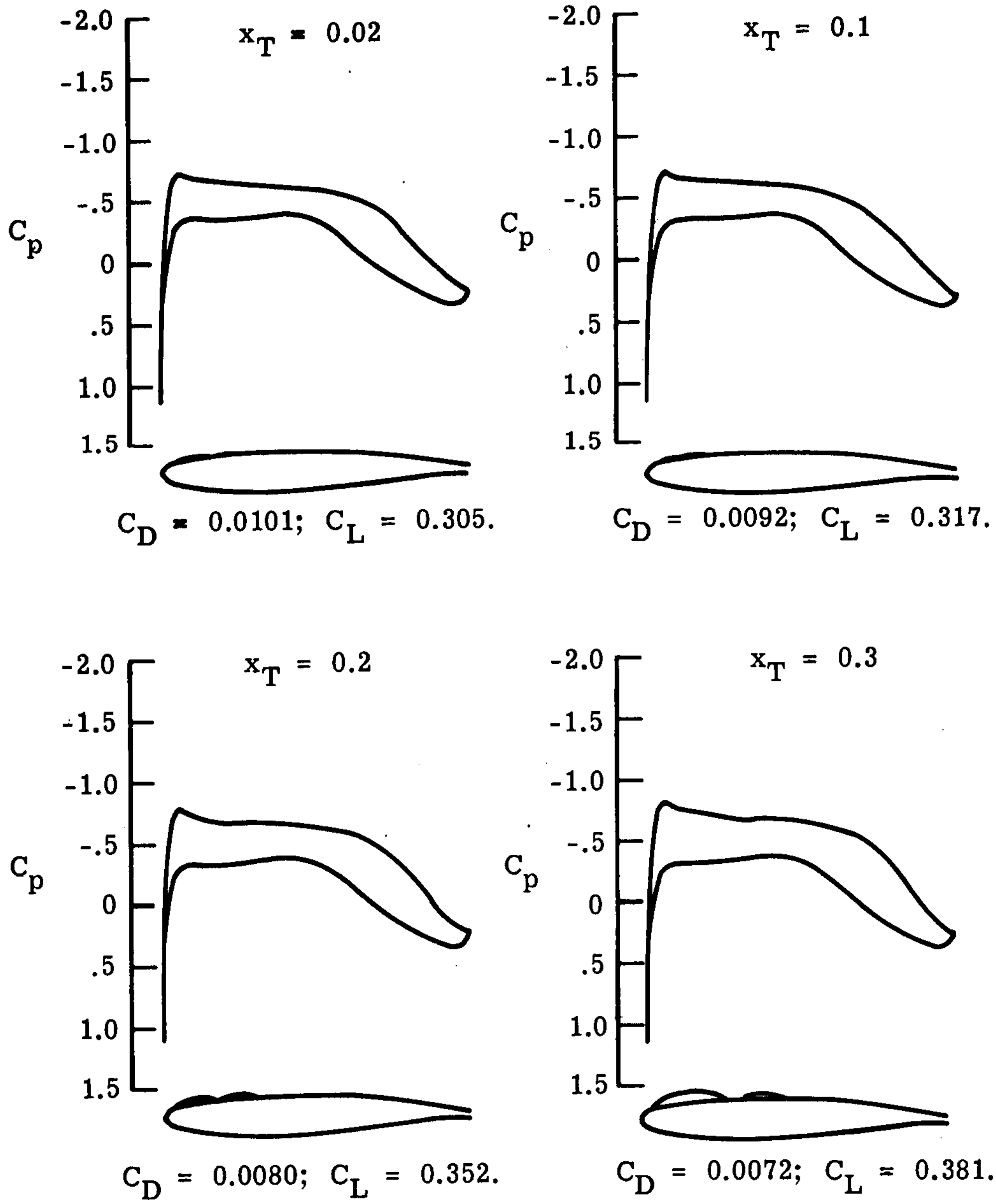


Figure 11.- Effect of transition location on the lift and drag of a supercritical airfoil. $M_\infty = 0.730$; $R = 6 \times 10^6$.

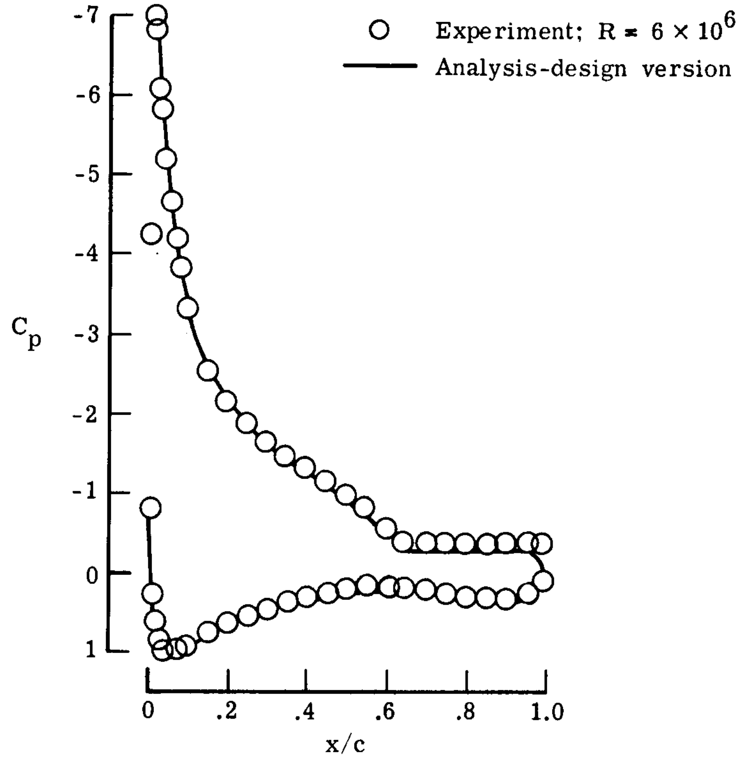


Figure 12.- Pressure distribution for separated flow for GA(W)-1 airfoil. $M_\infty = 0.15$; $\alpha = 16.04°$.

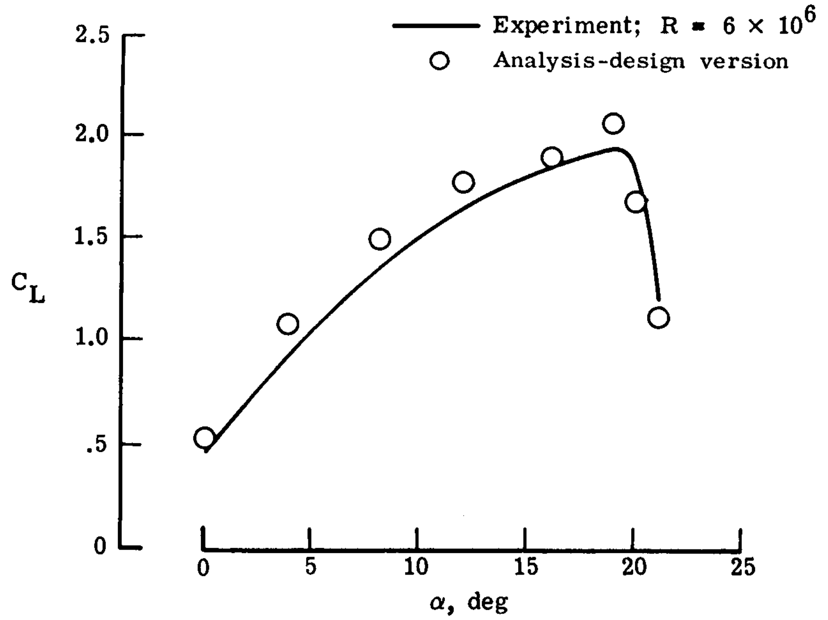


Figure 13.- Dependence of lift coefficient on angle of attack. $M_\infty = 0.15$.

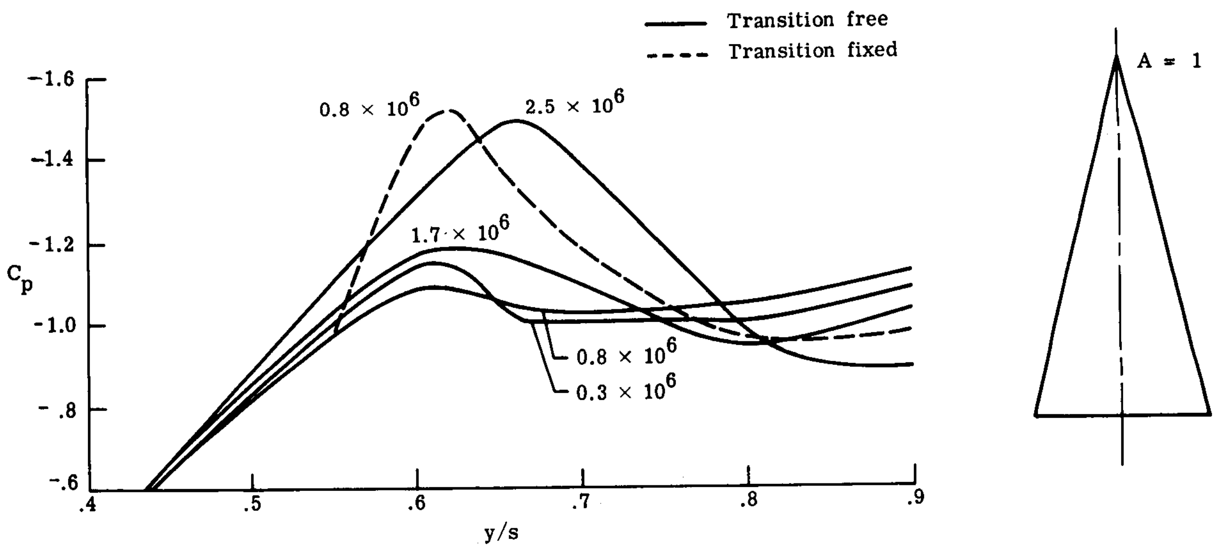


Figure 14.- Suction peaks for various Reynolds numbers (after Gregory and Love).