AIAA-80-0894

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AIAA INTERNATIONAL MEETING & TECHNICAL DISPLAY "GLOBAL TECHNOLOGY 2000"

May 6-8, 1980/Baltimore, Md.

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Abstract

Envisioned aerodynamic technology development and refinement contributions to acnieving air transportation economic expectations through the year 2000 are discussed. Cruise lift/drag ratios of current commercial transport airplanes are compared relative to a potential maximum level for fully turbulent flow. Ideas for improving aerodynamic cruise efficiency are then categorized as to their "evolutionary" or "revolutionary" potential. Advanced aerodynamic technologies currently being researched (e.g., laminar flow control, natural laminar flow, advanced transonic wing design) are reviewed. SST aerodynamic technology status is discussed along with an assessment of the chances of a U.S. SST within this time period. Advanced aerodynamic computing and testing techniques will play important roles in achieving the aerodynamic advances.

1.0 Introduction

The development of aircraft from the Wright Brothers' humble "Flyer" of 1903 to the magnificent machines of today illustrates an astonishingly rapid rate of progress in airplane design. This progress is the result of numerous technical advances in such fields as aerodynamics, propulsion, flight controls, structures, materials, and internal systems. Indeed, a characteristic feature of advances in aviation has been the need to advance on many fronts. Often progress has been delayed until the development of a critically needed technology.

This frontal advancement has most often been the result of the development of new military aircraft systems.

Private individuals, research laboratories operated by the Government, universities, and private companies, as well as industrial design and engineering teams, have all been involved in bringing the airplane to its present highly developed state. The aeronautical development achievements have come about by careful and painstaking work, interrupted occasionally by a brilliant insight or invention. Both the routine and the unusual have been and will continue to be important to the growth of aviation. Although technology has historically been the prime mover for aeronautical achievements, it has become less of a pacing item in recent years, especially in the commercial airplane field. Today, being able to do something does not mean that we should do it nor that we may even be allowed to do it.

Opportunities for applying new and advanced technologies will depend on a variety of factors reflecting the strong influences of economic, social, and political considerations. Nevertheless, future developments in aviation will remain responsive to technology advances. In fact, many of the technology advances will provide solutions to current problems, such as social acceptability of aircraft through noise and pollution reduction, improved safety, better fuel efficiency in view of the importance of rising fuel costs, and increased productivity and better economics, while responding to specific market needs.

This paper discusses aerodynamic technology development and refinement contributions to commercial air transports that are envisioned through the year 2000.

The views expressed are necessarily those of the authors but have been greatly influenced by our colleagues at Boeing and throughout the aviation industry, who are actively involved in providing the research and development foundations necessary for implementation of future aerodynamic advances. We have been equally influenced by those who have addressed the challenge of forecasting the future, although history has shown that projections tend to overestimate short-term accomplishments and underestimate long-term advances.

In section 2, the general nature of airplane technology advances is discussed. It is shown that both "evolutionary" and "revolutionary" improvements have contributed to previous aerodynamic advances leading to the

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current commercial airplanes. In section 3, ideas for improving aerodynamic cruise efficiency are categorized as to their "evolutionary" or "revolutionary" potential.

The idea that advanced high-speed airfoils do not provide a direct increase in lift/drag ratio is presented in section 4. Advanced airfoils, however, do provide the opportunity for improved wing design integration and therefore will result in better lift/drag ratios.

Much work is underway to provide "evolutionary" aerodynamic gains in many different areas, as is discussed in section 5. Means for providing span increases that produce proportionally large improvements in lift/drag ratio are discussed in section 6.0. "Revolutionary" aerodynamic advances are considered in section 7. These include various means for reducing viscous drag by altering the natural state of turbulent flow on large commercial aircraft. The possibility of a U.S. SST is considered in section 8. Anticipated advances in the aerodynamic designer's tools are discussed in Section 9. These include both computational aerodynamics and wind tunnel testing.

2.0 General Nature of Technology Advances

The general historic trend in transport aircraft technology development is illustrated in figure 1. The steady periods of technical evolution reflect the process of design refinement of a fairly fixed concept. The sudden dramatic improvements indicate the appearance of some major technical innovation, such as cantilever wings, pressurized cabins, jet engines, or swept wings.

It is therefore convenient to distinguish between the two types of progress as:

- "Revolutionary"—a breakthrough in which some new concept or technical development makes possible a new class of airplanes or significant performance improvements
- "Evolutionary"—a developmental process in which a particular class of airplanes is progressively refined

The history of airplane parasite drag reduction is shown in figure 2. The major reductions in parasite drag have occurred with revolutionary changes in the shapes of the airplanes (biplanes to propeller monoplanes to swept-wing jet aircraft) and with the incorporation of retractable landing gear.

Technological advances in aerodynamic cruise efficiency (ML/D) since the mid-1930's are shown in figure 3. Both evolutionary advances and revolutionary advances have made significant contributions to improved aerodynamic cruise efficiency. The revolutionary advancements were due mainly to cruise speed increases associated with the introduction of a new class of airplanes. The revolutionary advancement occurring in the late 1950's was the introduction of the swept-wing airplane with jet engines. In the early 1970's, the next revolutionary advancement was the introduction of the slender wing, jet engine supersonic transport. Within each class of airplanes, significant improvements in aerodynamic efficiency were achieved by means of continuing evolutionary advances.

The most recent new commercial transport airplanes have provided increased system efficiency and better economics while retaining high aerodynamic efficiency. These include the wide-body jets with turbofan engines. History has shown that successful aircraft almost always have lower operating costs than their predecessors, while offering service improvements in speed, range, or comfort.

Technical development is the integration of applied research, experiment, and engineering necessary to bring into practical operational use the new knowledge gained from research. Introduction of a new technology into commercial transport service requires a number of preconditions:

1. There must be an established need for the new technology. This need may, for example, reflect the inability of existing technology to provide a desired level of performance.
2. The benefits must be identified, particularly in terms of performance improvements, cost reductions, and technical risk. This implies that the new technology has achieved sufficient maturity so that data are available to balance cost versus benefits without incurring unacceptable technical risks.
3. A characteristic feature of technology development in aviation has been the need to advance on many fronts in order to utilize the potential of a new pacing technology. A classic example is the Boeing B-47, which has had a profound influence on current

commercial airplane designs. The B-47 was designed to exploit the performance of the jet engine. The final design included technical advances in many areas. Cruise aerodynamic advances included a thin, clean high-aspect-ratio wing with underwing pod-mounted nacelles. The high-lift system included Fowler flaps and flaperon lateral control. The advanced flight control system was composed of rigid feedback loop hydraulic power controls with automatic manual backup. This airplane also used the first production full-time stability augmentation system to eliminate undesirable dutch roll characteristics associated with the wing sweepback.

4. Finally, the opportunity to introduce the new technology must exist. Often in the past, military needs have provided the opportunity to develop a technology long before introduction into commercial service. Because of the immense cost in developing advanced aviation technology to the necessary level of maturity, Government-sponsored research is a vital part of the technology development process.

These necessary preconditions indicate that application of a new technology takes time. On the basis of history, one sees that 10 to 20 years pass between the first full-scale experimental use of a new advanced technology and its entry as a refined development into commercial service. In addition, there is an earlier time period associated with the lag between the first laboratory investigation and an assessment of its engineering feasibility prior to the full-scale test.

Consequently, discussions in this paper concerning aerodynamic expectations in the next 20 years are limited to aerodynamic concepts firmly based on present understanding in fluid mechanics and on concepts currently in research and development stages. Aerodynamic technology advances are discussed primarily in relation to their impact on cruise lift-to-drag ratio. Advanced technology is defined as technology that has not been certified for use on commercial transport airplanes.

3.0 Lift/Drag Ratio Improvement Categories

The history of airplane parasite drag reduction, shown in figure 2, indicates that modern-day jet airplanes have parasite drag levels approaching the best attainable values for fully turbulent flow profile drag. Assuming a minimum total drag level equal to fully turbulent profile drag plus minimum induced drag, a potential maximum lift/drag ratio can be defined. This potential maximum lift/drag ratio can then be used to establish the relative aerodynamic cruise efficiency of existing commercial jet airplanes.

The profile drag C_{D_P} is assumed equal to fully turbulent skin friction multiplied by an overspeed factor, K_{THICK}. The overspeed factor accounts for airplane thickness effects on the viscous drag. The induced drag, C_{D_I} is assumed equal to that associated with an elliptic spanwise load distribution.

Hence $$C_D = C_{D_P} + C_{D_I} \quad (1)$$

where $$C_{D_P} = K_{THICK}\ \tilde{C}_F\ A_W/S \quad (2)$$

and $$C_{D_I} = \frac{C_L^{\ 2}}{\pi AR_e} \quad (3)$$

C_L = Wing lift coefficient

AR_e = Effective wing aspect ratio = $b_e^{\ 2}/S$

A_W = Airplane total exposed surface area

b_e = Effective wing span

S = Reference wing area

$\tilde{C}_F$ = Overall average fully turbulent flow, flat-plate skin friction coefficient for the airplane.

For this case, it can be shown that potential maximum lift/drag ratio, $(L/D)_{MAX,\ POTENTIAL}$ can be expressed as:

$$(L/D)_{MAX,\ POTENTIAL} = \frac{\sqrt{\pi}}{2}\ \frac{b_e}{\sqrt{K_{THICK}\ \tilde{C}_F\ A_W}} \quad (4)$$

Calculations made of the overall average flat-plate turbulent flow skin friction coefficient and the average overspeed factor for existing swept-wing jet transport type airplanes are shown in figure 4.

The average overspeed factor, K_{THICK}, for all of the airplanes is seen to be about equal.

$$K_{THICK} \approx 1.19 \qquad (5)$$

The average skin friction coefficient is less for airplanes with large surface areas. This reduction in friction drag occurs because of higher Reynolds numbers associated with the larger airplane component lengths.

An effective wetted area, $A_{W,EFF}$, can then be defined as

$$A_{W,EFF} = A_W \, (C_F/0.002) \qquad (6)$$

with $C_F/0.002$ given by the curve in figure 4.

Combining equations 4, 5, and 6 shows that the potential maximum lift/drag ratio for fully turbulent flow depends only on the effective wing span and the overall surface areas:

$$(L/D)_{MAX,\ POTENTIAL} = 18.2 \frac{b_e}{\sqrt{A_{W,EFF}}} \qquad (7)$$

The geometry ratio of wing span to square root of the effective surface area has been used in figure 5 to correlate the flight test measurements of maximum lift/drag ratios of existing subsonic transport-type airplanes.

Existing airplanes achieve approximately 80% of potential maximum lift/drag ratios. As indicated in this figure, miscellaneous drag sources account for about 20% of the total drag. Approximately 40% of the total airplane drag is the turbulent flow profile drag and 40% is the induced drag.

Advanced aerodynamic concepts that eliminate or reduce the miscellaneous drag sources will individually provide rather small, although important, increases in lift/drag ratio. These concepts can therefore be considered as "evolutionary" concepts.

Evolutionary technical advances that increase the effective span offer the possibility of proportionally large improvements in aerodynamic efficiency, since the maximum lift/drag ratio varies directly with the wing span.

Technical advances that reduce the friction drag below the fully turbulent flow levels offer the greatest potential improvements in L/D_{MAX}.

In the sections that follow, we will review aerodynamic technology advances that offer the possibility of evolutionary or revolutionary improvements in lift/drag ratio. First, however, we will review another important area of aerodynamic research: airfoil technology development.

4.0 Advanced Airfoil and Wing Design Opportunities

Airfoil and wing technology has come a long way since the introduction of standard body commercial jet transports. This progressive development leading to the current advanced high-speed airfoils is illustrated in figure 6.

Advanced high-speed airfoils do not provide a direct increase in airplane lift/drag ratio, per se. This advanced technology does, however, provide the ability to integrate an improved total configuration that has as one of its attractions an improved airplane L/D. Prior to the fuel crisis, the then-available airfoil technology was used, at least in part, to increase aircraft cruise speed. Airfoil technology improvements, however, can be exploited in several ways: increased wing thickness, increased wing lift, or decreased wing sweep. With the current emphasis on fuel efficiency, the best choice will usually be a combination of the possible variations, as shown in figure 7.

Advanced airfoils and new wings as currently designed for subsonic aircraft are probably close to the maximum achievable potential with fixed geometry designs. Moderate additional improvements will be achieved through the use of improved theoretical transonic flow analyses, and improved three-dimensional wing design methods, together with wind tunnel testing advances.

5.0 "Evolutionary" Aerodynamic Advances

There is much research and development work currently underway that offers the promise of "evolutionary" aerodynamic gains; that is, trying to do what we have done before but better. Historically, both "evolutionary" and "revolutionary" aerodynamic gains have often required "revolutionary" advances in other technology areas. The cantilever wing, low-drag engine cowls, and retractable landing gear were technology advances in stuctures, propulsion, and systems that provided desired reductions in parasite drag. Technology advances in other disciplines will continue to be a source of evolutionary as well as revolutionary aerodynamic improvements.

5.1 Interference Drag Reduction

One important area where evolutionary aerodynamic advances are always possible is the reduction of interference drag. Interference drag is caused by the complex flow-field interactions between adjacent aircraft components. Typical interference regions include wing-fuselage, wing-nacelle, fuselage-nacelle, fuselage-empennage, and wing-tail. Although considerable research has been directed toward understanding and predicting interference effects between the various airplane components, continued research will remain a necessity. Present techniques for eliminating unfavorable aerodynamic interference depend on a combination of wind tunnel testing, potential flow analyses, and engineering judgment based on experience.

Figures 8 and 9 show examples of where the combined use of computational aerodynamics and wind tunnel testing provided improvements in aerodynamic interference.

A wing strake fairing that was analytically designed through iterative analysis using a three-dimensional inviscid flow program is shown in figure 8. The fuselage surface flow in the area of the wing-root junction experienced a strong adverse pressure gradient that ultimately separated the boundary layer in this region. Streamlines that approach the wing-root junction were calculated on a baseline configuration without a wing strake. A wing strake was then designed over the streamlines by adjoining the highlight of the strake with the streamlines.

The strake design was subsequently wind tunnel tested to assess the drag performance. The computational method does not have the capability to predict drag changes resulting from the relatively minor configuration modification that suppressed local boundary layer separation. The wind tunnel test results indicate about a 1% reduction of total airplane drag in the cruise lift range.

The development of a favorable overwing pylon-mounted nacelle is shown in figure 9. The use of an axisymmetric nacelle and symmetric pylon was shown to produce a large aerodynamic drag penalty. The nacelle and pylon were redesigned by analysis at a subcritical Mach number. Wind tunnel tests of the contoured nacelle and strut showed essentially interference-free performance. Further modification during the test provided a slight additional improvement in performance.

The technique for controlling the effects of component interference generally includes shaping and contouring to avoid excessive supervelocities and adverse pressure gradients. Although considerable effort has been directed toward understanding and predicting interference effects, additional research is still needed. The viscous effects that strongly affect flow behavior in junctions between adjacent aircraft components cannot be predicted by present analytical methods.

Understanding and elimination of unfavorable aerodynamic interference is an area where advanced analytic and testing techniques are likely to produce important drag reductions.

5.2 Roughness and Excrescence Drag Reduction

Roughness or excrescence drag is caused by relatively small protrusions or recesses on an airplane surface. These excrescences are often the unavoidable result of using practical materials and manufacturing techniques. They include such items as surface waviness, surface finish, projecting or countersunk fasteners, panel joints, air intake and exhaust openings, lights, antennae, and probes, and gaps around doors, windows, and control surfaces. Estimates have shown that roughness drag on a subsonic transport can contribute as much as 3 to 5% of the cruise drag.

There has been much research into the fundamental mechanisms of roughness and excrescence drag over the years. Several approaches have been identified as applicable for reducing the drag of the various roughness items. The most obvious is to eliminate the excrescence or reduce its height. The surface can be considered hydraulically smooth and to have low roughness drag if the excrescence height is less than the local sublayer thickness of the boundary layer.

NASA has sponsored various studies, including an ongoing test program to explore the feasibility of producing smooth surfaces with films or coatings applied to the wing and to the empennage. There currently is no known process that is economically feasible for applying films over large curved surfaces. However, sprayed-on coatings, which are relatively easy to apply, appear to offer some potential for drag reduction. More data are needed to identify drag reduction benefits and application and maintenance costs, and to determine the long-term durability of surface coatings in an airlines' operating environment.

Future reductions in roughness and excrescence drag will occur, however, as a result of technological advances in materials and in manufacturing techniques. Improved three-dimensional boundary layer calculations will provide a better assessment of design tolerances necessary for reduced roughness drag.

5.3 Trim Drag Reduction

Another probable aerodynamic improvement of the evolutionary type is a reduction in trim drag through the use of active controls. Existing commercial transport airplanes are designed to have inherent longitudinal static stability. Basic aerodynamic characteristics combined with the relative locations of the wing, the tail, and the airplane center of gravity require a rather large down-load on the tail to trim the airplane. This results in a positive trim drag.

The inherent longitudinal stability requirement of an airplane with active controls can be relaxed so that the center of gravity can be located further aft relative to the wing, thereby reducing trim drag. The required horizontal tail is smaller, resulting in an additional savings in drag and weight. The configuration changes and potential benefits are illustrated in figure 10.

Stability augmentation in the form of yaw dampers, Mach trimmers, and autothrottles has been in common use on commercial airplanes for many years. These systems, however, have been of limited authority so that a failure would not result in unacceptable handling qualities. Reliability of the existing systems is good. There is confidence that the use of augmented stability can be expanded with the advanced technology becoming available. A limited initial application of relaxed stability to new aircraft and to derivatives of current airplanes is foreseen.

6.0 Induced Drag Reduction

One of the major sources of drag for current commercial jet transport airplanes, as previously discussed, is induced drag. It is well known that the induced drag can be reduced by increasing the wing aspect ratio with larger wing spans. Increasing wing span has a large leverage on aerodynamic efficiency. As shown in figure 5, the lift/drag ratio varies directly with the wing span, provided the wetted area is held constant.

Commercial transport airplanes are typically designed to achieve specific mission objectives (e.g., range, payload, speed), with low cost as a primary figure of merit. The optimum wing aspect ratio is generally selected as a trade between lower fuel usage with an aerodynamically efficient higher aspect ratio wing, and lower weight with a structurally more efficient lower aspect ratio wing.

The present generation of high subsonic jet transport airplanes has wing aspect ratios of approximately 7 or 8. These airplanes were designed before the fuel crisis and the subsequent increases in the price of fuel. The fuel prices and concerns for the future availability of fuel may exert more leverage in the design optimization process in favor of higher wing spans. Similarly, technology advances that reduce wing weight may also result in higher optimum wing spans.

6.1 Non-Aerodynamic Factors Leading to Increased Wing Aspect Ratio

Two significant structural material developments will contribute to a reduction in wing weight. First, a family of advanced aluminum alloys with improved mechanical properties has been developed. These weight-saving alloys are being used in the new Boeing 757 and 767 airplanes, as a result of an extensive and successful 5-year development program.

Another major technical development is the advanced composite material structure. Composite materials offer very high strength-to-weight and stiffness-to-weight ratios and could significantly reduce airplane structural weight. Despite their potential advantages, composite materials are not currently widely used in commercial airplanes. The greatest deterrent to widespread usage is the lack of experience with composites under actual service conditions, which will be required to achieve the necessary credibility. Current applications of composite structural materials in commercial airplanes are in secondary structure not critical to safe flight. The full potential of composite structures will be realized only when used in primary structural components. Because of technical and production challenges, and the large capital expenditures necessary to support composite production capability, the progressive application of composite materials will continue to be a planned evolutionary process.

Active load relief systems may also increase the optimum aspect ratio for wings. Extensive system studies and flight demonstrations are being conducted to evaluate means for relieving the bending moments in a wing at critical structural design conditions through computer-controlled aerodynamic surfaces on the wing. Weight reductions are possible through the alleviation of maneuver, gust, and fatigue loads and the suppression of flutter. A full utilization of this approach requires the development of systems having the necessary level of redundancy and reliability. Development of such systems is being actively pursued.

6.2 Advanced High-Speed Airfoil Integration

Advanced high-speed airfoil technology contributes significantly to our ability to utilize high-aspect-ratio wings practically. This is because advanced airfoil technology can be exploited by appropriate combinations of reduced wing sweep, increased thickness, and higher lift for a given design cruise Mach number.

Increased wing thickness and reduced wing sweep allow higher wing aspect ratios for minimum weight changes. Additionally, when the aspect ratio is increased, the optimum lift coefficient for the wing also increases. The advanced airfoil sections can provide higher lift with minimum increases in compressibility or form drag.

6.3 Winglets

The concept of using end plates or wingtip fins to reduce induced drag has long been understood. Interest in wingtip fins has been renewed in the past few years. Theoretical and experimental investigations have lead to development of aerodynamically efficient wingtip fins, which are commonly called winglets. Winglets alter the lift distribution and trailing-edge vortex structure of the wing. Aerodynamic forces caused by the trailing-edge vortex system are ultimately felt in the form of pressure forces that act on the wing-winglet combination. Winglets produce a higher effective span in a way that generally results in lower wing bending moments, relative to a wing span extension that provides equivalent drag reduction. However, the length of a winglet must be approximately twice that of a span extension to achieve the same induced drag reduction.

Winglets are being investigated for applications to existing transport airplanes as well as to future designs. Results concerning application of winglets to existing airplanes indicate that the net benefits of incorporating wingtip fins is dependent upon the basic wing design. For example, studies indicate that winglets show attractive potential for the KC-135, figure 11, but very little potential benefits for the Boeing 747 airplane.

An assessment of the net benefits of winglets requires detailed knowledge of the structural characteristics of the basic wing design. Consequently, winglets will initially be adapted to derivative airplanes where the structural characteristics of the wing are rigorously known and the assessed benefits are shown to be favorable.

7.0 "Revolutionary" Aerodynamic Advances to Reduce Viscous Drag

Viscous or skin friction forces account for approximately 40% of the total drag on current subsonic jet transport airplanes. Skin friction drag originates in the thin boundary layer region near the surface of the airplane where viscosity effects are large. The flow within the boundary layer may be either laminar, transitional, or turbulent. At high Reynolds numbers, turbulent flow skin friction drag is many times larger than laminar flow skin friction drag.

The natural state of the boundary layer on commercial jet transport airplanes is turbulent. The most obvious and most technically advanced scheme to reduce skin friction is to prevent turbulence by delaying the transition process. An alternative approach to viscous drag reduction is to decrease the level of the turbulent shear stress but to permit the flow to remain turbulent. With low skin friction drag, the optimum airplane design is changed since larger wing areas and aspect ratios are acceptable. The resulting larger spans produce significant reductions in induced drag.

Both approaches for reducing skin friction are being investigated in current industry and/or NASA research programs.

7.1 Natural Laminar Flow

The practical achievement of laminar flow offers the potential for substantial drag reduction. For any given laminar flow, however, there is a finite value of Reynolds number at which the flow becomes unstable and tends to undergo transition to turbulent flow. This "critical Reynolds number" is significantly exceeded on the various components of commercial transport airplanes.

The transition from a laminar to a turbulent boundary layer is greatly influenced by the pressure gradient of the external flow. A decrease in pressure (i.e., an acceleration of the flow over the surface) has a stabilizing effect on a laminar boundary layer, so that transition tends to occur at a higher Reynolds number. Conversely, an increase in pressure or deceleration in local flow is highly destabilizing. Early application of this basic fact led to the development of the NACA low-drag airfoil sections. On these airfoils, the position of maximum thickness is located aft so that a large portion of the airfoil section is exposed to favorable pressure gradients.

Past wind tunnel tests have indicated that low drag could indeed be achieved. The most striking drag reductions were obtained by the British in the famous King Cobra experiments of 1945. As shown in figure 12, the section profile drag measured on the King Cobra was equal to approximately 35% of that for an equivalent thickness turbulent flow airfoil section. These low drag levels were obtained only after precise hand smoothing of the wing surface and extreme care to avoid bug impingement on the leading edge during flight tests.

The laminar boundary layer is critically sensitive to a number of factors that include—

- Surface roughness and waviness
- Leading-edge sweep
- Junction areas such as the wing-body intersection
- Acoustic disturbances either from the engines or nearly turbulent flow areas
- Operational disturbances such as insect deposits, rain, and ice

The major factor preventing consistent achievement of natural laminar flow has been premature boundary layer transition caused by insect impingement at or near the leading edge. Many possible solutions have been investigated. Recent NASA-Dryden experiments indicate that the leading edge can be kept clean by a continuous spray of water during takeoff and climb. It still remains to be proved whether a flush slot or series of holes can be properly located to keep both the upper and lower surface clean without causing premature transition when not in use.

The NASA-Dryden Research Center will be conducting flight tests on an F-111 airplane with natural laminar flow airfoil gloves on the outer wing panels. The installation, as shown in figure 13, will permit varying the leading edge sweep. Predictions of the profile drag variation with sweep angle, made for a number of Reynolds numbers, are shown in figure 13. The forthcoming flight test results are expected to add significant knowledge regarding the effects of compressibility, Reynolds numbers, and sweep on transition.

7.2 Laminar Flow Control

Even with a very smooth, clean wing surface with low sweep, natural laminar flow is restricted to transition Reynolds numbers on the order of 15×10^6. With laminar flow control (LFC), much more extensive areas of laminar flow can be achieved at higher Reynolds numbers and larger airplane sizes. In this approach, as illustrated in figure 14, a small amount of boundary layer air is sucked through the skin, thereby thinning and stabilizing the boundary layer. Ideally, the skin should be porous, but in actual practice it has been found possible to obtain extensive laminar flow with suction through narrow spanwise slots spaced a few inches apart.

Laminar flow with LFC is susceptible to the same type of destabilizing disturbances as natural laminar flow; however, to a much smaller degree. At this time, LFC appears to have a higher potential than natural laminar flow to achieve large skin friction reductions on commercial transport airplanes.

Some results obtained recently indicate, as shown in figure 14, a 70% improvement in fuel efficiency for an advanced technology LFC airplane relative to current wide-body jet transport airplanes. The effect of LFC alone for a resized design of this type is estimated to approach a 45% increase in fuel efficiency.

Much research has been devoted to the development of the laminar flow control concept. The USAF-Northrop X-21A program in the early 1960's was a major effort to demonstrate the feasibility of LFC on large subsonic aircraft. Laminar flow on the X-21A, shown in figure 14, was repeatedly maintained over virtually the entire wing. While the X-21A showed that laminar flow could be obtained in flight, the program was terminated before much information could be obtained about maintenance, operational, and economic aspects of an LFC airplane.

Technology developments since the pioneering work with the X-21A aircraft by Northrop and the Air Force offer the possibility of a more practical LFC system. Advances in computational aerodynamics permit development of advanced high-speed airfoil and wing designs with pressure distributions conducive to laminar flow. Boundary layer stability calculation methods that have been recently developed can be used to optimize the suction distribution to retain laminar flow. Advanced structural materials and manufacturing techniques should allow the economic development of smooth surfaces.

NASA is sponsoring extensive laminar flow control research. The work, both within NASA and through contracts with the industry, covers many of the practical aspects of developing a workable LFC system. This is structured to develop and integrate the various LFC subsystems into a validation airplane. Flight testing of this airplane in a simulated airline environment is planned to provide necessary maintenance, reliability, economic, and performance data so that the aircraft industry will be in a position to make a realistic assessment of the possible application of LFC to future commercial transport airplanes.

This LFC research and development work will require a number of years to produce the necessary information. It is unlikely that LFC could be considered practical for airplane designs before the late 1990's. The technical challenges are indeed formidable but the potential benefits are significant.

7.3 Turbulent Shear Stress Reduction

In the past few years, there has been considerable interest in the possibility of viscous drag reduction by altering the structure of turbulent boundary layers.

Some of the schemes that have been considered to reduce turbulent shear stress are illustrated in figure 15. Major problems associated with each scheme are also summarized. The major effect of most of the skin friction reduction schemes that alter the turbulent structure is thickening of the laminar sublayer.

At present, research activities and understanding of the basic machanisms for reducing turbulent shear stress are in an early stage of development. Research on these types of activities will continue with the hope of discovering a feasible and effective concept.

8.0 U.S. Supersonic Transport

One of the most controversial subjects in airplane technology for the last decade has been the supersonic transport. Until 1971, the United States Government and The Boeing Company were steaming ahead to build a commercial supersonic transport. But after strong opposition the program was terminated.

The French-British joint SST venture, meanwhile, continued and resulted in a significant technical achievement: the Concorde. The Concorde has been highly popular with the passengers who have flown in it, despite the high premium fares. The useful life of the Concorde as a commercial vehicle is, however, limited because it carries too few passengers and uses too much fuel.

Following the SST cancellation, an assessment was made of the status of the technology. Items considered as the major technical problems were identified. Table I contains a summary of these items. Finding solutions for these problems was then emphasized.

8.1 SST Technology Development

The state of the art in supersonic cruise technology has been steadily advanced by the small but vital and productive NASA Supersonic Cruise Research program. As a result of coordinated efforts of the NASA in-house research, contracts with industry, and additional industry research and development studies, important advances have been made particularly in aerodynamics, structures, and propulsion. Solutions to the major technical problems of 1971 have been identified. Either the problem is no longer a concern, or else the steps needed to bring about a solution have been clearly defined. As can be seen from table 1 and figure 16, considerable progress has been made since 1971.

Propulsion technology

Advances of greatest importance have occurred in propulsion. The advances consist of basic technological progress in engine materials. turbomachinery blade design. blade cooling technology. and in variable-cycle engines. Cycle variability allows the engines to operate as turbofans in subsonic flight. reducing takeoff and landing noise and raising subsonic cruise efficiency. The variable-cycle engines operate as turbojets for efficient supersonic flight.

Another important feature of the variable-cycle engine is the ability to shape the velocity profile of the jet at the nozzle exit. Coannular nozzles, with the high-velocity, high-temperature jet on the outside of the exhaust stream and lower velocity fan air in the center, have demonstrated significant noise reductions.

Structures technology

A significant advance in the stuctures technology area has been the development and application of finite-element modeling and advanced computational methods to large, flexible, supersonic-transport-type wings. The rapid response of the advanced computational technology allows evaluation of innovative ideas and approaches that could not have been considered in the past. Current efforts include the incorporation of nonlinear wind tunnel loads data into the aeroelastic analyses.

Significant advances have been made in titanium manufacturing. One of these advances is the increased capability to manufacture aluminim-brazed titanium-honeycomb for high-efficiency structural components. Superplastic forming and concurrent diffusion bonding is another promising new structural area. Advanced composites may also contribute to more efficient lightweight structures.

Aerodynamic technology

Aerodynamic technology advances to date have been evolutionary in nature. The supersonic cruise aerodynamic improvements, as shown in figure 17, include—

- Improved spanwise thickness distribution
- Optimization of wing planform, camber, and twist
- Blended wing-fuselage arrangement for reduced wave drag and friction drag

Figure 17 also includes projected lift/drag ratio levels for future advanced configurations considered achievable with continued aerodynamic research.

Figure 18 illustrates the supersonic wing design method that has been developed to include real-flow limitations that cannot be directly calculated by current computational methods. Use of this wing design approach has contributed to the improved lift/drag ratio of the SST since 1971.

Considerable research has been directed at improving the low-speed lift/drag ratios that provide enhanced landing and takeoff characteristics. Lower drag contributes indirectly to reduced community noise, since less engine power is required. Supersonic wing planforms typically have highly swept and thin leading edges. Leading-edge flow separation occurs at the high lift coefficients of takeoff and landing on these highly swept wings. This produces additional drag.

Two solutions are being actively researched to provide improvements in the low-speed/lift drag ratios. One approach, as illustrated in figure 19, is to use aerodynamic design methods to develop leading-edge geometries that suppress the leading-edge separation and thereby retain attached flow to higher lift coefficients.

An alternative approach, as shown in figure 20, uses a unique leading-edge flap design to control the strength of the vortex that results from the leading-edge separation. The controlled vortex provides a thrust force on the leading-edge flap and acts as an aerodynamic bulbous nose to provide attached flow on the wing behind the flap.

8.2 U.S. SST Possibilities

Significant improvements can be expected with respect to range, fuel consumption, environmental, and economic characteristics of a future U.S. SST by an optimum design integration of the aforementioned technical advances.

One of the most important factors affecting economics of the SST is the cost of fuel. Increasing the fuel efficiency can therefore be expected to have significant impact on improved economics. Fuel efficiency for the SST is compared with that for existing wide-body subsonic jet airplanes in figure 21. A 1978 estimate based on technology advances since 1971 shows a substantial improvement over the 1971 SST. An advanced technology objective for a large payload SST is also shown. This advanced configuration will require further improvements in the variable-cycle engine and additional weight savings from advanced structural materials. The challenge for the aerodynamicist will be to develop the aerodynamic shape characteristics to contain the passengers while retaining high aerodynamic efficiency.

Boeing recently completed an in-depth economic study of a family of advanced supersonic transport airplanes. Ten airplanes were defined according to size, payload, and range. Operating costs were then calculated and used to determine the tourist class yield surcharge required for each supersonic airplane to achieve the same return on investment as on a reference subsonic airplane. Additionally, key economic factors were varied and the impact of these variations upon the nominal surcharge was determined. Results from the economic study are shown in figure 22 for a fuel price of $2.00/gal (1980 dollars). The surcharge for the advanced SST, indicated in the figure, would be approximately 15% relative to the reference subsonic airplane. This figure also illustrates that a further improvement in fuel efficiency could result in zero surcharge for the SST.

Today a Concorde passenger pays a large surcharge—about twice the economy fare. Considering the Concorde's popularity, the economic viability of a future SST requiring a much smaller surcharge (corresponding to the economic study results) appears highly probable.

In summary, it appears technically feasible to have an SST that could be operated with economic success and with acceptable environmental characteristics. Difficult technical problems still remain. The financial problem is enormous. Possible Governmental participation makes the program especially sensitive to political pressures. The U.S. SST is still viewed negatively by many people in the United States. The "revolutionary breakthrough" for the SST may be in achieving the public acceptance and political support necessary for an SST development program.

9.0 Wind Tunnel Testing and Computational Aerodynamics

The aerodynamic design tools, which include both computational aerodynamics and wind tunnel testing, will play important roles in achieving the aforementioned evolutionary and revolutionary aerodynamic advances through design integration and advanced aerodynamic concept development. The computer will not replace the wind tunnel. The important question is how to use the computer on the one hand, and the wind tunnel on the other, in a complementary way to enhance the design process, as indicated in figure 23. The strengths and limitations of the wind tunnel testing and computational testing are indeed complementary, as shown in table 2.

9.1 Wind Tunnel Testing

Traditionally, the airplane designer has looked on the wind tunnel as his main aerodynamic tool. The increased complexity and broadened performance envelopes of modern airplanes have resulted in a progressively increasing demand for wind tunnel testing as a vital part of the aerodynamic design process, as shown in figure 24. The current emphasis on improved fuel economy will require improved quality of testing as well as development of new facilities.

The accuracy of current wind tunnel measurements for providing full-scale drag predictions is limited by a number of factors, as shown in figure 25. Some possible near-term wind tunnel advancements based on current and development efforts are summarized in table 3. Major new developments requiring significant capital expenditures will probably be restricted to Government facilities. Indeed, an important objective for Government agencies is to foresee requirements for development at test facilities and to have them operational when they are needed for new projects. The construction of the high Reynolds number cryogenic National Transonic Facility at NASA-Langley, and the new 80- by 120-ft test section for the 40- by 80-ft subsonic tunnel at NASA-Ames are examples of near-term developments that will alleviate two of the current major limitations of wind tunnel testing.

It is anticipated that a primary role of these unique national wind tunnels, for industry, will be to solve special aerodynamic problems and to provide information that is unobtainable from other facilities. Much of the experimental development work of new aerodynamic concept applications to commercial airplanes will continue to be conducted in university or privately owned wind tunnels. The near-term improvements for these facilities will include—

- New data acquisition systems to provide high production rates to minimize test time
- Rapid online data analysis to provide guidance during

the test to maximize the amount of useful information

- Computer control of model and tunnel parameters to increase accuracy of the data
- Extensive use of computational methods to expand and interpolate the experimental data base

In addition, novel flow visualization techniques and sophisticated new instrumentation will provide more accurate measurements and enhanced physical understanding, with minimum disturbance to the flow field.

9.2 Computational Aerodynamics

Advances in computational aerodynamics in the past 20 years have been dramatic. Twenty years ago, our computational capabilities were mainly limited to two-dimensional inviscid flow field analyses. Three-dimensional linear theory methods were just under development. Today we routinely conduct inviscid analysis of complete airplane configurations in subsonic and supersonic flow, as well as wing-body configurations in transonic flow. Example applications of these inviscid analysis capabilities are shown in figure 26.

A significant amount of progress has also been made in the past several years in our ability to calculate three-dimensional boundary layers over increasingly complex shapes. The coupling of nonlinear inviscid calculation methods with three-dimensional boundary layer calculation methods, as shown in figure 27, is emerging as a current production tool.

Additional progress has been made in developing specialized techniques to predict the effects of certain classes of separated flows. Among these are methods that represent the separated flow boundaries by vortex sheets, whose strength and location are determined iteratively using the three-dimensional nonlinear inviscid codes. Applications of these techniques to produce the flow-field characteristics of a two-dimensional, high-lift system and of a leading-edge vortex of a slender three-dimensional wing are shown in figures 28 and 29, respectively.

The evolutionary developments of our computational methods have required "revolutionary" developments, particularly in computer technology. Between 1950 and 1980, advances in computer technology resulted in computing speeds increasing by a factor of 10 every 5 years, while the cost of computing a given flow field has decreased by a factor of 10 every 10 years. There is evidence that developments in the next 20 years will be equally dramatic because—

- Computer technology continues to provide bigger and better machines
- Computational methods to date have demonstrated such value that higher level management supports continued development and use of the methods in the design process
- Major research programs supported by the U.S. Government and industry, as well as those of foreign countries, are showing definite progress in developing methods that will provide closer approximations to the fluid physics

Different levels of computational aerodynamics methods are shown in figure 30. More advanced methods will not supersede earlier methods. Instead, advanced methods will be used in conjunction with earlier methods to provide a heirarchy of design tools to be used successively in guiding new aerodynamic designs, from a conceptual idea to a final definition.

10.0 Concluding Remarks

Discussions in this paper of aerodynamic expectations have emphasized aerodynamic efficiency improvements of commercial transport airplanes. We expect that the next generation of transport airplanes will be similar in form to today's airplanes; but with evolutionary improvements in aerodynamics supported by gradual application of revolutionary advancements in other technologies such as flight controls and structures. The new airplanes will have better wing designs, better nacelle installations, and larger wing spans. The most likely revolutionary development is expected to be a revitalized U.S. SST program.

We have not discussed the ramifications of alternative fuels on airplane aerodynamic design characteristics. It is considered technically feasible to design airplanes propelled by liquid methane, liquid hydrogen, or even nuclear fuel. However, the economics and systems development problems of advanced fuels do not make near-future applications to commercial airplanes appear economically feasible.

It was pointed out that several years are required to develop a new technology, from initial research to mature status ready for practical application. There is evidence, however, to suggest a general narrowing of the time interval between discovery and application in the physical sciences. Such an acceleration in pace of development in aerodynamics is promoted by technical advances in the "design tools," but is tempered by the necessity of increased demands of credibility development and economic assessment. The field of aerodynamics is still strewn with an unlimited list of challenges. Aerodynamics is far from achieving a mature technology status. Future possibilities and promises for aerodynamic achievements are very rich, indeed.

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Table 1. SST Technical Problems of 1971

1971 MAJOR UNRESOLVED QUESTIONS	1979 STATUS
• OZONE AND SIMILAR ENVIRONMENTAL CONCERNS	• MORE ACCURATE FORECASTS SHOW 1971 PREDICTIONS TO HAVE BEEN WRONG. CURRENT EFFORTS CONCENTRATE ON BETTER UNDERSTANDING OF ATMOSPHERIC PHYSICS AND CHEMISTRY
• AIRPORT NOISE	• SOLUTIONS IDENTIFIED. CURRENT EFFORTS CONSIST OF DEFINING REQUIRED VALIDATION AND ITS COST
• SUPERSONIC CRUISE RANGE FACTOR	• 20% IMPROVEMENT
• SUBSONIC CRUISE RANGE FACTOR	• 22% IMPROVEMENT WITH VARIABLE-CYCLE ENGINE
• AEROELASTIC PROBLEMS	• ADVANCED MATHEMATICAL MODELS PROVIDE MEANS OF SOLUTION. CURRENT EFFORTS ADDRESS INCLUSION OF WIND TUNNEL LOADS DATA IN MATHEMATICAL MODELS
• FUEL TANK SEALANTS	• RESOLVED. CURRENT EFFORTS ADDRESS HIGHER MACH NUMBERS
• TITANIUM SANDWICH FEASIBILITY FOR HEAVILY LOADED STRUCTURE	• RESOLVED. CURRENT EFFORTS ADDRESS FURTHER IMPROVEMENTS AND DEVELOPMENTS (e.g., SUPERPLASTIC-FORMED DIFFUSION BONDING)

REF: A. SIGALLA (1979)

Table 2. Comparison of Wind Tunnel Testing and Computational-Aerodynamics Simulations

ITEM	WIND TUNNEL TESTING	COMPUTATIONAL AERODYNAMICS
• GEOMETRICAL SIMILARITY (SIMILAR SHAPES)	• "CORRECT" GEOMETRY EXCEPT FINE DETAILS AND IN LOCAL SUPPORT ATTACHMENT AREAS	• "CORRECT" GEOMETRY IS POSSIBLE (EXCEPT FINE DETAILS) FOR SIMPLIFIED ANALYSES • "SIMPLIFIED" GEOMETRY FOR COMPLEX ANALYSES
• KINEMATIC AND DYNAMIC SIMILARITY (SIMILAR FLOW VELOCITIES) (SIMILAR FORCES)	• "EXACT" FLOW PHYSICS	• "APPROXIMATE" FLOW EQUATIONS (CAN BE VERY LIMITING)
	• "APPROXIMATE" BOUNDARY CONDITIONS (e.g., WALLS, SUPPORT, AEROELASTICITY)	• "EXACT" BOUNDARY CONDITIONS
	• USUALLY "INCORRECT" PARAMETERS (e.g., REYNOLDS NUMBER)	• "EXACT" FLOW PARAMETERS WHEN CONTAINED IN APPROPRIATE EQUATION; MAY NOT APPEAR IN SIMPLIFIED EQUATIONS (e.g., INVISCID FLOW)
• MODEL DEFINITION/ CONSTRUCTION AND MODIFICATIONS	• LONG TIME, COSTLY, DIFFICULT TO MODIFY	• EASE VERY DEPENDENT ON USER INTERFACE
• CHANGE OF FLOW CONDITIONS (α, MACH)	• EASY, FAST	• EASY, NOT ALWAYS FAST OR CHEAP
• DESIGN CAPABILITY	• ONLY THROUGH MINOR MODEL MODIFICATIONS	• YES, TWO MODES: –ANALYSIS MODE BY ITERATION –DIRECTLY IN DESIGN MODE FOR SPECIAL LIMITED APPLICATIONS
• ACCESSIBILITY	• LIMITED	• GENERALLY GOOD
• LIMITATIONS	• MODEL SIZE • FLOW PARAMETERS • SUPPORT, WALL INTERFERENCE	• ACCURACY OF EQUATIONS • COMPUTER SPEED • COMPUTER STORAGE

Table 3. Near-Term Wind Tunnel Advancements

CURRENT PROBLEMS OR LIMITATIONS	NEAR-TERM DEVELOPMENTS
• WIND TUNNEL TO FLIGHT EXTRAPOLATION (REYNOLDS NUMBER SIMULATION)	• CRYOGENIC WIND TUNNEL (NASA-LANGLEY)
	• IMPROVED THEORETICAL EXTRAPOLATION METHODS
• WALL INTERFERENCE	* ADAPTIVE WALL DEVELOPMENT (CONTOURS AND/OR POROSITY)
	• COMPUTATIONAL AERODYNAMIC SIMULATION ADVANCES
• MODEL SUPPORT SYSTEM INTERFERENCE	* MAGNETIC SUSPENSION AND BALANCE SYSTEM
	• COMPUTATIONAL AERODYNAMIC SIMULATION ADVANCES
• LARGE-SCALE HIGH-LIFT SIMULATION	• VERY LARGE-SCALE, LOW-SPEED TUNNEL (NASA-AMES)
	• COMPUTATIONAL AERODYNAMIC SIMULATION ADVANCES
• TUNNEL UTILIZATION	• COMPUTER CONTROLLED TUNNEL OPERATION
	• COMPUTER CONTROLLED MODELS
	• RAPID ONLINE DATA ANALYSIS SYSTEMS
	• USE OF COMPUTATIONAL AERODYNAMICS TO EXPAND AND INTERPOLATE DATA BASE

*IF DEVELOPED, WOULD PROBABLY BE PART OF A NATIONAL FACILITY BECAUSE OF LARGE CAPITAL EXPENDITURE

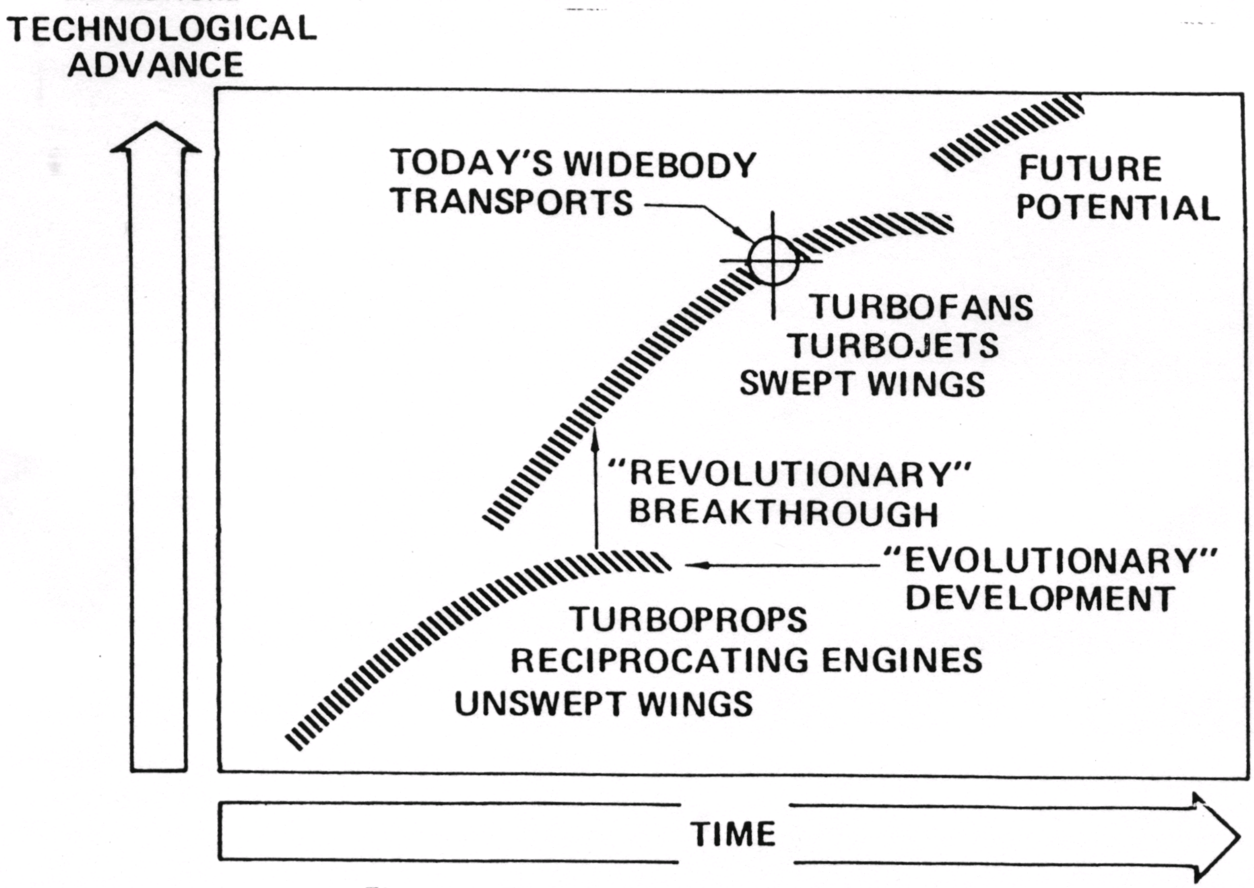


Figure 1. Transport Airplane Technology Advance

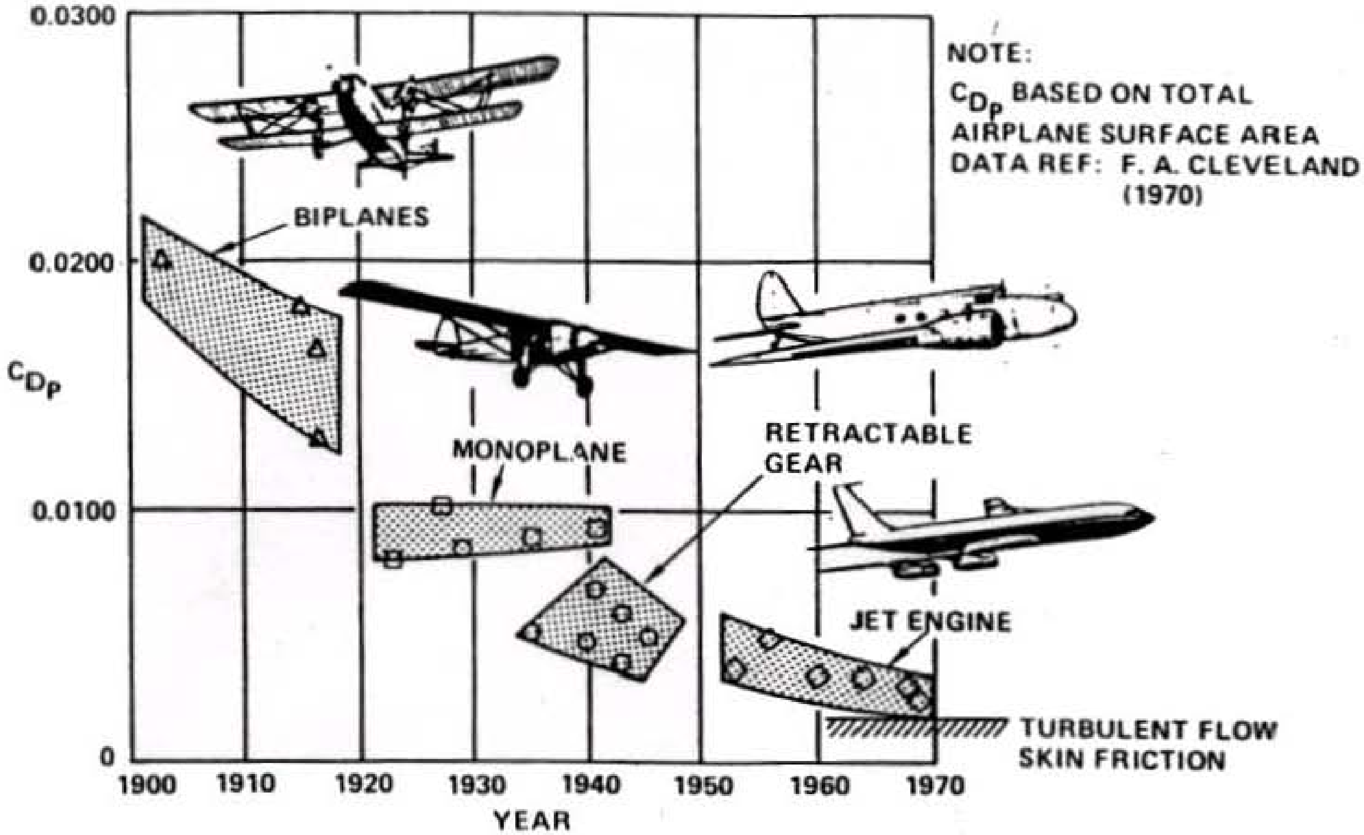


Figure 2. History of Airplane Parasite Drag Reduction

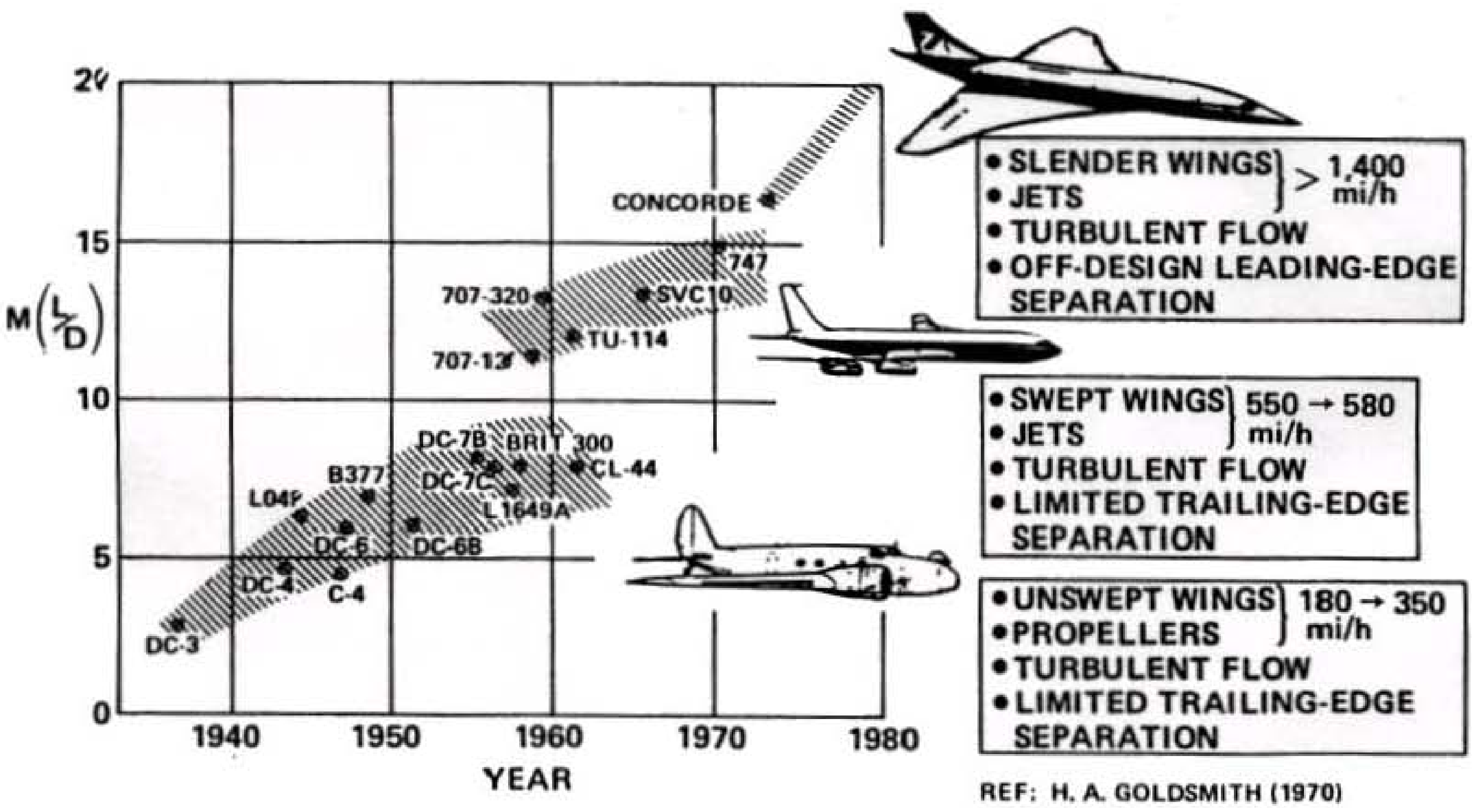


Figure 3. Aerodynamic Efficiency Improvements

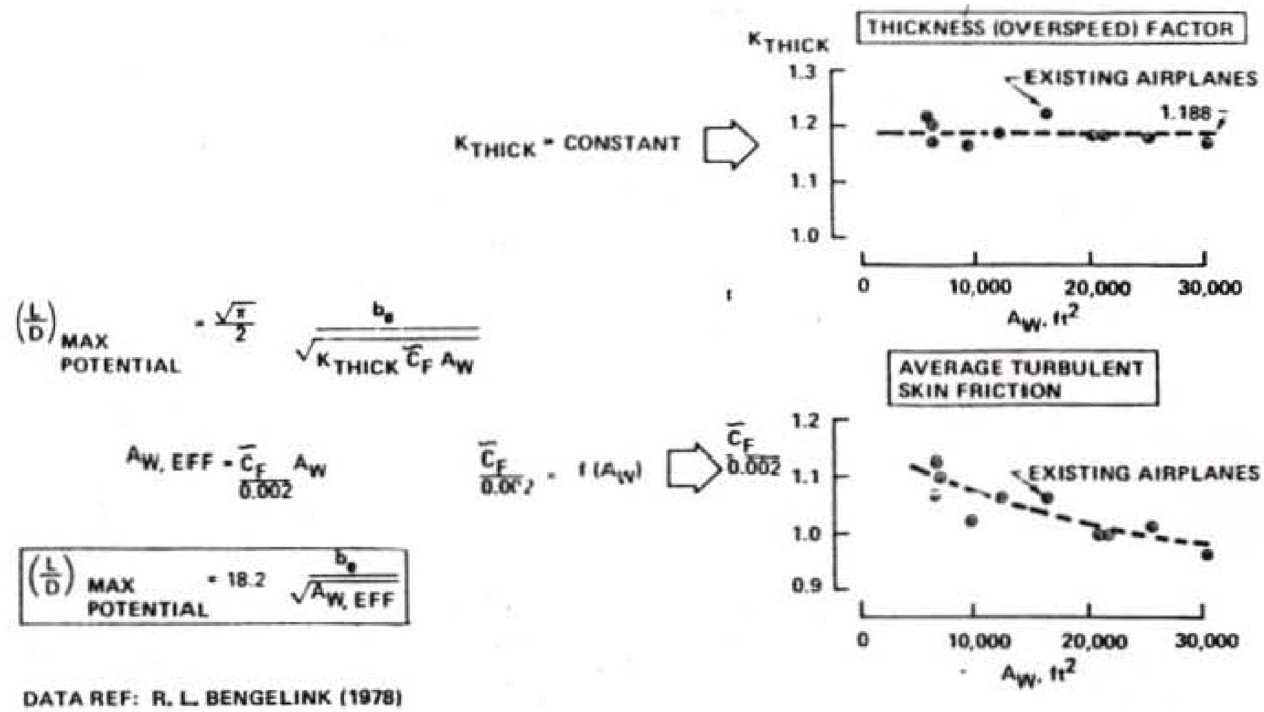


Figure 4. Conventional Transport Airplane Lift/Drag Ratio Potential

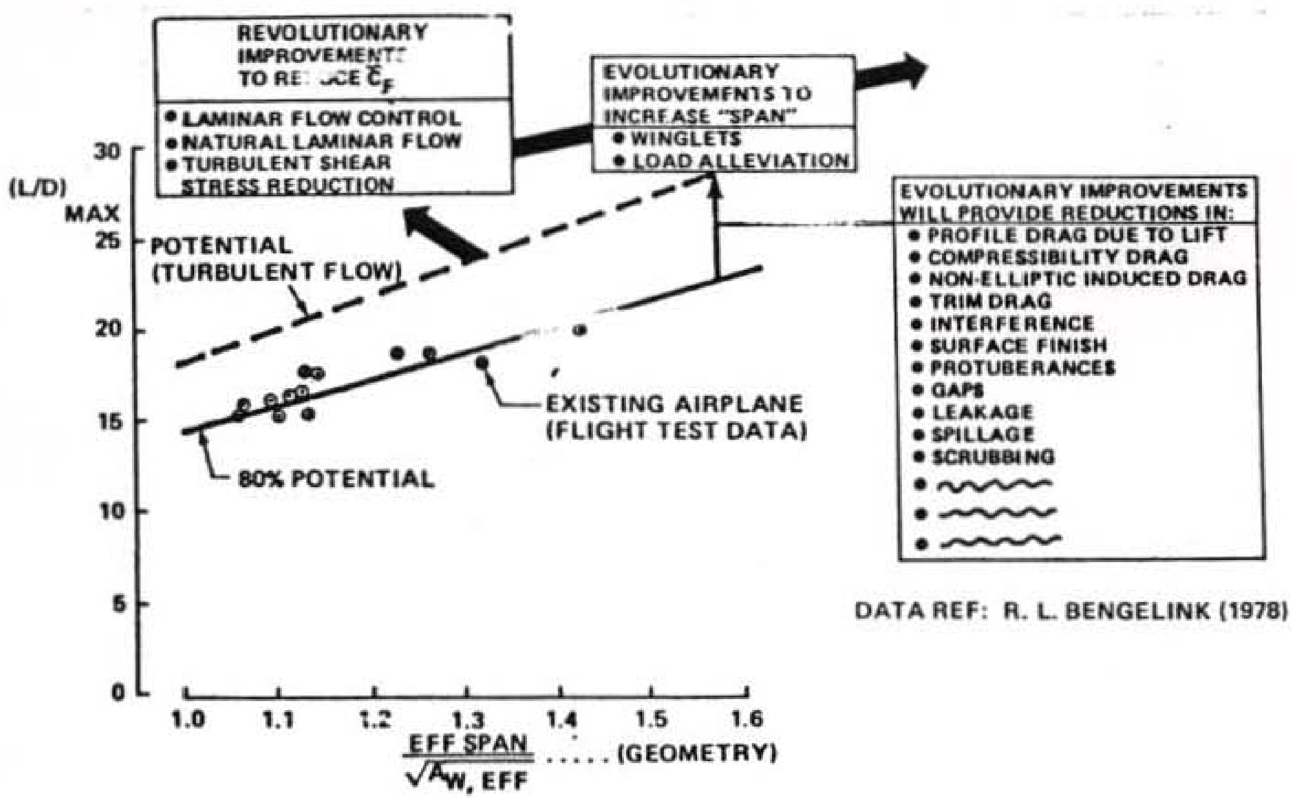


Figure 5. Subsonic Transport-Type Airplane Maximum Cruise Lift/Drag Ratio

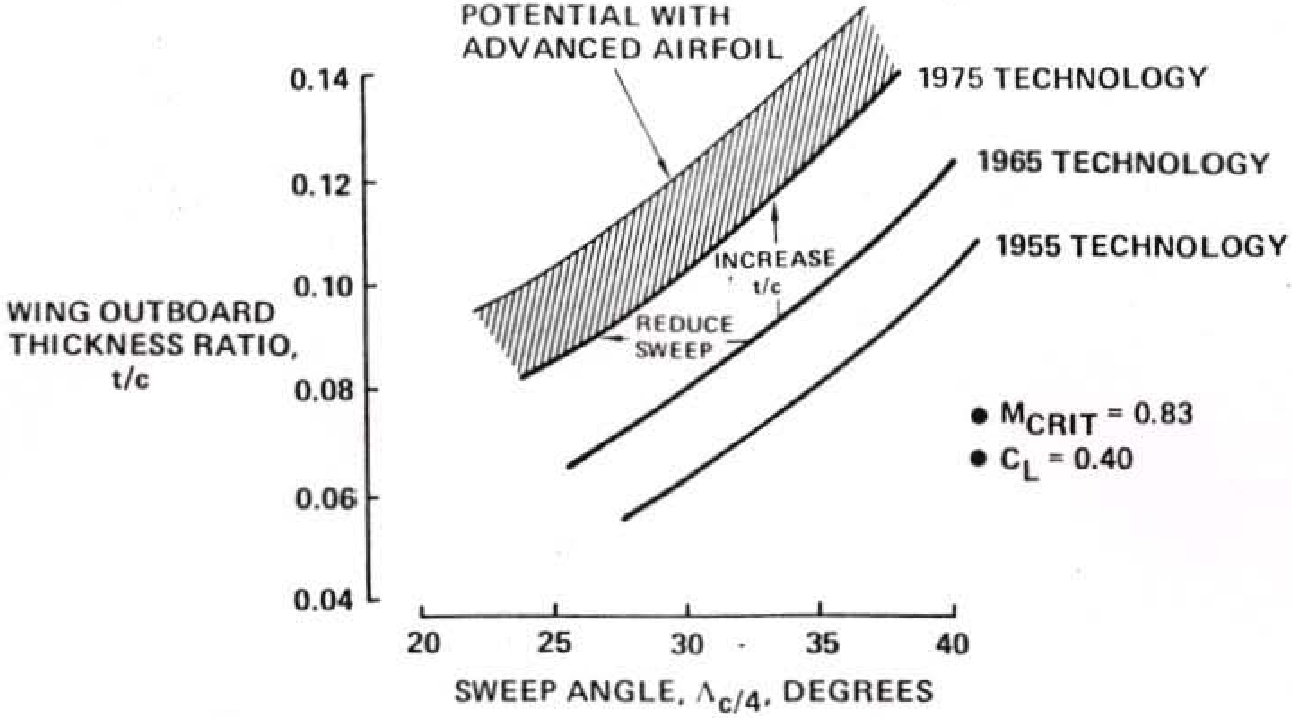
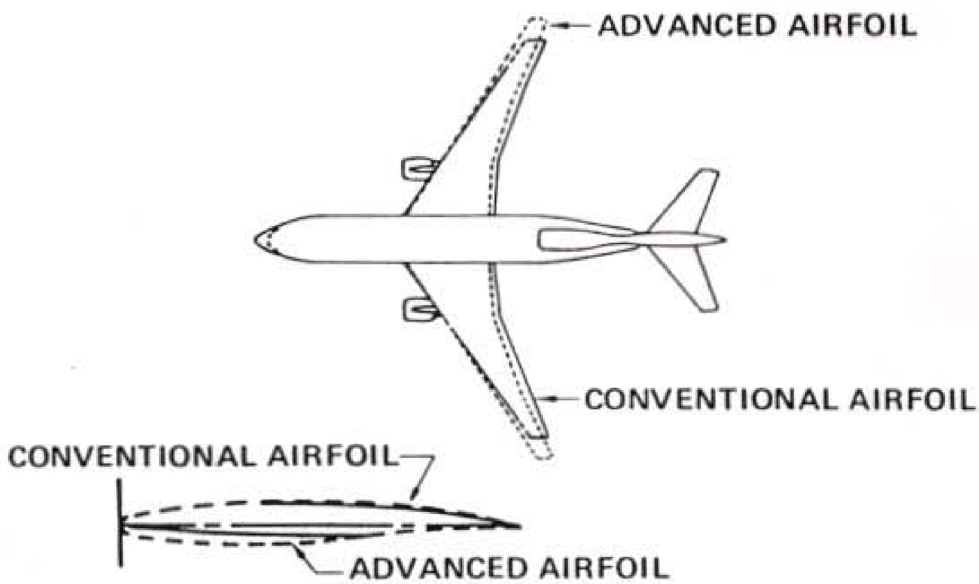


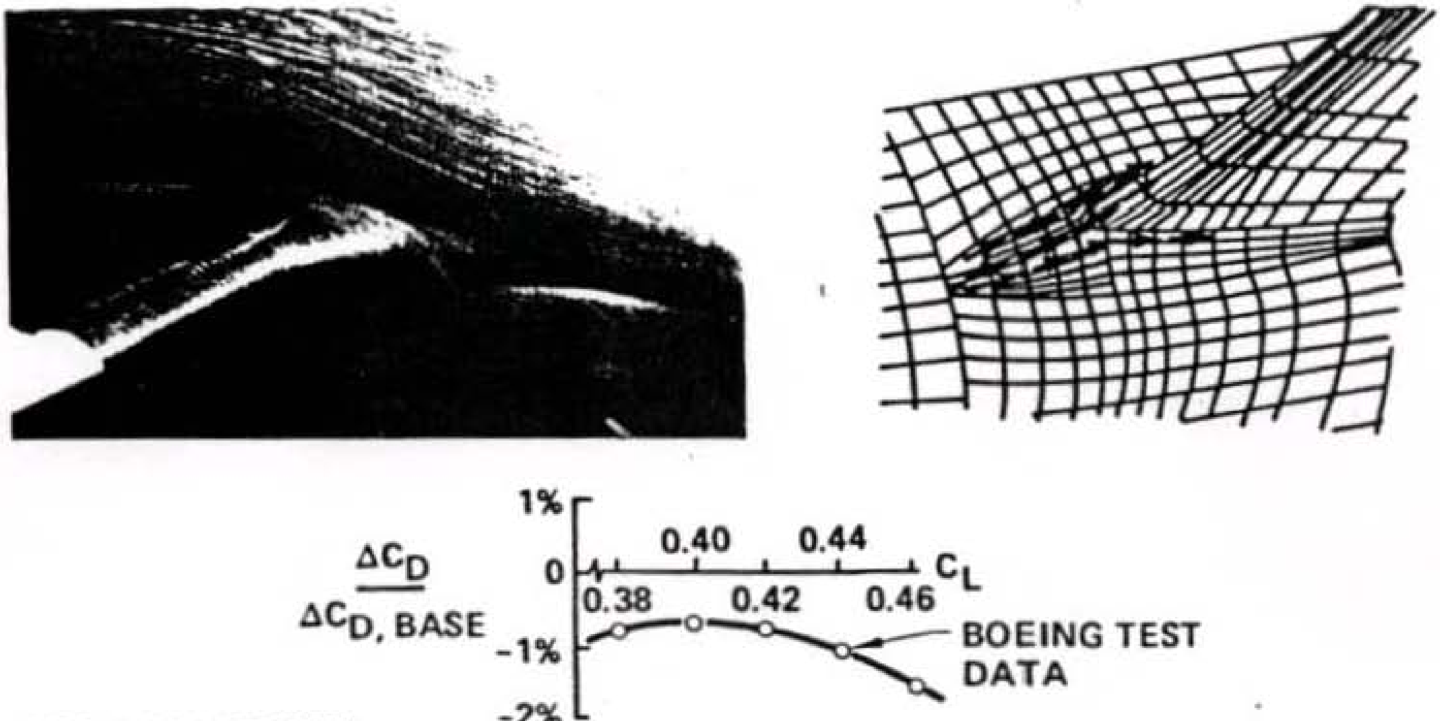
Figure 6. Progress in Airfoil Development



HIGHER ASPECT RATIO AND CRUISE SPEED OPTIMIZATION PROVIDE:

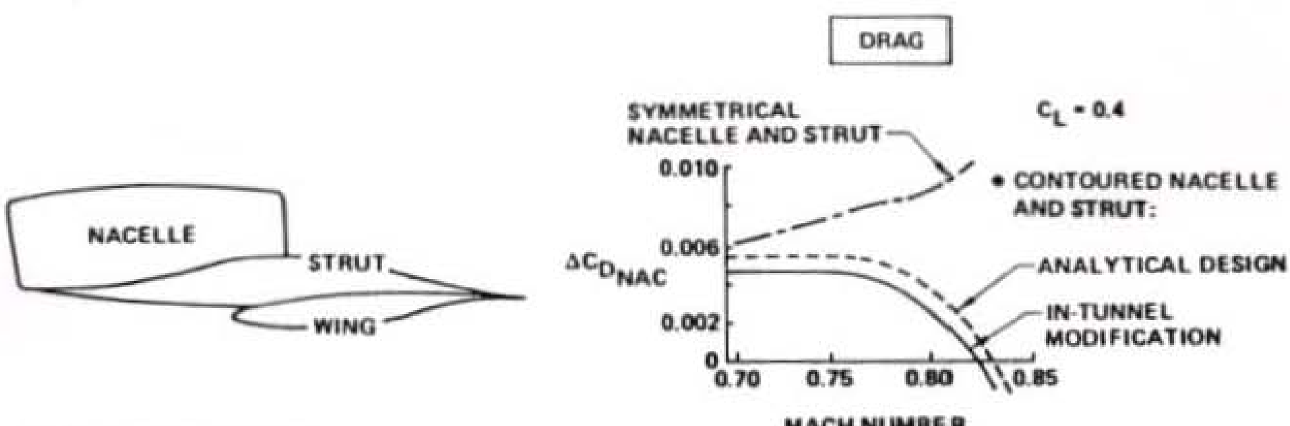
- HIGHER CRUISE L/D
- LOWER TRIP FUEL
- REDUCED ENGINE SIZE
- INCREASED FUEL VOLUME
- IMPROVED LOW-SPEED PERFORMANCE
- LOWER NOISE

Figure 7. Advanced Wing Design Opportunities



REF: B. DILLNER (1979)

Figure 8. Wing Strake Design Integration



REF: W. B. GILLETTE (1977)

Figure 9. Overwing Nacelle Design Integration

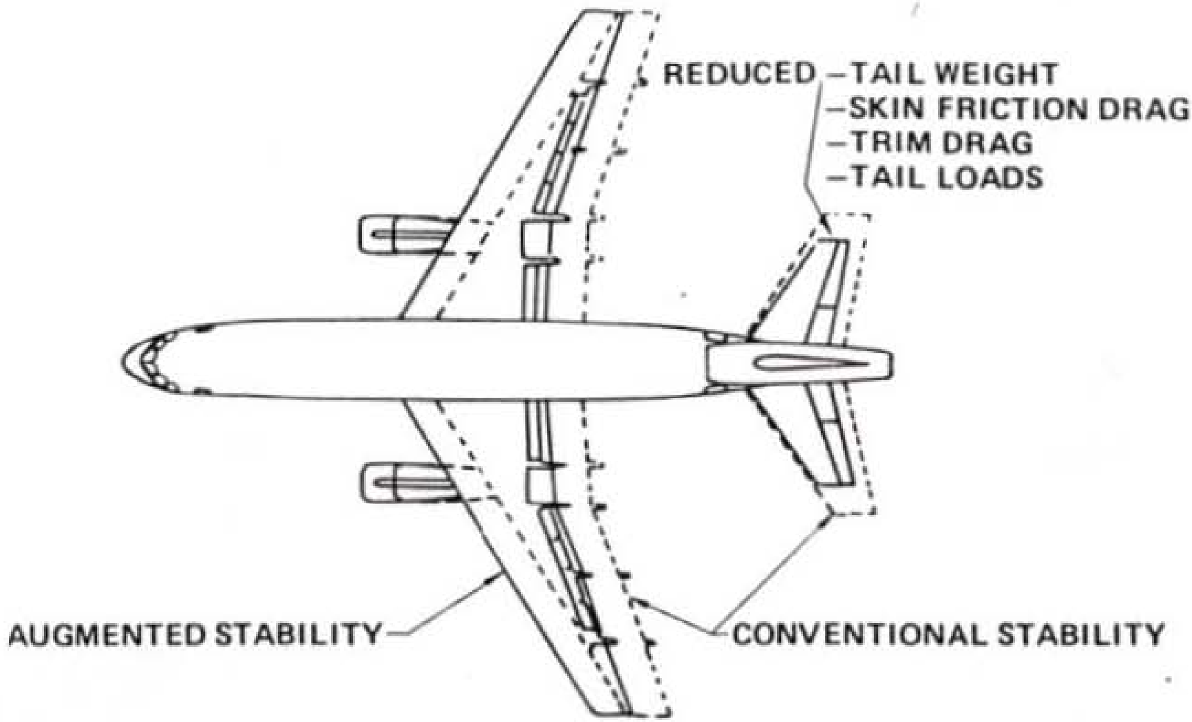


Figure 10. Aerodynamic Benefits From Augmented Stability

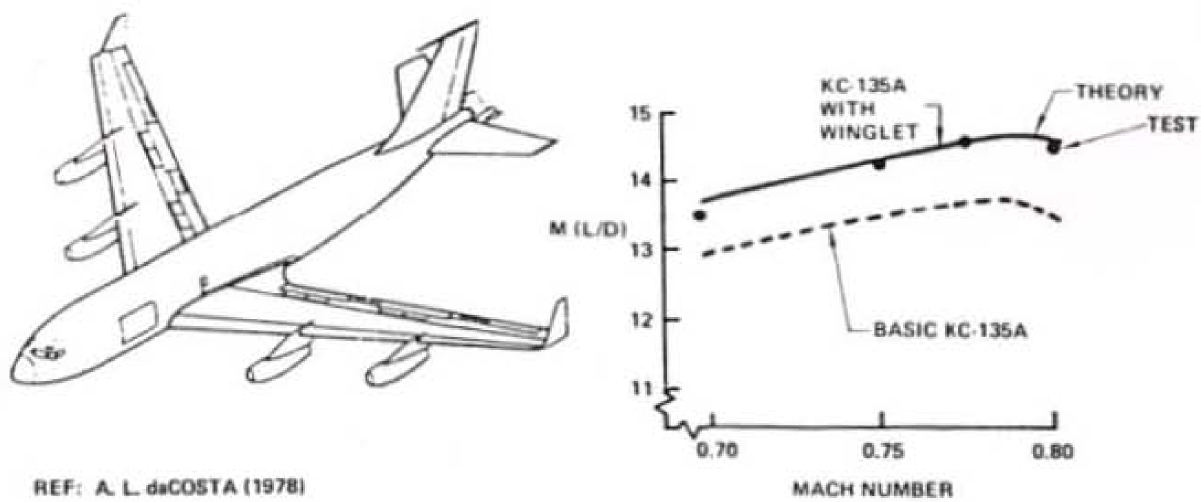


Figure 11. Winglet Aerodynamic Benefits

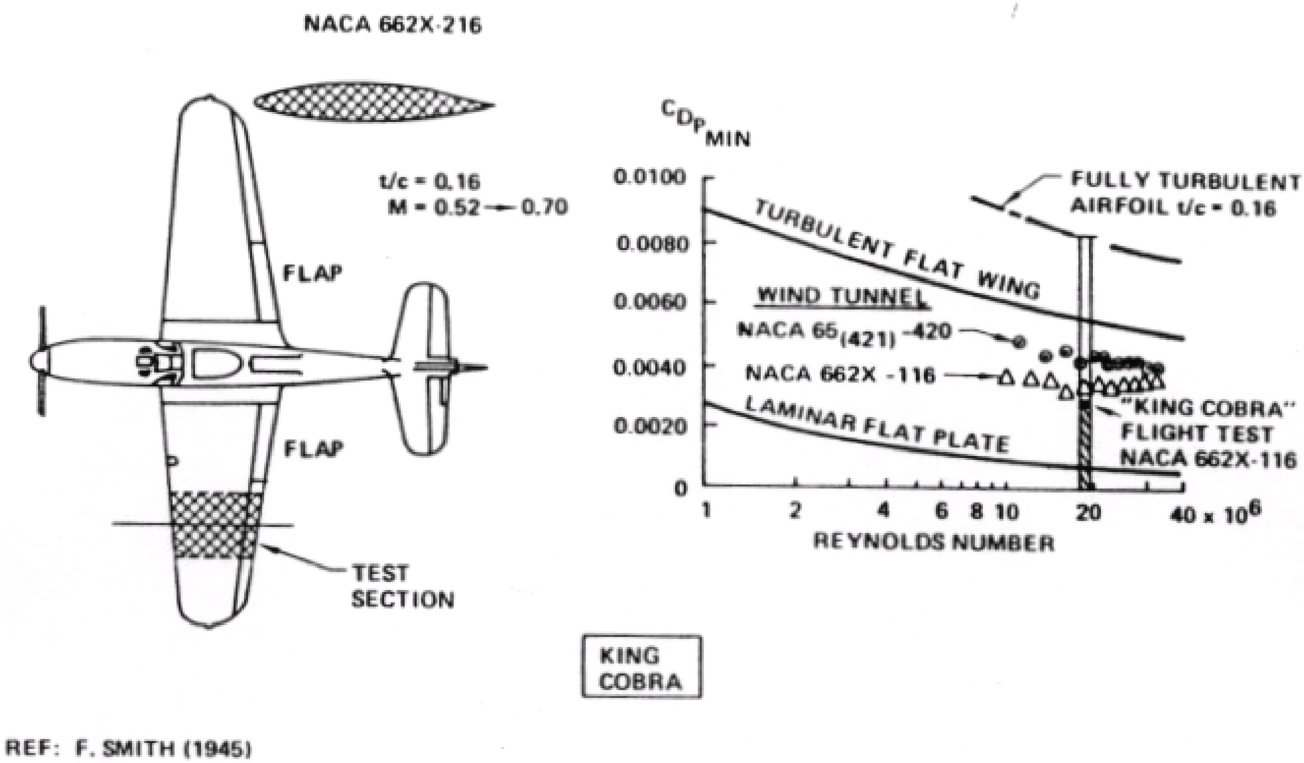


Figure 12. Natural Laminar Flow on the King Cobra

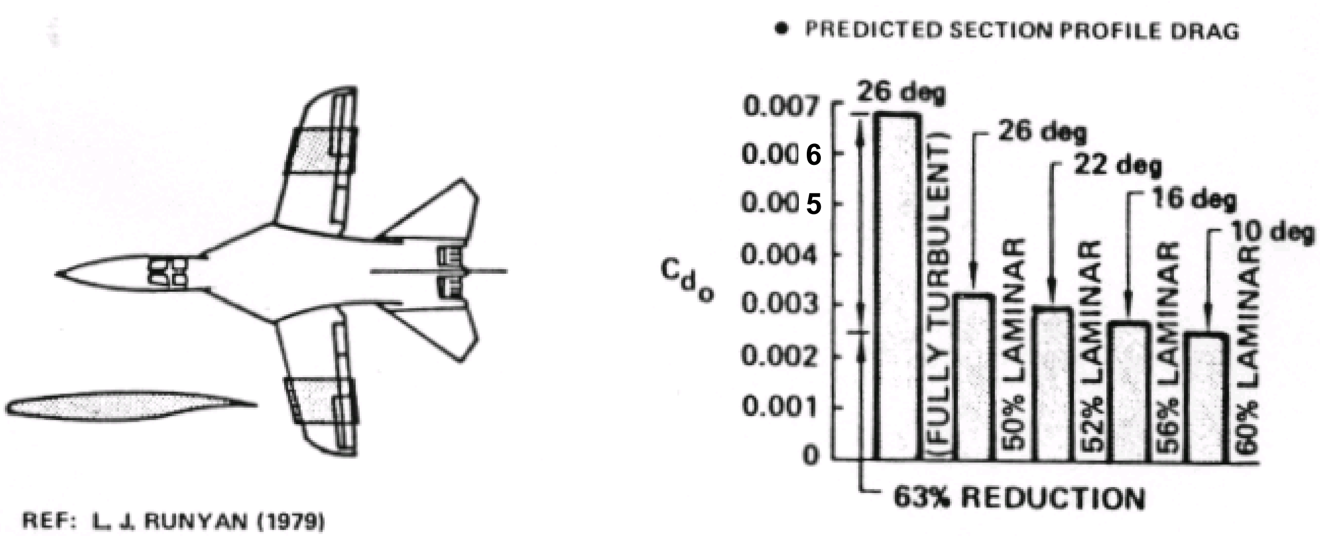


Figure 13. F-111 Planned Natural Laminar Flow Flight Test Program—1980

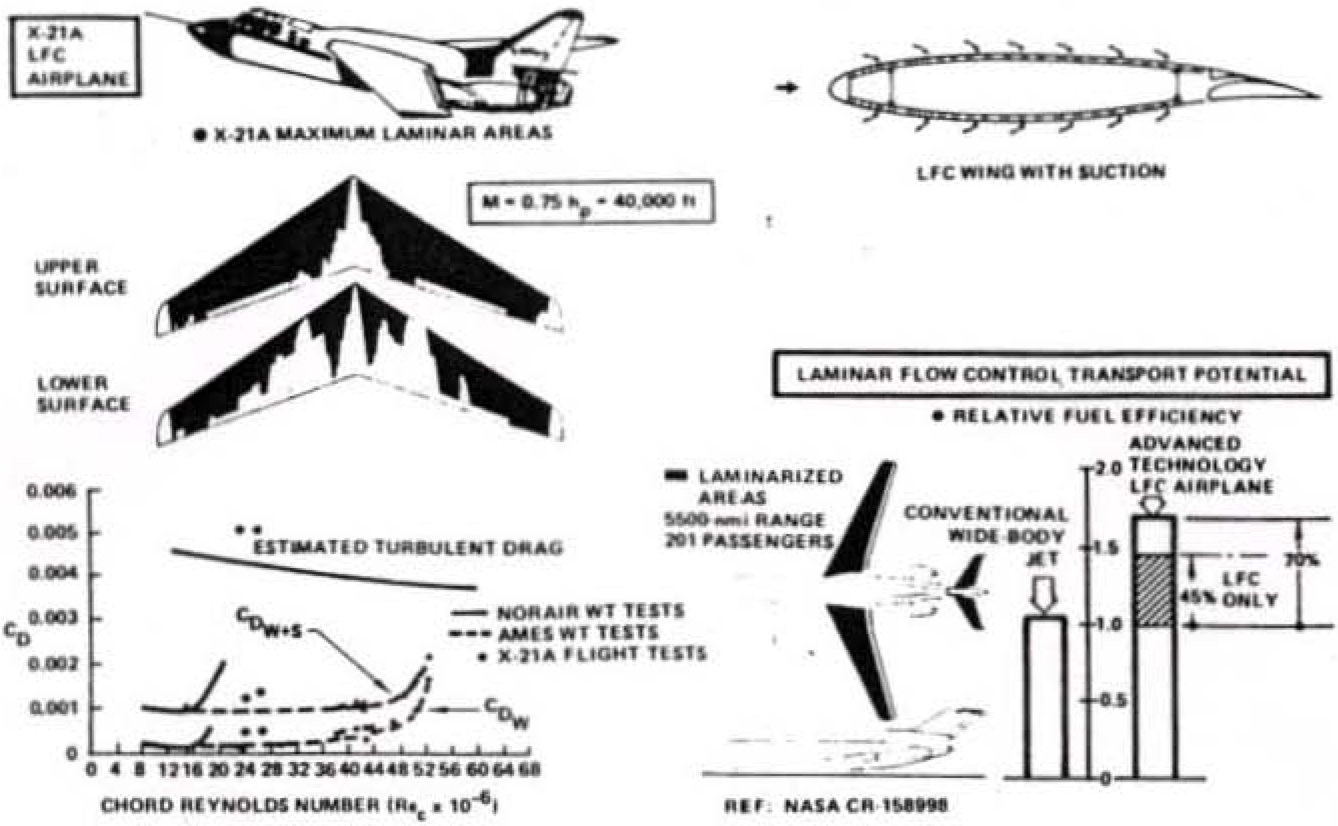


Figure 14. Laminar Flow Control

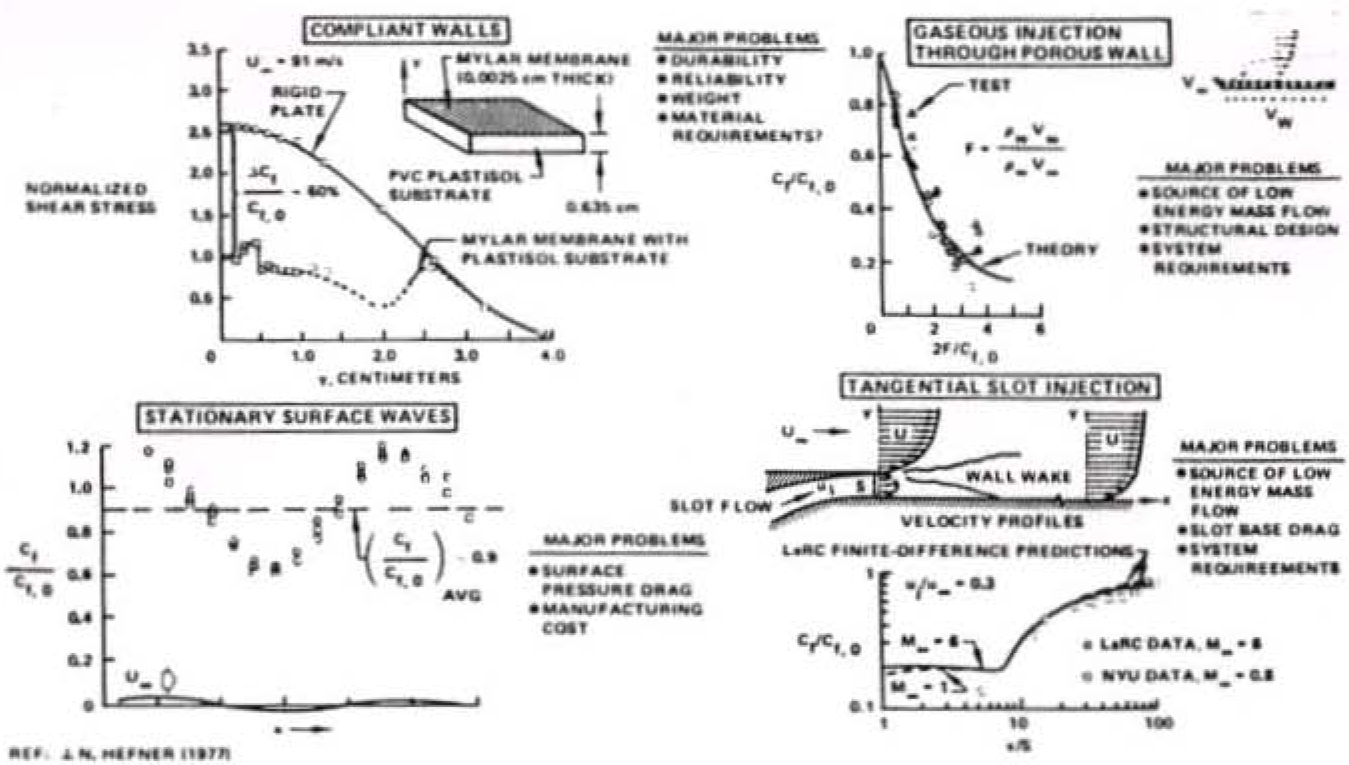


Figure 15. Schemes to Reduce Turbulent Shear Stress

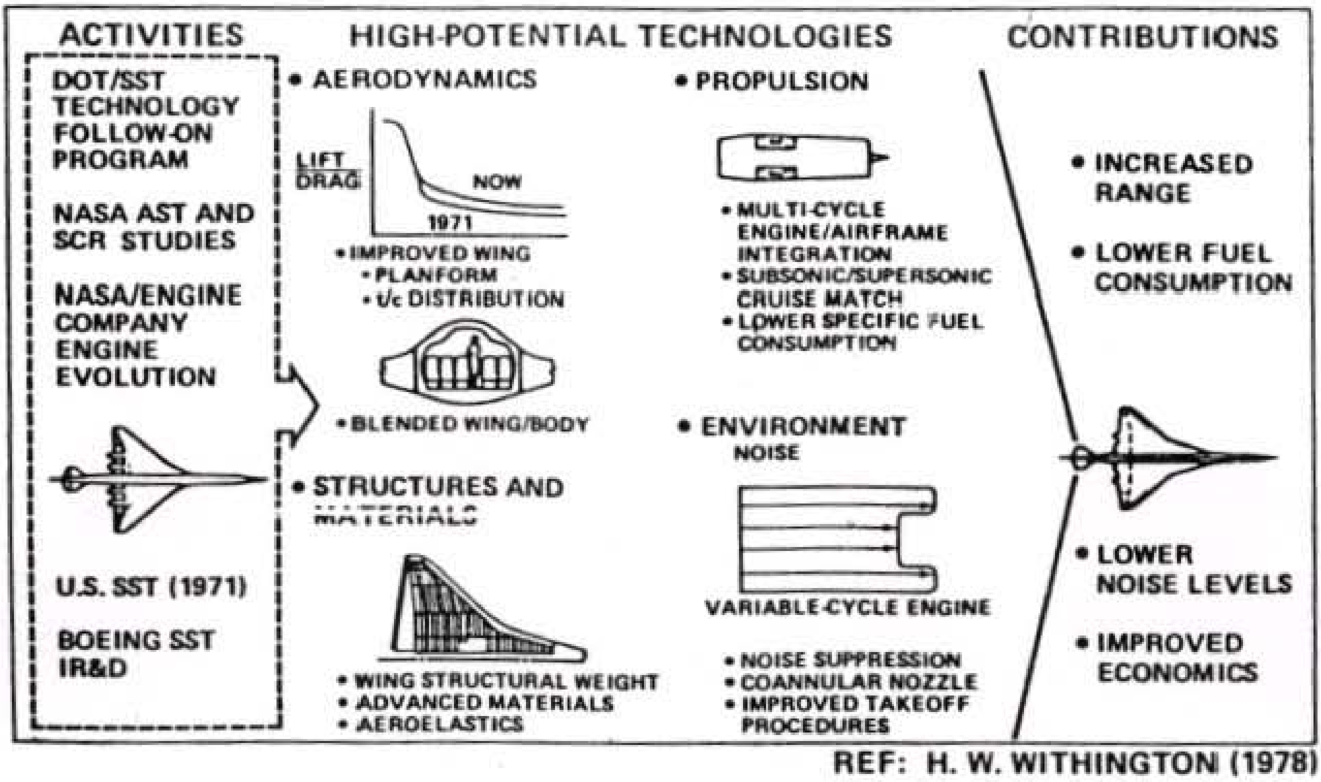


Figure 16. Recent SST Accomplishments

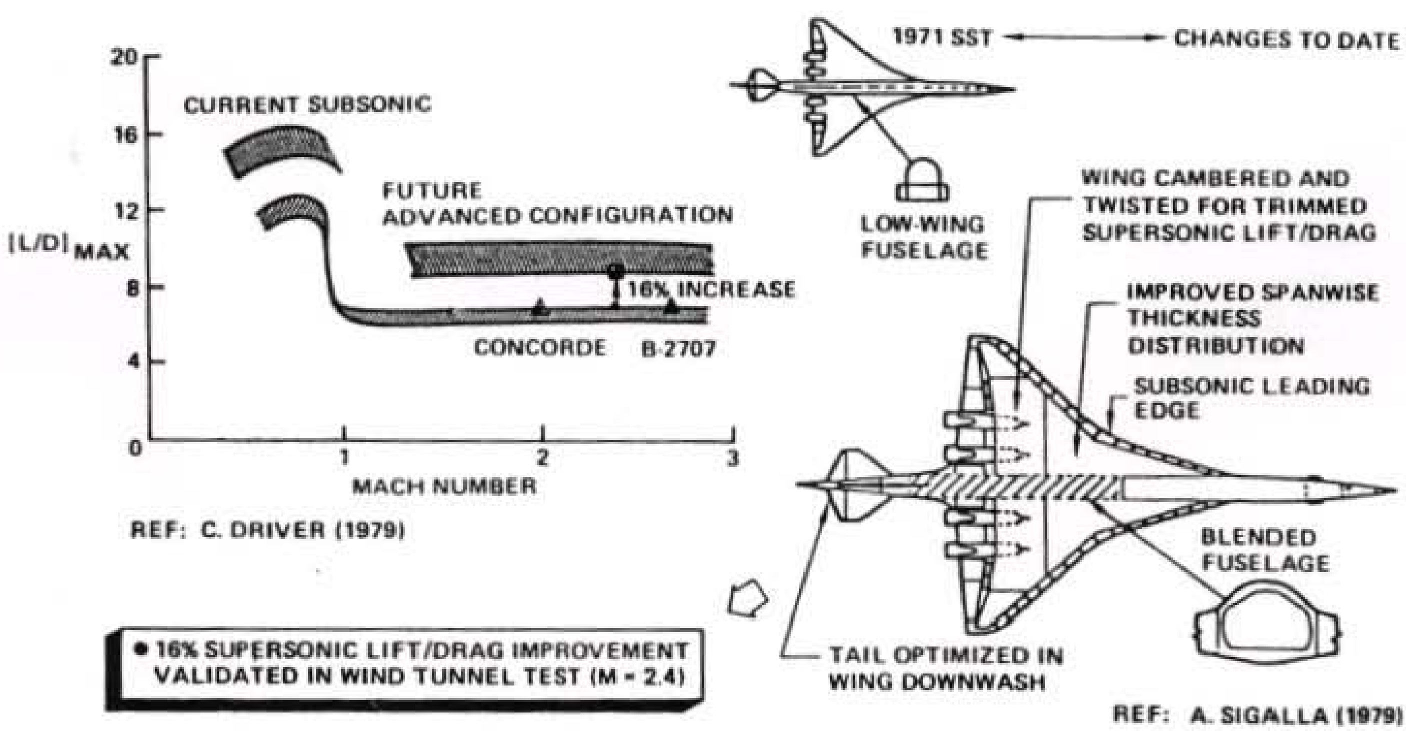
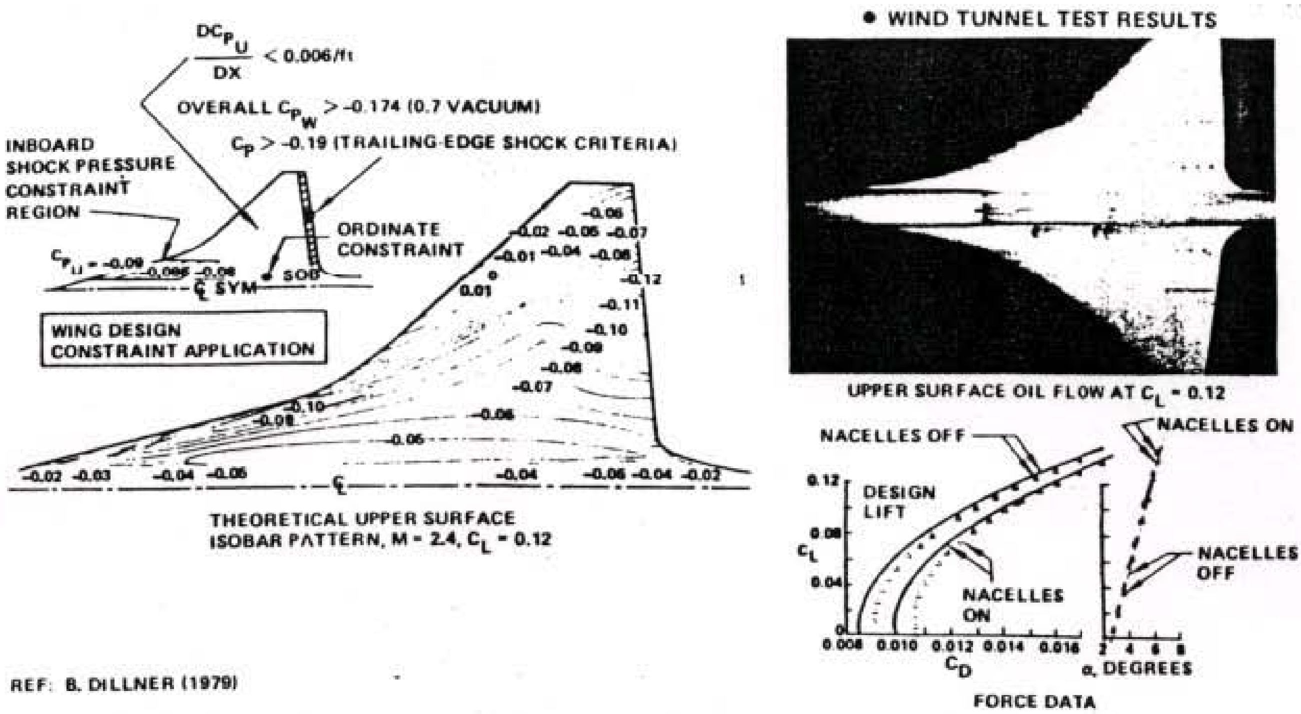
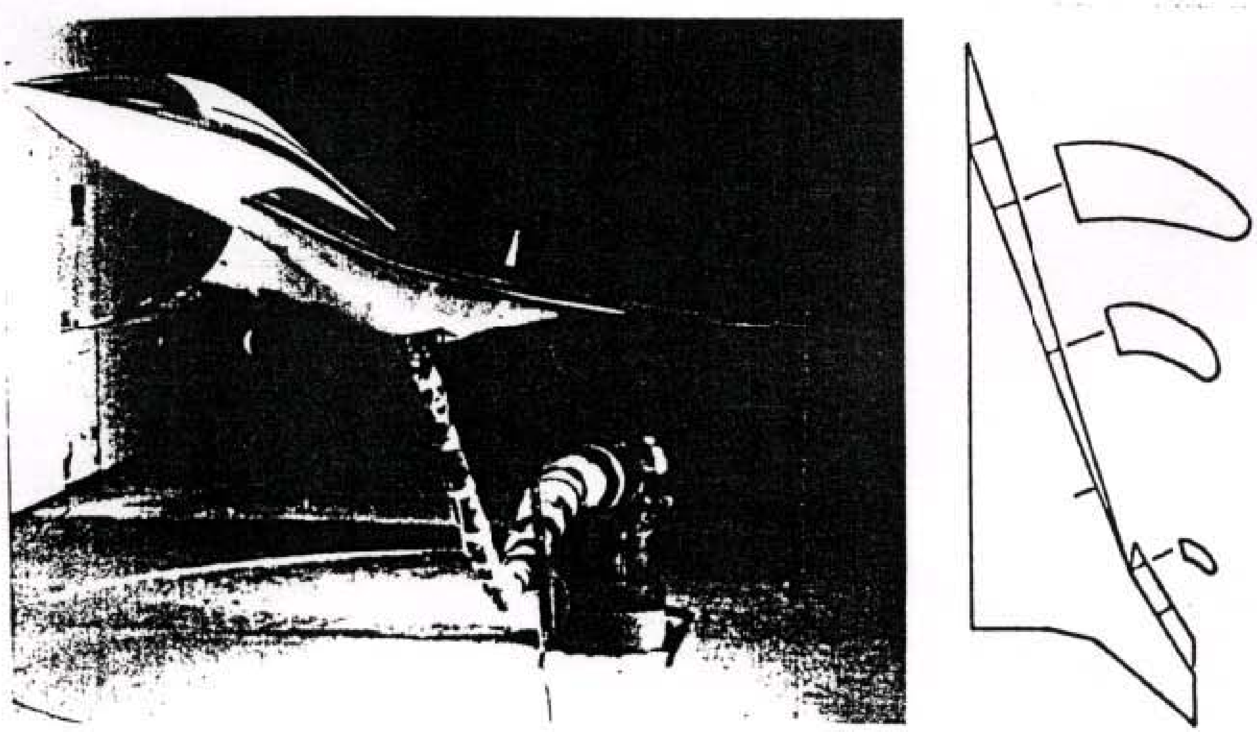


Figure 17. Supersonic Cruise Aerodynamic Efficiency Improvements



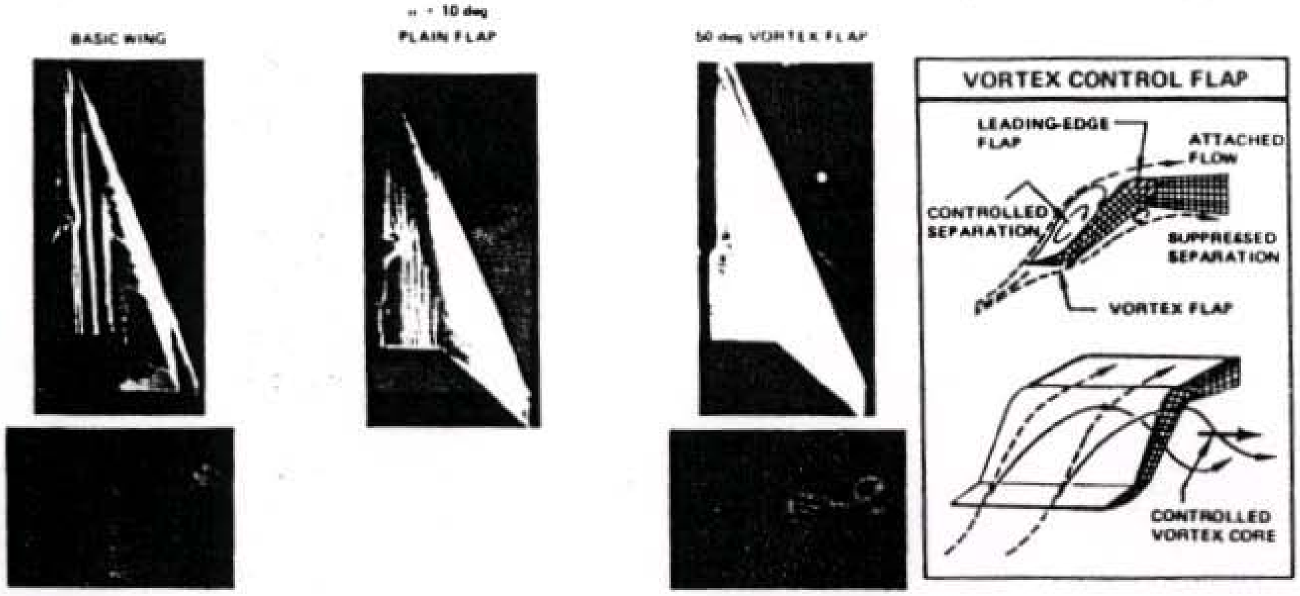
REF: B. DILLNER (1979)

Figure 18. Supersonic Aerodynamic Wing Design Technology



REF: P. L. COE, JR. (1979)

Figure 19. Arrow Wing Low-Speed Aerodynamic Research—Attached Flow Concepts



REF: L. J. RUNYAN, W. D. MIDDLETON, J. A. PAULSON (1979)

Figure 20. Arrow Wing Low-Speed Aerodynamic Research—Vortex Control Concepts

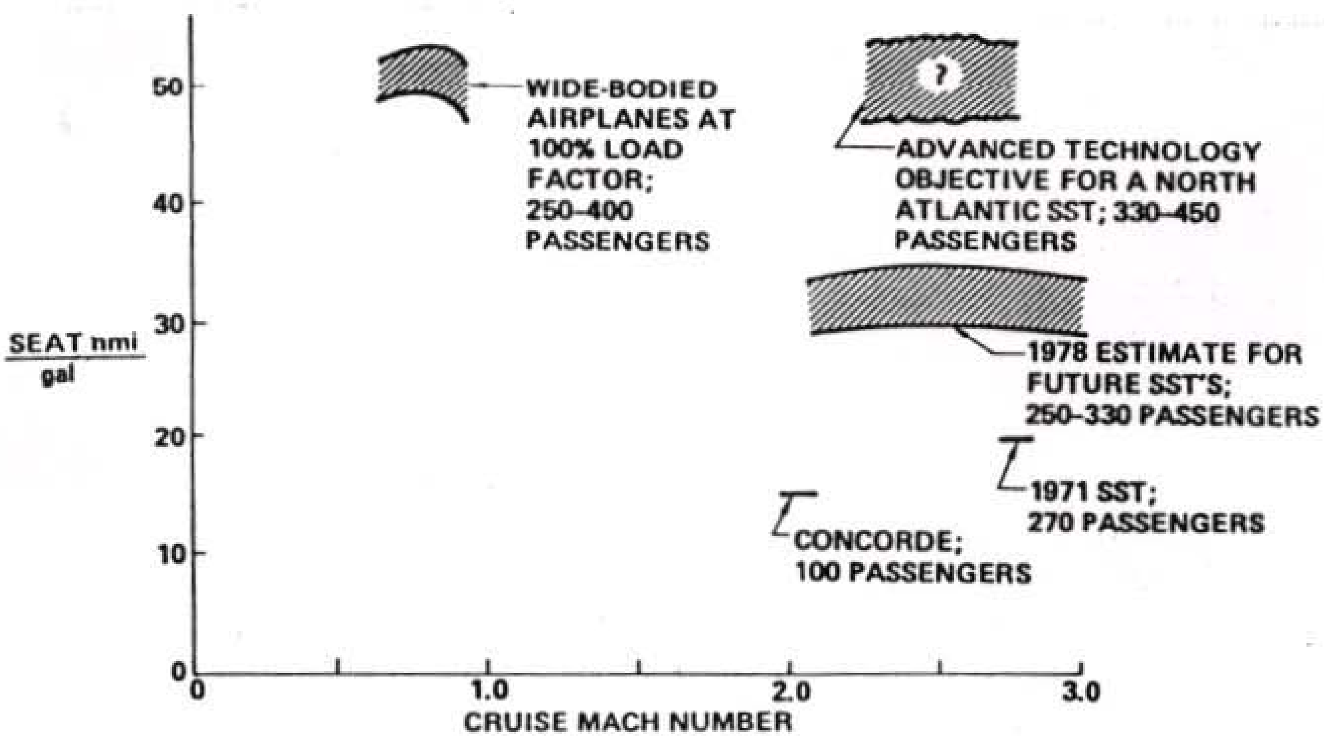


Figure 21. SST Fuel Efficiency Potential

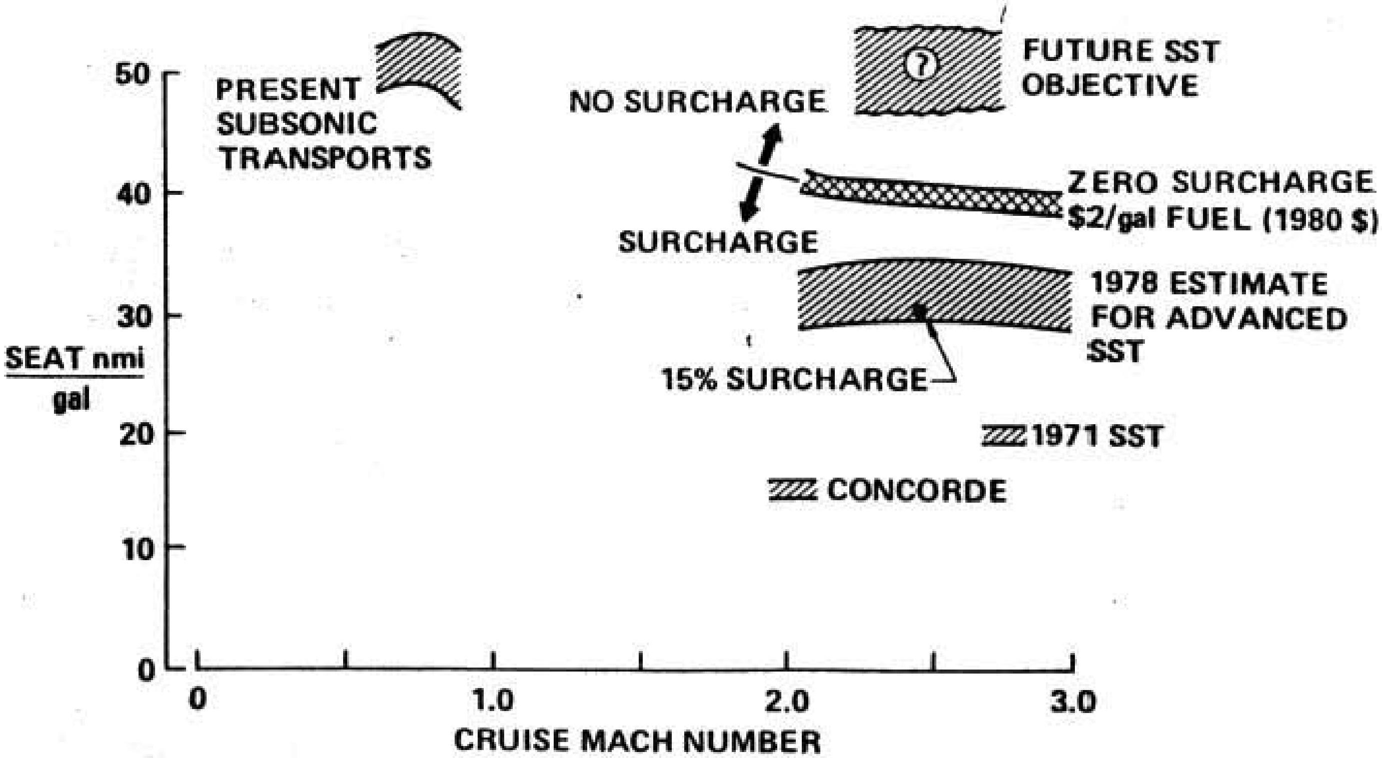


Figure 22. SST Economic Potential

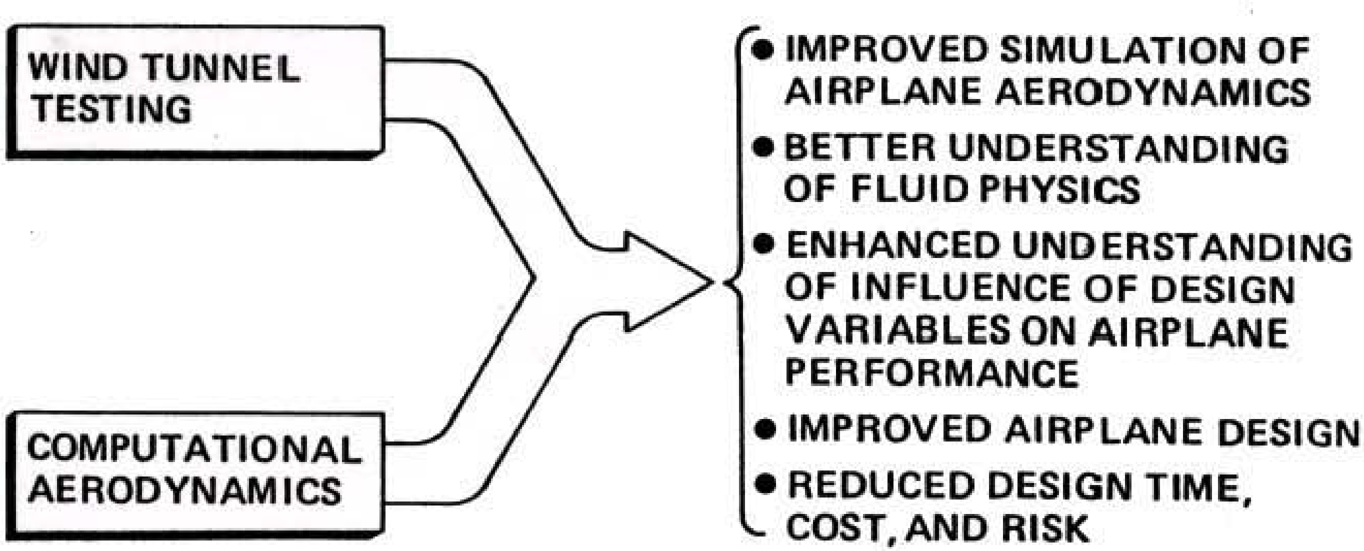


Figure 23. Benefits of Advanced Aerodynamic Design Tools

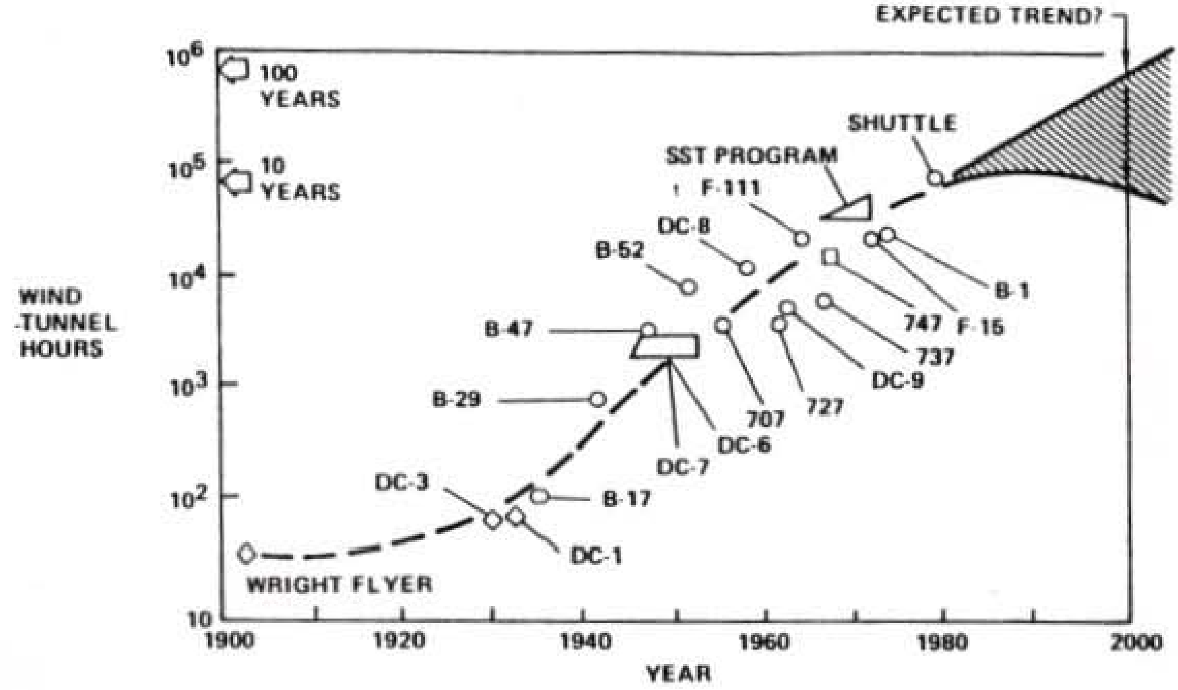


Figure 24. Wind Tunnel Usage to Develop Major Aircraft

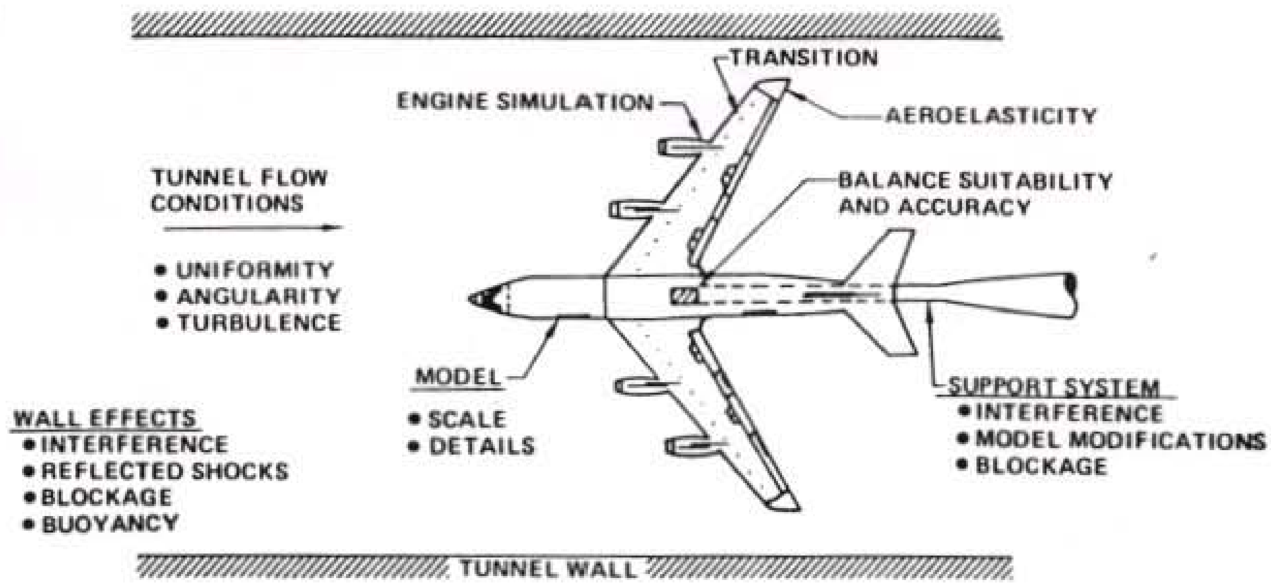


Figure 25. Factors Affecting Drag Measurement Accuracy for Full-Scale Predictions

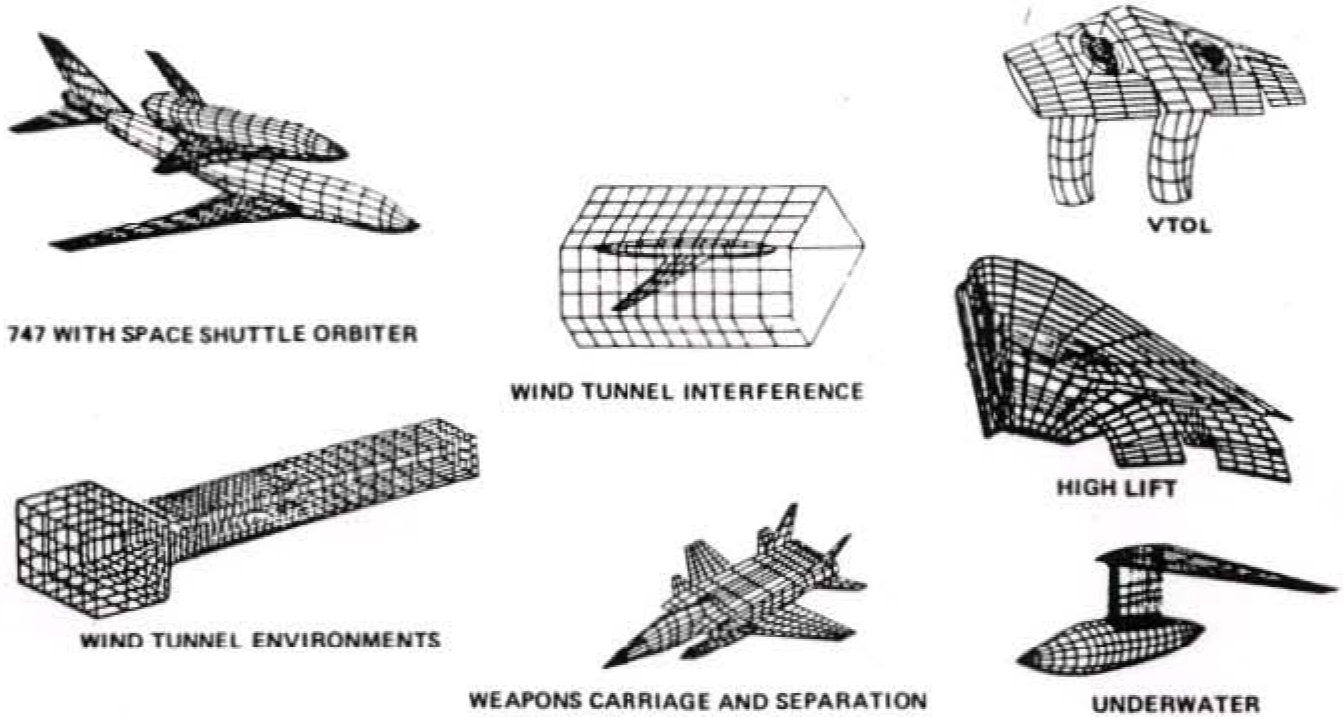


Figure 26. Nonlinear Inviscid Program Applications

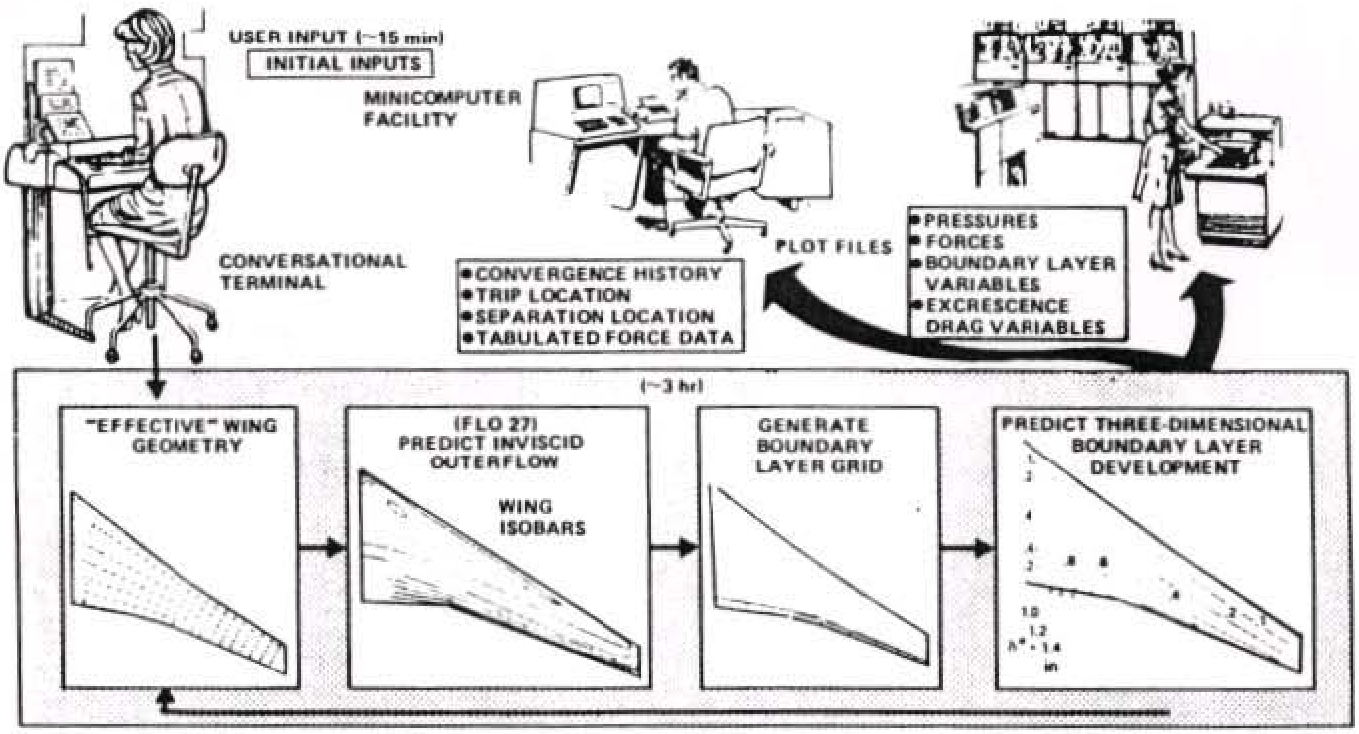


Figure 27. Three-Dimensional Viscous Transonic Wing Analysis

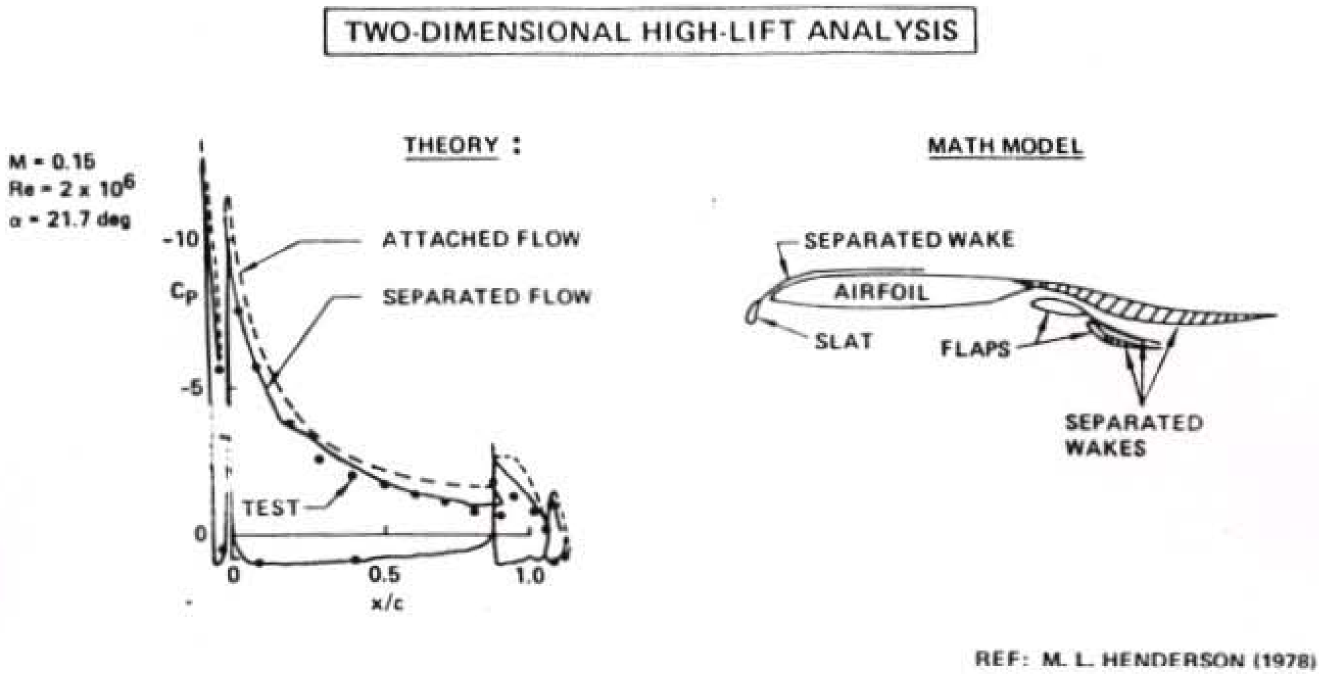


Figure 28. High-Lift Separated Flow Prediction

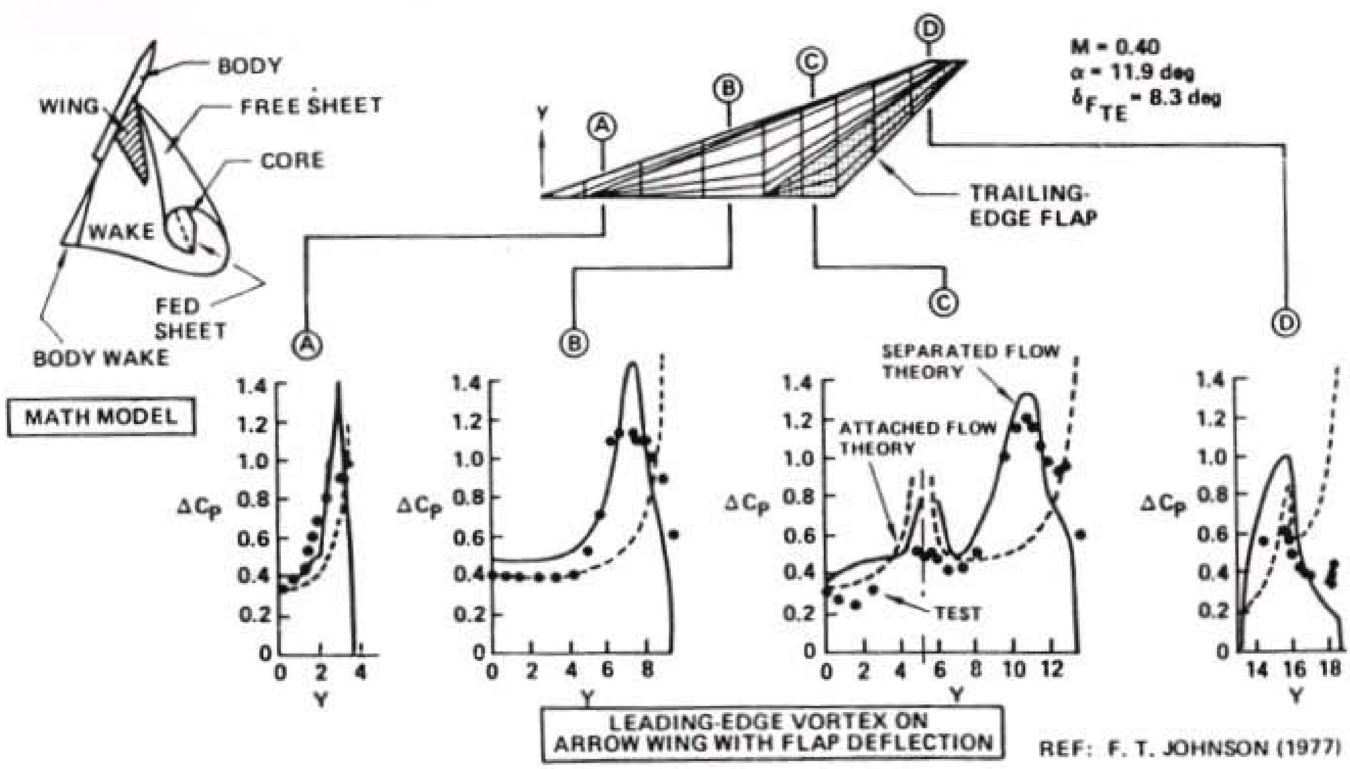


Figure 29. Slender Wing Separated Flow Prediction

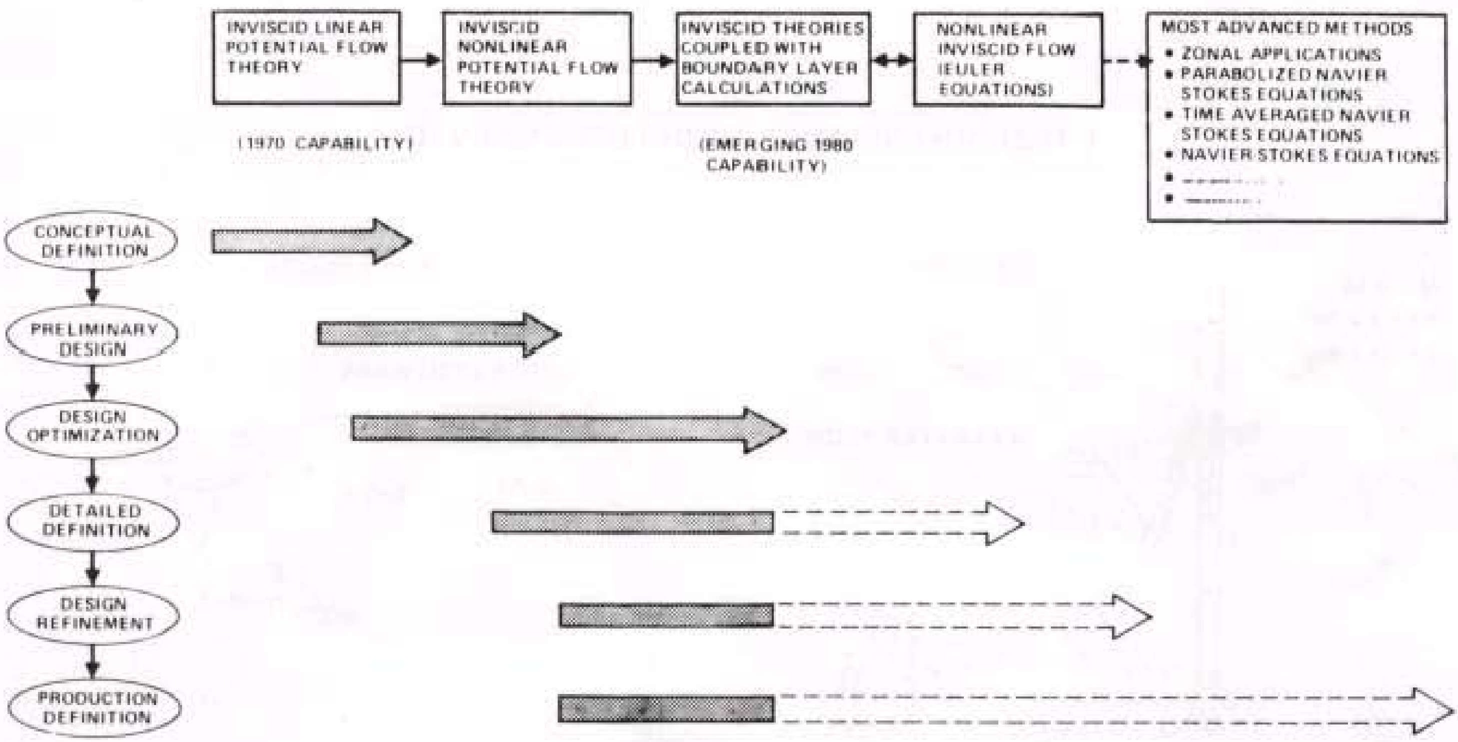


Figure 30. Design Applications of Practical Computational Aerodynamic Methods