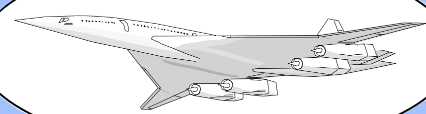
Revolutionary and Evolutionary Aspects of "Breakthrough" Supersonic Technologies



The National Research Council

Presentation to the

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Brenda M. Kulfan
Boeing Commercial Airplane Group

B.M. Kulfan

Topics

- "Evolutionary" and "Revolutionary" Aspects of New Technology Development
- "Idea Driven" and "Product Driven" Technology Development Strategies
- Impact of Timing and Selection of Technology Development Options
- HSCT Technology Development Strategy
- Quantum Theory of Design Development
- Aerodynamic Impact and Tools
- Technology Projection - Goals for the Aerodynamic Advances
- Aerodynamic Evolutionary and Revolutionary Opportunities
  - Subsonic Cruise
  - Supersonic Cruise
- Aerodynamic Tool Improvements
  - Non-Linear Design Optimization
  - Viscous Drag Predictions
  - High Reynolds Numbers
- Sonic Boom Elements and Low Sonic Boom Technology Focus

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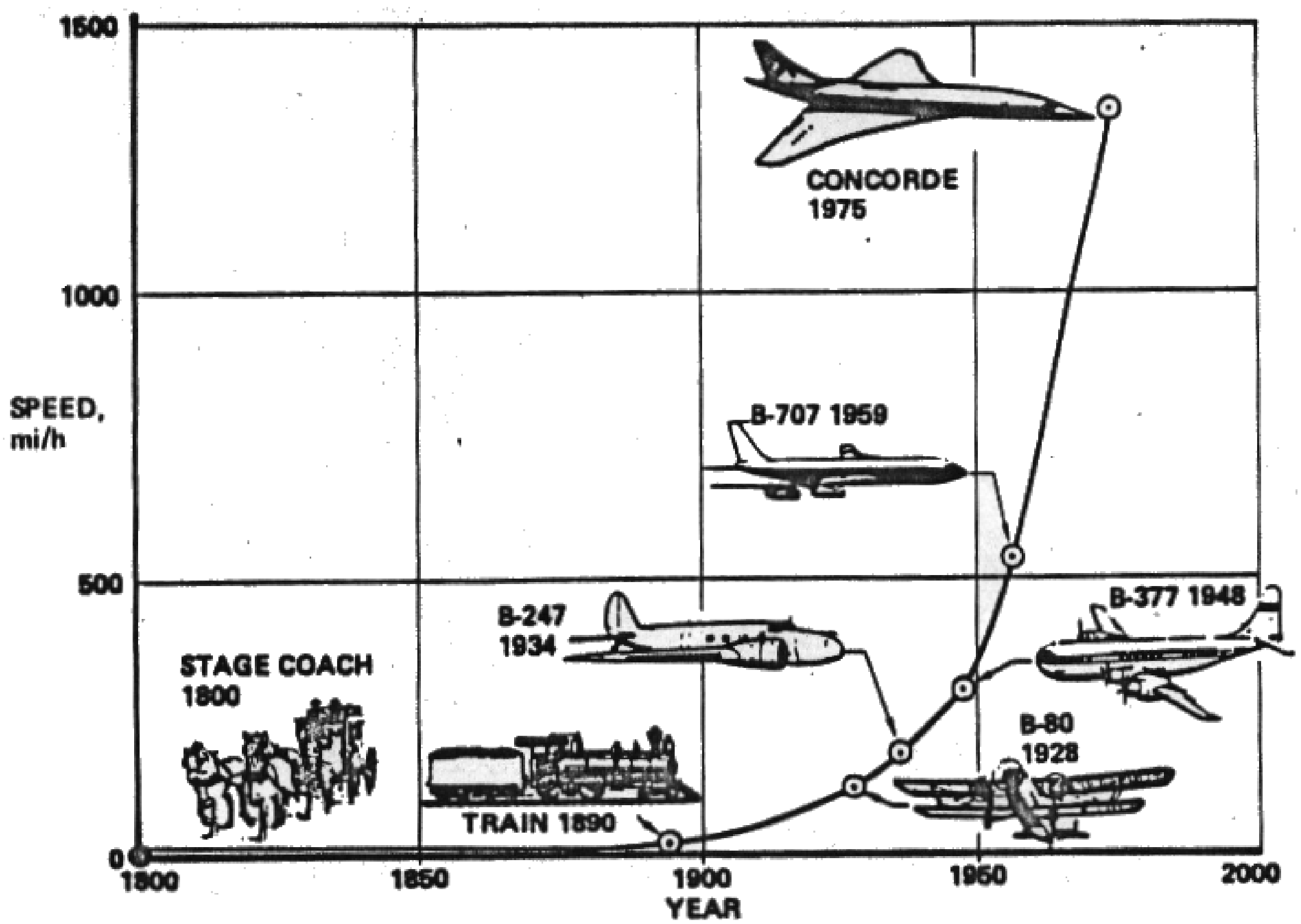
INTRODUCTION

The development of a viable supersonic commercial transport airplane will be very dependent on the identification, development and application of the appropriate level of the advanced technologies.
In this paper we shall discuss various strategies and approaches to aid in the identification of which technologies should be the focus of the advanced technology development programs.
Two general types of of advanced technology developments have lead to the immense technical advances in the field of aviation. These include "Revolutionary" and "Evolutionary" advances. Any effective technology development program must focus on both types.
There has been a paradigm shift in the technology development processes. The historic "idea driven" approach has generally been replaced by the currently favored "product driven" approach. It will be shown that some effort must be directed at retaining some element of the "idea Driven" in order to maintain a wealth of innovative concepts for future applications.
The generic nature of the timing of the development of a critical technology on the potential market share for a new commercial aircraft will be presented. This will provide some insight on the importance for selecting the appropriate level of technology as well as developing efficient design , analysis and application processes to secure a major share of the available market for a new commercial aircraft.
An example will be shown to illustrate the fact that all of the HSCT prior studies have usually considered assessments of often radical innovations or technical applications.
A quantum theory of design development will be shown that typifies the usual design development process.
Cruise Aerodynamics has a significant impact on a HSCT. A major element of the "Technology" of Aerodynamics are the tools of the aerodynamist. A technology projection process will be shown as a means to identify aerodynamic technology advancement potential. Some important areas for the improvement of the aerodynamic tools are discussed.
The fundamental elements of sonic boom will be discussed along with recommendations for sonic boom critical technology developments.

COMMERCIAL TRAVEL SPEEDS : 1800 TO 2000



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The Development of aircraft from the Wright Brothers humble flyer of 1903 to the magnificent machines of today illustrates an astonishingly rate of progress in airplane designs. This progress is the result of numerous technical advances in such fields as aerodynamics, propulsion, flight controls, structures, internal systems and manufacturing. Indeed, a characteristic feature of the advances in aviation has been the need to advance on many fronts.

Private individuals, research laboratories operated by the Government, universities, and private companies, as well as the industrial design and engineering teams, have all been involved in this development process.

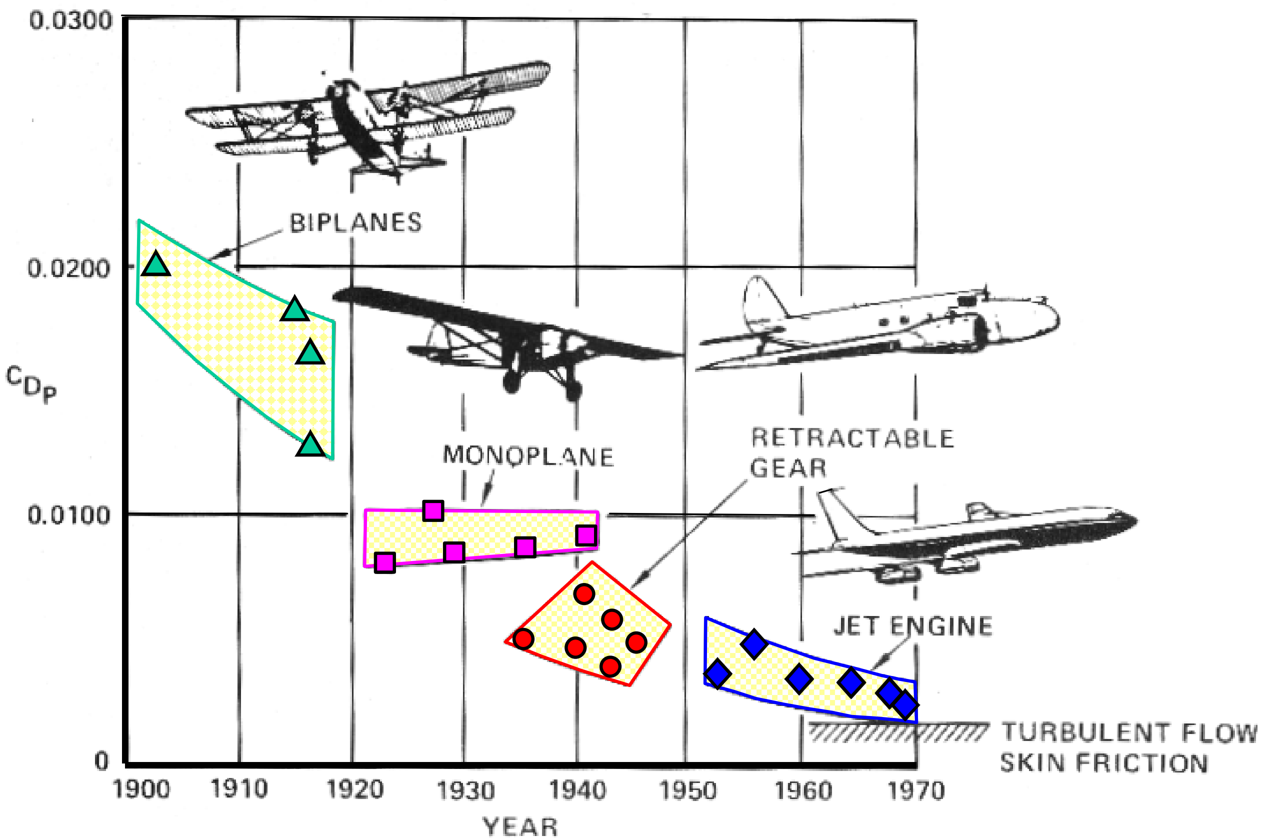
The aeronautical development achievements have come about by careful and painstaking work, interrupted occasionally by a brilliant insight or invention. Both the routine and the unusual have been and will continue to be important to the growth of aviation.

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 influence of economic, social, and political considerations.

Many of the technology advances for a High Speed Civil Transport, HSCT, will provide solutions to current problems such as social acceptability of aircraft through noise and pollution reduction, better fuel efficiency and increased productivity and better economics while responding to specific market needs.

HISTORY OF AIRPLANE PARASITE DRAG REDUCTION



CD_P Based on Airplane Wetted Area

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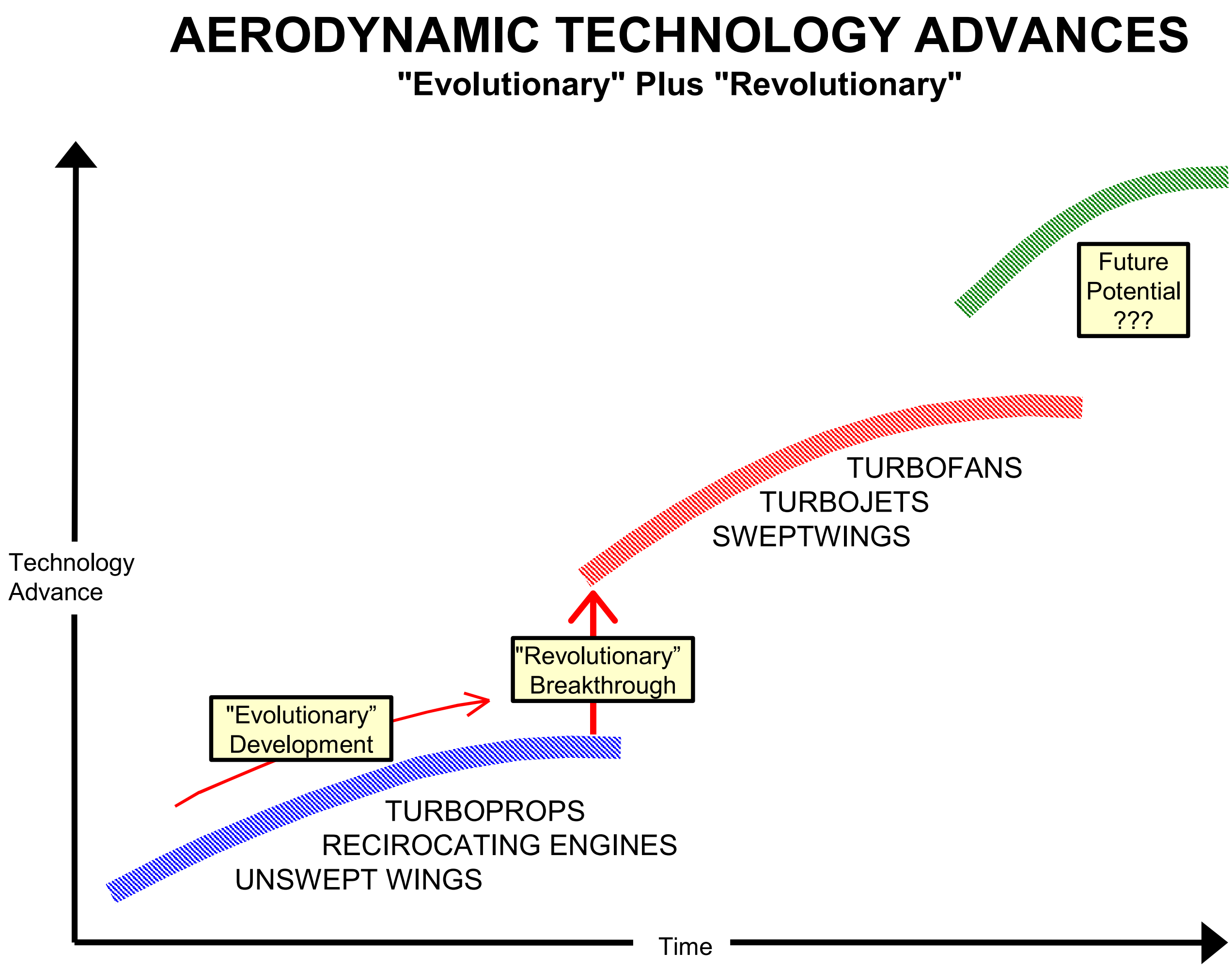
This figure shows the history of the reduction in parasite drag with time. Both the evolutionary and revolutionary reductions in drag are dramatic. The modern day transport aircraft has a parasite drag level that is approaching the turbulent flow skin friction drag.

The major reductions in parasite drag have occurred with revolutionary changes in the shapes of the airplane. These include changing from biplanes to propeller monoplanes with retractable landing gear to swept wing jet aircraft. However it is also seen that the steady evolutionary improvements were also significant.

Currently the parasite drag of a subsonic airplane is approaching the level of fully turbulent skin friction drag.

For a subsonic transport aircraft the viscous or parasite drag is on the order of 30 % higher then the fully turbulent friction drag level due to that profile drag due to thickness and lift, and the excrescence drag.

The viscous drag of thin slender supersonic transport aircraft, which has virtually no profile drag and reduced excrescence drag, is less then 10% higher then the turbulent flow skin friction level.



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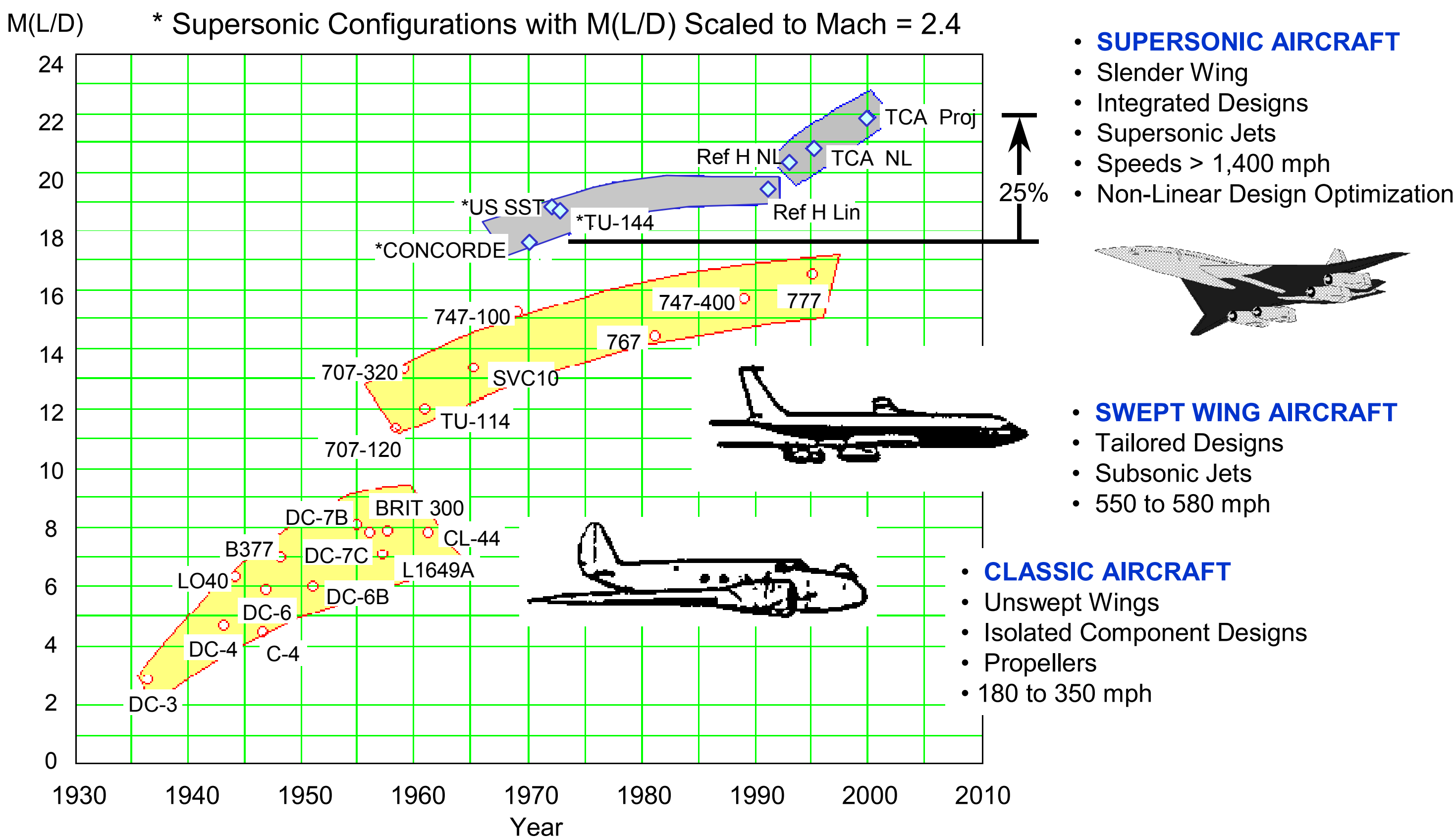
The general historic trend in transport aircraft technology[1] is shown in the figure.
The steady periods of technical evolution reflect the process of design refinements of a fairly fixed concept.

The sudden dramatic improvements indicate the appearance of some major technical innovation such as the cantilever wing, pressurized cabins, jet engines or swept wings and ultimately the slender wing for supersonic flight.

It is , therefore, convenient to distinguish between two types of Progress:

- "Revolutionary" - a development process characterized by significant rather sudden advancements. These are typically due to such things as: development and utilization of new concepts, new technologies, or innovative use of technological advances in related technical disciplines.
- "Evolutionary" - a development process in which a particular class of airplanes is progressively advanced typically due to improved understanding, refined processes and perhaps a series of minor or supporting technology breakthroughs.

AERODYNAMIC EFFICIENCY IMPROVEMENTS



AN EFFECTIVE TECHNOLOGY PROGRAM FOR THE DEVELOPMENT OF A VIABLE COMMERCIAL SUPERSONIC AIRCRAFT MUST INCLUDE BOTH "EVOLUTIONARY" AND REVOLUTIONARY" TECHNOLOGY DEVELOPMENTS

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This illustrates the general improvement in aerodynamic cruise efficiency, (M L/D) for transport type of aircraft with time.

Both evolutionary and revolutionary advances have made significant contributions to the aerodynamic cruise efficiency.

The revolutionary advancements were due mainly to cruise speed advances that occurred as the fundamental class of airplanes changed from "Classic" aircraft to "Swept Wing" aircraft to "Supersonic" aircraft. The revolutionary advancement occurring in the late 1950's was the introduction of the jet engine along with the swept wing aircraft. 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 were achieved by means of continuing evolutionary advances. The combined evolutionary advances, in fact, exceed the revolutionary advances.

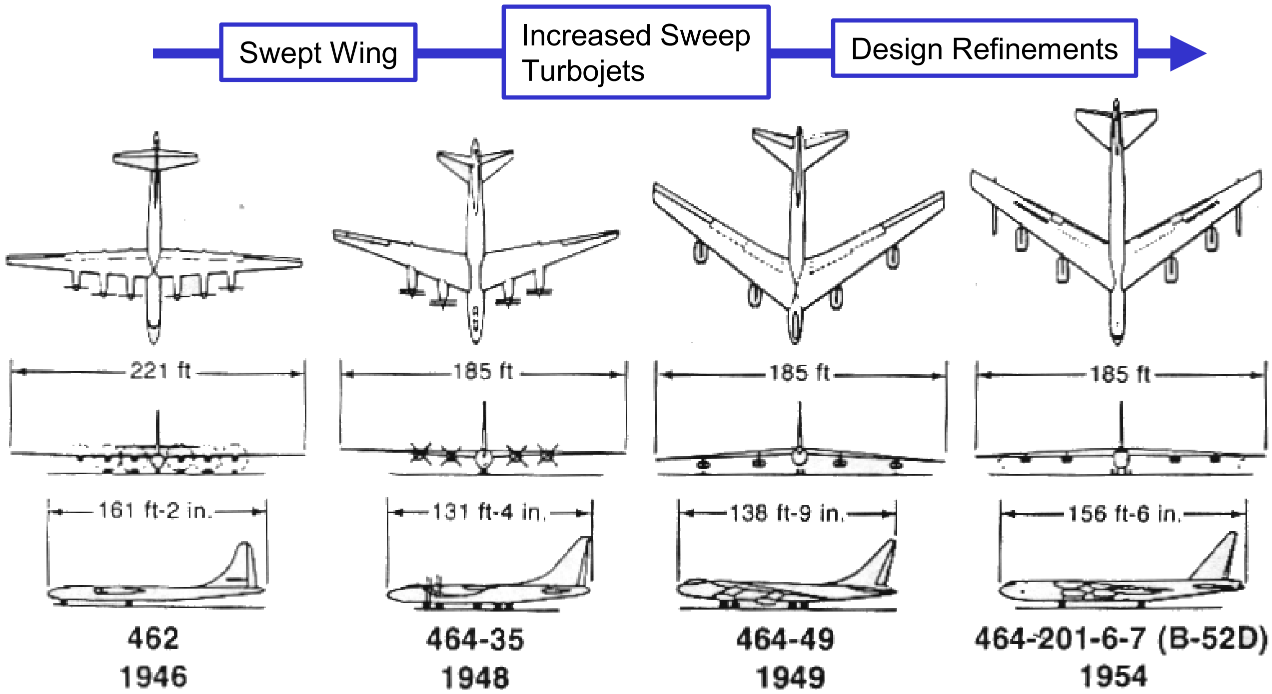
The improvements include evolutionary gains due to improvements associated with improved understanding, techniques and processes, and " revolutionary" improvements associated with the adaptation and utilization of technology improvements.

In this figure, the values of aerodynamic efficiency for the supersonic configurations have all been adjusted to a Mach number of 2.4. This normalizes the large differences in cruise Mach numbers (Concorde Mach = 2.1, US SST mach = 2.7 and HSCT mach = 2.4) and allows the advancements in the aerodynamics to be clearly seem.

It is clear that an effective technology program for the development of a viable commercial supersonic aircraft must identify and also actively plan for both types of technology developments.

B-52 DESIGN DEVELOPMENT

“EVOLUTIONARY’ PLUS “REVOLUTIONARY”



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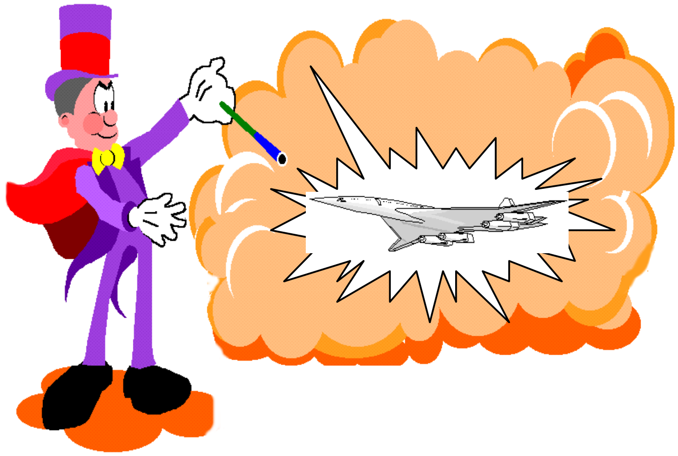
This illustrates the development process leading to the B52. This is an example where the design process itself included both evolutionary and revolutionary technology advances.

This is indeed the general nature of the development studies for both the US SST and the recently completed High Speed Civil Transport studies.

Introduction of a New Technology



- There must be an Established Need
- Benefits and Risk Must be Identified
- Typically There is a Need to Advance on Many Fronts
- The Opportunity to Introduce the New Technology Must Exist
- There is Typically a Long Time Between Validation and Implementation

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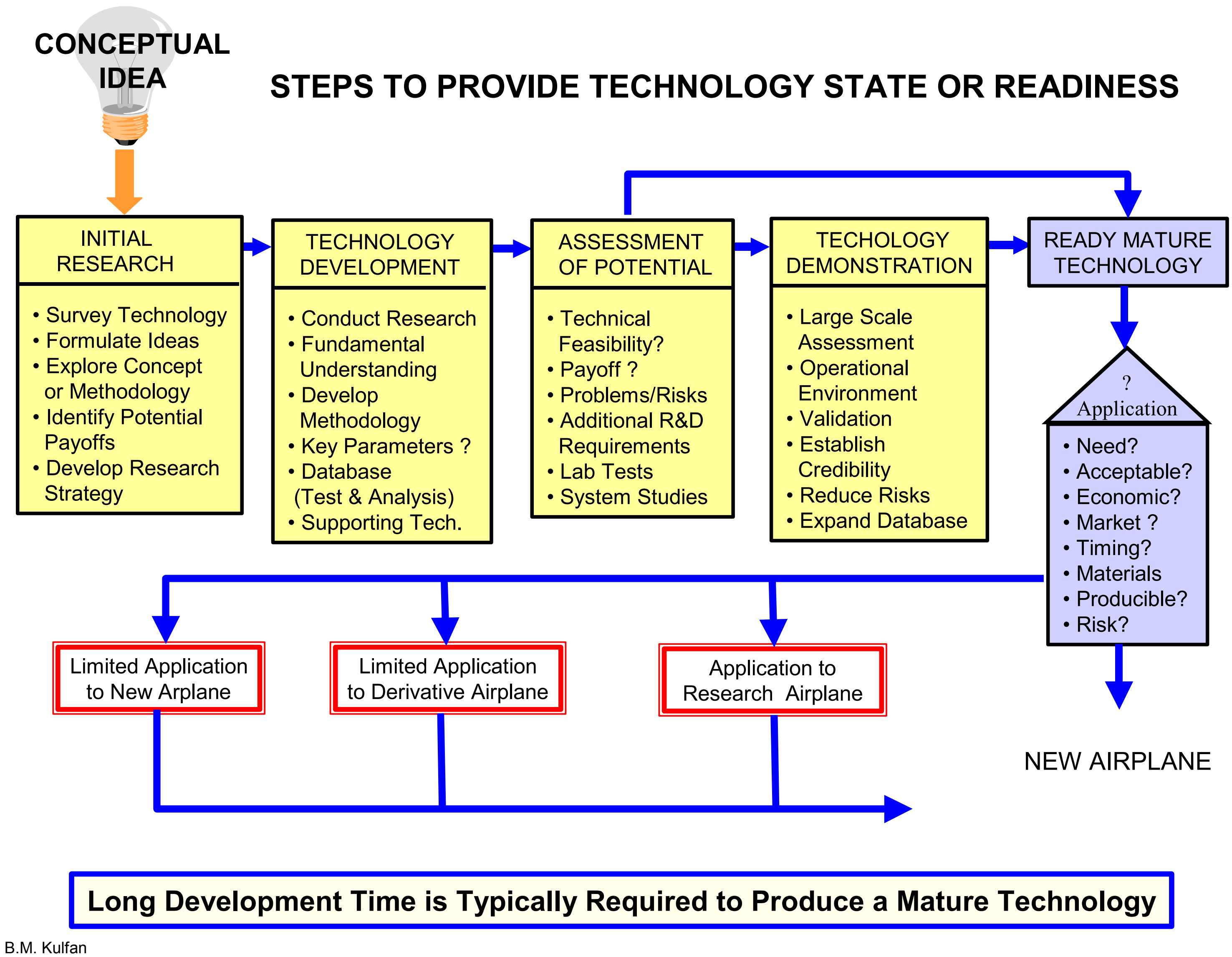
Technical development is the integration of applied research, experiment and engineering necessary to bring into practical operational use, the new knowledge gained from research. Introduction of a new technology into commercial transport service requires a number of preconditions:

1. There must be an established need for the new technology. This need may reflect the inability of existing technology to provide a desired level of performance or to meet community noise or engine emissions design requirements.
2. The benefits must be identified, particularly in terms of performance improvements, environmental impact, 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 to utilize a new pacing technology. A classic example is the Boeing B-47, which had a profound influence on current commercial airplanes designs, The B-47 was designed to exploit the performance of the jet engine. The final design incorporated many technical advances. The basic configured featured a thin clean high aspect ratio wing with underwing pod-mounted nacelles. The high lift system included Fowler flaps and flaperon lateral control. The airplane also used the first production full-time stability augmentation system to eliminate the undesirable dutch roll associated with swept wings.
4. The opportunity to introduce the new technology must exist. Often in the past, military needs have provided the opportunity long before the introduction into commercial. Because of the immense cost in developing the advanced technology to the necessary level of maturity, Government-sponsored research is a vital part of the development process

These necessary preconditions indicate that the application of a new technology takes time. On the basis of history, typically 10 to 20 years pass between the first full scale or flight demonstration of a new technology and its application to commercial aircraft.



The development program required to bring a revolutionary technology to a mature state typically involves a number of stages including:

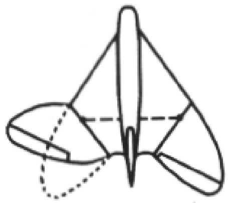
- Initial basic research
- Technology development phase
- Assessments of payoff potential
- Often a technology demonstrator program is required
- This leads to the ultimate state of a ready mature technology

Depending on the risk, need and payoff, the technology may first be used in limited application to either a new airplane or on a derivative airplane, or perhaps to a research airplane. Extensive application to a new airplane may then follow.

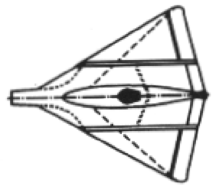
Historically, 10 to 20 additional years pass between the first full-scale experimental use of a revolutionary new mature technology and it's entry as a refined development on a commercial aircraft[1]. This is in addition to the previously discussed time period associated with evolving the technology from it's conception as an idea to its development into a mature technology ready for potential application.

Hence in general a long developing time of many years, historically on the order of 20 years, must be considered in planning to utilize a mature new revolutionary technology for commercial airplane applications.

AERODYNAMIC CONFIGURATION INNOVATIONS

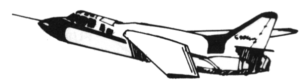


Messerschmitt (Lippisch)
Variable Sweep Wing
Patent (1941)

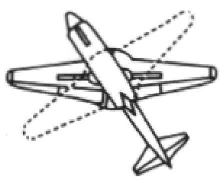


Lippisch Delta Wing
Supersonic Fighter (1944)

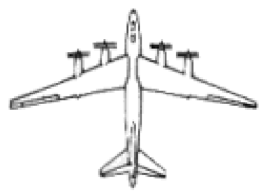
Junkers Swept Forward Wing
Bomber Testbed (1944)



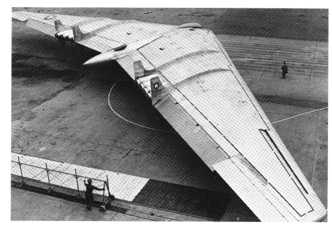
X-21A Laminar Flow Control Airplane (1960)



Blohm and Voss (Vogt)
Oblique Wing Fighter
Concept (1944)



Swept Wing
Busemann (1935)
R. T. Jones (USA)



Northrup Flying Wing

Most Innovative Aerodynamic Concepts were established 50 to 65 Years Ago

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Aerodynamics together with structural and manufacturing considerations largely define an airplanes exterior contours. The size and shape of the aircraft is ,however, typically associated with technological progress in aeronautics.

It can be argued with some degree of validity, that the vast majority of existing aircraft were established (al least on paper) 50 to 65 years ago. The swept wing , conceived by Busemann (1935) and about the same time by R. T. Jones, and the development of the delta wing planform by Lippisch together with the Jet engine conceived by Whittle are the basis for almost every modern high-speed airplane configuration.

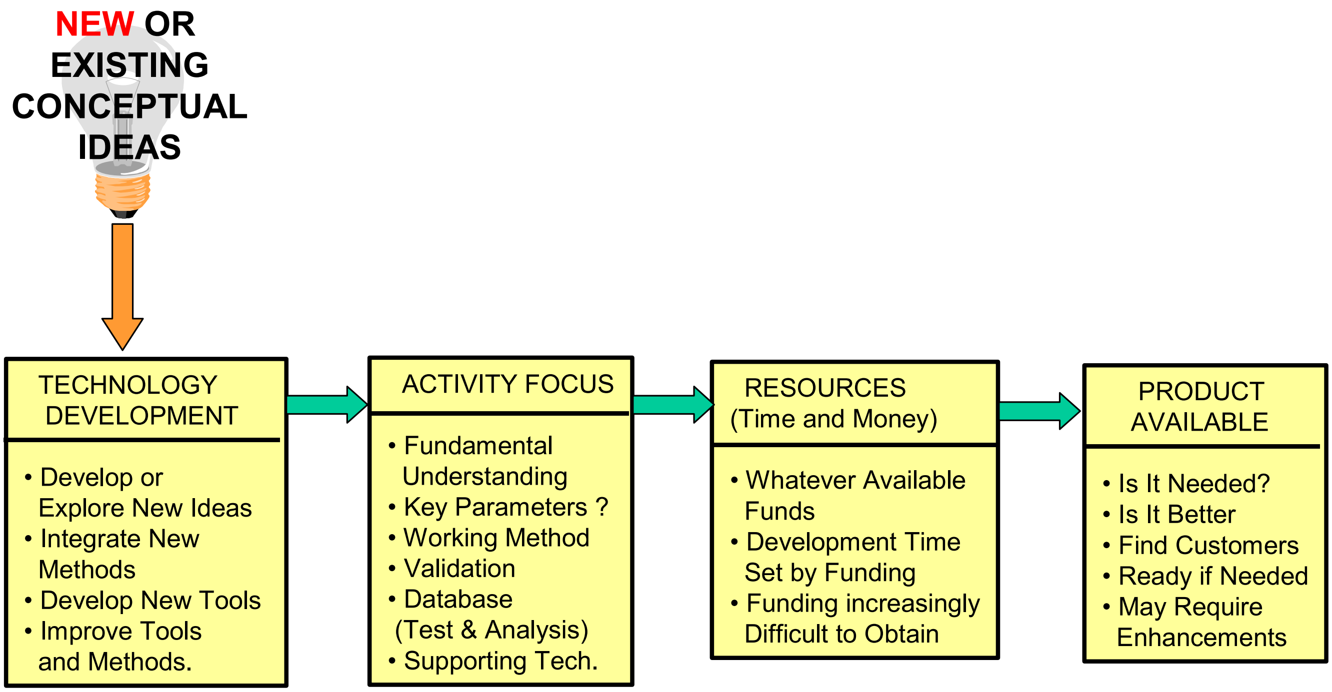
During the decade between 1935 and 1945, visionaries foresaw a range of configurations that even today can be considered very modern. These include the swept forward wing pioneered at Junkers in the early 1940's, the oblique wing originally conceived by Vogt at Blom and Voss in 1943, and variable sweep wings, a patent for which was issued to Messerschmidt in 1941 for the concept by Lippisch.

The variable sweep oblique wing was first proposed nearly 60 years ago and was first tested in a wind tunnel in 1945. In recent years the oblique wing proposed by R. T. Jones led to the oblique wing deminstrator program in 1978.

The flying wing, conceived by Jack Northrup over 65 years ago is an example of an aerodynamic concept that may be very dependent on developments in avionics for stability, control, load alleviation and flutter suppression for a practical application.

Other aerodynamic technologies also have their basis in work conducted more then 60 years ago. Early investigators in the achievement of low drag by suction included Holstein (1940), Loftin and Burrows (1949) and Pfenninger (1946, 1949). This led to the pioneering work with the X-21A aircraft by Northrop and the Air Force in the 1960's. More recent flight test development activities in the 1990's include the laminar flow control experiments on the Boeing 757 and the F-16XL supersonic flight test program.

"IDEA" DRIVEN TECHNOLOGY DEVELOPMENT
~ HISTORIC MODEL ~



This is the historic model for developing a new technology and is often called "Idea" driven technology, or technology "push" method.

Based on either a new or existing unique conceptual idea, a research activity may be started to develop this technology. Indeed one of the key elements in this environment is the opportunity to seek out and explore new ideas without any imposed drastic limiting constraints.

The technology development phase may have as it's goal developing or exploring the new idea or perhaps integrating or developing new tools or methods.

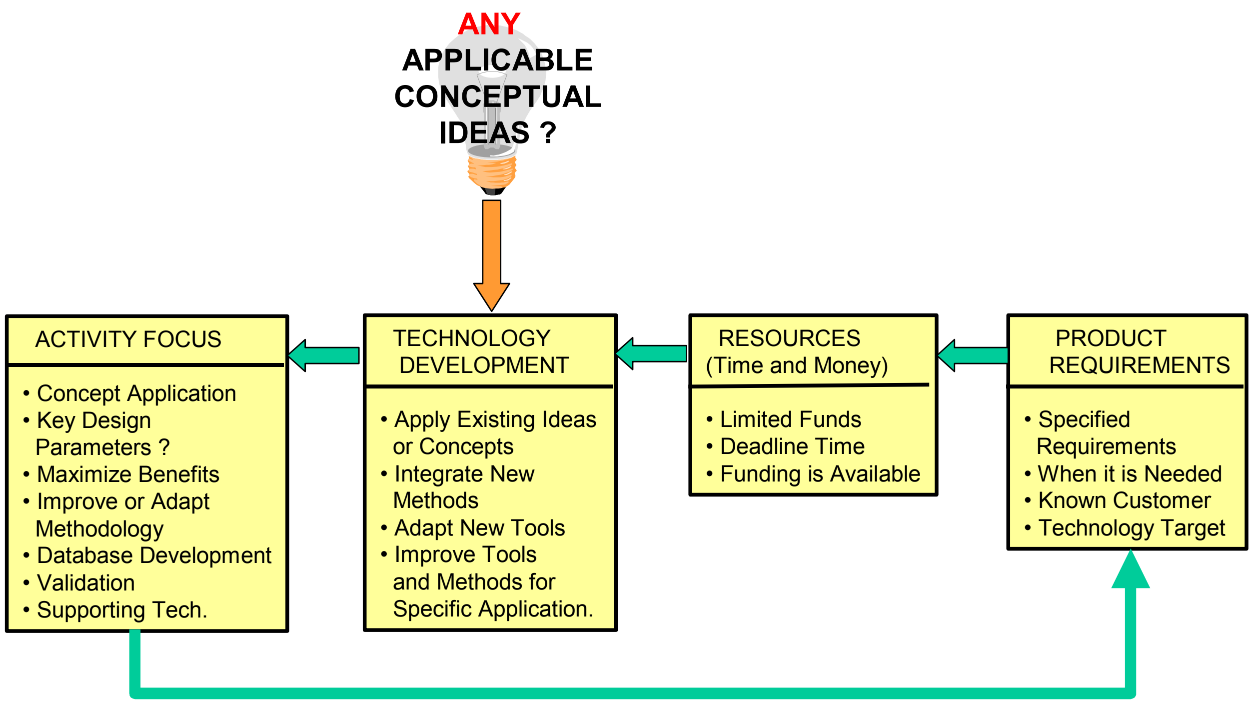
The activity focus is on developing a fundamental understanding of the new concept or method. Allowances are made to permit exploring and determining any key or critical parameters associated with the concept.
The research activities will include the necessary database to validate the concept or method and to seek out the necessary supporting technologies.

The available resources for such a program are seldom fixed. The development time is consequently greatly dependent on the outside interest and the level of funding. In today's research environment, funds to carry on such research are extremely difficult or impossible to find.

If the research program is successful and a product is proven and available there comes the search for a customer. Often the technology may wait years for a need finally emerges.

This historic process that has lost favor in present day economics, however, is responsible for nearly all of the significant technology advancements in aerodynamics.

“PRODUCT” DRIVEN TECHNOLOGY DEVELOPMENT
~ MODERN MODEL ~



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The current technology development model is “product” driven and is often called the technology “pull” method.

In this approach, based on some specific need(s) of a customer a research program is launched. The requirements for the technology are known. The resources including both time and funds are specified and development funds are available.

The technology phase will basically apply existing ideas or concepts or will focus on the development of new or improved methods. The activity focus will be heavily guided by the product requirements.

This method of technology development seems best for advancing a known concept or methodology and hence is the best model for evolutionary technology advances.

“IDEA” DRIVEN TECHNOLOGY DEVELOPMENT

:

ADVANTAGE:

- Allows Relatively Unconstrained Creative Thinking
- Source of Almost All Aerodynamic Innovations and Advanced Technologies
- Best Approach for Conceiving New Technologies

DISADVANTAGE:

- May Lead to Unused Innovations - No Customer(s)
- Seldom a Schedule
- Funding Today is Difficult to Obtain

EXAMPLE AERODYNAMIC TECHNOLOGIES DEVELOPED BY THIS PROCESS

- NACA Airfoils and Cowl Shapes
- Supersonic Critical Airfoils
- Swept Wings
- Natural Laminar Flow Applications
- Laminar Flow Control
- Hybrid Laminar Flow Control
- Original Supersonic Design and Analysis Methods
- Skin Friction Prediction Methods
- Supersonic Area Rule
- Supersonic Nacelle / Airframe Integration
- Most CFD Codes (Full Potential, Euler , Navier Stokes)
- Leading Edge Vortex Prediction Methods
- Delta Wing
- Arrow Wing
- Variable Sweep Wing
- Variable Sweep Oblique Wing
- Exotic Wing Planforms (eg “M” Wing, “box” Wing)
- Turbulent Flow Viscous Drag Reduction (eg Riblets)
- Sonic Boom Prediction and Design Methods

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This summarizes the characteristics of the “idea” driven or “push” method of technology development. The major advantage is this creates an environment for relatively unconstrained thinking and is usually the best approach for conceiving new concepts or methods.

As shown by the examples, this has been the development process for almost all aerodynamic innovations and advanced technologies.

The major disadvantages for this approach include:

- many innovations have gone unused for lack of a customer
- the availability of the end product is seldom known because of the lack of a demand for a schedule.
- Indeed. It is quite impossible to “schedule” a major technology breakthrough or conception of a new idea
- Perhaps the greatest disadvantage, is that currently neither government or industry will fund such a totally unconstrained effort.

"PRODUCT" DRIVEN TECHNOLOGY DEVELOPMENT
~ MODERN MODEL ~

ADVANTAGE:
- Best Approach for Adapting or Improving a Technology Concept
- Customer for the Technology is Known
- Focused Activity for Defined Development time
- Current Approach Required For NASA / Industry Funding

DISADVANTAGE:
- Seldom Allows Innovative or Creative Thinking
- Cannot "Schedule" Invention
- Few if Any Innovative Technologies Conceived by this Approach
- Focus is usually on "results" and not on "Understanding"

EXAMPLE AERODYNAMIC TECHNOLOGIES ADVANCED BY THIS PROCESS
- Low Sonic Boom Configurations
- Non-Linear Aerodynamic Design Optimization
- HLFC Application Assessments

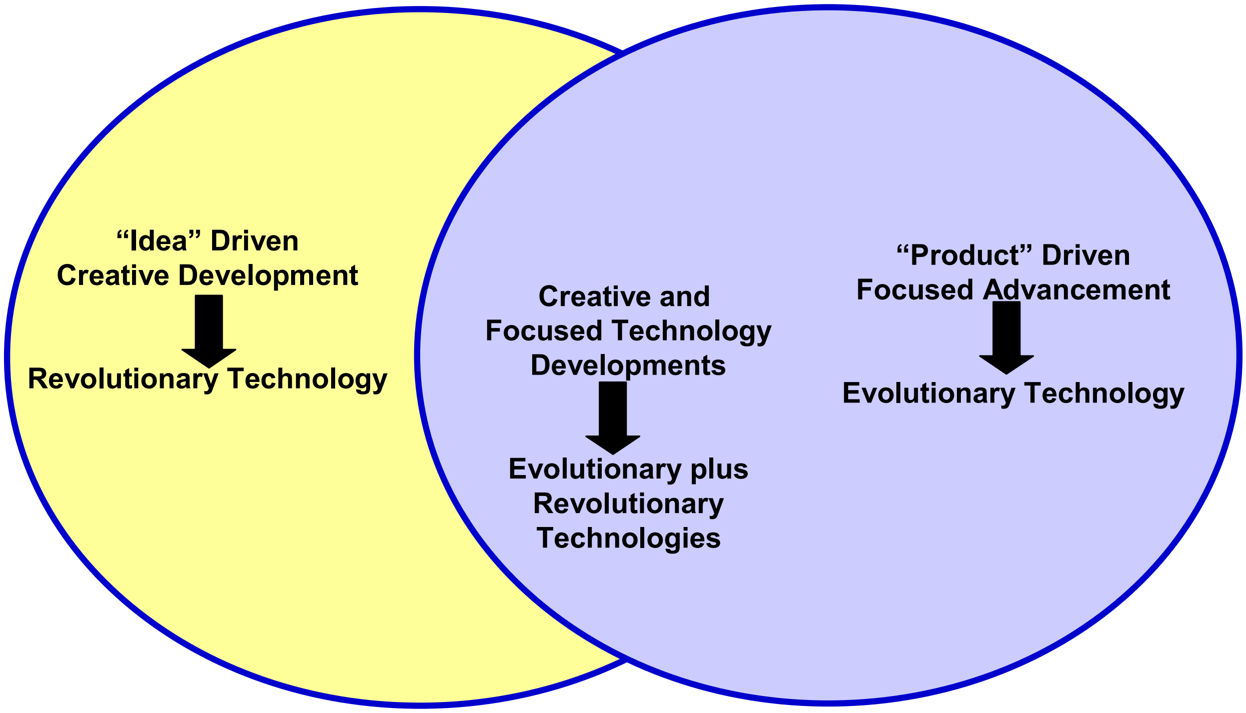
This summarizes the characteristics of the "product" driven or "pull" method of technology development.

This is the currently favored technology development model. The customer is know and the available funding provides for a focused activity for a defined development time. If the development has not been completed within the resources constraints there may be enough leverage to get the necessary additional resources.

This perhaps is the best approach for adapting or advancing a known technology concept or method as shown by the examples above.

The major disadvantages include:
- This seldom allows for either unconstrained innovative or creative thinking, for it is essentially impossible to rigidly schedule a new idea or invention
- Few if any new innovations result from this approach.
- Because of the focus on results, not enough time or activity are focused to allow for a complete understand of the concept and for the identification of any key parameters.

PROPOSED TECHNOLOGY DEVELOPMENT MODEL



Efficient and Effective Technology Development while Maintaining a Wealth of Innovative Concepts and Solutions for Potential Future Applications

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The most effective model for technology development, as shown in the figure, would be to provide for the effective combination of both types of technology development activities.

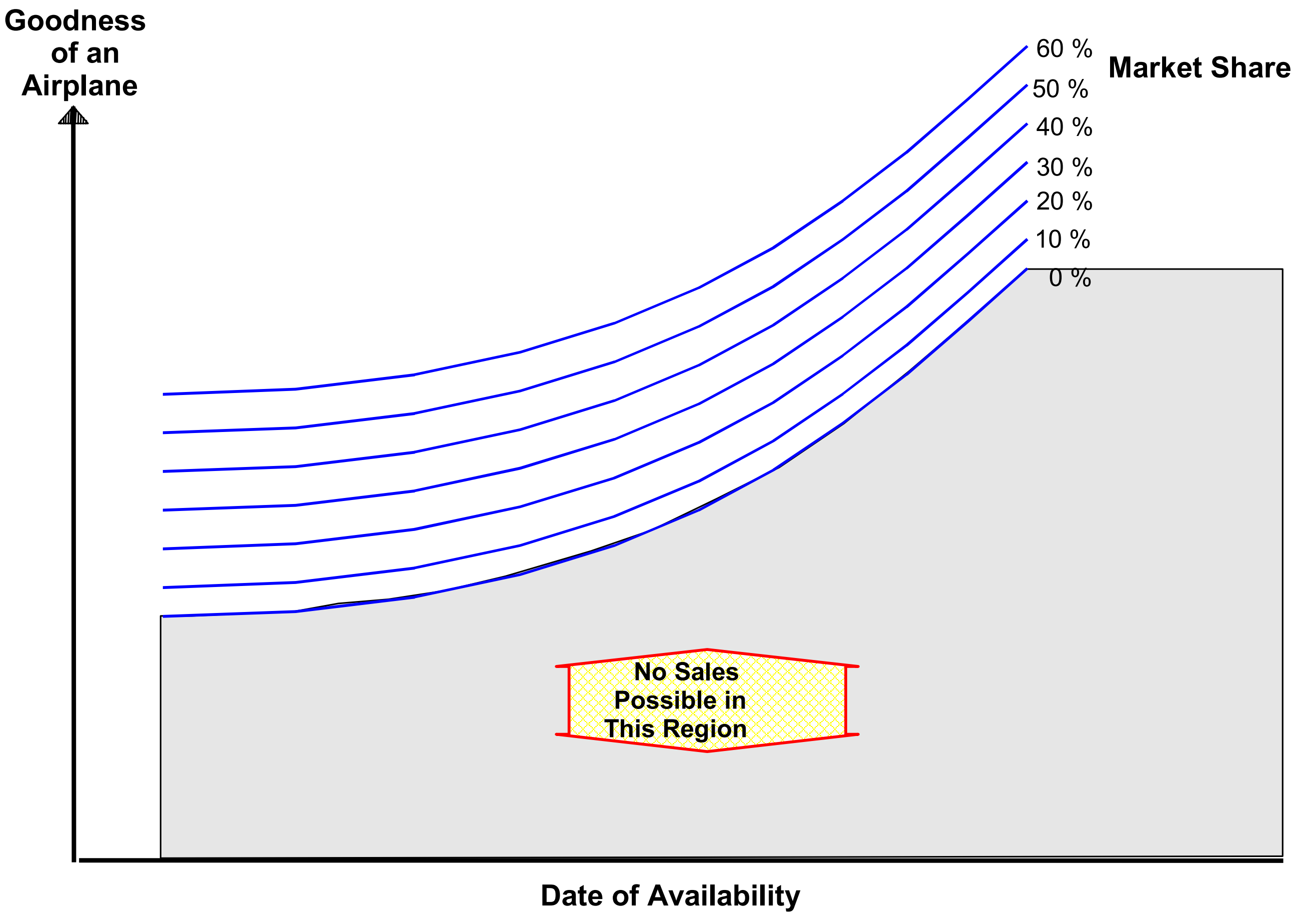
With this model, "Idea Driven" innovative technology driven research will continue even in periods where there may be no requirement for "Product Driven " technology activities. The idea driven technology development would naturally proceed through a continual process of identification of potential technology gains, risk assessments and identification of the probable research requirements necessary to produce a mature technology. This is most likely the source of the "Revolutionary Technology" Developments.

The technology delivered for a specific new application can be drawn from the technology base produced by the "Idea Driven" research and then greatly advanced to the necessary state of maturity by the "product driven" focused technology development process. This is the primary model for "Evolutionary Technology" advancements.

This will also insure that we maintain a wealth of innovative options and practical solutions for potential future aircraft applications.

Adaptation of this recommended technology development model, by NASA, academia and the industry will enable the United States to maintain is leadership in commercial as well as military aviation.

Variation of Market Share With Goodness and Availability Date



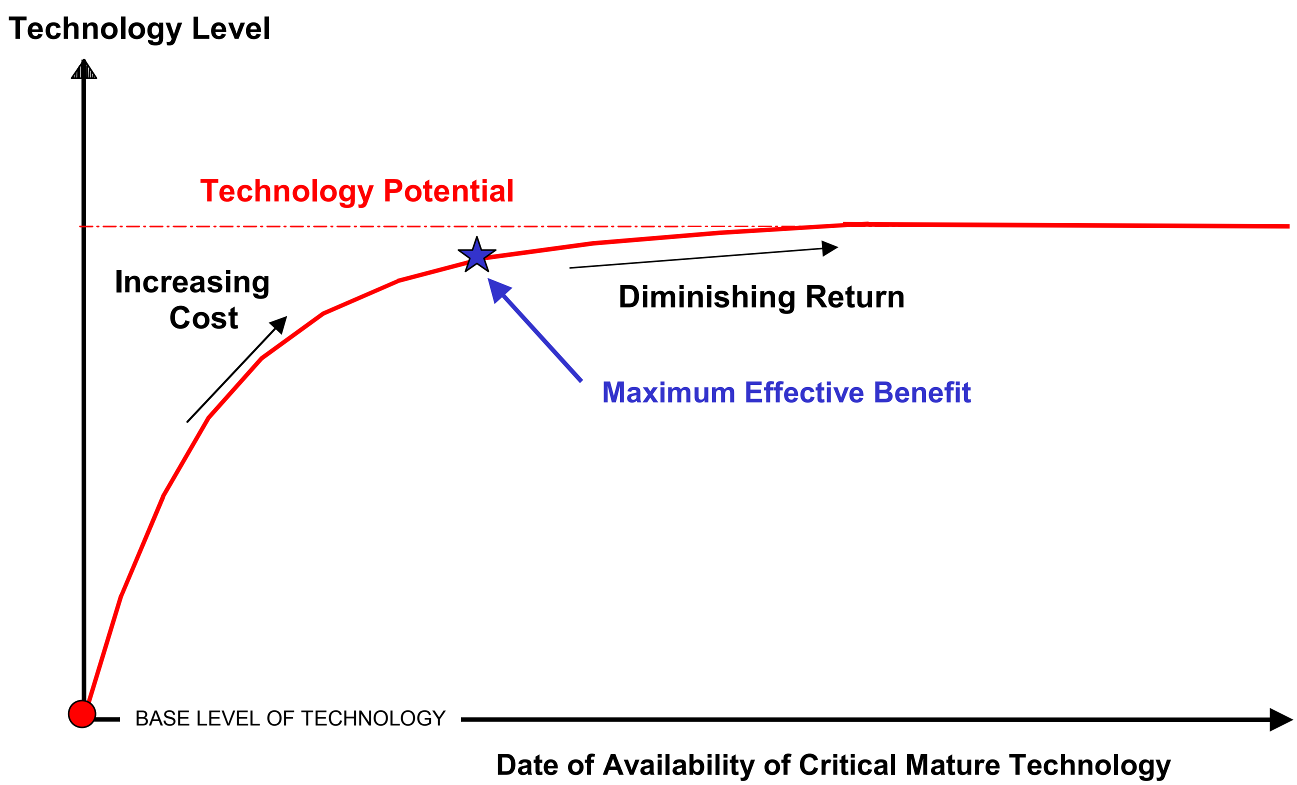
In a competitive commercial market environment, the size of the captured market share for a manufacturer, is usually highly dependent on two factors:

- the goodness of the airplane relative to the customer's needs
- the date of availability of the new airplane

The relationship is shown conceptually above. Note that there is a region where no sales are possible, if the product does not meet the minimum goodness levels or is available too late. The required "goodness Levels" and delivery date are both set by the airlines requirements.

A key factor in defining the "goodness" of an airplane is often the critical technology level in the airplane necessary to meet the customers needs.

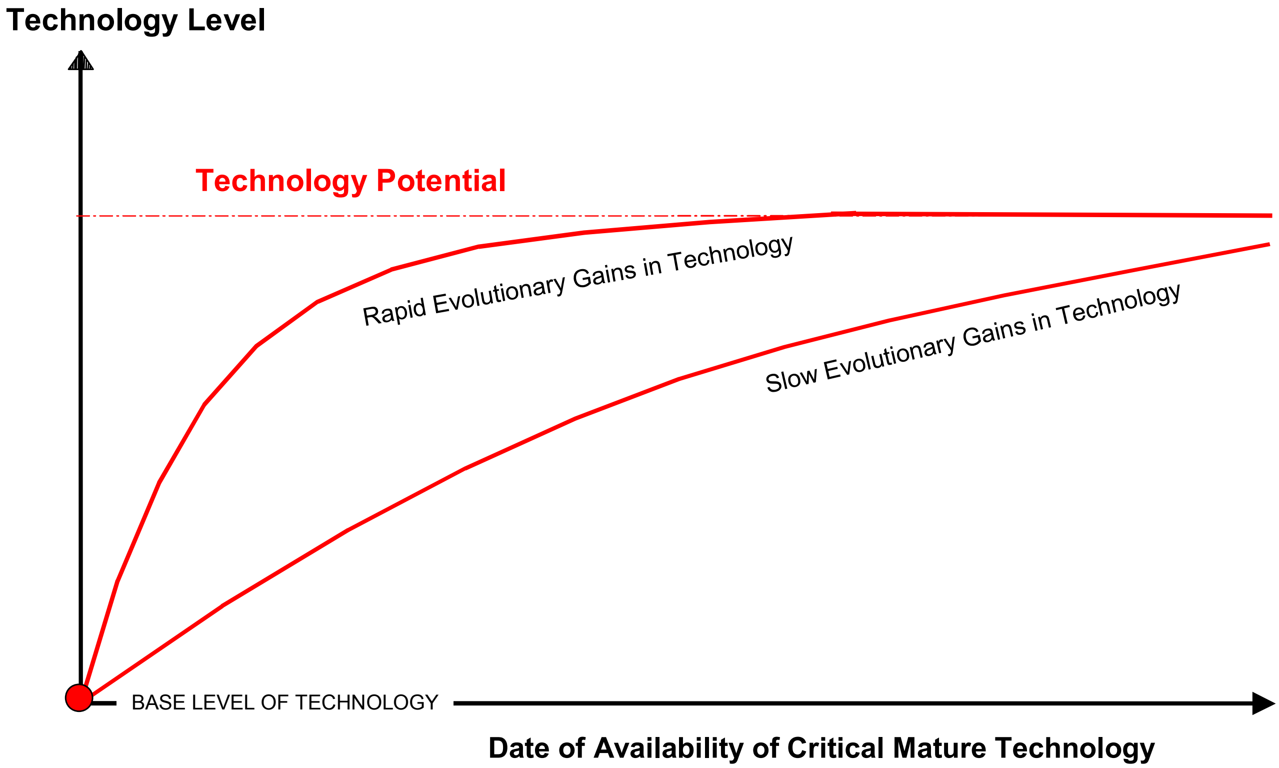
Evolutionary Technology Development



The evolutionary development of the critical technology level is shown conceptually in the figure above. Initially, large gains in the technology maybe relatively easy to obtain. Ultimately a point of “Maximum Effective Benefit” is reached where additional technology gain comes at great cost and long development times.

A reliable technology projection is necessary to determine this maximum effective benefit in order to effectively utilize technology development funds, and to limit the ultimate development times.

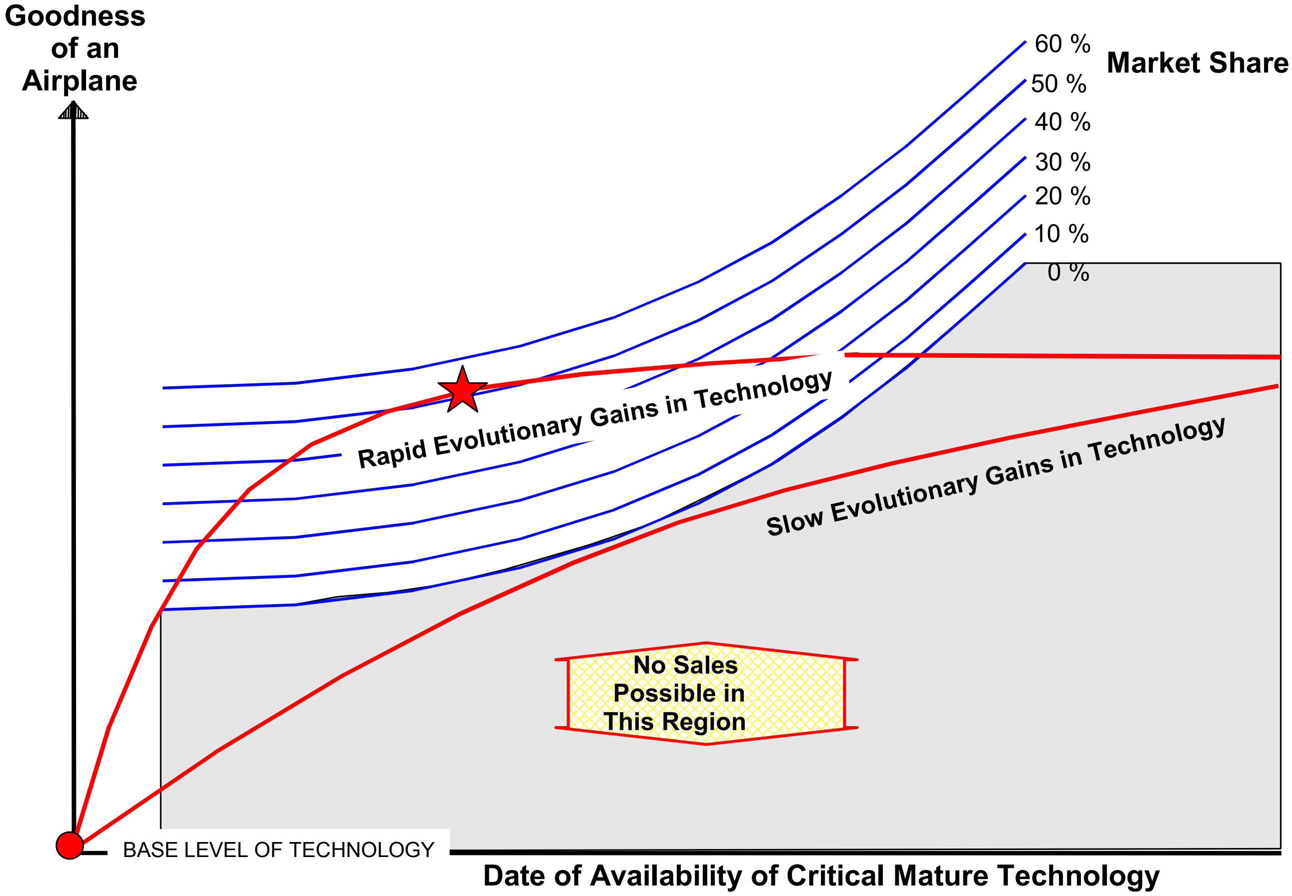
Evolutionary Technology Development Times



The rate of the evolutionary development of a technology is very dependent on the interest and focus of the development activity, as well as the level of funding dedicated to support the development process.

In some instances the technology gains may inherently require a long and tedious development process to bring the technology to the necessary degree of maturity for potential commercial airplane applications.

Effect of Evolutionary Technology Development Times



Proper Funding and the Rate of Technology Development Can Dramatically influence the Potential Market Share for a New Airplane.

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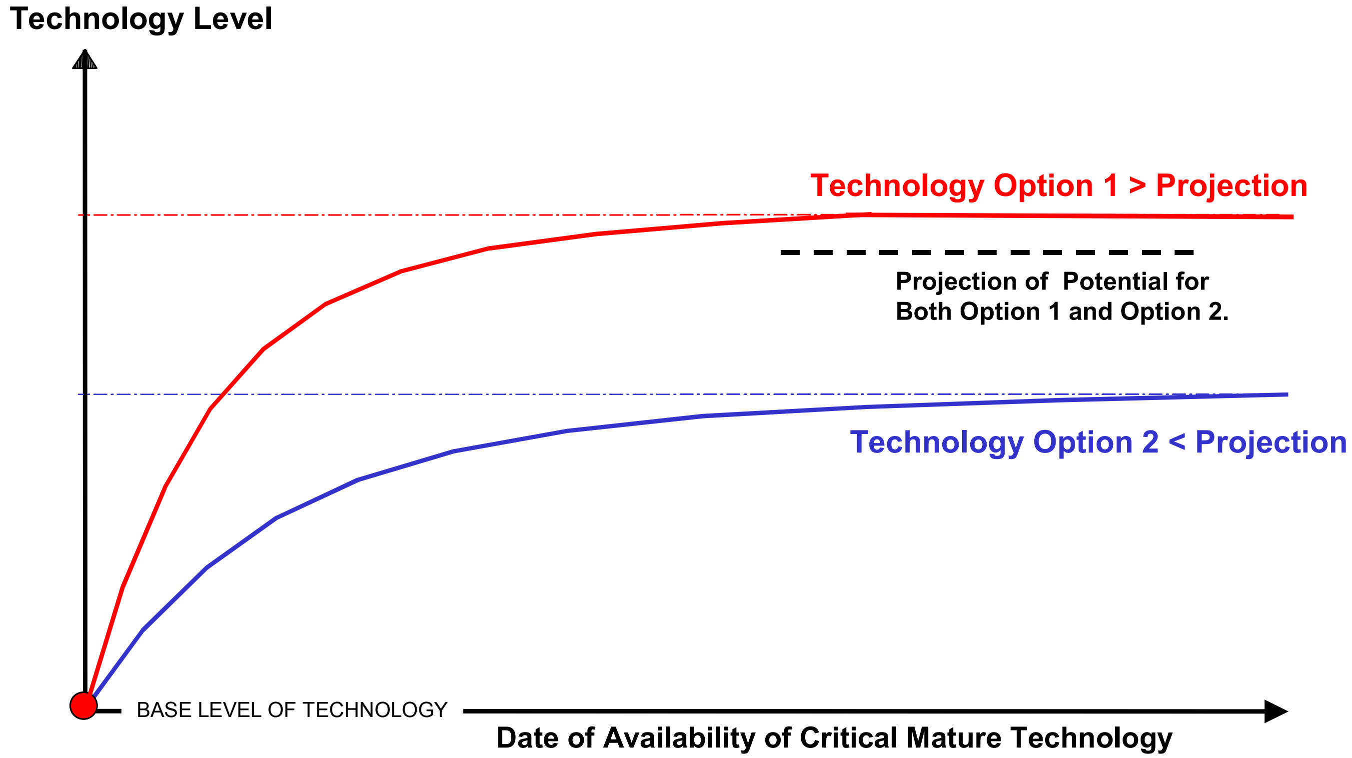
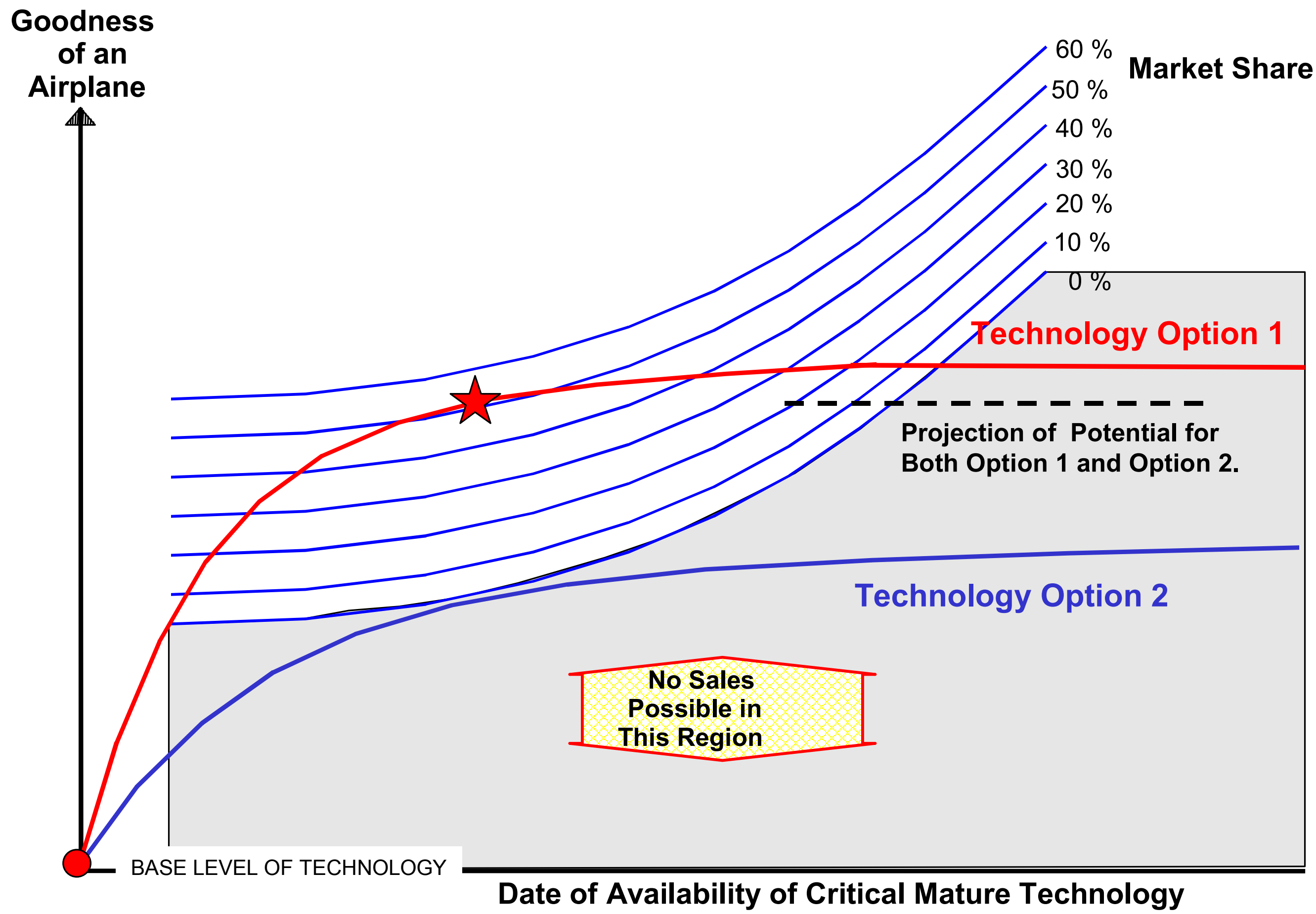
As shown in the figure above, the rate of development of a critical mature technology may determine whether or not it is possible to capture any share of a new airplane market with a certain level of technology.

Projection of Technology Potential



This illustrates the evolutionary growth potential for two technology options.
Typically the potential benefit for each technology is estimated and consequently has some degree of uncertainty. In this example it is assumed that the initial projections indicate equal potential for both technology options.
Technology option 1 ultimately exceeds the projected technology potential, where as technology option 2 falls short of the projection.



It is Important to Accurately Assess the Potential for Technology Improvement as Well as to Develop the Right " Technology

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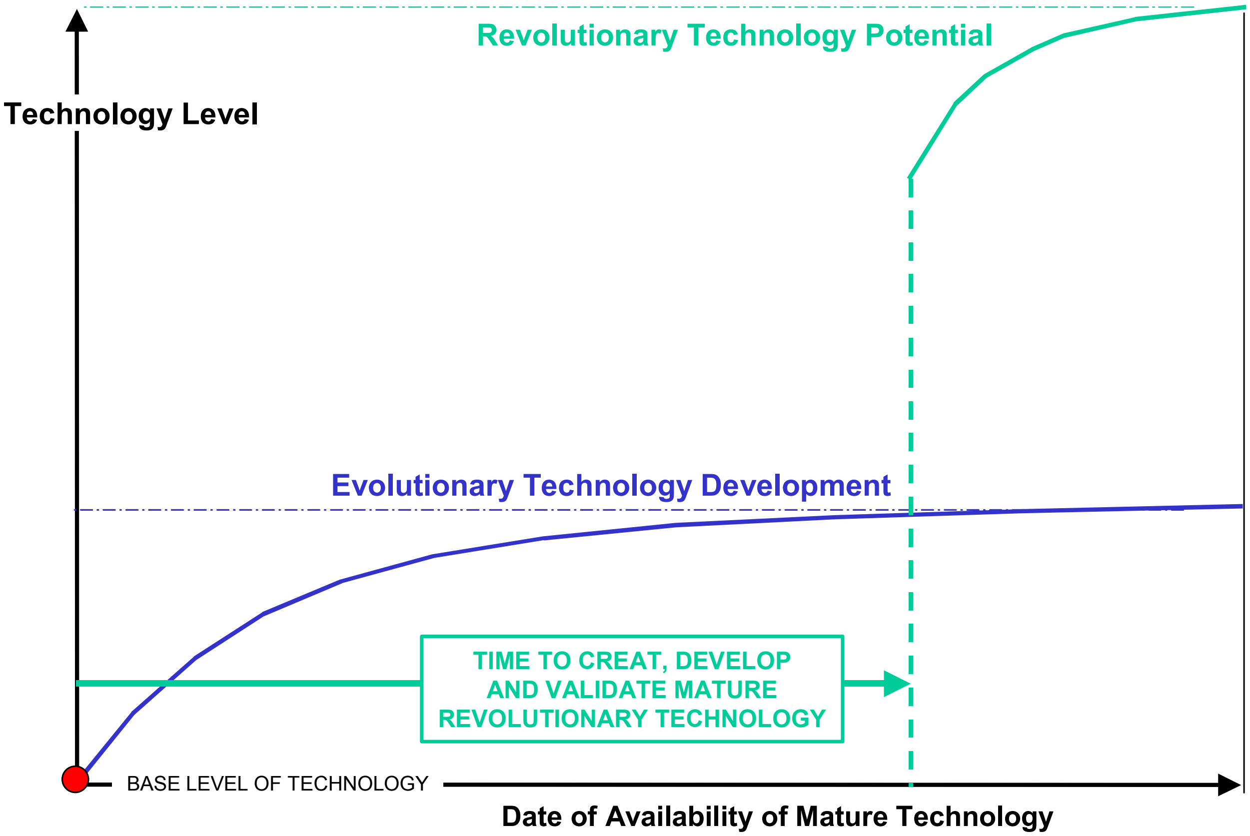
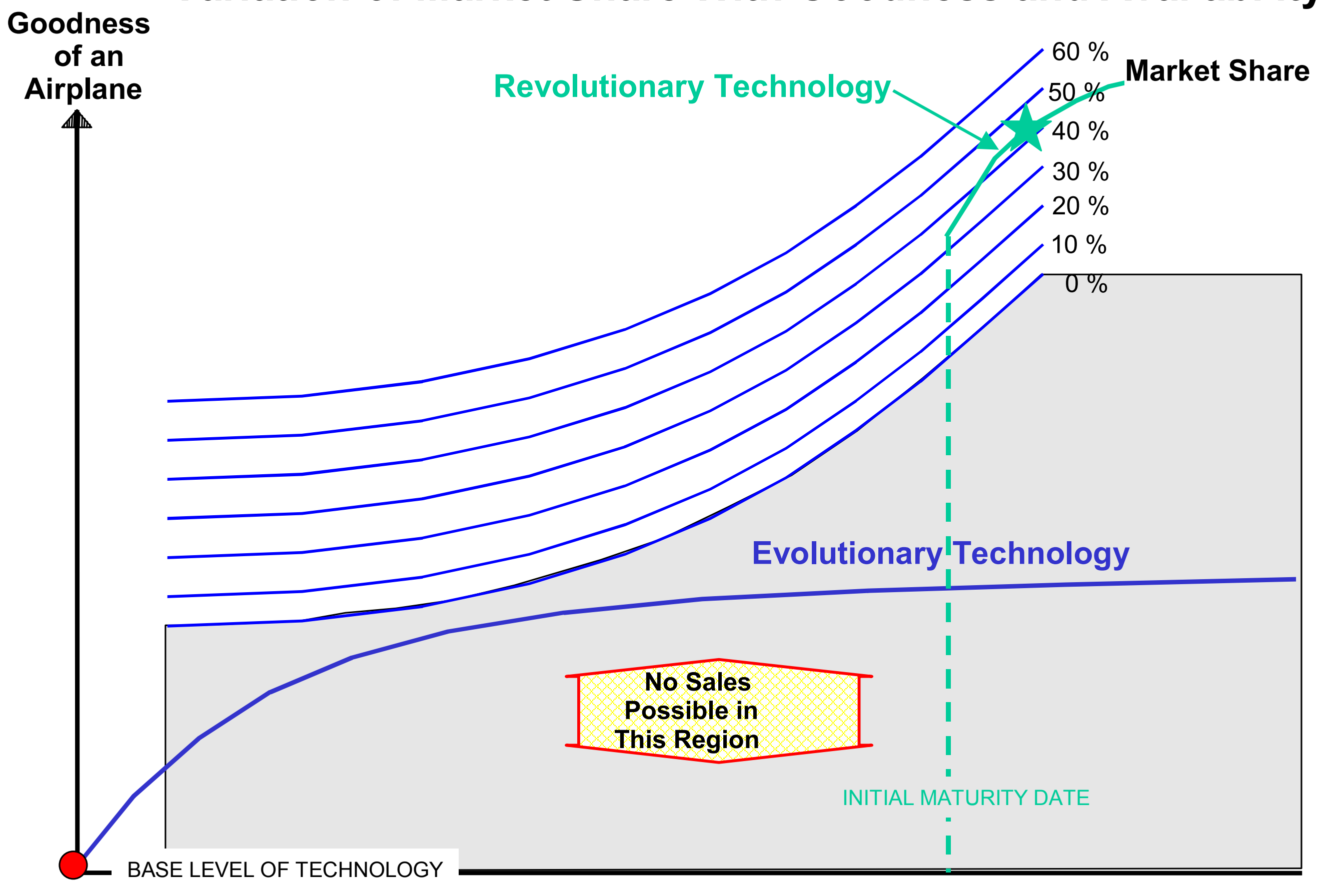
It is seen in the figure above that it can be vitally important to accurately assess the relative benefits and payoff for various new technology options. Since funding restrictions often will limit the number of technology development activities, the technology development program(s) with highest potential for successful gains typically need to be reliably identified.

Evolutionary vs Revolutionary Technology Development



This compares the general technology development trend for an evolutionary technology with that of a new revolutionary technology. Note that there is typically a very long time required to bring a revolutionary technology to the state of maturity necessary to allow application to a commercial aircraft. As previously mentioned, this may be on the order of 20 years.

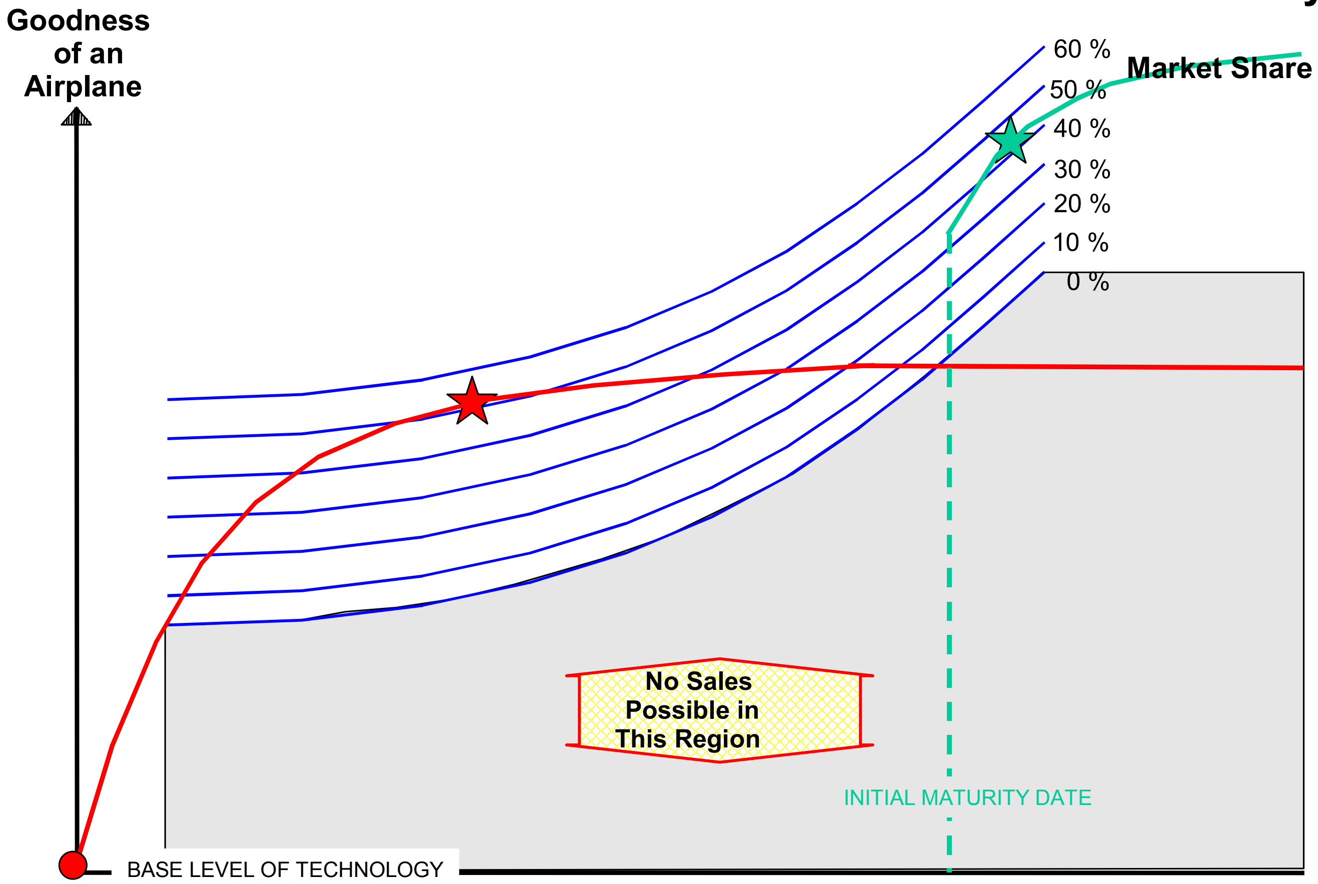
Variation of Market Share With Goodness and Availability Date



A Revolutionary Improvement in the Critical Technology May be Required. There is Typically A Long Time Required to Develop a Mature Technology

In this illustrated example, there indeed may be a requirement for an revolutionary technology advancement in order to meet the market needs.

Variation of Market Share With Goodness and Availability Date



Adequate Funding and Selection of the Appropriate Critical Technology May both be Required to Capture Any Share of a New Airplane Market.
**** The Best Technology Breakthrough May Not be the Best Technology ****

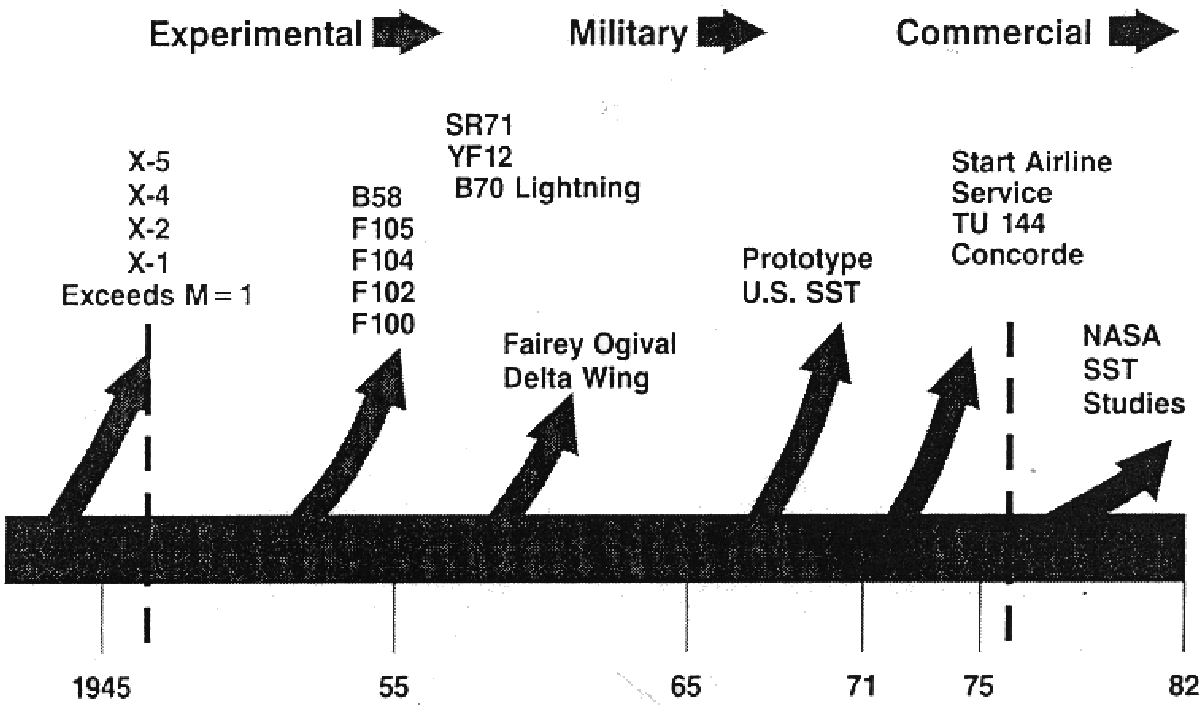
B.M. Kulfan

This compares the impact of a significant evolutionary technology improvement with that for a major revolutionary technology advancement.

In this example, because of the long development time for the revolutionary technology, the development and utilization of the evolutionary technology would actually capture a larger market share for this particular application.

Of course, future aircraft configuration opportunities, beyond this example application, would indeed benefit from the revolutionary technology.

Evolution of High-Speed Transport



There Has Been Limited Technology Transfer From Military to Commercial Supersonic Airplane Programs Because of the Widely Different Design Objectives and Criteria

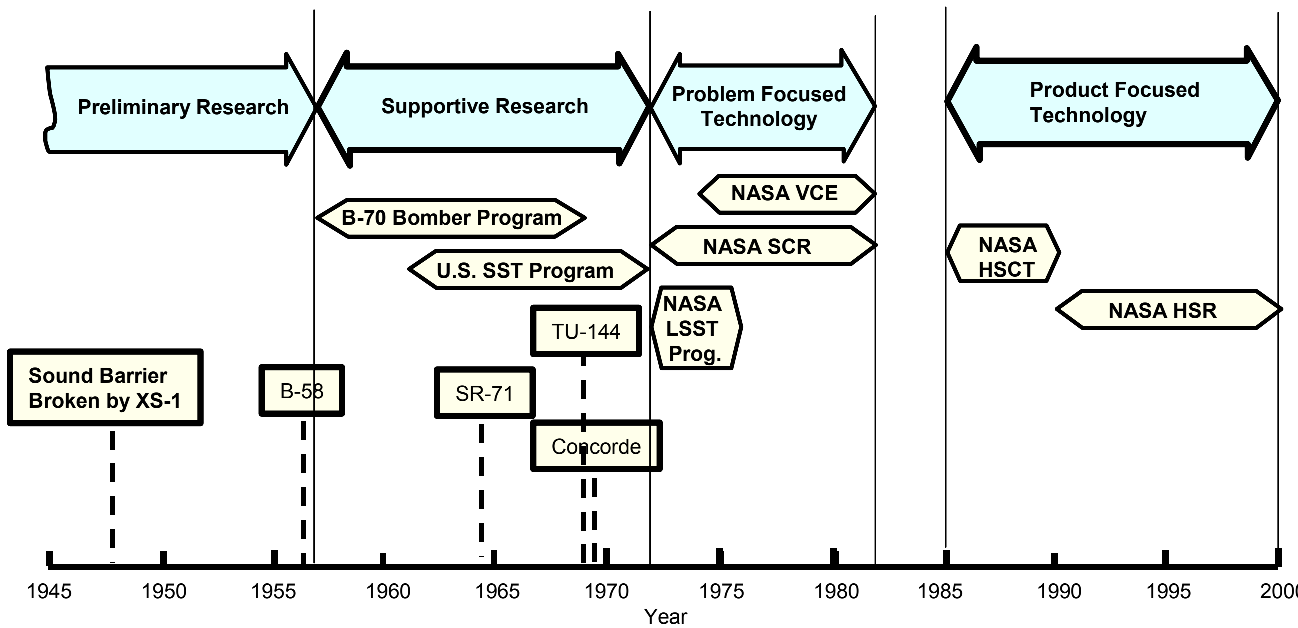
Supersonic flight capability started in the late 1940s with the Bell XS-1 when Mach 1 was first exceeded. The basic high speed research programs were followed by military programs such as the F104, F-105, B-70, and SR-71.

Experience from these military programs formed the basis for the start of the prototype US SST.
Often military fore runners have been essential to advanced commercial undertakings. The military design requirements for a supersonic aircraft, however, are vastly different then those for a commercial supersonic transport.

Economic and performance considerations such as price, profitability, and risk are different between the commercial arena and the military arena. Mission requirements, including range, equipment , passenger provisions are different. Operational requirements such as airport and community noise considerations, utilization, and airport compatibility are also drastically different. Design requirements are different. Long heat soak time, operational life, reliability, safety, maintainability goals, and growth considerations are also different.

The impact of a commercial supersonic transport on the ozone layer and the effects of sonic boom are significant considerations for commercial operation.
Consequently the enormous burden of developing the necessary technology has been shared primarily by NASA and the aviation industry.

Phases of NACA/NASA Research on Supersonic Cruise Technology



A substantial portion of the NACA/NASA aeronautical research has been devoted to the considerations of problems associated with manned flight at supersonic speeds. The purpose of this research was to develop a technology base that would permit the military services and the aerospace industry of the United States to take full advantage of the recognized potential of High-speed flight.

The NACA/NASA program to provide a continuously viable supersonic technology base has evolved through four distinct phases.

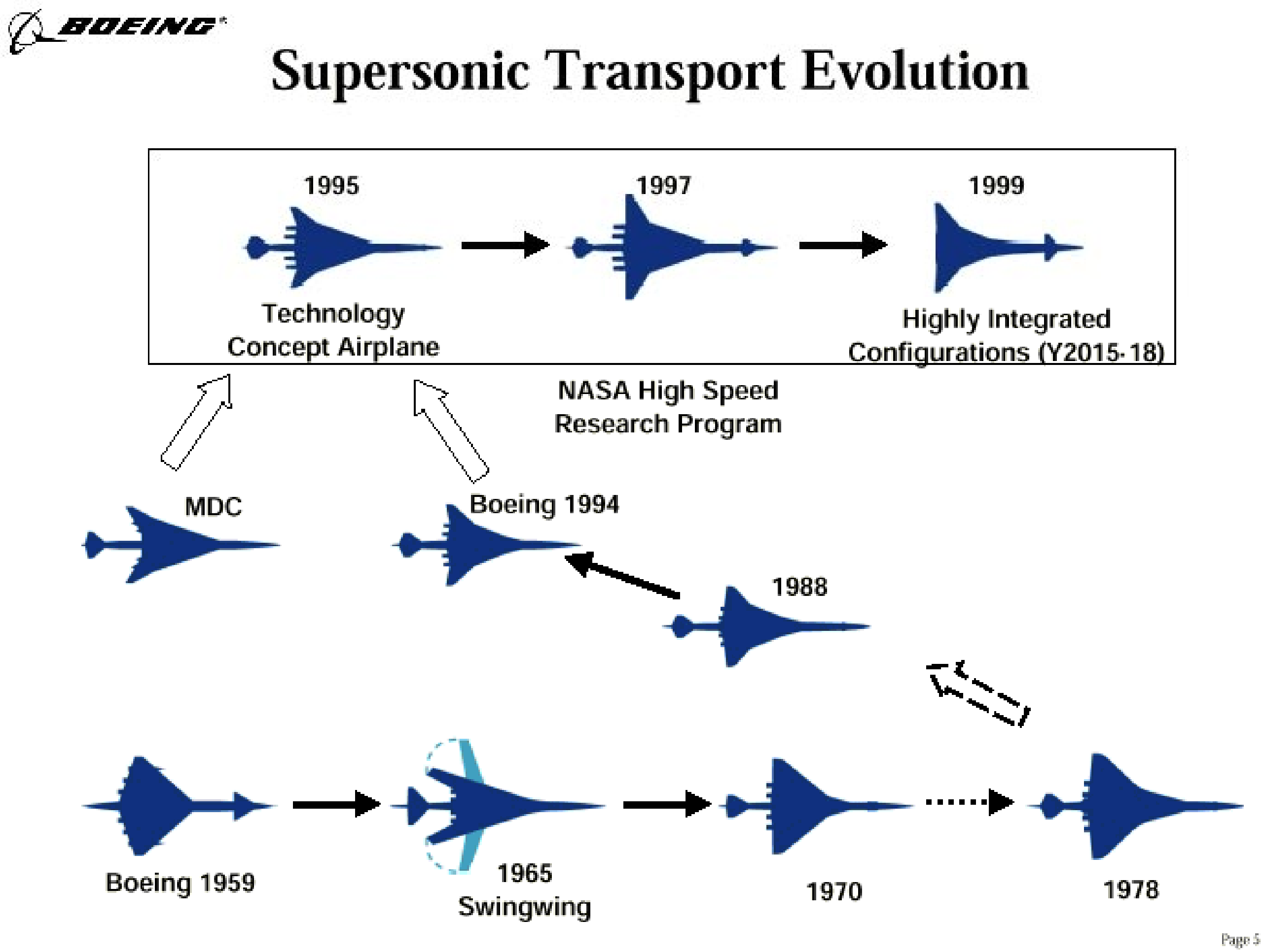
The initial phase was the preliminary research effort that started in the mid-1930s during the NACA era. In this phase, NACA developed the facilities and experimental tools for the study of supersonic related problems and helped to prove the feasibility of supersonic flight.This technology base was used to help the development of the B-58 Dash bomber, the century series of fighters, and the SR-71 supersonic reconnaissance airplane. All of these had relatively short supersonic flight capability.

The second phase started in 1958 slightly before the formation of NASA and lasted till 1971. NASA's principal task in this era was to conduct specific research in support America's effort to develop a supersonic cruise bomber (B-70), and a commercial supersonic transport, US SST.

Following the cancellations of the B-70 and US SST programs, the research efforts were directed at the solution of specific technical problems. During this period, NASA also funded an effort by the Boeing Company to study the feasibility of commercial boom-free low-supersonic flight. During this activity , the variable sweep oblique wing concept was studied in some depth.

The fourth phase started in about 1990 and has lasted through 2000.. The coordinated NASA research, and NASA funded Industry research, and industry funded research were focused on developing the technologies to assess the feasibility of economically viable, technically feasible and environmentally acceptable commercial supersonic flight, and to provide the technology base for developing an American commercial high speed transport.

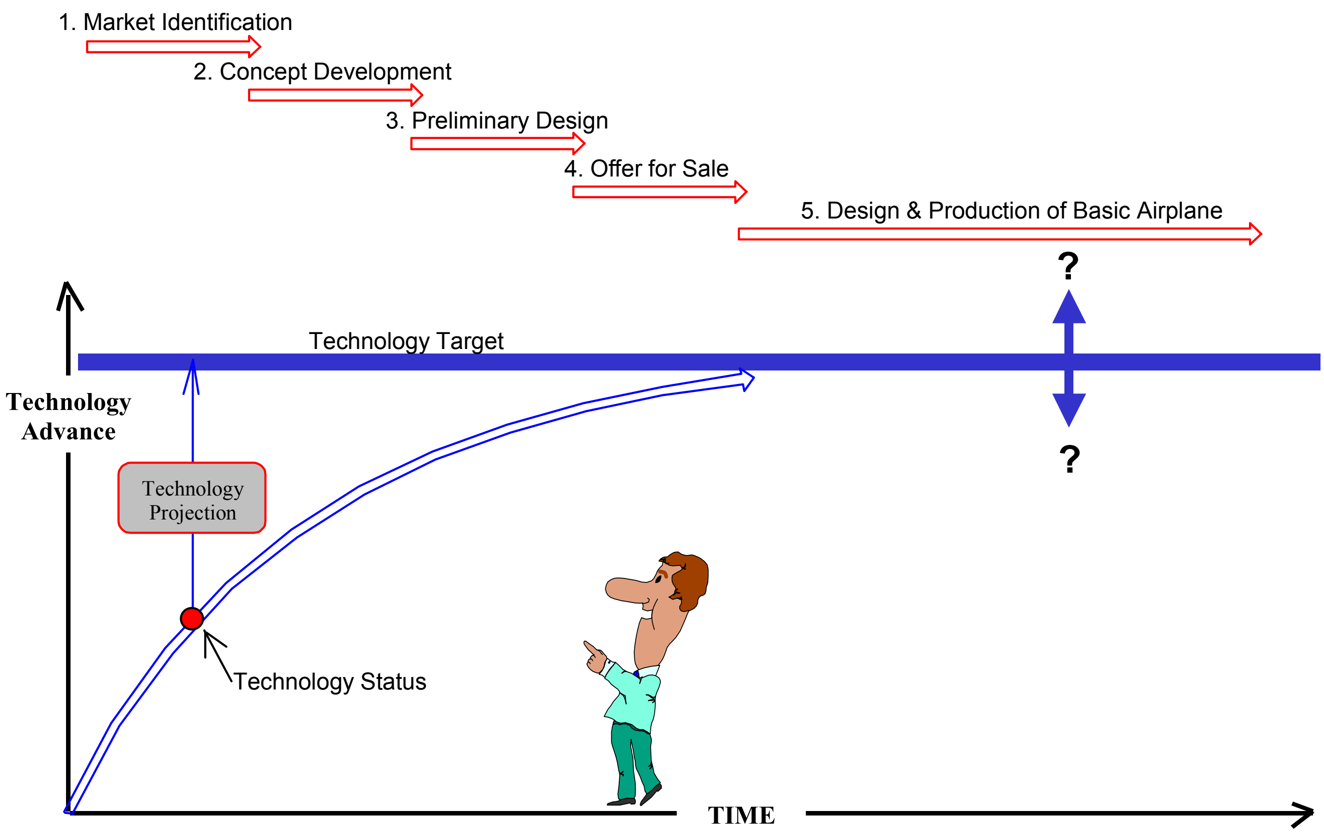
Through each of the NASA research phases , significant technology advancements were made in many fronts.



This shows the evolution of the current HSCT concepts from an early Boeing configuration in 1959. This concept, itself, evolved from prior NASA research "SCAT" configurations. It is seen that the evolution of the current supersonic aircraft configuration involved a process of both "Revolutionary" and "Evolutionary" technology and aircraft concepts developments.

HSCT DEVELOPMENT STRATEGY

Technology Development Proceeds in Parallel With Design Development



In a typical new subsonic commercial aircraft program, the existing advanced technology forms the base for typical development process that includes: Market Identification, Concept Development, Preliminary Design, Offer for Sale, and the Design and Development of the Basic Airplane.
Contrary to a new subsonic aircraft program, a High Speed Civil Transport development can not be built totally utilizing an existing technology base. Consequently a different development strategy has been used.

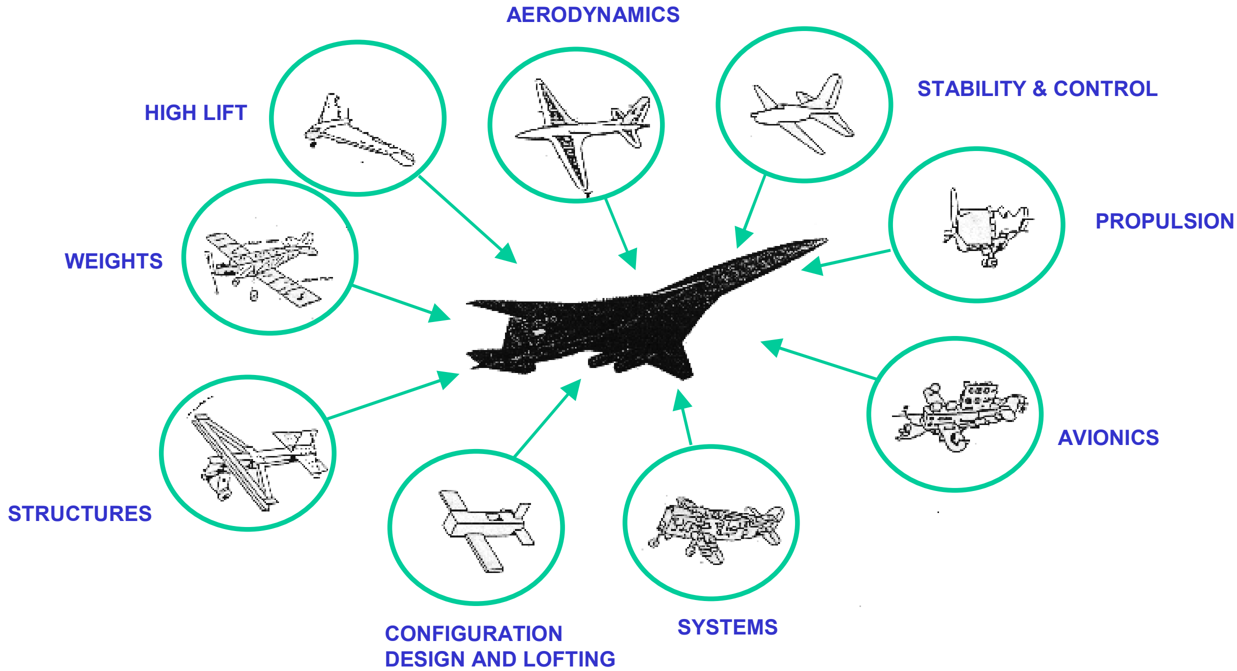
Technology projections have been made by all of the technical disciplines to assess what the technology would be available if supported by appropriate research and development programs over a specified time period.

These technology projections were then used in configuration studies to assess the viability of a supersonic commercial aircraft and to define the nature and priority of the necessary technology programs. As long as the HSCT appears to be viable, then funding could be justified to support the required technology development.

The technology development activities were then focused on meeting the projections and if necessary updating the projections. The need to appear viable was essential to allow the continuing technology activities.

The ultimate goal with this strategy was to provide the necessary technology base for the design and production of a viable new airplane by the offering for sale time period.

MULTI-DISCIPLINE AIRCRAFT DESIGN

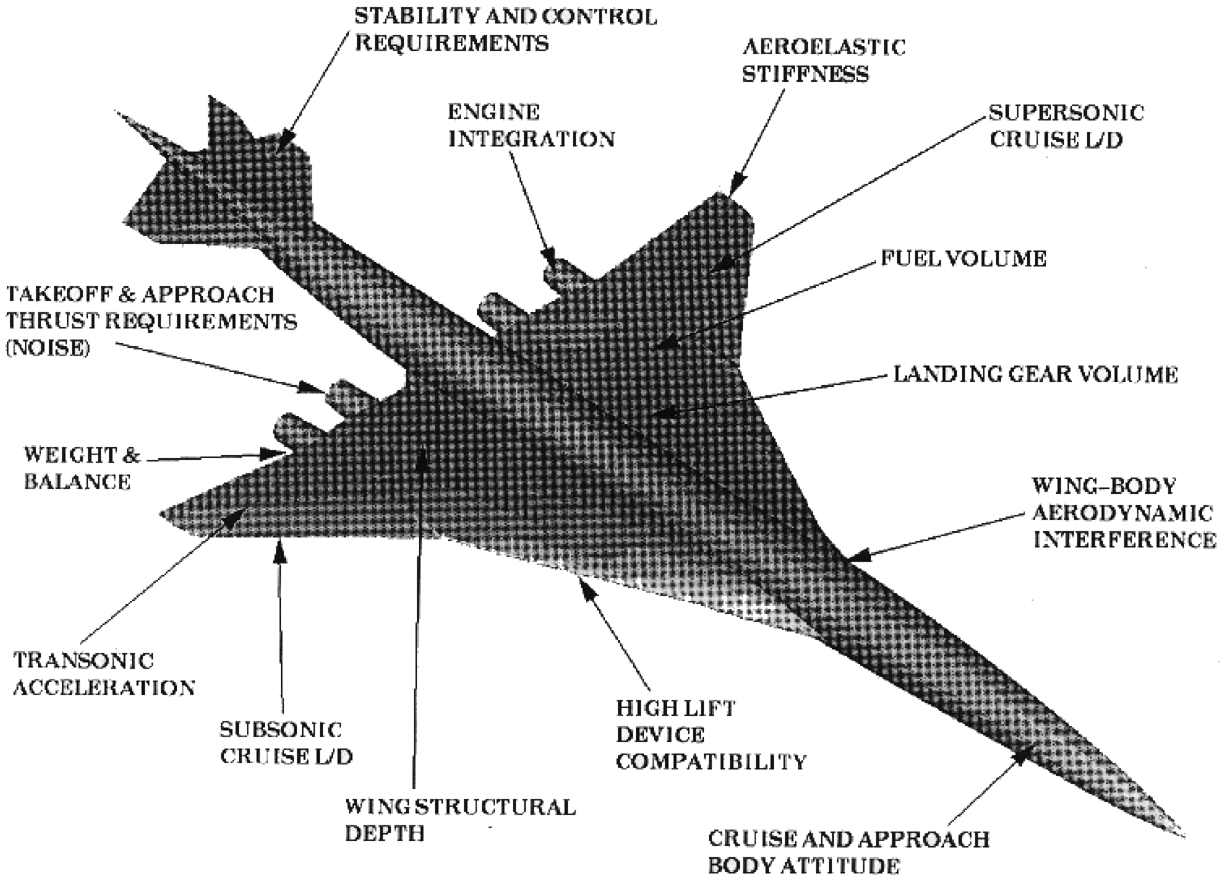


DESIGN: TEAM OF EXPERTS WITH IDEAS AND EFFORTS TOWARDS A COMMON GOAL.

The HSCT, as in any airplane development program multi-disciplinary design optimization and integration . The design team is made of a team of experts with ideas and efforts directed towards a common goal.

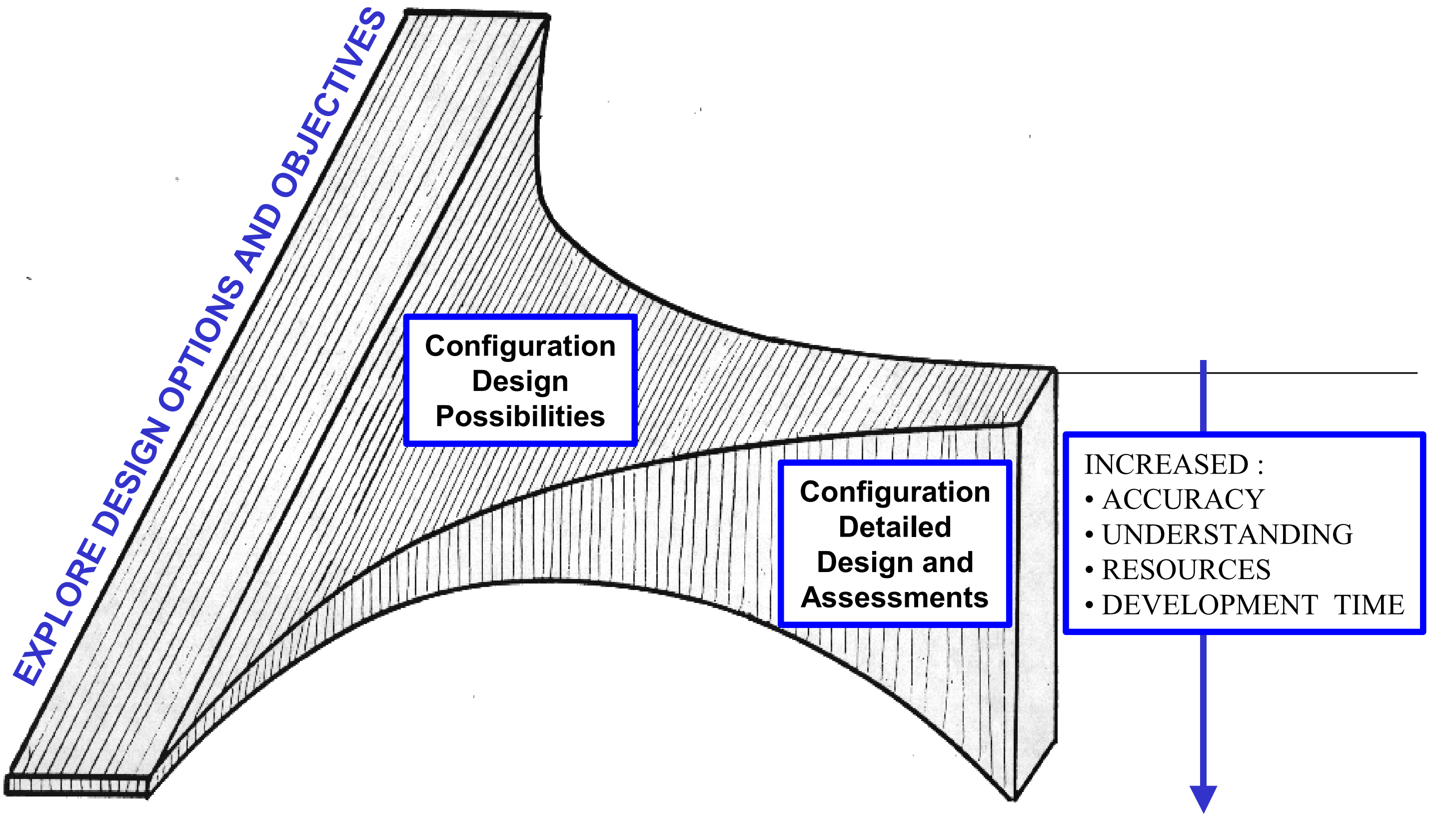
This requires many trade and benefits studies and trades since the visions of the "perfect" airplane are often different for the team members. An essential ingredient for a successful program is to identify the most critical technology options from all of the various technical disciplines.

FACTORS INFLUENCING PLANFORM SELECTION



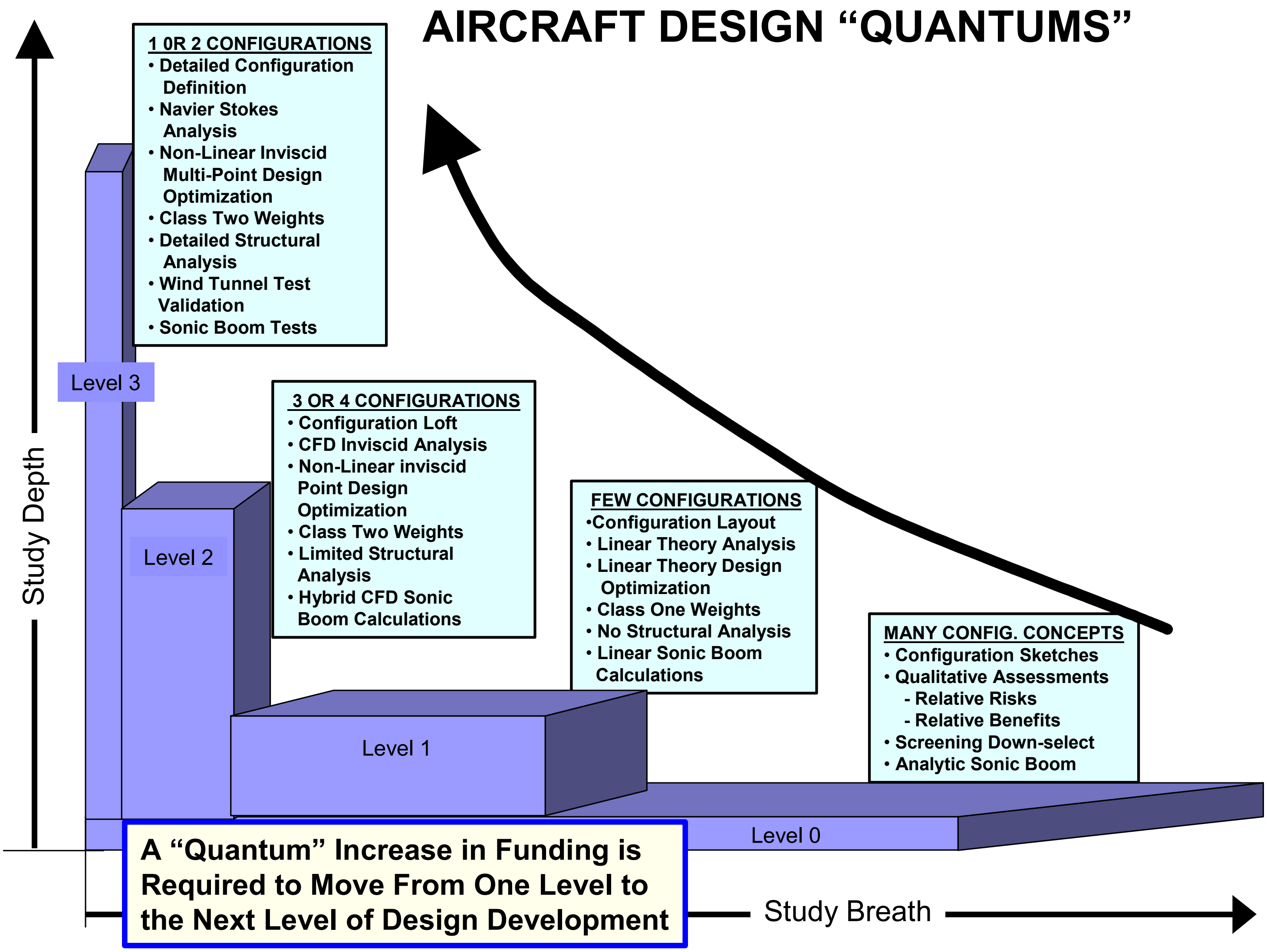
This figure illustrates many of the design features for a typical HSCT. The definition of each of these design features involves design trade studies involving aerodynamics, structures and weight considerations, propulsion system, and systems design and along with relative benefits versus risk assessments.

TYPICAL INCREASED FOCUS DESIGN APPROACH



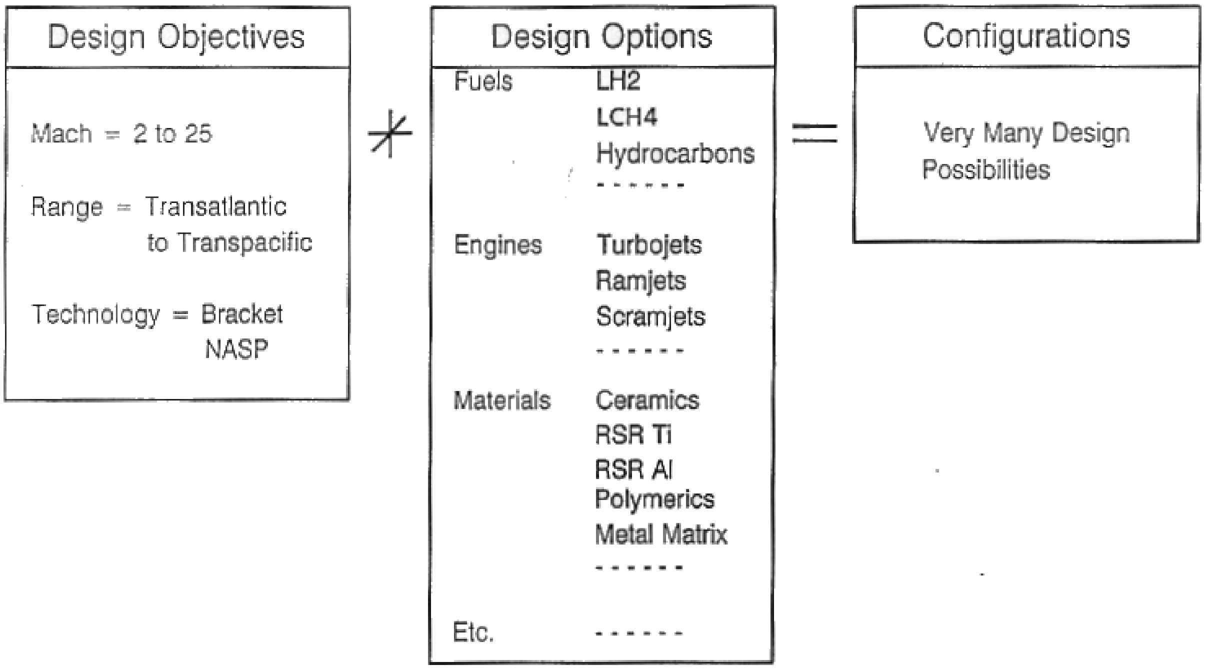
This conceptually illustrates the typical design development process to explore the design space for an advanced airplane concept.

The development efforts will initially scope or assess many different design options and objectives. The number of design possibilities is reduced as the design cycle progresses and the depths of the design development and assessments are dramatically increased.



In reality, the study will need to proceed by jumps to increasing levels of design depth. To move to a different level of design will require a minimum quantum increase in funding, other wise the lower level assessments and the quality of the answers are merely repeated.
This is very similar to trying to climb a flight of stairs. If one only puts in enough energy to raise the foot to half the height of the next stair, then it will be impossible to reach the next step no matter how often one tries.
The figure illustrates the typical changes in the design and analysis methods as a design proceeds from level to level.
For a new study with an extensive number of design options, a level 0 type of down select process may be conducted. Based on the initial design objectives, configurations sketches or simple layout drawings may be developed for a number of possible configuration, technology and design options.
A Systematic qualitative assessment process is then used to assess the relative benefits and risks for each concept. Based on the ordering of the combined assessments, the design space is reduced to focus on the most likely to succeed options.
Level 1 and above, will start the detailed design development process in increasing depth as the number of configuration options is further reduced and the degree of sophistication of the design and analyses methods increase.
This is the process that was used in the initial Boeing / NASA HSCT study.

INITIAL NASA / INDUSTRY HSCT STUDY



An example of the quantum design approach, is the initial NASA funded HSCT study initiated in 1985.

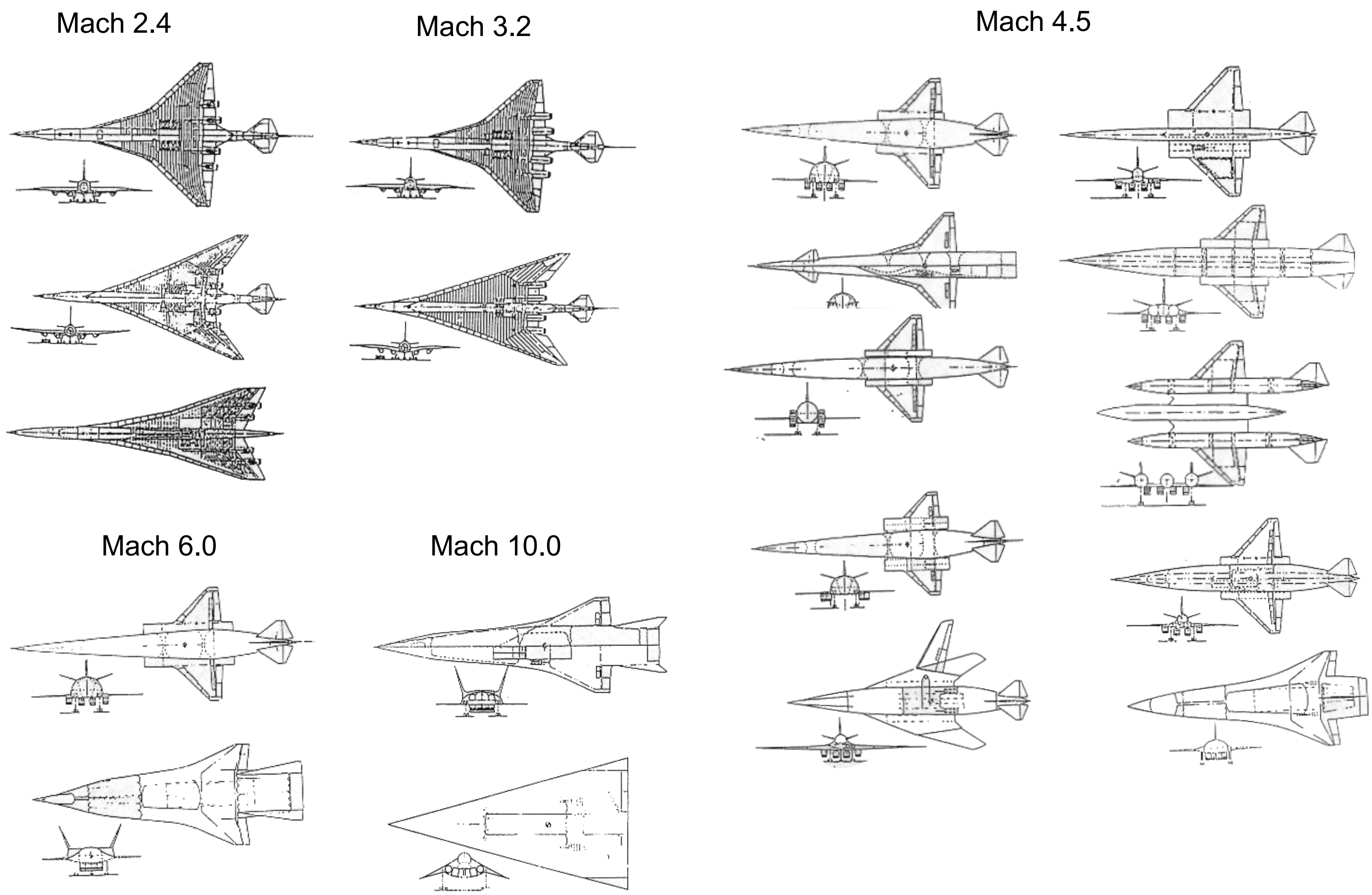
At that time it was envisioned an anticipated technology spin off from the National Aerospace Plane, NASP, would provide a technology base to greatly open up the possibilities for a High Speed Civil Transport.

The design objectives to be considered included:

- Design Mach from Mach 2 to 25
- Range requirements from transatlantic to transpacific
- Technology levels before and after a successful “NASP” program

There were identified many conventional and innovative design options for each discipline, depending on the design Mach number. This resulted in a nearly impossible number of design variations to be considered.

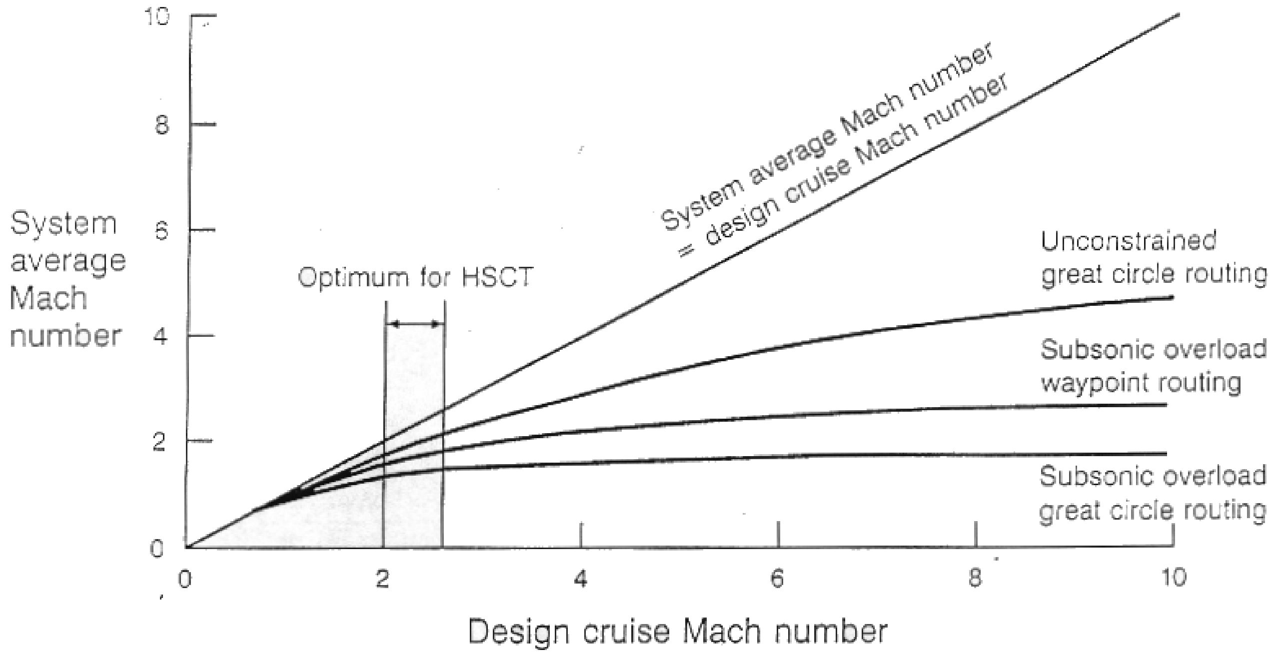
NASA / Boeing Initial HSCT Study Phase 1 Configurations



The design mach number space was reduced to a five specific Mach numbers corresponding to natural limits of various technology and design options.

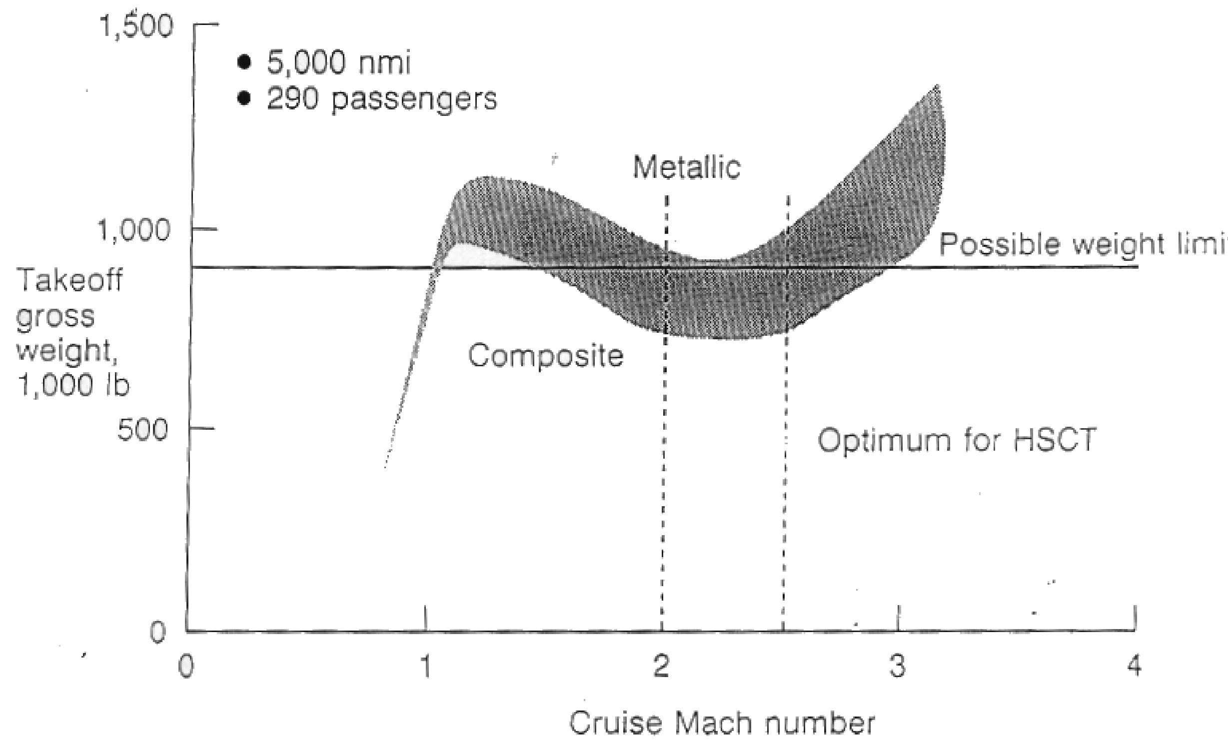
Configuration concepts were developed for each design Mach number regime. As shown above, many innovative or revolutionary concepts and technologies were considered.

Effect of Increasing Cruise Mach Number on the System Average Mach Number



The results of the initial level one studies clearly identified the most appropriate design Mach number range. Further more it can be seen that operational limits and constraints indicated that little system average Mach number is gained for flying much above Mach 2 to 2.5.

Effect of Cruise Mach Number on Maximum Takeoff Weight



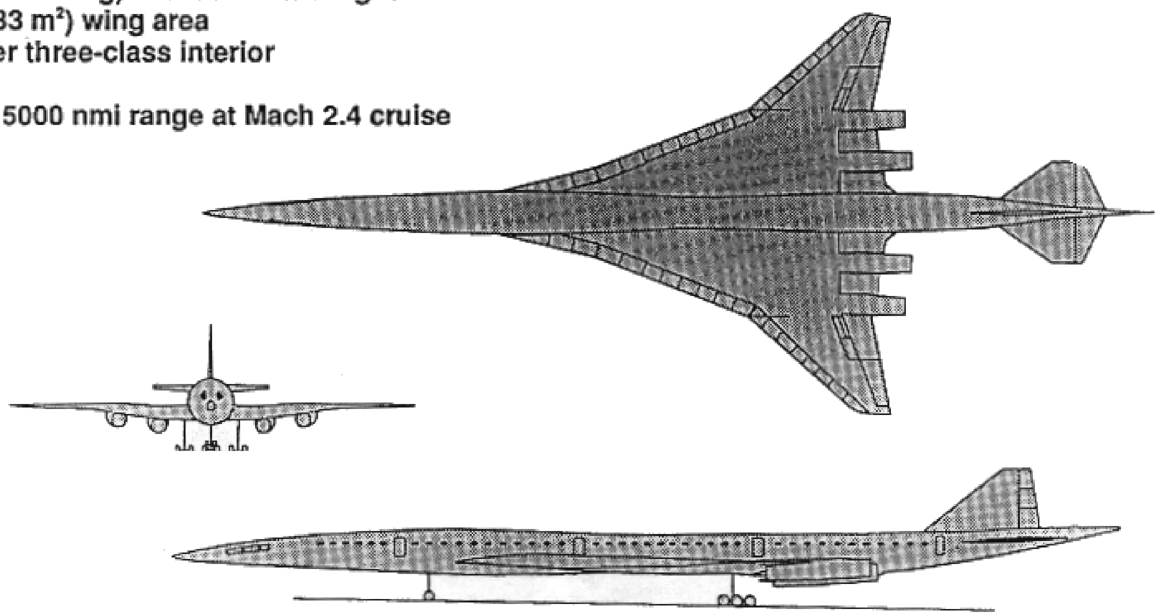
The next level of the study then reexamined the Mach number range between Mach 2 and Mach 3. Again a number of innovative configurations were developed and assessed in increasing depth.

The results as shown above, indicate that the most desirable option for a viable HSCT is a Mach 2 to Mach 2.5 composite airplane.

1992 Baseline Configuration

720 000 lb (326 592 kg) max. takeoff weight
7700 ft^2 (715.33 m^2) wing area
309 passenger three-class interior

Designed for 5000 nmi range at Mach 2.4 cruise

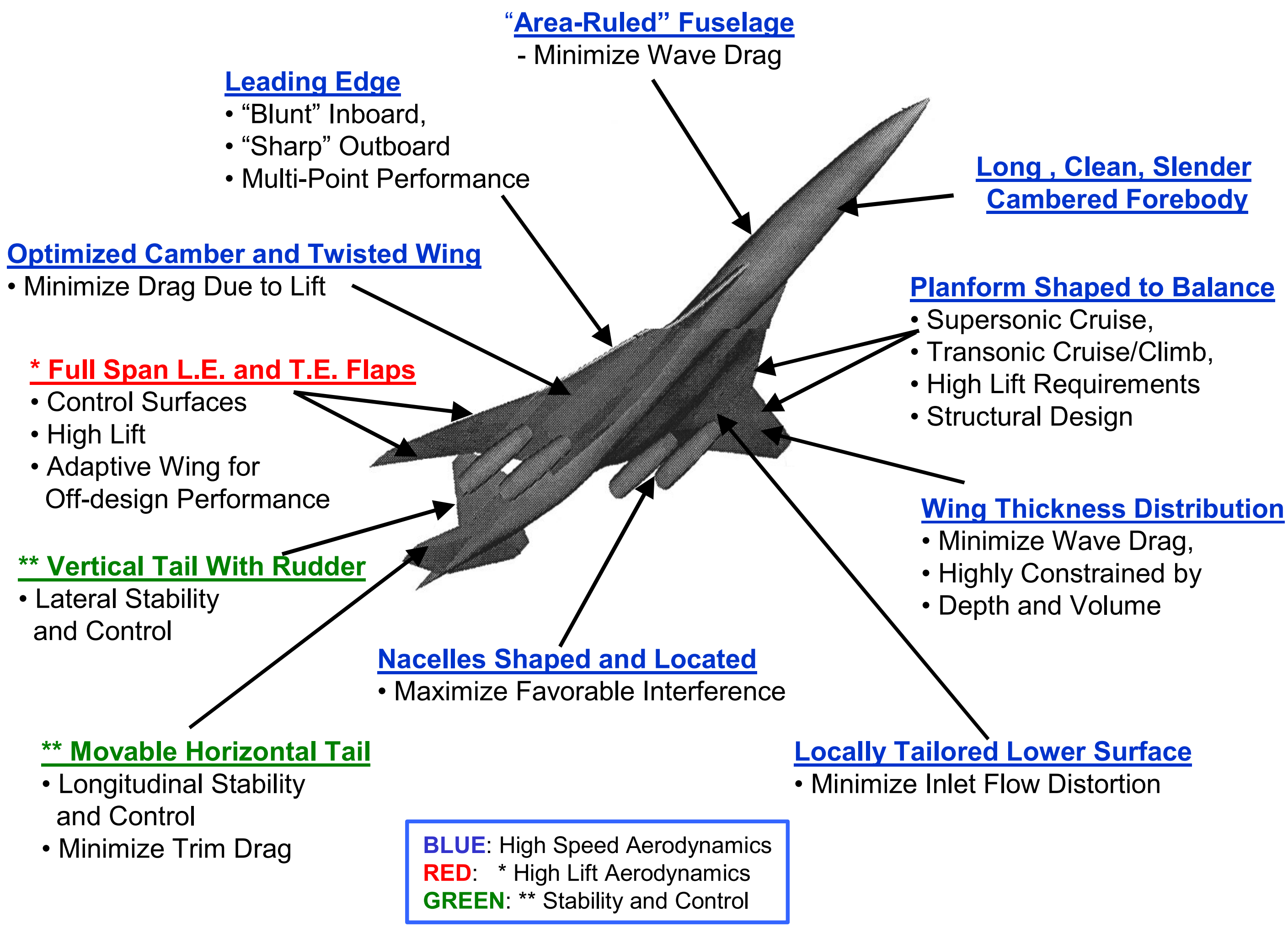


Through out all of the Commercial Supersonic Transport Development Studies, Many Different and Often Radial Concepts Have Been Considered. Generally all Studies Have Lead to Relatively Simple Configurations With Highly Innovative Components.

Increasing the depth of the studies and decreasing the range of design options ultimately lead to the 1992 HSCT baseline Configuration. This is in reality a rather conventional looking concept that has many highly innovative design components.

Through out all of the commercial supersonic transport development studies, many different and often radically concepts have been considered. Generally, all of the studies have lead to relatively simple airplane concepts with highly innovative components.

Aerodynamic Design Features of a High Speed Civil Transport



This Illustrates the general aerodynamic features of a typical supersonic transport configuration.
The wing planform shape is specified to provide a balance between the supersonic cruise, transonic cruise/climb and high lift conditions. The wing leading edge is blunt inboard and sharp outboard to control the nature of the flow on the wing and to maximize the overall performance. The wing has optimized camber and twist to reduce the supersonic cruise wave drag due to lift and induced drag. The wing thickness distribution is usually highly constrained by wing volume and localized depth requirements and designed to minimize the volume wave drag within the constraints.
Full span wing leading and trailing edges provide an "adaptive' wing geometry for control, to minimize off -design drag and to maximize high lift performance.

The fuselage is generally long and slender, cambered and "area ruled" for minimize supersonic cruise wave drag and trim considerations.
The nacelles are located aft under the wing and positioned and shaped to minimize wave drag and maximize favorable interference effects. The local wing surface in front of the inlets is tailored to provide acceptable inlet flow distortion.

The vertical tail is thin , swept for low wave drag and has a rudder for control purposes. The movable horizontal tail provides longitudinal control and low trim drag.
The primary aerodynamic factor affecting the features of the airplane is the consideration of the high speed cruise performance.

Impact of Aerodynamic Drag on an HSCT

1 % Improvement in (L/D)max at Mach ~ 2.4:

- **~ 1 Drag Count (CD = 0.0001)**
- **Reduces Airplane Gross Weight by 10,000 Pounds**
- **Saves 7,500 Pounds of Fuel**
- **Is Equivalent to a 2,000 Pound Reduction in Structural Weight**

Subsonic Drag Impact:

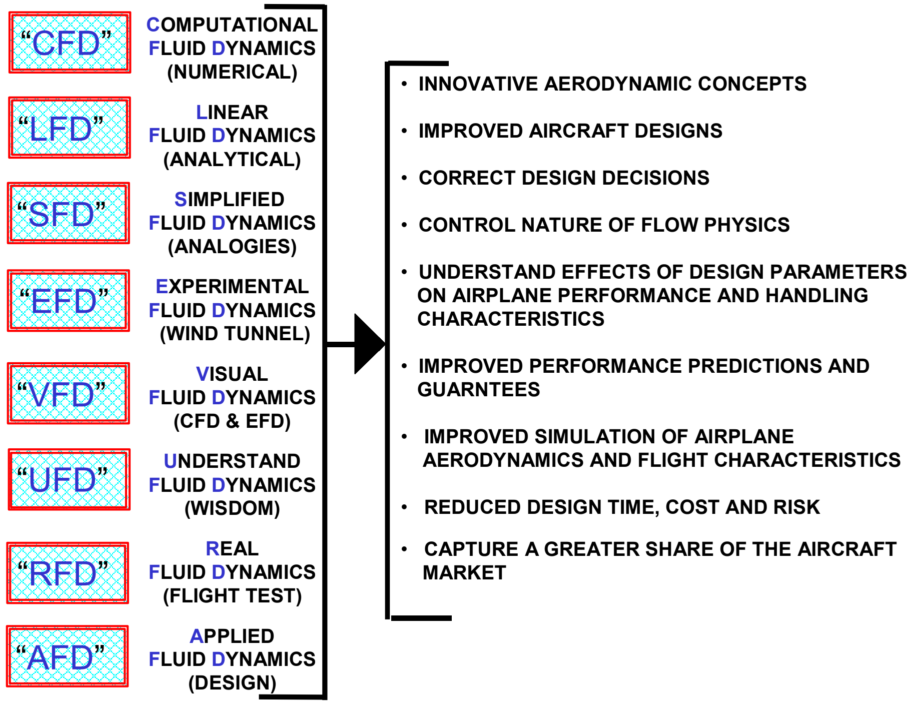
- **4 Counts Drag at Mach 0.90 to 0.95 ~ 1 Count drag At Mach ~2.4**

Reductions in the cruise drag of an HSCT configuration through design improvements has a highly leveraged effect on the size and performance of an HSCT.

An improvement in supersonic drag of 1% , which is approximately 1 drag count, (DCD ~ 0.0001), will result in a reduction of approximately 10,000 lb. for the Maximum Takeoff Gross Weight, MTOW. This also results in a fuel saving of about 7,500 lb.
The net benefits are equivalent to reduction in the structural weight of approximately one ton.

A reduction four counts of drag at the subsonic overland cruise Mach number of 0.95, has approximately the same effect of one count drag reduction at cruise. There are however, more drag counts at the subsonic cruise Mach number because of the higher cruise lift coefficient and the associated higher drag due to lift level.

AERODYNAMIC DESIGN AND ANALYSIS TOOLS



The major technologies for aerodynamics include the tools shown above, that are used for the design and analysis activities.

The primary tools of the aerodynamist consist of:

CFD: "Computational Fluid Dynamic" design and analysis methods that are able to capture the details of the flow physics.

LFD: "Linear Fluid Dynamics" Design and analysis methods based on Linear theory. These tools are very useful for preliminary design and trade studies and still are an important of the non-linear design processes. The analytical equations and the concept of superposition provide a direct understanding of many of the supersonic design concepts and flow phenomena

SFD "Simplified Fluid Dynamics" are methods that are based on simple flow analogies and concepts that provide rather accurate assessments of the flow characteristics as well as a fundamental understanding of the flow phenomena. Some examples include Whitham's Theory for sonic boom calculations, Polhamus suction analogy for vortex flow on sharp edge slender wings, and the T* method for compressible flow skin.

EFD: "Experimental Fluid Dynamics" which includes the wind tunnel test facilities and testing techniques.

VFD: "Visual Fluid Dynamics" obtained either by specialized wind tunnel test techniques of detailed CFD viscous flow calculations can provide great insight into the nature of complicated flow phenomena.

UFD: "Understanding Fluid Dynamics" which is perhaps the most important tool of all. All of the other "tools" involve tools and methods. This tools is the power of wisdom that includes knowledge of fundamental flow physics, the characteristics of a good design and appropriate design guidelines and criteria.

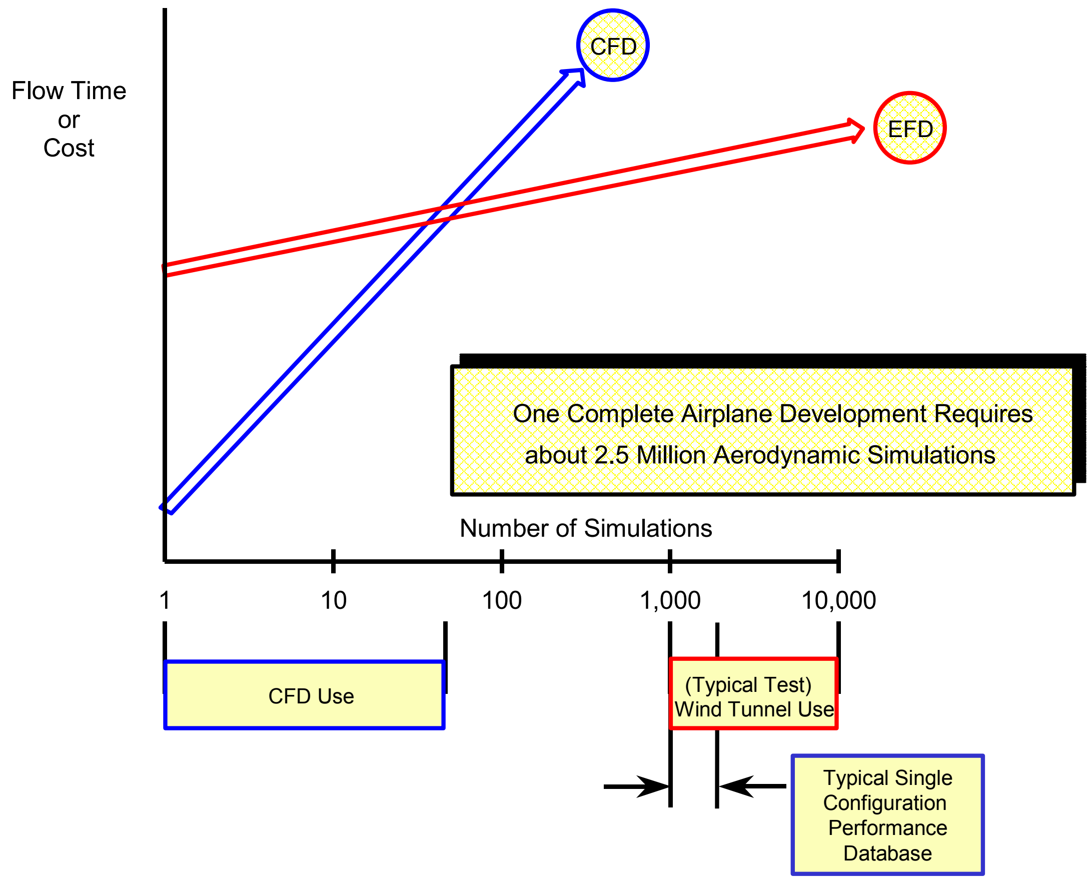
RFD: "Real Fluid Dynamics" or flight testing programs which are the ultimate verification of our aircraft designs and performance capability.

AFD: "Applied Fluid Dynamics" utilizing all the aerodynamic tools to develop efficient aerodynamic designs, and to conduct fundamental design studies to explore, to identify key design variables and design sensitivities, and to solve complicated flow physic problems .

Of all of these tools UFD, Understanding Fluid Dynamics, perhaps has the greatest impact on conceiving innovative concepts or solutions, as well as being able to adequately assess options and potential improvements.

Let us examine some of the needs for technology advancements in these tools, since these can have a major impact on the viability of an HSCT.

Cost and Flow Time Characteristics of Wind Tunnels and CFD

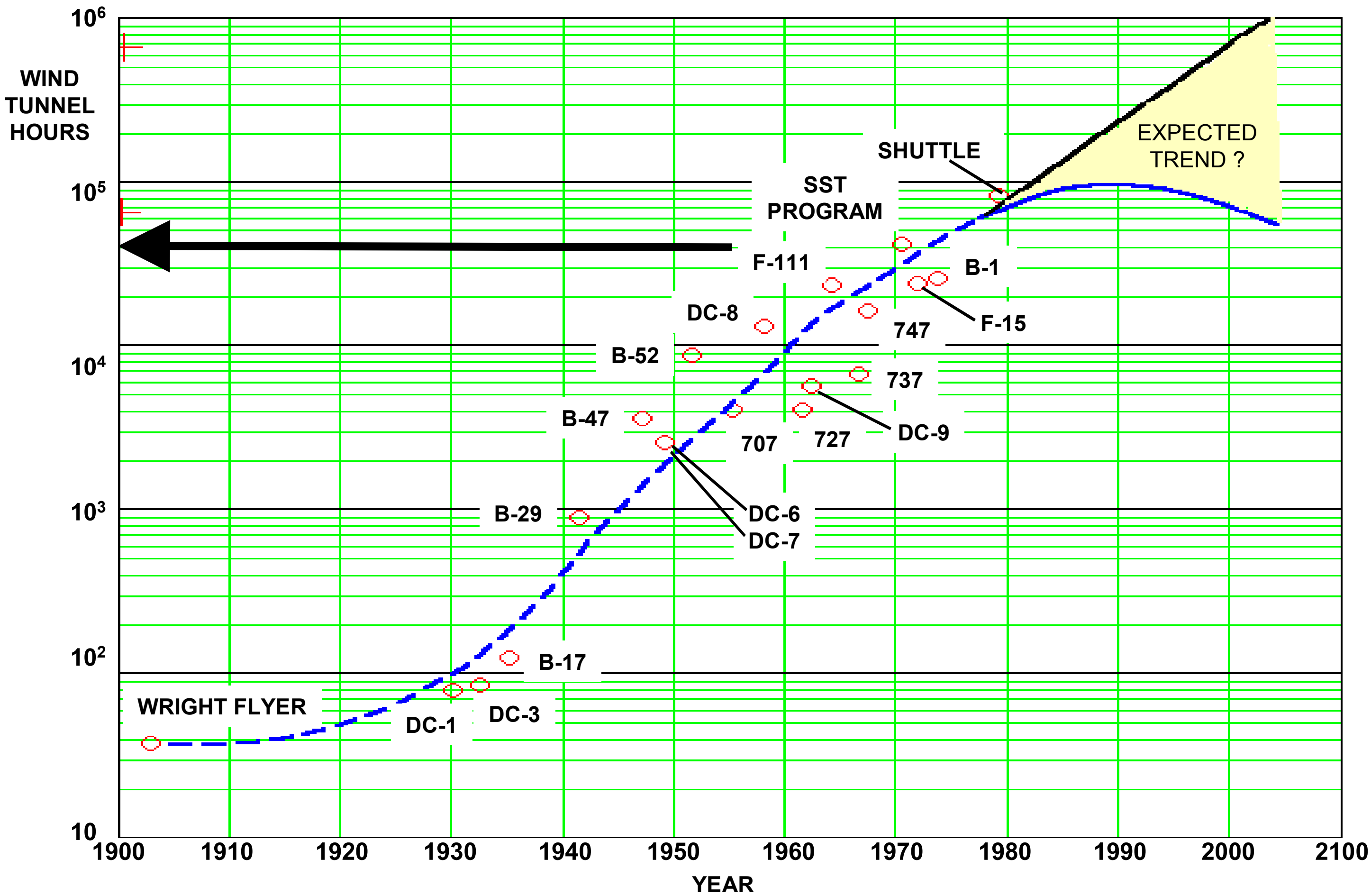


This conceptually illustrates the relative cost and flow time characteristics of wind tunnel and CFD. It is obvious that CFD and EFD are both required elements in our aerodynamic tasks and processes.

Currently, CFD is best used to provide analyses for a relatively few number of analyses (i.e. Simulations) of a configuration. EFD is best used for generation of a large database as well as validation of CFD predictions.

This does illustrate that both classes of tools will still be used in any design development study.

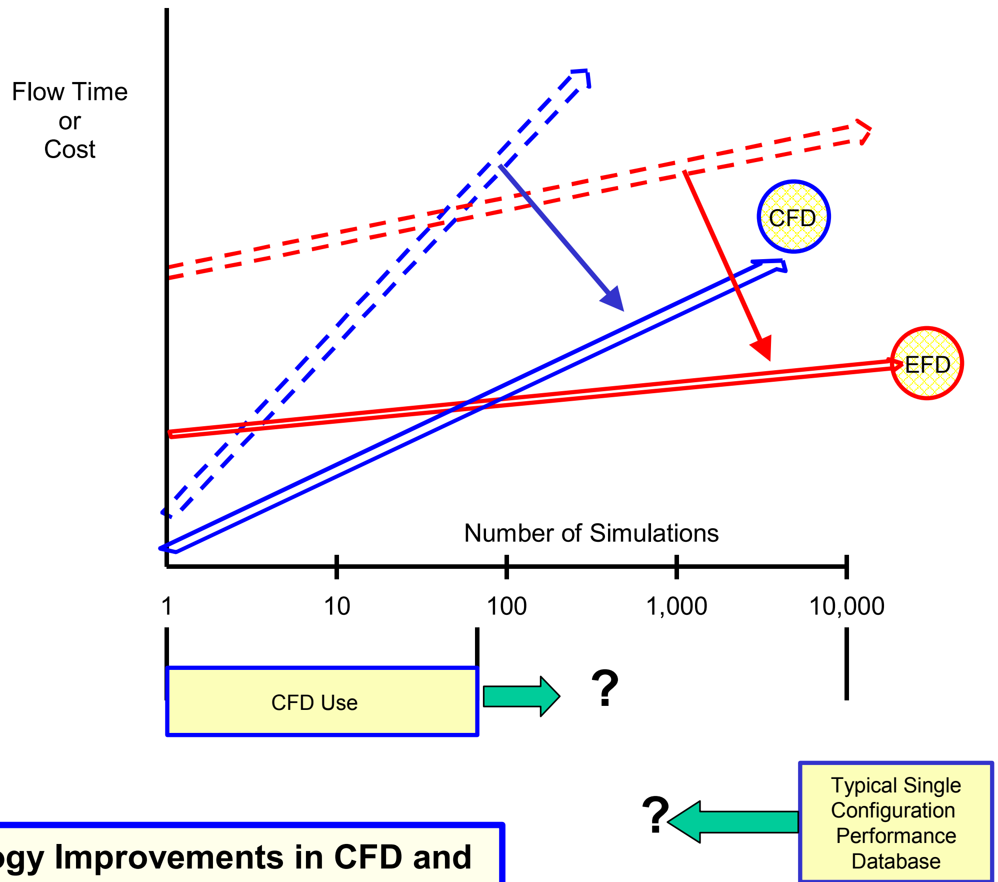
WIND TUNNEL USAGE TO DEVELOP A MAJOR AIRCRAFT



This shows the tremendous increase in wind tunnel test time to develop a new airplane configuration from the time of the Wright Brothers Flyer to the modern commercial transport aircraft. The test development time for the US SST prototype was approximately 40,000 hours. This is equivalent to testing 24 hours a day, 365 days a year for about 5 years.

This increasing trend of required test development with new airplane programs, could not continue because the associated costs would prohibit the development of an economically viable aircraft. The appropriate use of advanced CFD design and analysis tools was expected to reverse this trend . This has indeed been the case.

Technology Improvements in CFD and EFD



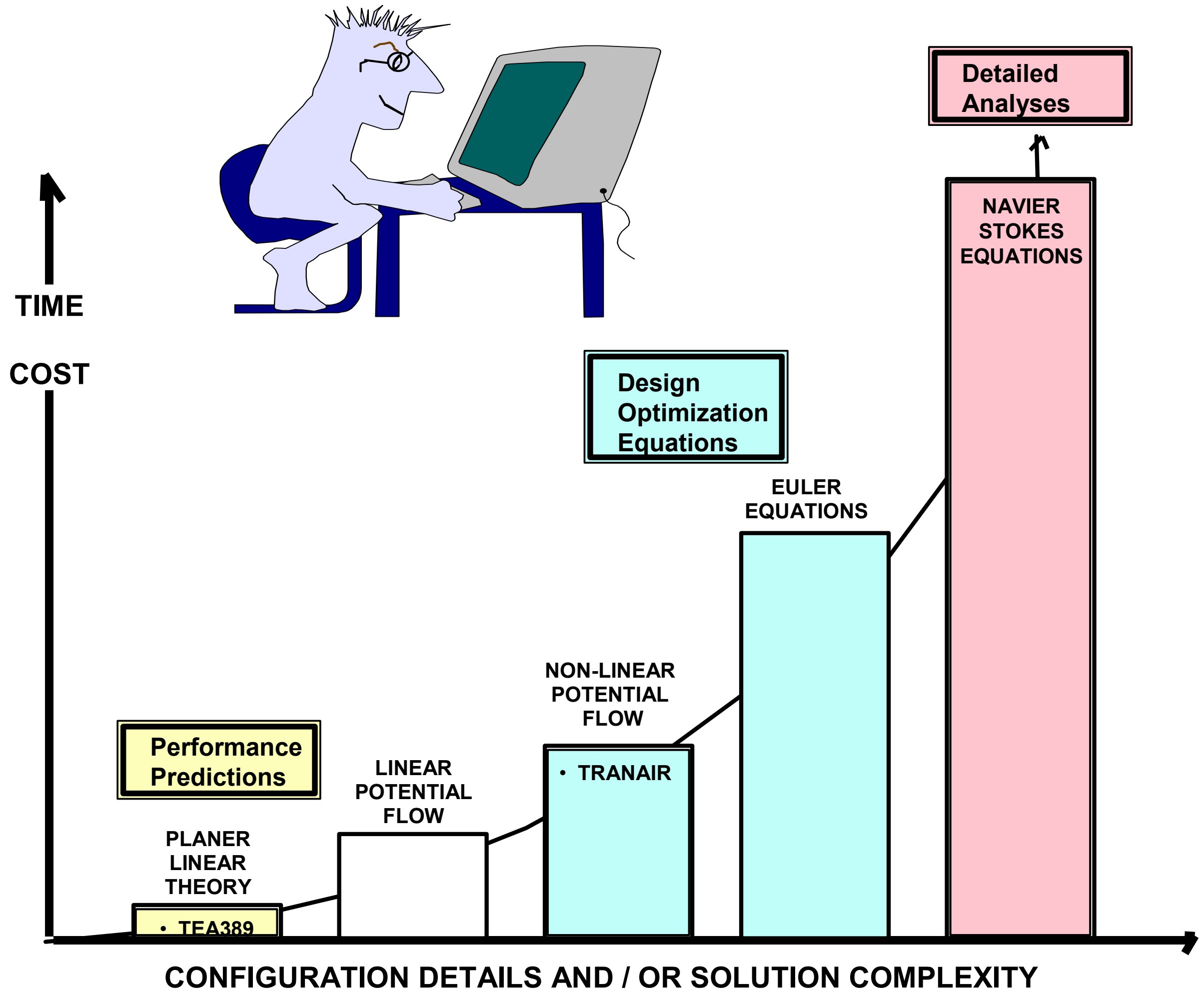
Technology Improvements in CFD and in EFD will Dramatically Reduce the Cost and Timing of the Design Process

It is very important to improve the efficiencies and quality of our CFD methods and EFD processes for as previously shown, both the process speed and the airplane goodness have a direct impact of the possible market share for a new airplane.

Improvements in EFD should include faster and cheaper model construction, faster acquisition of data, and higher quality data with improved diagnostic techniques.
Numerous improvements are possible for CFD that most certainly involves validation of the methodologies.

It is envisioned that proper use of CFD in conjunction with wind tunnel testing could be used to enhance and interpolate the test database and conceivably dramatically reduce the number of required airplane solutions.

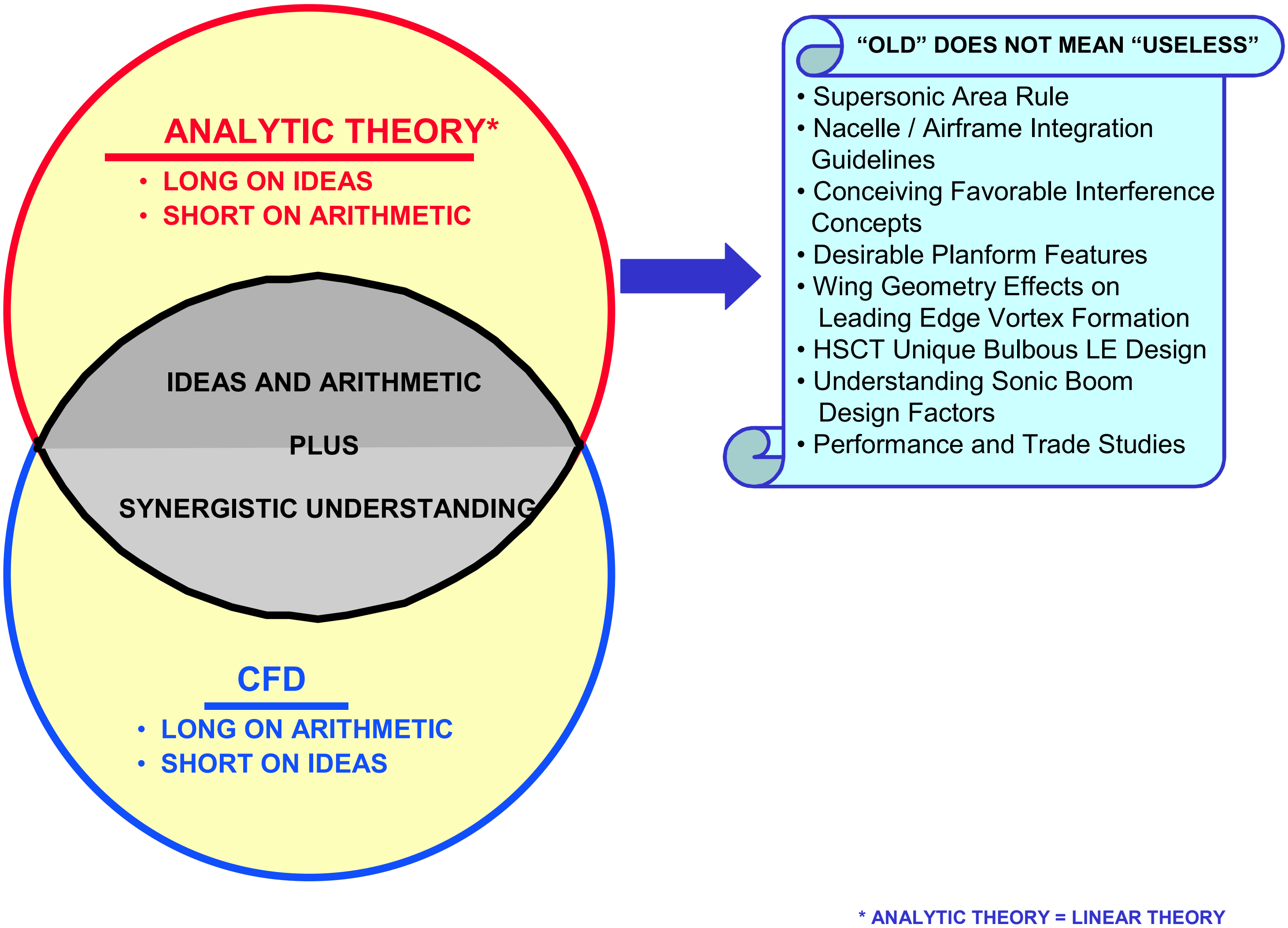
CFD ANALYSIS QUANTUMS



This illustrates the current impact on cost / solution time that is associated with the increased complexity of the CFD codes.

Proper selection of the CFD code for any specific application can certainly reduce the cost and flow time for the design and analysis activities.

An important part of the CFD development and validation studies is, therefore, to identify the appropriate tool to use for any specific application.



One of the great joys of my career was to meet and become friends with Dr. Robert T. Jones. He possessed, among many other things, the remarkable ability to share his wisdom which he often blended with a touch of humor.

One time when discussing linear theory and CFD, he said with a twinkle in his eyes : Linear theory is long on ideas but short on arithmetic, but CFD is long on arithmetic but short on ideas.

Although, linear theory can provide some unique insights and ideas, it does require both understanding and care to correctly apply the theory because of its numerical and flow physics limitations. Some of the achievements obtained with linear theory that are still of great use today and will also be for the near future are shown in the figure.

Similarly, the non-linear methods may require a basic understanding of the inherent limitations of the methodology. In addition, the nature of the current CFD solution processes can result in significant differences in the predictions by different methods.

The advanced CFD codes can provide a detailed insight in to the nature of the flow characteristics on complicated configurations and for conditions where wind tunnel testing is not possible. The non-linear design optimization methods also offer the promise of substantial performance gains.

The best strategy is to use both CFD and linear theory and exploit the benefits of each. This will provide both the "ideas" and the "arithmetic" plus the added bonus of increased synergistic understanding and design capability.

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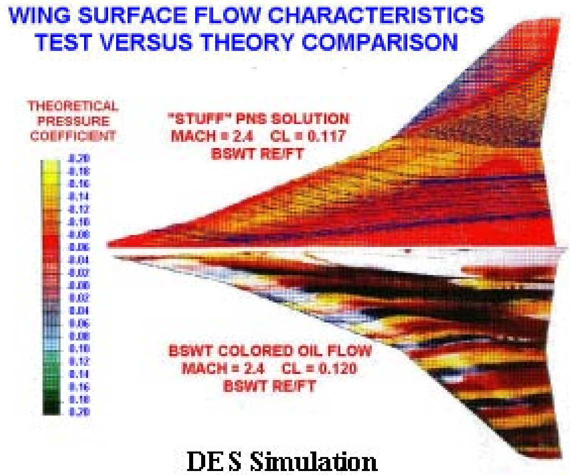
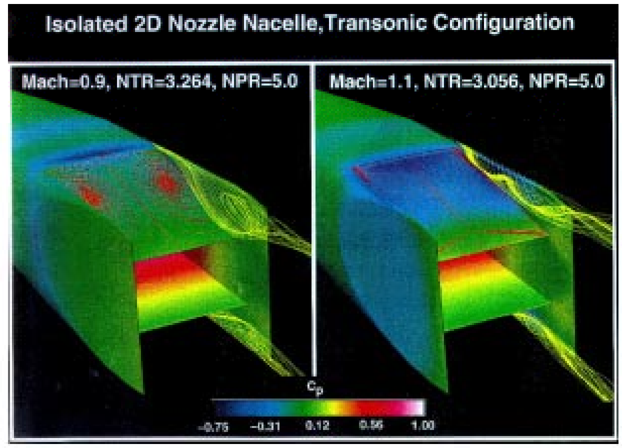
Results of Various Navier Stokes Computations





DES Simulation of a Ground Jet

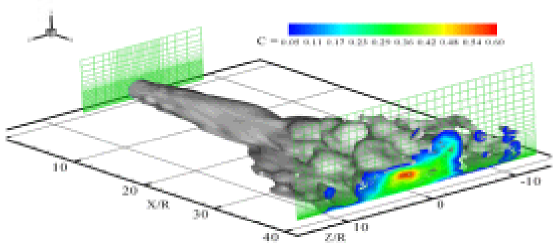
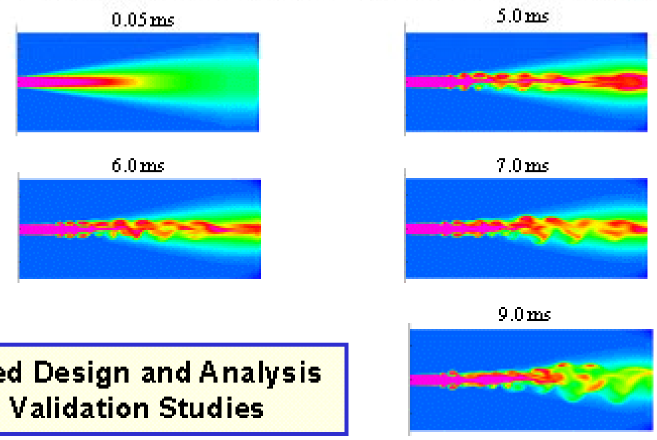


Fig. 5.6. DES calculation for 3-D wall jet, fine grid, Re=10 000.

Entropy Computed with WIND using DES for a M = 0.8 Jet into M = 0.1 Freestream



CFD Offers Incredible Insight and Sophisticated Design and Analysis Capabilities But Needs Carefully Orchestrated Validation Studies

The current and emerging Navier Stokes Codes can provide an in-depth insight into the nature of the flow over a complete configuration as well as for localized regions on the airplane as shown by these four examples.

The figure in the upper left is comparison of the predicted surface flow patterns with the colored oil flow measurements that were obtained in the Boeing Supersonic Wind Tunnel, BSWT. The model geometry was the Ref H configuration developed during the HSCT studies. The predictions were made with the parabolized Navier-Stokes program , STUFF.

The viscous flow predictions appear to accurately model the local surface flow phenomena. The visual fluid dynamics,VFD, provided by both CFD and the test results, EFD can provide further understanding of the fluid dynamics, UFD.

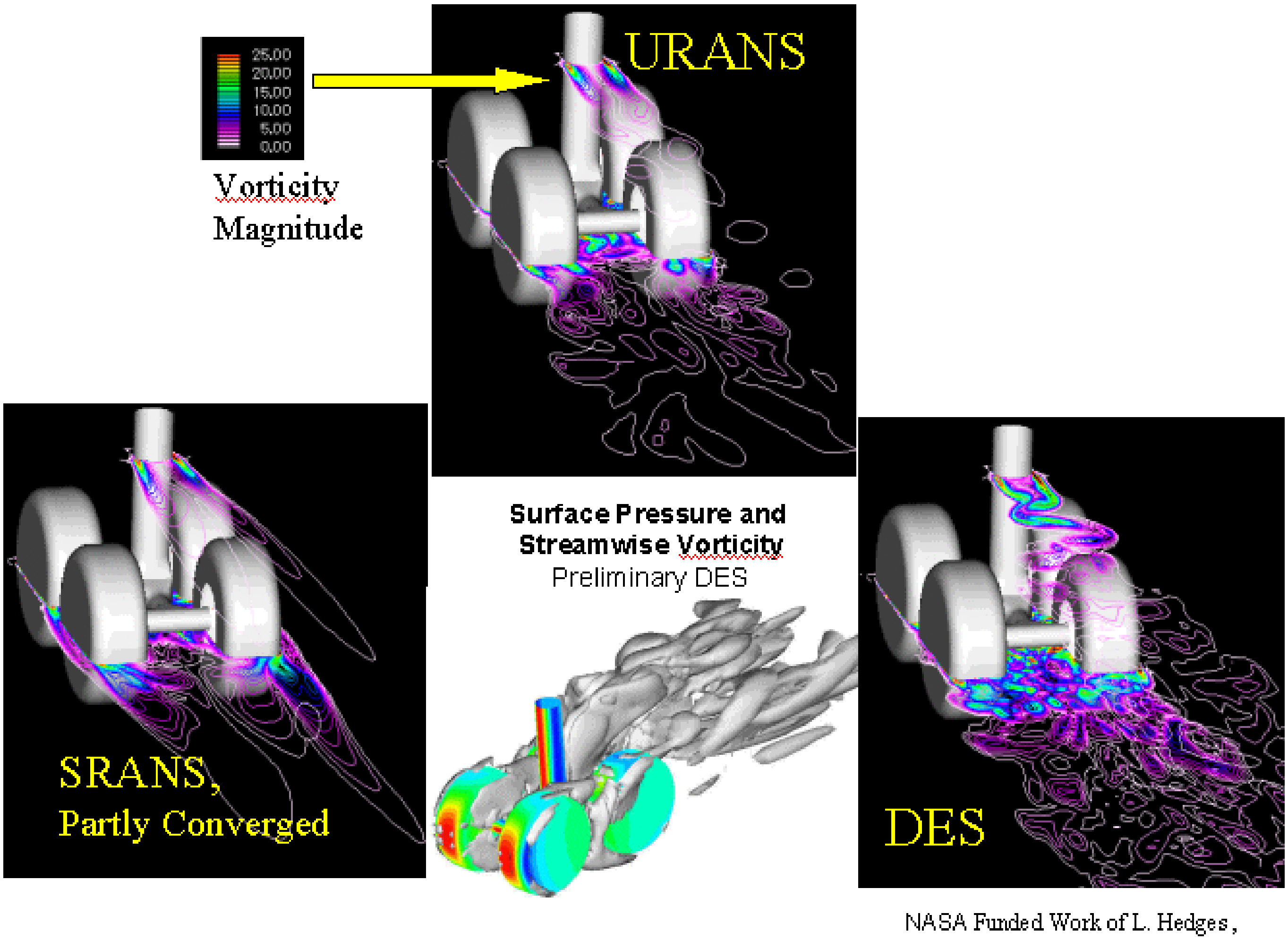
The figure in the upper right shows predictions of the flow characteristics over a 2D nozzle for different Mach numbers and nozzle flap angles. The predictions were made using the OVERFLOW Navier - Stokes program.

The figure on the lower left shows the results of a Detached Eddy Simulation, DES, analyses of the complex characteristics of a 3-D wall jets were completed. These results appear to predict the qualitative behavior of the complex jet flow.

The figure on the lower right shows the entropy distribution in an axisymmetric M = 0.8 jet into a M = 0.1 outer stream as computed with a 3D DES simulation over a time period of 9ms. While there is much to learn about how to make these simulations quantitatively accurate, results so far are encouraging

It is seen that the Navier - Stokes solutions can capture and provide insight into some rather complicated flow phenomena. However a great and significant need is to conduct coordinated theoretical prediction and test validation studies

Calculation of Separated Flown About a Landing Gear



This shows how the recent advances in dealing with massively separated that allows the aerodynamist to tackle incredibly complicated flow phenomena like separated flow around a landing gear.

The results above include partly converged steady Reynolds averaged Navier Stokes analysis, SRANS, unsteady Reynolds averaged Navier Stokes analysis, URANS, and detached eddy simulation, DES, analyses. The DES solution appears to capture more of the flow details.

The task of validation of the analyses of complicated flows becomes increasingly difficult but highly important. An answer from an unvalidated CFD tool may not be an answer at all.

Technology Projection

- **Is an HSCT Feasible, Acceptable and Viable?**
- **What are the Critical Technologies?**
- **How Much Greater Improvements Are Possible**
- **What should be the Focus of Technology Development?**
- **Do We Need to Search for New Ideas?**
- **Time to Retire?**

As previously shown, the ability to predict realistic and achievable goals for technology advancements is an important part of the technology development process.

In the case of the HSCT, the projections are used to assess if an HSCT can be feasible, acceptable and viable as well as to justify the necessary technology activities. The projected levels of possible gain are significant in identifying the critical technologies upon which to focus the technology effort.

The projections also provide an indication of how much greater gain is achievable and when the point of diminishing return has been reached. If we do not know where we are going, then how will we know when we arrive?

If the projected gains are not sufficient, this tends to justify a search for new and perhaps radical revolutionary ideas.

Of course if we have reached the pinnacle of success and achieve all that is possible, then perhaps it is time to retire.

In this paper we shall use a projection process [2,3] to help identify if the potential gains in aerodynamic efficiency of an evolutionary nature, are sufficient or must one seek out radical revolutionary solutions

Subsonic Drag Polar Approximation

$$CD = \underbrace{CDo}_{\text{Non Lift Dependent Drag}} + \underbrace{\frac{CL^2}{\varepsilon \pi AR}}_{\text{Lift Dependent Drag}}$$

Lift Dependent Drag

* Induced Drag
* Profile Drag Due to Lift
* Drag Rise Due to Lift
* Trim Drag
* ??

Non Lift Dependent Drag

* Friction Drag
* Profile Drag Due to Volume
* Drag Rise
* Interference Drag
* Excrescence Drag
* Miscellaneous Drag

We shall use a "Tops Down" approach to assess the potential subsonic cruise drag improvements relative to current technology and methods.

The drag elements for a subsonic aircraft can be grouped into two drag categories. These include those that are strongly dependent on lift, and those that are not.

The Non-lift dependent drag consists of:

- Friction drag
- Profile drag due to thickness.
- Compressibility drag
- Interference drag
- Excrescence drag and miscellaneous drag

The lift-dependent drag items, which tend to vary with the square of the lift coefficient, include

- Induced drag
- Profile drag due to lift
- Compressibility drag due to lift
- Trim Drag

The drag polar can then be approximated as a simple quadratic equation.

Tops Down L/D Analysis

- **(L/D)max at (M L/d)max Subsonic Aircraft**

LOWER BOUND DRAG:

- Fully Turbulent Flow Friction Drag
- Elliptic Load Induced Drag ε=1
- Planar Wings

$$CD = CFave \frac{Awet}{Sref} + \frac{CL^2}{\pi\, AR}$$

$$Awet\ adj = Awet \frac{CFave}{0.0021}$$

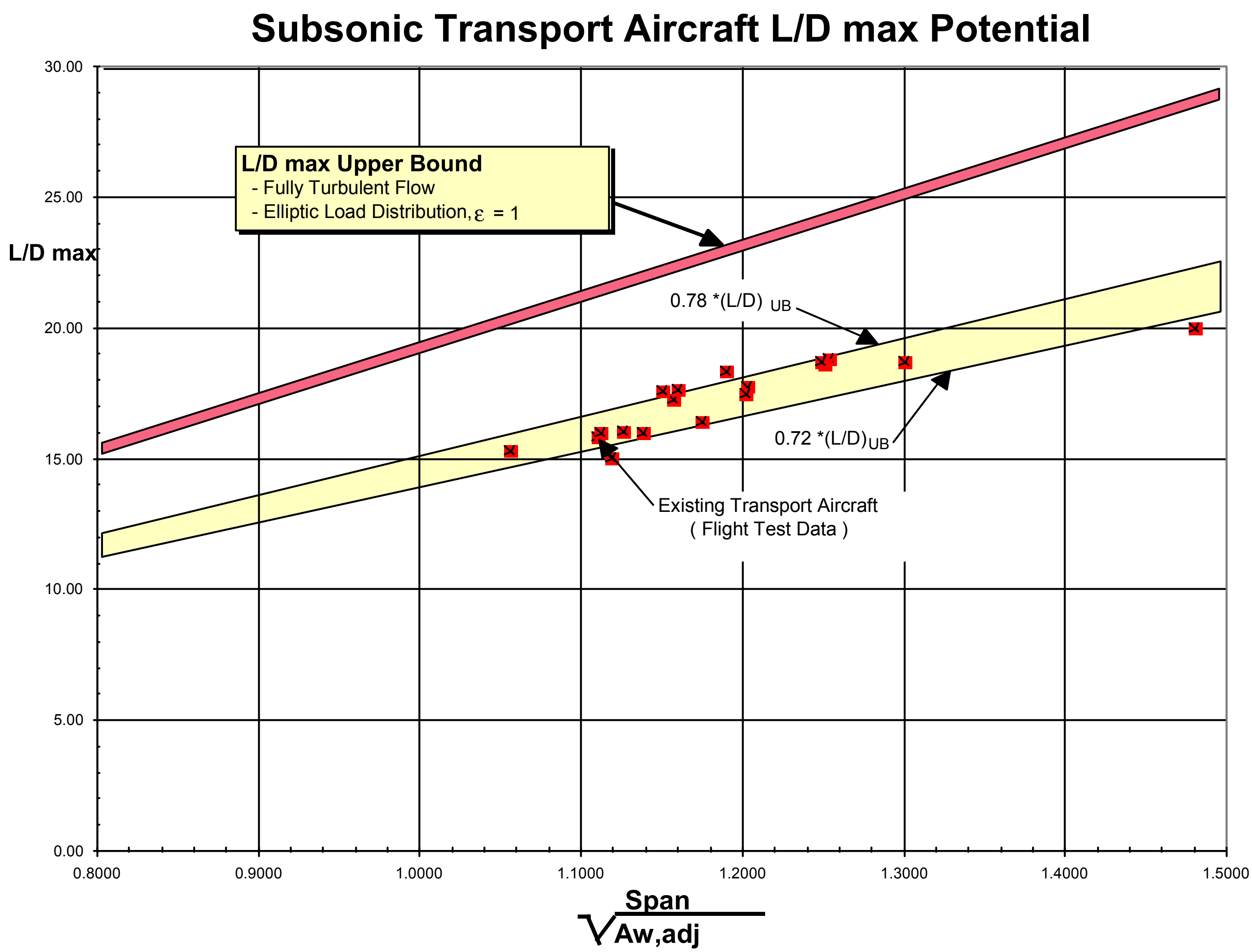
$$L/D\ max\ pot. = 19.34 \frac{b}{\sqrt{Awet\ adj}}$$

For subsonic transport aircraft the lower bound drag components can be considered to include:

- Minimum CDo equal to fully turbulent flow flat plate skin friction drag.
- Minimum drag due to lift equal to the induced drag for planar wing configurations with elliptic load distributions .

An adjusted wetted area will be used to normalize the effects of Reynolds number variations on the viscous drag.
The adjusted wetted area is equal to the actual wetted area times the ratio of computed average skin friction coefficient to a reference skin friction coefficient of 0.0021.

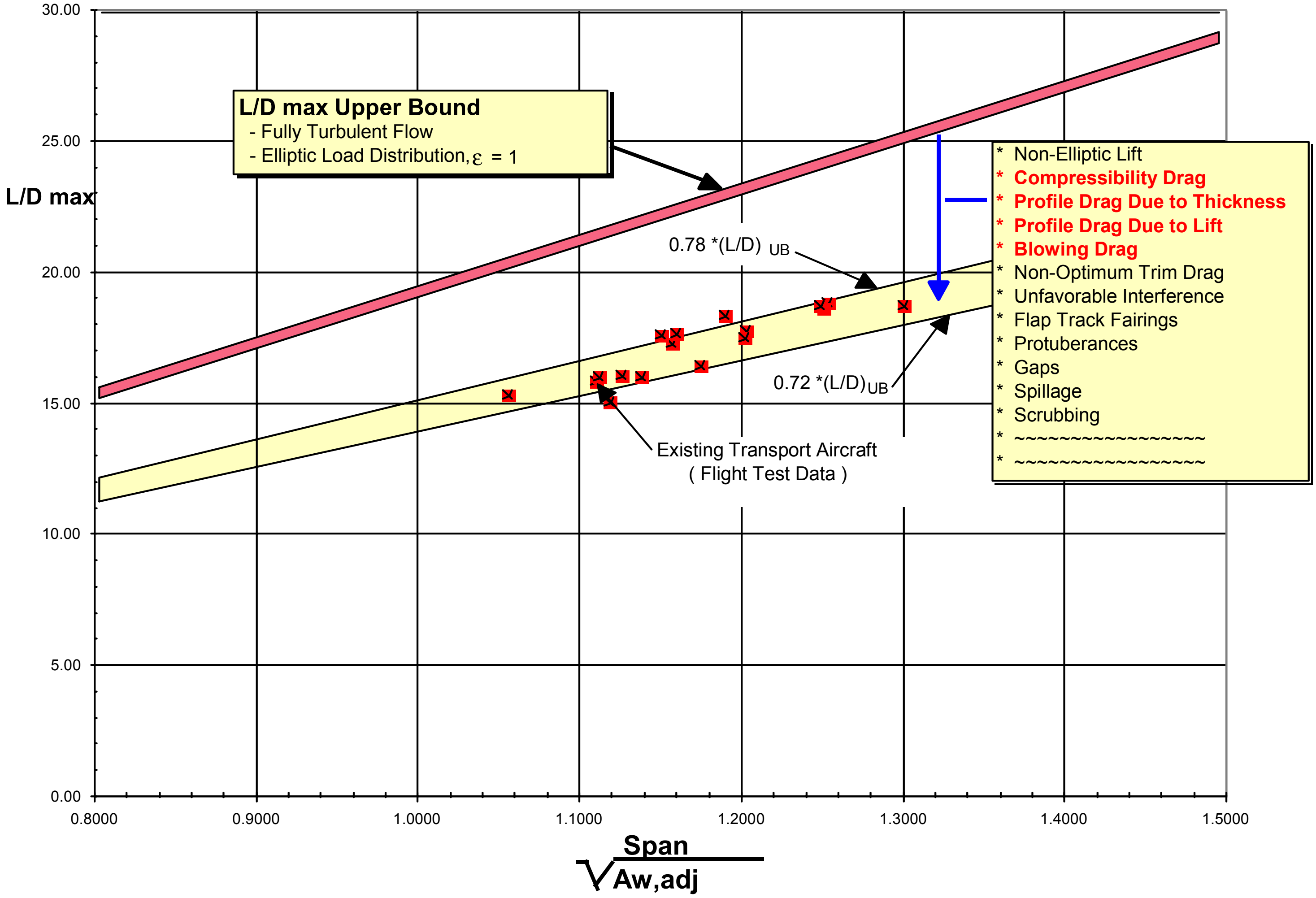
The "Tops Down" L/D max for subsonic transports is then equal to 19.34 times the wing span divided by the square root of the adjusted wetted area.
An "effective" span is used for aircraft having non-planar wing geometries such as tip fins. The "effective' span is the span of an equivalent planar wing that has the same induced drag as the non-planar wing.



The values of L/Dmax at the Mach number corresponding to (M L/D)max are shown for existing subsonic transport aircraft based upon flight test data.
The existing subsonic commercial transport aircraft achieve about 72% to 78% of the "upper limit" aerodynamic efficiency.

Comparisons of an aircraft design with the upper bound is a convenient way to assess the performance efficiency of a particular design. It is will be shown as a useful way to identify potential performance gains due to design improvements.

Subsonic Transport Aircraft Do Not Achieve L/D max Potential



The subsonic aircraft configurations fail to achieve this Upper Bound Lift / Drag level because of a number of additional drag items as shown in the figure. The most Significant of these additional drag items include:

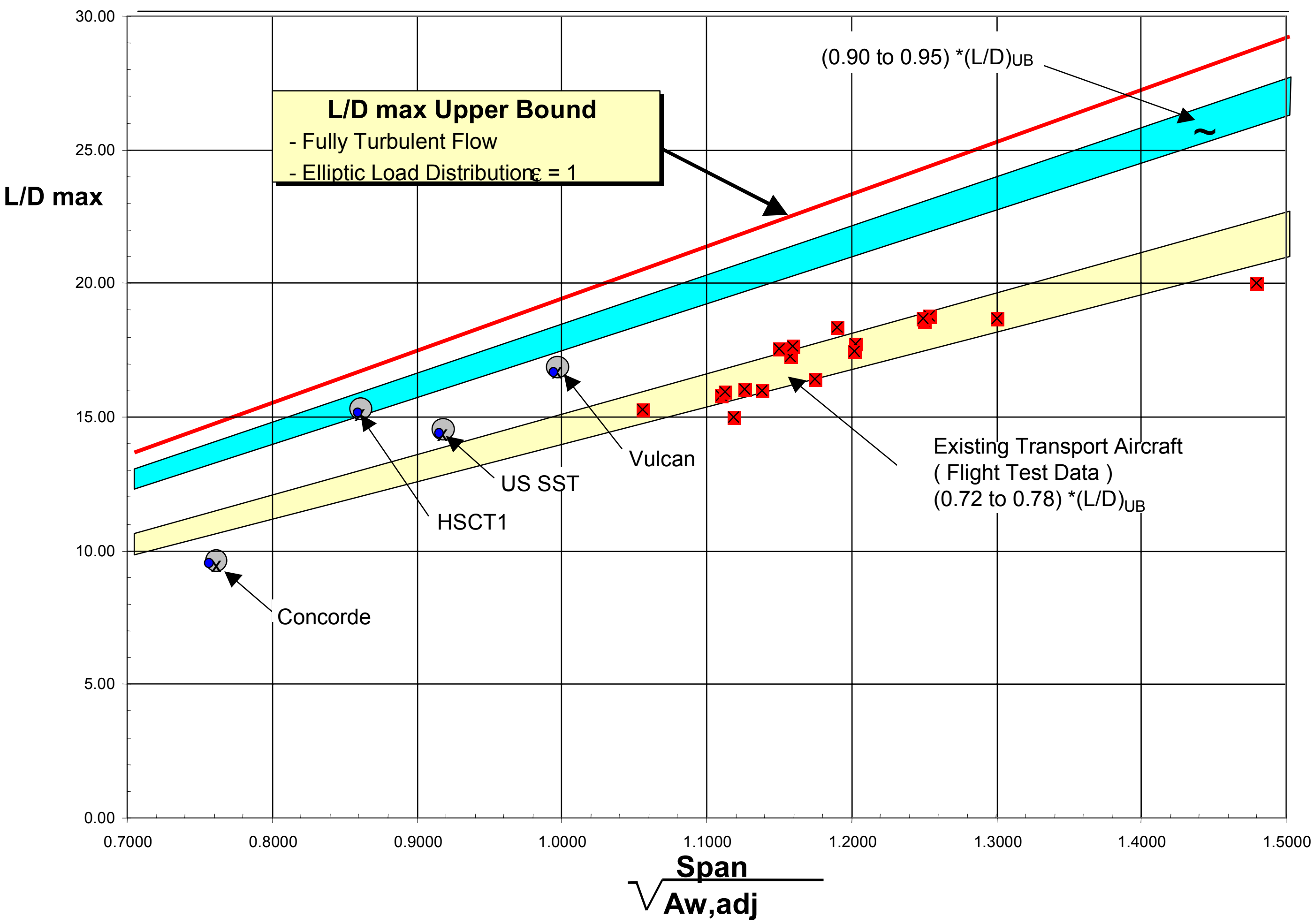
- The relatively thick airfoils and wide fuselages result in a profile drag increase over the viscous friction drag by approximately 20% to 25 %.

- At the long range cruise Mach number, subsonic aircraft typically have 15 to 20 counts of drag rise ($\Delta CD = 0.0015$ to 0.0020).

- The spanwise load distributions based on structural design trades, tend to depart from the ideal load distribution. The typical spanwise load distributions are more heavily loaded near the wing root. This together with an increase in profile drag due to lift typically increases the induced drag approximately 10% to 12% above the ideal level.

These three drag items account for a 15% to 18% reduction in L/D from the Upper Limit L/D levels.

Subsonic Transport Aircraft L/D max Potential: Mach = 0.9

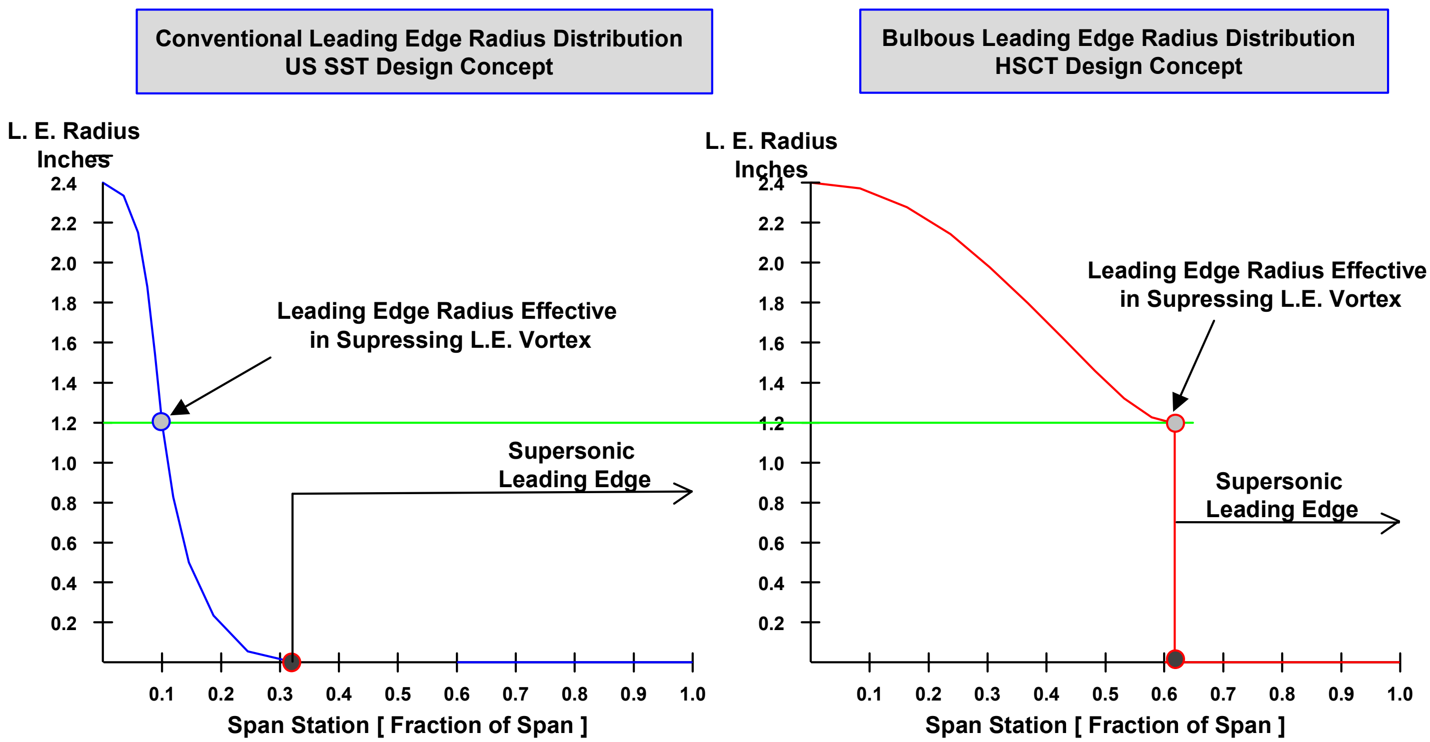


Commercial supersonic aircraft configurations tend to be long, thin and slender and cruise at relatively low lift coefficients. The subsonic viscous drag is essentially equal to flat plate skin friction drag.

The typical over land subsonic cruise Mach number for an HSCT of approximately 0.9. The is well below the drag rise. Mach number. Hence there is no drag rise at the cruise mach number.

Consequently, it is expected that an HSCT cruising with optimized flap settings should achieve well in excess of 80% of the corresponding upper limit for L/Dmax at subsonic cruise conditions.
The current HSCT configurations are also expected to have a significant improvement over the US SST because of it's unique bulbous leading edge design.

Effect of Unique Bulbous Wing Leading Edge Radius Concept



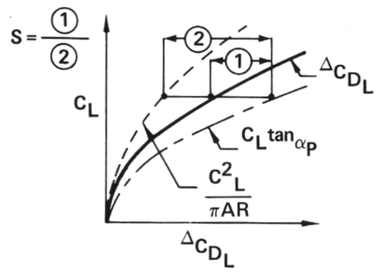
Previous leading edge vortex studies[4] have indicated that the suppressing the formation of the leading edge vortex at off design conditions can significantly increase the aerodynamic efficiency.

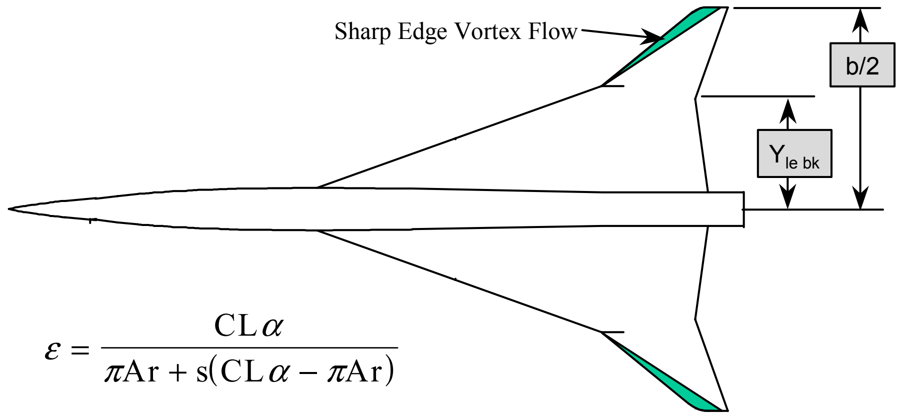
This can be accomplished by designing the wing to resist the progressive inboard movement of the leading edge vortex with angle of attack. It is shown that one of the key design parameters is the magnitude of the wing leading edge radius, particularly in the mid to outer span portion of the wing.

Based on these results, a bulbous leading edge radius concept was developed for the HSCT configurations. Experimental and analytical results have confirmed that substantial gains in off design aerodynamic performance were achieved with the bulbous leading edge concept relative to a conventional leading edge design.

The above figure shows a comparison current HSCT bulbous leading edge radius distribution with that for the US SST.

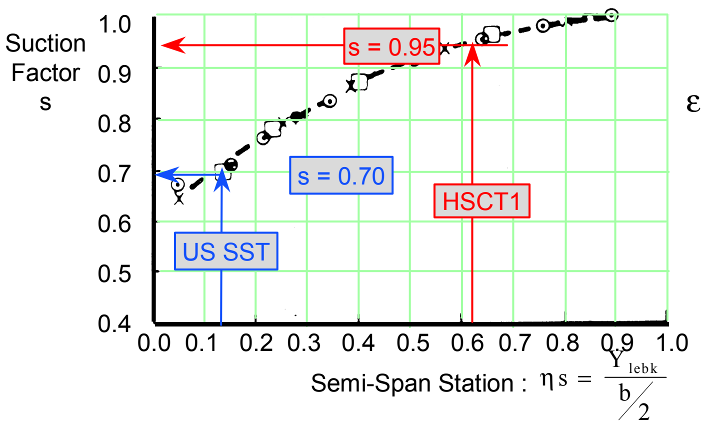
Effect of Leading Edge Vortex on Leading Edge Suction



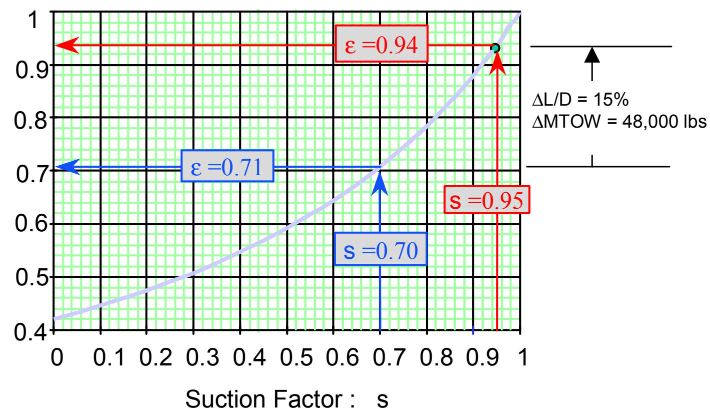


$$\varepsilon = \frac{CL\alpha}{\pi Ar + s(CL\alpha - \pi Ar)}$$

Effect of Outboard Leading Edge Vortex on Suction Factor



Span Efficiency Factor versus Suction Factor

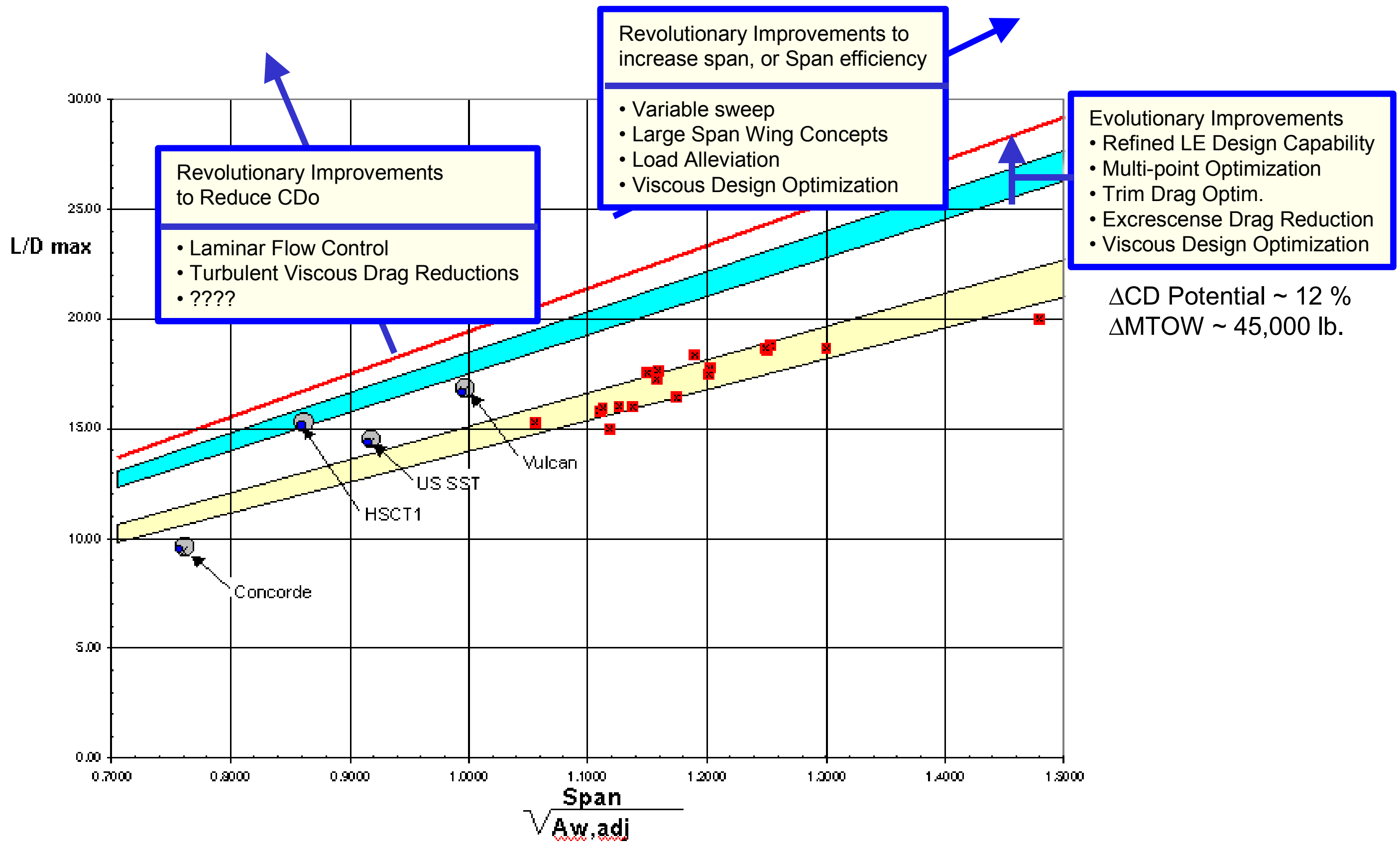


This shows the powerful effect of the bulbous leading edge radius.
The drag due to lift efficiency of a wing is defined by the leading edge suction Factor,S. As shown in the figure above, the leading edge suction factor is defined as:

$$s = \frac{CL \bullet \tan\alpha - CDL}{CL \bullet Tan\alpha - \left(\frac{CL^2}{\pi \bullet AR}\right)}$$

The leading edge suction factor can be calculated easily from any drag polar.
The span wise load efficiency, ε, is another measure of the drag due to lift efficiency of a wing. A value of ε =1 corresponds to the drag due to lift of the optimum elliptic load distribution. The maximum value of L/D varies inversely with the square root of ε.
The spanwise efficiency factor,e, can be related to the leading edge suction factor s as shown in the figure.
The results from the previous leading edge vortex studies[4] indicated that leading edge suction factor at any angle of attack is dependent on the spanwise station for which the leading edge vortex is suppressed by the basic airfoil geometry. Outboard of this station the wing is assumed to use flaps to suppress the vortex formation. The chart indicates the most outboard station on the HSCT1 for which the the subsonic leading edge has a significant leading edge radius. The US SST is also shown. This implies that the HSCT1 could achieve a suction factor of 0.95.
As shown in the figure on the right, that relative to the US SST design concept, the current HSCT configurations achieve a 15% increase in L/D which is equivalent to a reduction in MTOW of 48,000 lb.

Subsonic Transport Aircraft L/D max Potential: Mach = 0.9
Mach = 0.9



Evolutionary improvements to improve the subsonic aerodynamic efficiency include:

- Develop a refined leading edge design capability, This will first require validation of the CFD codes to predict the development of the leading edge vortex.
- Conduct viscous multi-point design optimization using the validated CFD prediction methods
- Conduct a full configuration design optimization to minimize trim drag.
- Exploit the structural materials concepts and manufacturing methods to dramatically reduce the excrescence drag.

The greatest potential for innovative technology reductions in Cdo, is the use of laminar flow control , or hybrid laminar flow concepts. This will require a complete design integration study along with an operational risk assessment to determine if this is an appropriate advanced technology concept to pursue.

Revolutionary concepts to further reduce the drag to lift would require adapting concepts that have increased span, such as larger span wings or perhaps variable sweep.
The spanwise load distribution could conceivably be improved through the use of active load alleviation methods.
The use of viscous design optimization that properly accounts for the leading edge vortex formation. This most likely require a major improvement in design capability and may possibly be classified as an innovative technology.

Supersonic Drag Polar Approximation

$$L/D\ max = \sqrt{\frac{0.5}{KE \times CDo}}$$

$$CD = CDo + KE \times CL^2$$

Lift Dependent Drag

* Induced Drag
* Wave Drag Due to Lift
* Lift Interference
* Trim Drag

Non Lift Dependent Drag

* Friction Drag
* Wave Drag Due to Volume
* Interference Drag
* Excrescence Drag
* Miscellaneous Drag

Using an approach very similar to the subsonic tops down method, we can identify the potential for supersonic cruise drag reductions.
The supersonic drag polar can be represented as a two term parabolic equation consisting of the non-lift dependent drag, CDo, plus the lift dependent drag KE x CL^2.

The non-lift dependent drag includes:

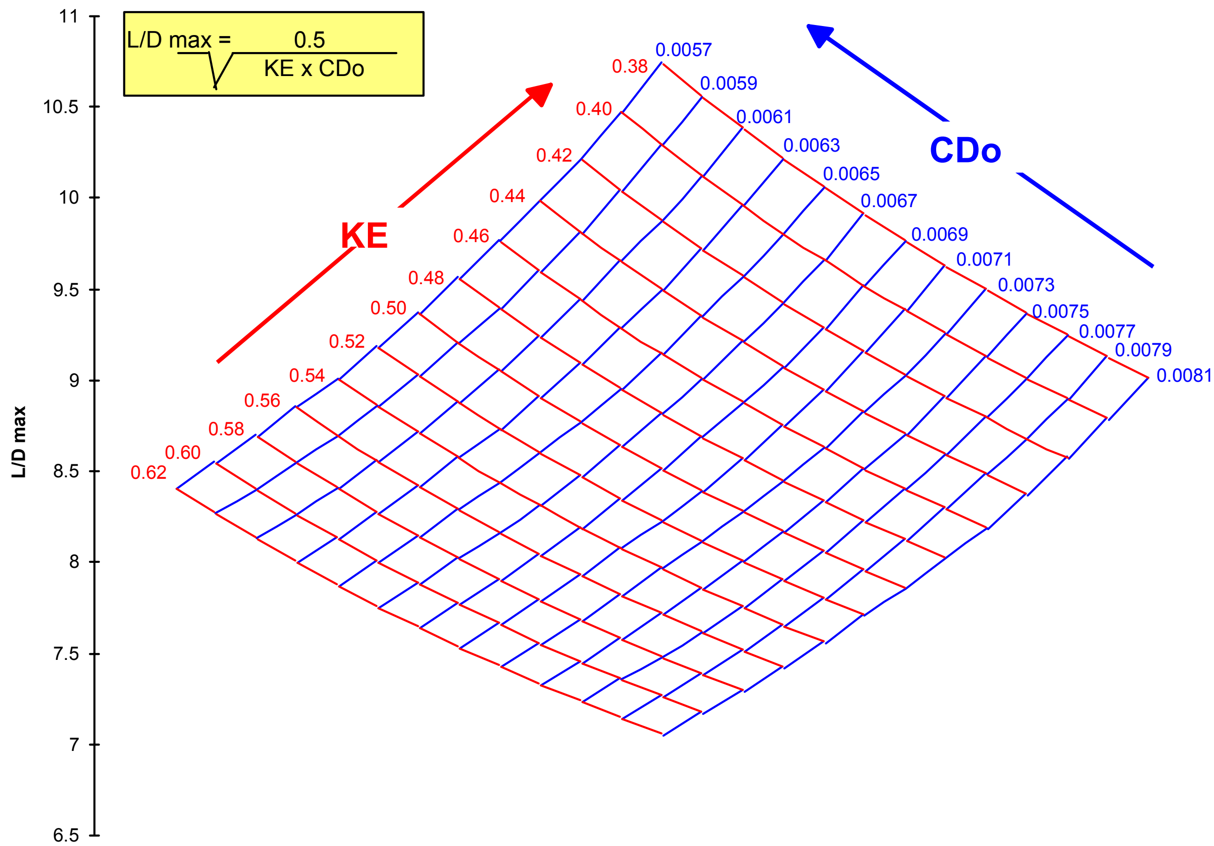
- Friction drag
- Wave drag due to volume
- Volume interference drag
- Excrescence and other miscellaneous drag items.

The lift dependent drag consists of :

- Induced drag
- Wave drag due to lift
- Lift interference effects
- Trim drag.

Based on the parabolic drag polar representation, it can be shown that L/Dmax varies inversely with the square root of the product of CDo and the drag due to lift factor KE.

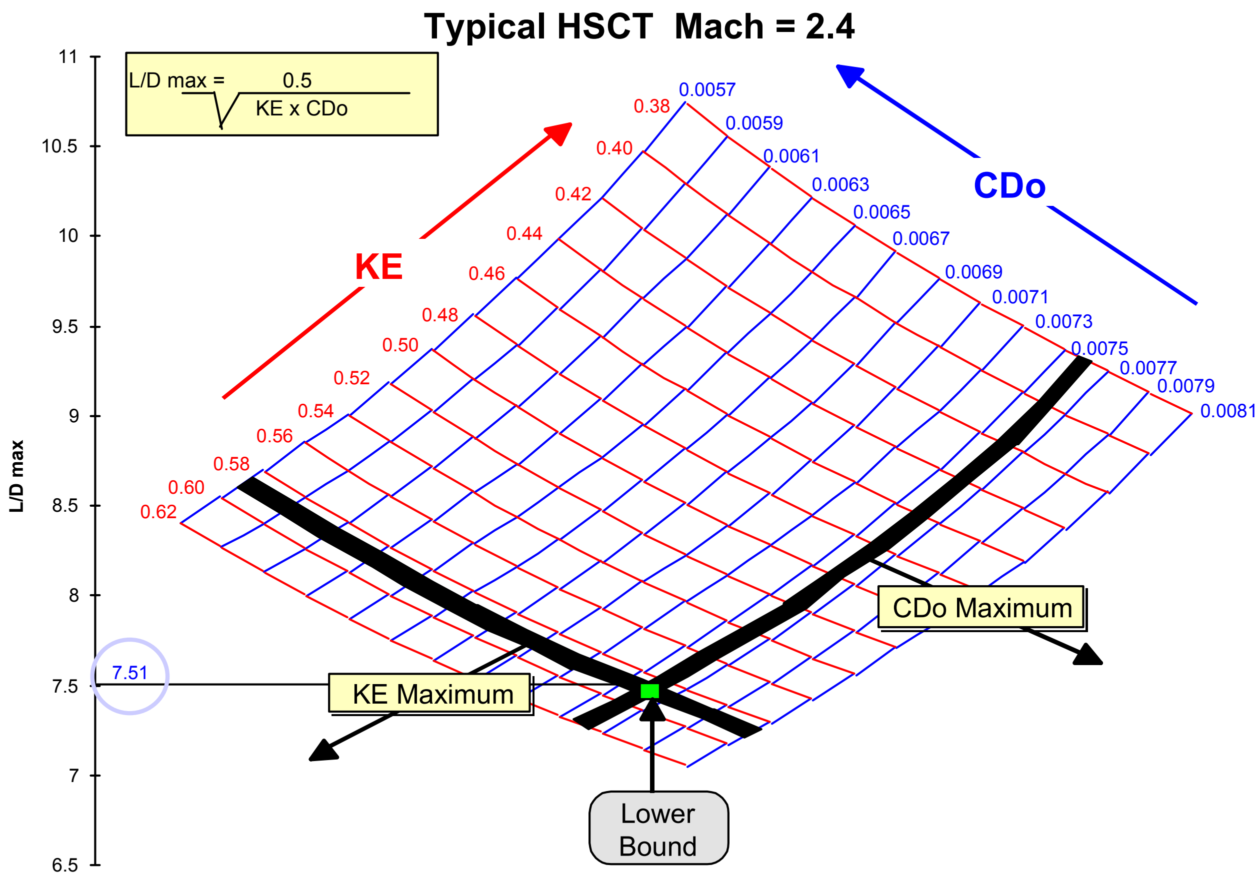
HSCT Aerodynamic Performance Design Space



L/Dmax contours can be calculated for various values of KE and CDo to map out the potential design space for a supersonic configuration.
A convenient way to view the dependency of L/Dmax on CDo and KE is in the form of a carpet plot. This is the form that will be use to develop the region of acceptable designs for a specific supersonic configuration.

In the discussions that follow, it is assumed that the gross overall features of any configuration remain fixed. These include such things as wing area, wing volume, location on the wing on the body, body volume, nacelle overall size, and planform shape.
What we wish to determine is the region of acceptable aerodynamic designs. We will then determine what is considered to be the overall upper limit of achievable L/Dmax for that specific configuration.
To do this we will identify values of CDo and KE that are considered too high for an acceptable design. We will then use fundamental aerodynamic concepts to determine lower bounds of achievable CDo and KE, which corresponds to the upper bound for aerodynamic efficiency.

Lower Bound for L/D max



CDo is considered “too high” if the non-lift-dependent drag exceeds the sum of:

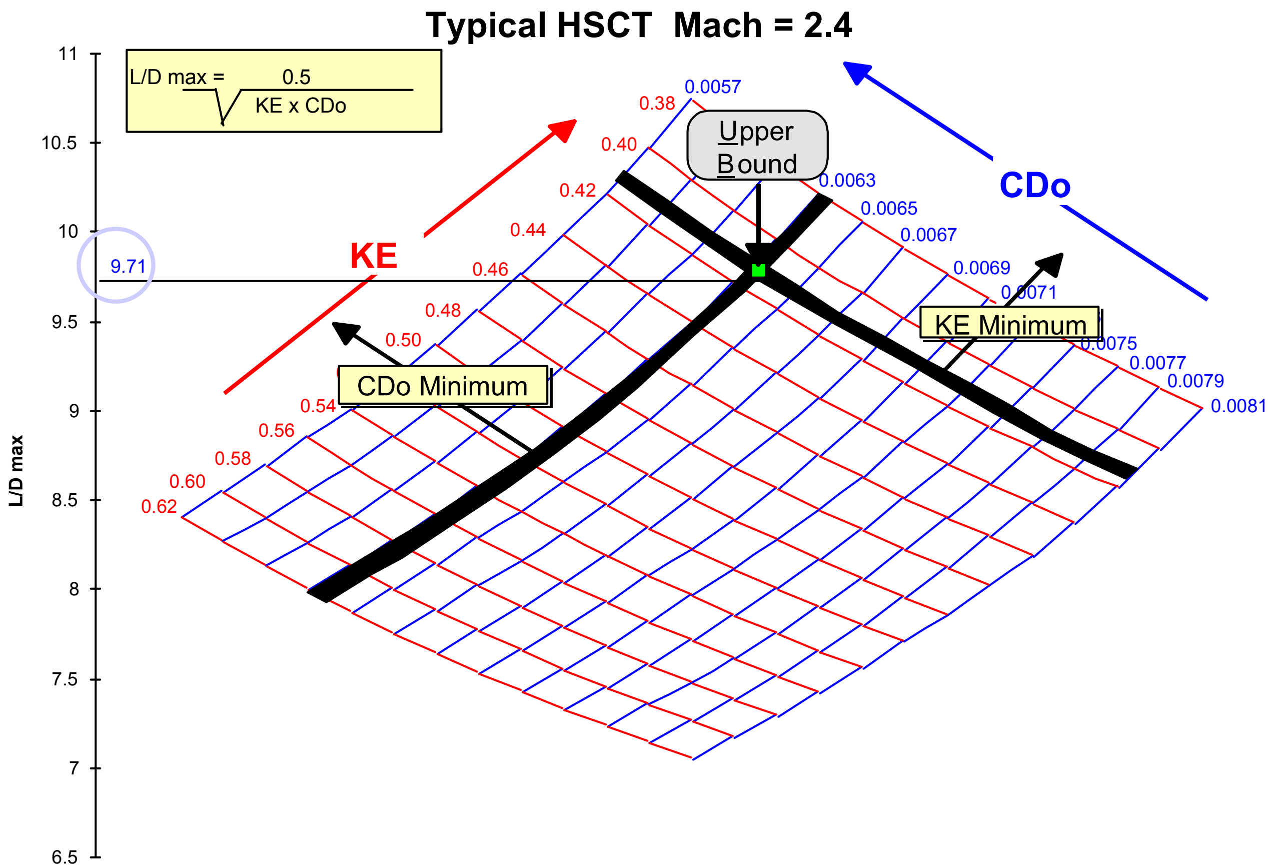
- CDF = Fully turbulent flow flat plate skin friction drag.
- CDW = The sum of the isolated wave drag of each of the configuration components. This corresponds to a design with no net favorable aerodynamic interference.
- CDmisc = Current technology miscellaneous drag including excrescence drag.

The most common causes of CDo being too high are:

- Unfavorable wing / body interference drag for a non-area-ruled body.
- Nacelles designed and / or located to produce volume wave drag interference.
- Large out of contour bumps such as landing gear fairings
- Separated flow over the wing upper surface or in the vicinity of the nacelle / diverter intersection with the wing.

The zero lift drag can actually be worse then this acceptable upper limit for CDo.
As an upper limit for KE we assume that the drag due to lift should be no worse the drag of a thin flat symmetric wing design with no leading edge suction.
We also assume no favorable interference lift or trim drag. the drag drag due to lift for a very poor design can exceed this limit
The intersection of the “CDo Maximum” boundary and the “KE Maximum” boundary determines the lower bound for L/D max. This lower bound for L/Dmax essentially corresponds to the Concorde aerodynamic efficiency level.

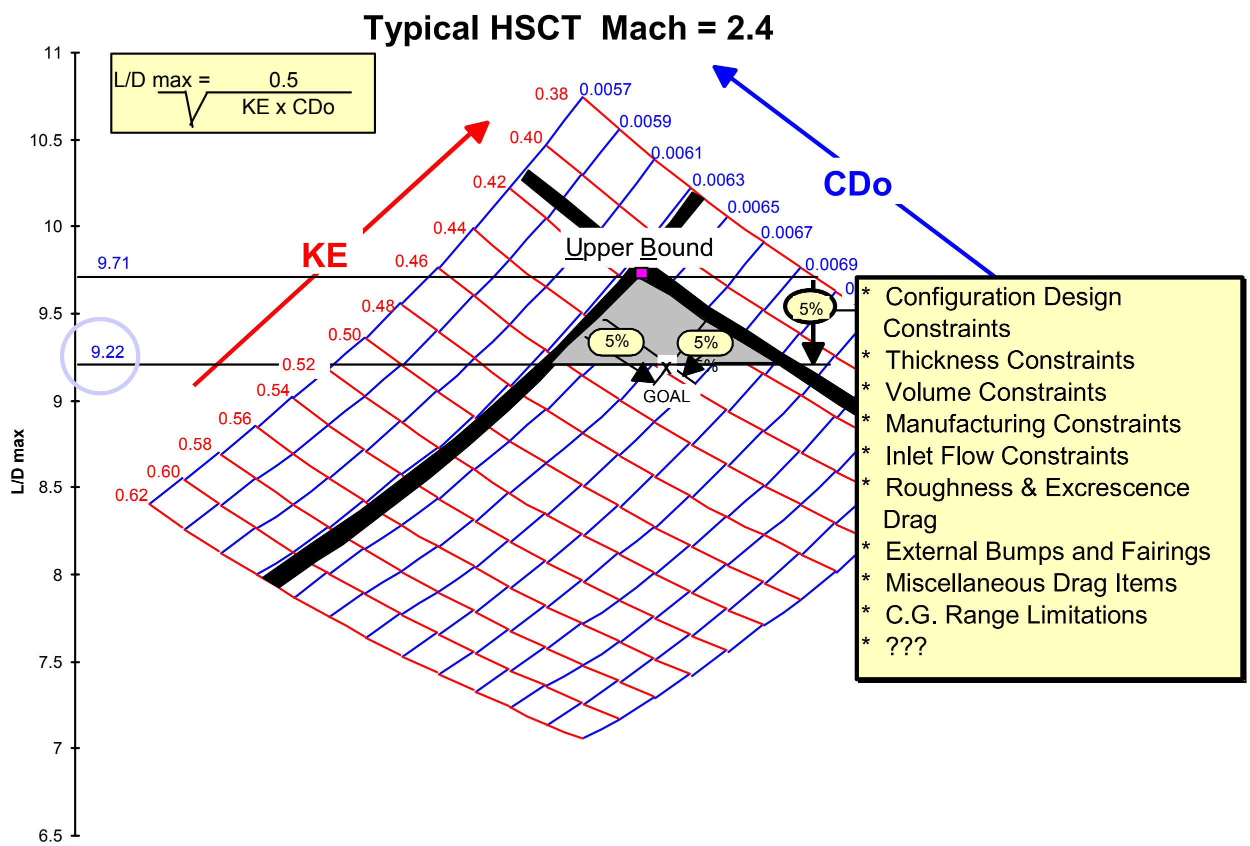
Upper Bound for L/D max



Simple aerodynamic fundamentals aero can be used[2] to estimate the lower bounds for both the zero lift drag and the drag due to lift.

The intersection of the CDo "too low" boundary with the KE "too low" boundary defines the upper bound for L/Dmax

Realistic Goal for L/D max Improvements



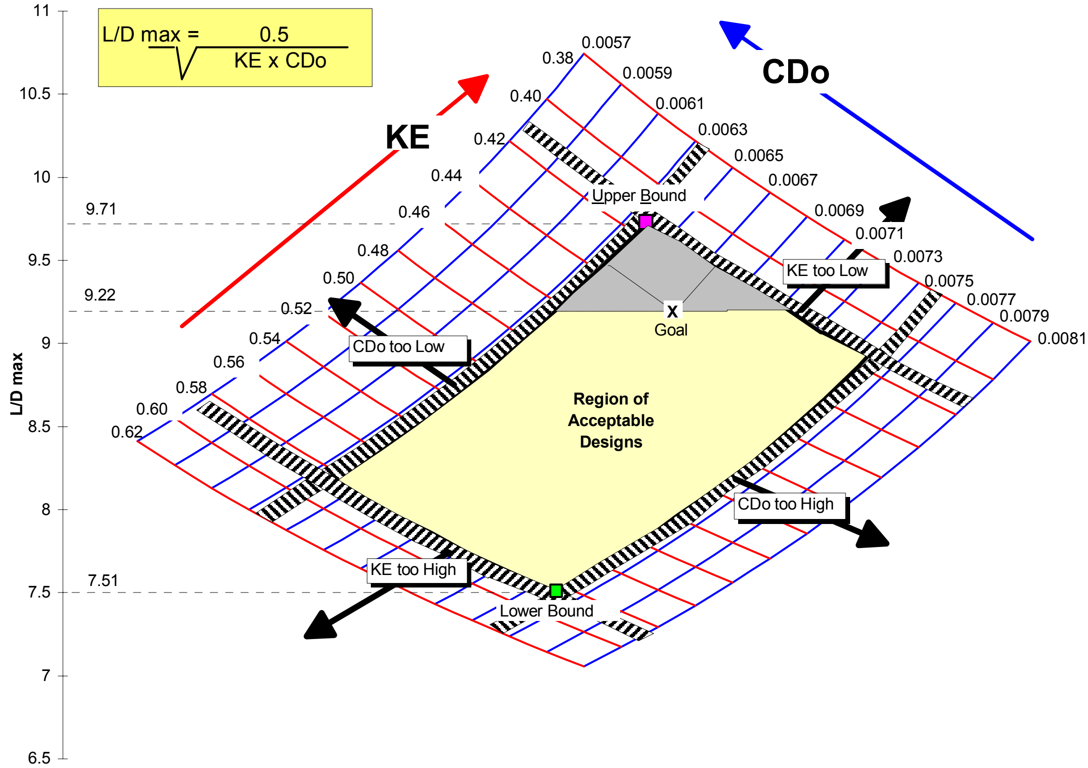
In general, the upper bound level for L/Dmax is not achievable because of practical configuration design considerations and constraints.

These constraints for a supersonic transport aircraft include such factors as:

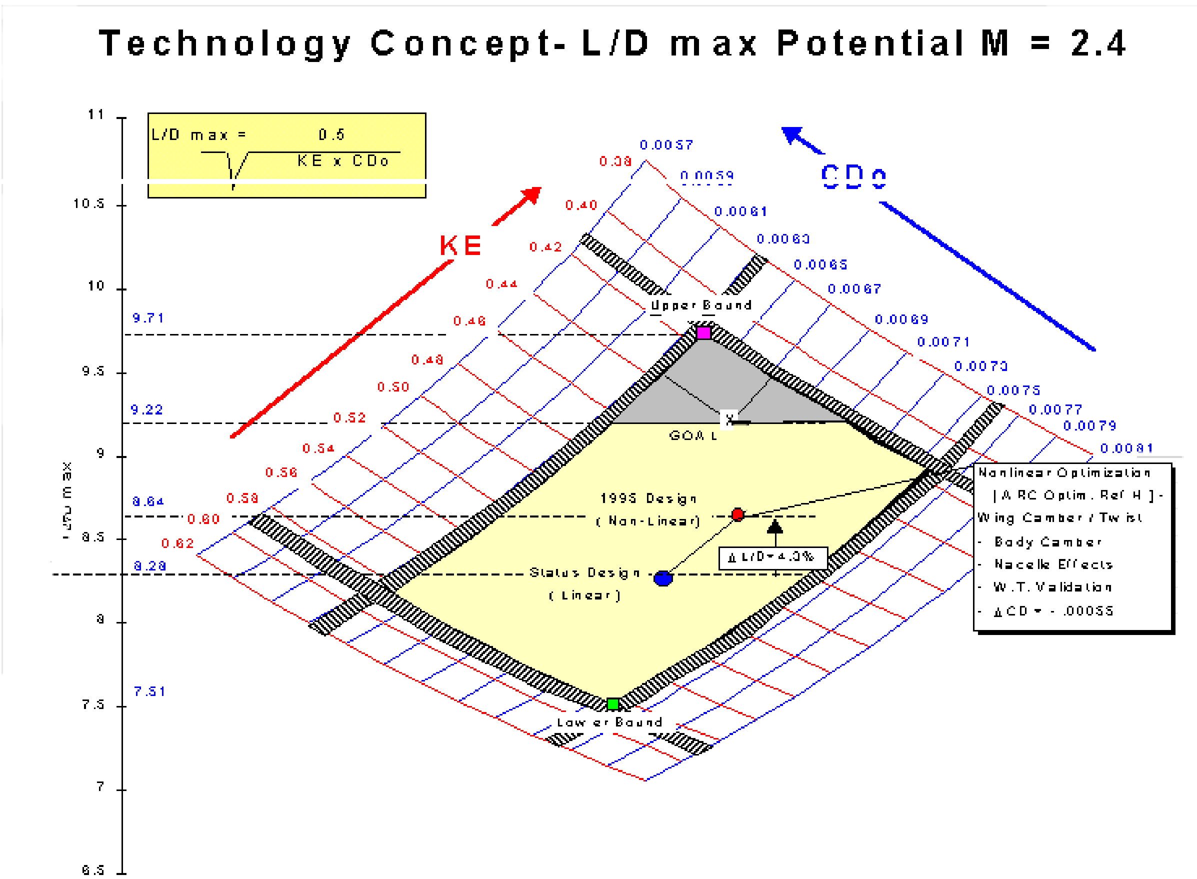
- Configuration thickness and volume constraints
- Manufacturing and surface curvature constraints
- Inlet flow constraints
- Ground clearance effects on aftbody upsweep
- External bumps and fairings
- Roughness and excrescence drag
- Cruise center cg gravity limitations
- Miscellaneous drag items

A "goal" L/Dmax equal to 95% of the achievable L/Dmax is generally used to account for these effects.

Technology Concept- L/D max Potential M = 2.4



Combining the upper and lower boundaries for zero lift drag, CDo, and for drag due to lift factor, KE, defines the region of acceptable designs for a specific configuration. This acceptable design region is shown for the a typical HSCT in the figure above.



The calculated design space can be used to identify the level of aerodynamic efficiency of a specific design relative to the upper and lower L/D bounds.

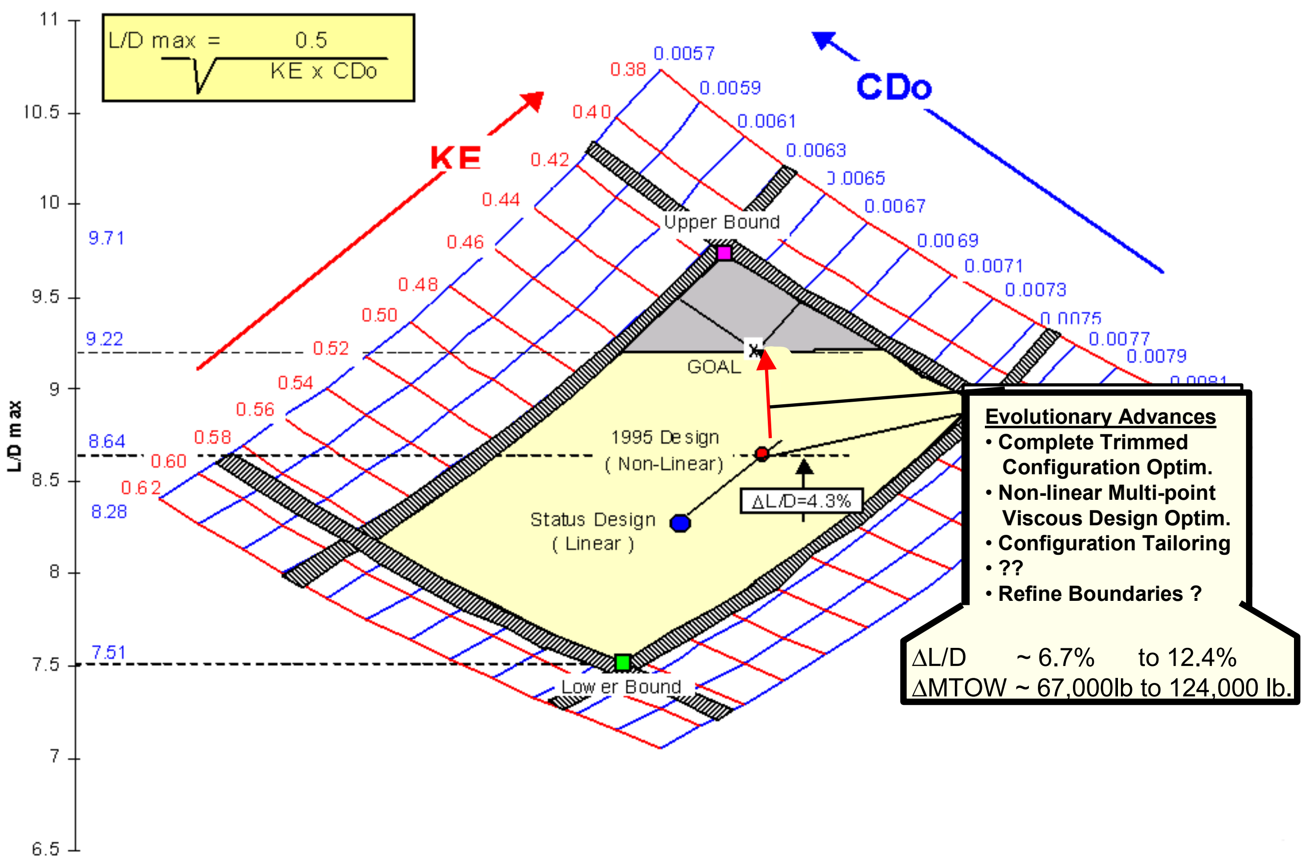
In the above example, the baseline linear theory status design had an L/Dmax that is approximately 10% greater than the lower bound corresponding to the Concorde technology level. This configuration achieved favorable aerodynamics effects from a combination of:

- Reduced wing / body drag from body area ruling interference effects
- Favorable nacelle / airframe volume wave drag effects
- Reduced drag due to lift from the linear theory camber / twist design plus wing reflex to reduce the adverse nacelle on camber effects.
- Favorable nacelle lift interference effects.
- Favorable trim drag

Also shown is the performance improvements achieved to date using nonlinear design optimization. The non-linear design achieved a drag reduction at cruise of 5.5 drag counts ($\Delta CD = -0.00055$) for the wing / body / nacelle configuration. This is equivalent to an increase in L/Dmax of 4.3%.

The design variables included wing camber and twist, body camber, and some wing inboard leading edge thickness increases.

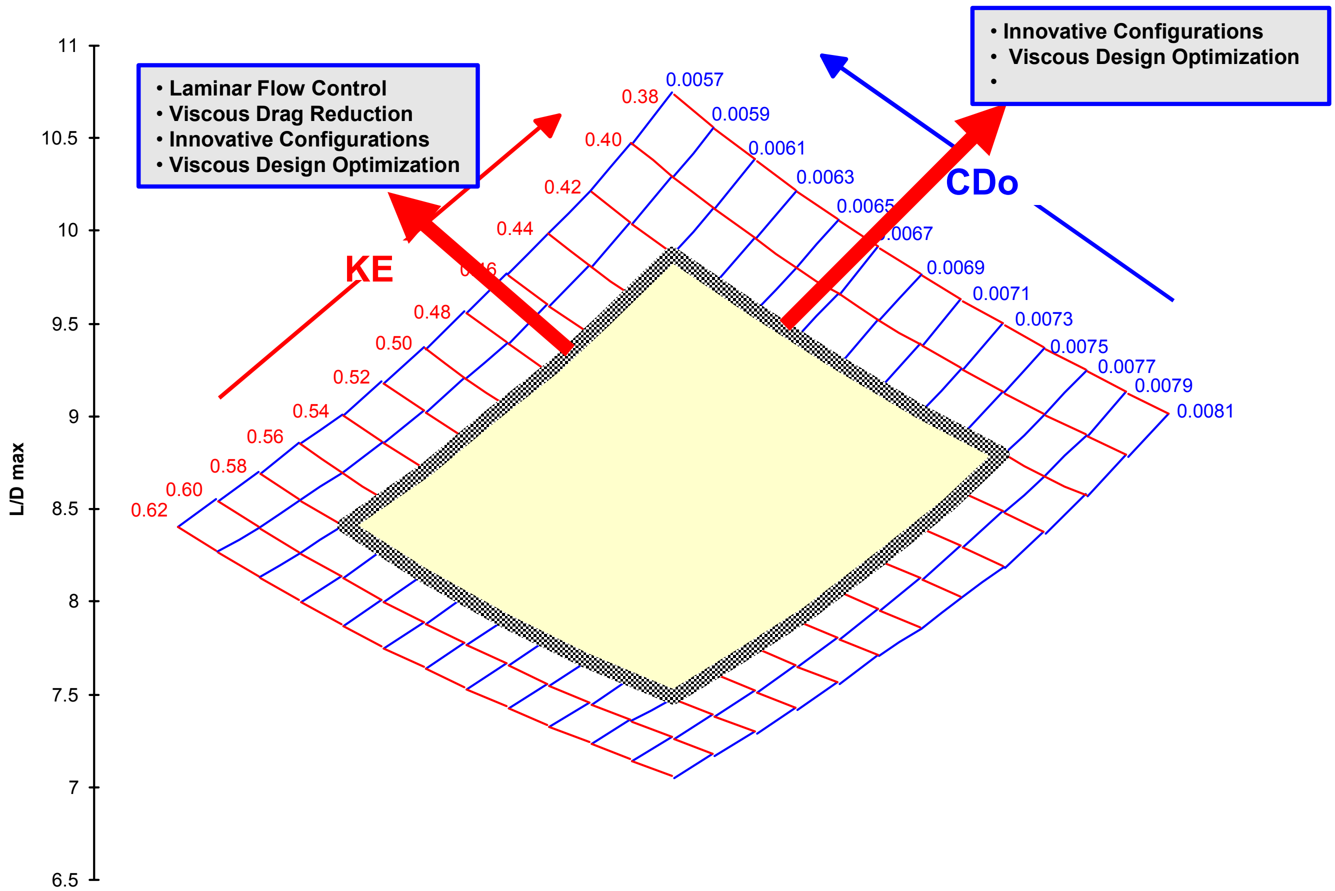
Technology Concept- L/D max Potential M = 2.4



This identifies some of the evolutionary development activities to increase the current level of performance capability to the projected goal levels.

These include complete trimmed configuration viscous optimization and multi-point viscous optimization. In addition, the process to refine the predicted boundaries should be improved.

Impact of Revolutionary Technology Improvements

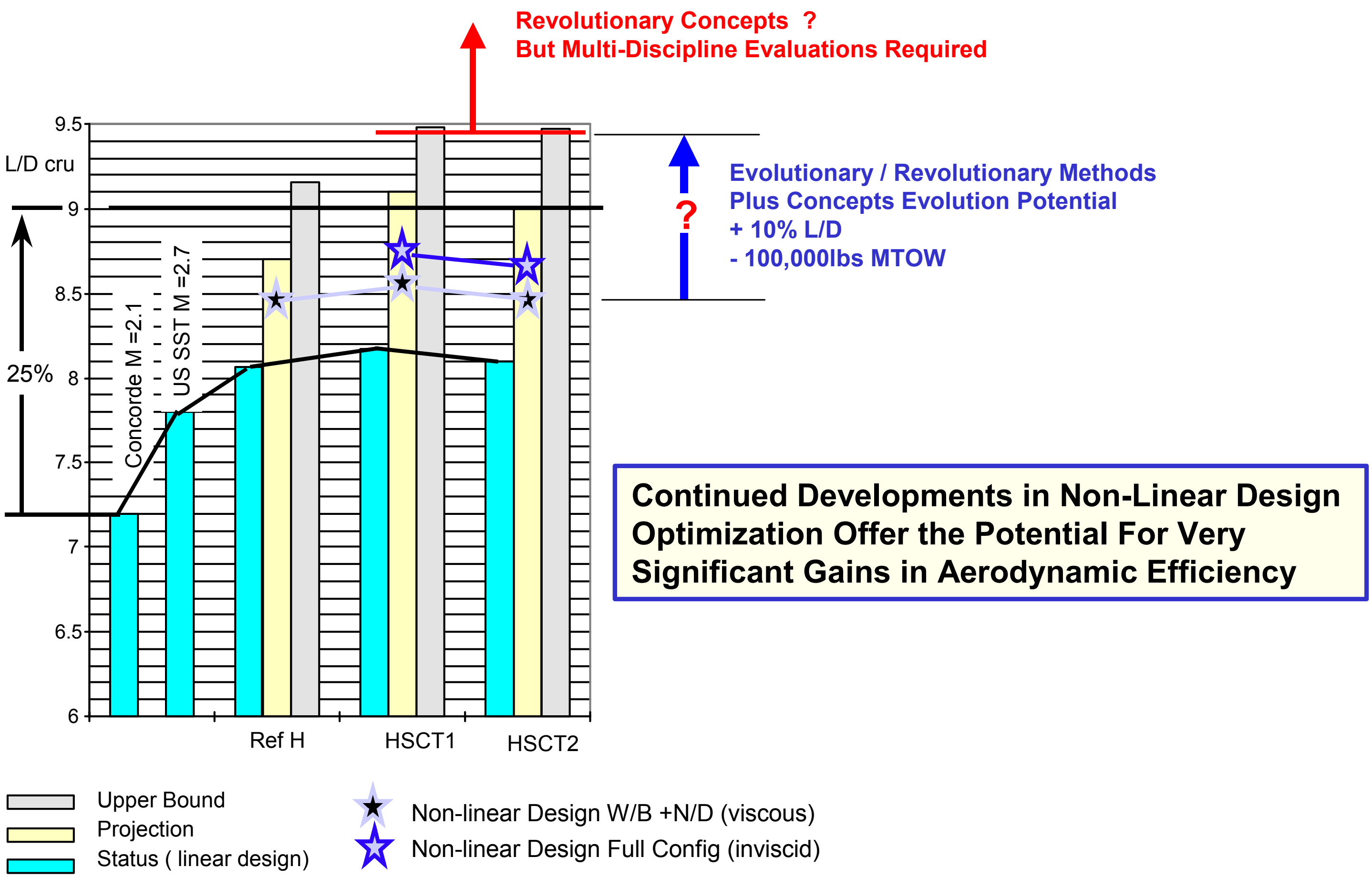


The Revolutionary technology advances include a change to an advanced configuration arrangement or adaptation of methods to reduce the viscous drag such as laminar flow control.

Of course, any change in the base configuration arrangement must involve the entire design team through a multi-discipline design optimization procedures.

Aerodynamic Design Efficiency Comparisons

HSCT: Mach = 2.4



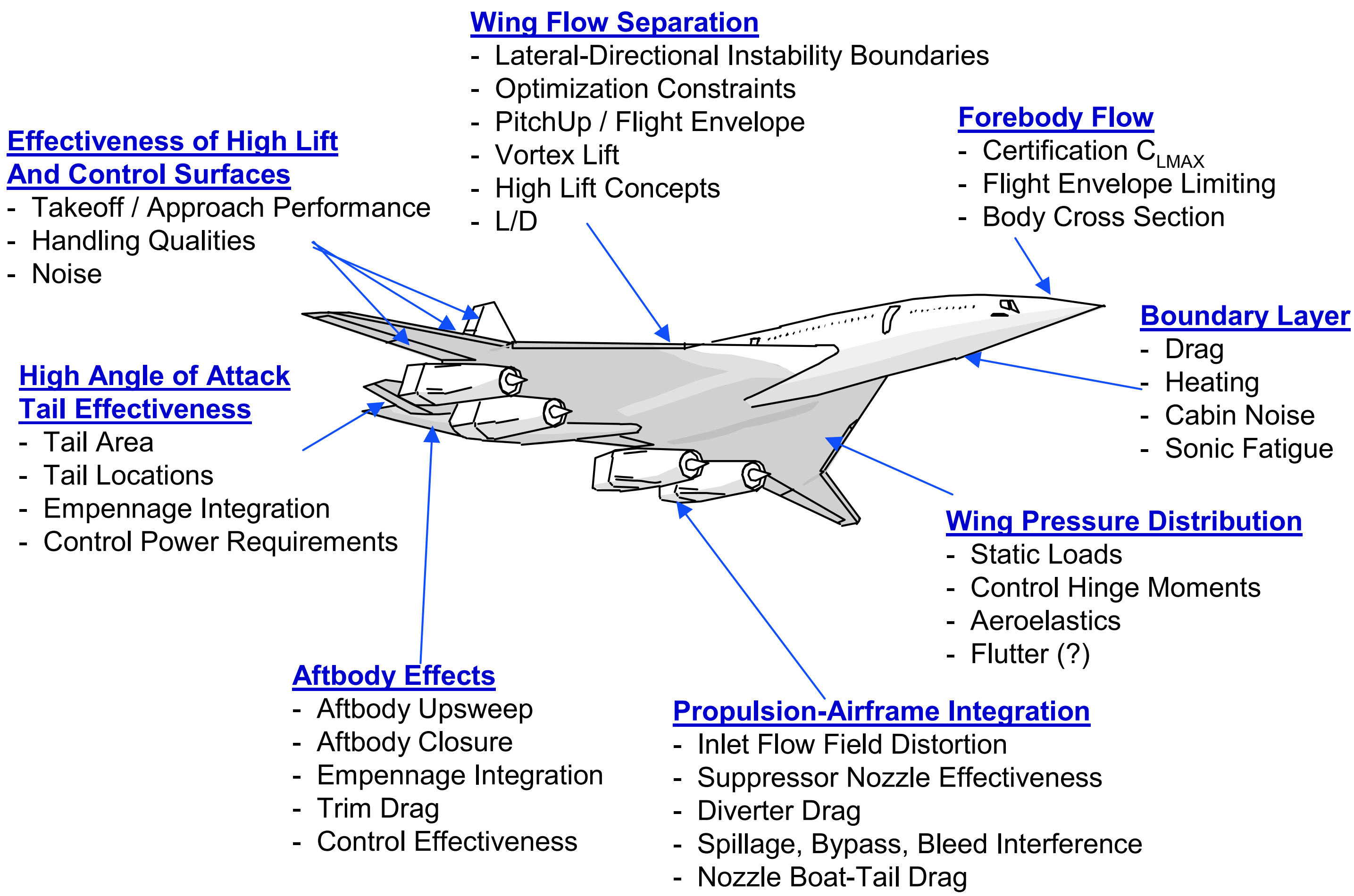
This shows the progress in the improvement in cruise L/D from the Concorde to the present day type of HSCT configuration.

The linear design, advanced technology projections and upper bound levels are shown for the HSCT configuration.

In addition, results of the analyses of the non-linear designs are shown. The viscous analyses of the inviscid non-linear designs typically has shown a loss in aerodynamic performance,

It is shown that there is a potential for a further 10 % improvement for the projected upper bound levels. This would require evolutionary and, or revolutionary methods development plus design refinements for the configuration.

Aerodynamic Design Features Affected by Reynolds Number

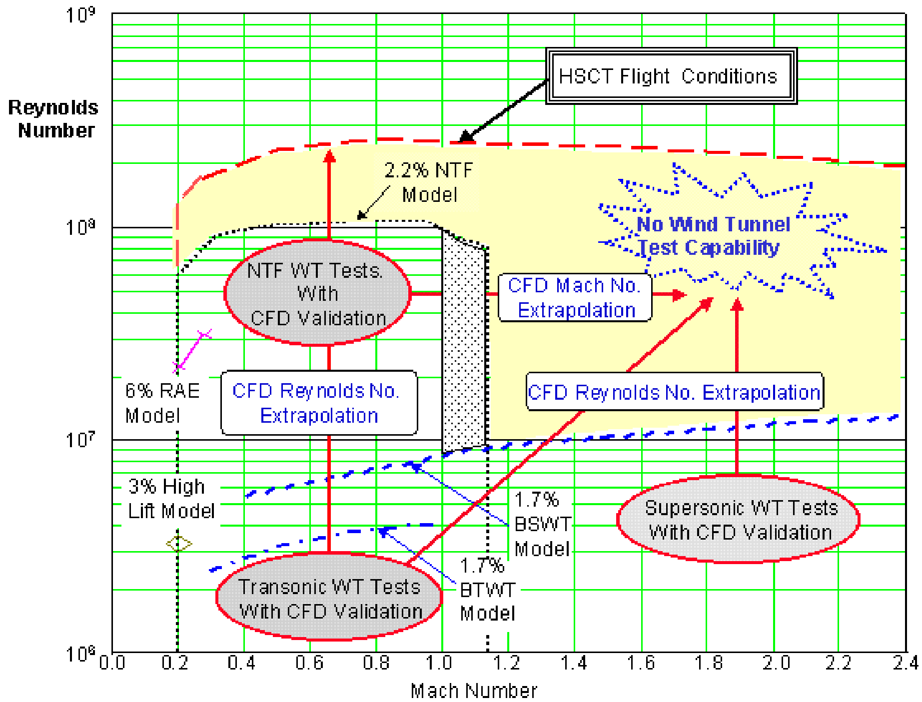


The nature of the flow over the configuration and the effectiveness of the control surfaces can also be very dependent on the Reynolds Number as indicated in the figure above. This can affect many elements of the overall performance characteristics of the configuration.

The wind tunnel is used in conjunction with the emerging CFD design and analysis tools in the aircraft design process as well as in the generation of the performance database.

There are current limits on high Reynolds number test capabilities. In addition the CFD codes need to be validated for prediction of high Reynolds number effects.

Testing Capability and Full Scale Prediction Strategy



Carefully Coordinated CFD and EFD Studies are Required to Validate the Use of the CFD Tools for HSCT Flight Conditions

As shown in Figure above, the current wind tunnel capabilities are unable to represent full-scale conditions for an HSCT configuration.

Two options are generally available to the aerodynamist:

1. Use the wind tunnel to validate and calibrate the CFD methods. The CFD methods are used to predict full scale conditions. This is the typical design process approach.

2. Calibrated CFD methods are used to extrapolate the wind tunnel data to full scale conditions. This is typically the approach to generate the extensive performance database required for the development of a commercial aircraft configuration

General Reynolds Number Concerns

- **CAN WE MAKE CORRECT CONFIGURATION DECISIONS ?**
- **WILL WE WRONGLY REJECT POTENTIAL HIGH (L/D)max CRUISE CONFIGURATIONS OR LIMIT THE DESIGN POSSIBILITIES?**
- **ARE WE DEVELOPING THE RIGHT HIGH-LIFT SYSTEMS AND CONTROL CONCEPTS?**
- **WHEN IS TESTING AT LOW REYNOLDS NO. ADEQUATE?**
- **WHEN IS TESTING AT HIGH REYNOLDS NUMBER REQUIRED?**
- **CAN CFD CODES VALIDATED WITH LOW REYNOLDS NUMBER TEST DATA, ADEQUATELY PREDICT FORCES, MOMENTS AND FLOW CHARACTERISTICS AT FULL SCALE CONDITIONS ?**

High Reynolds Testing Plus Extensive Code Validation Are Very Necessary to Properly Predict and Understand Full Scale Conditions

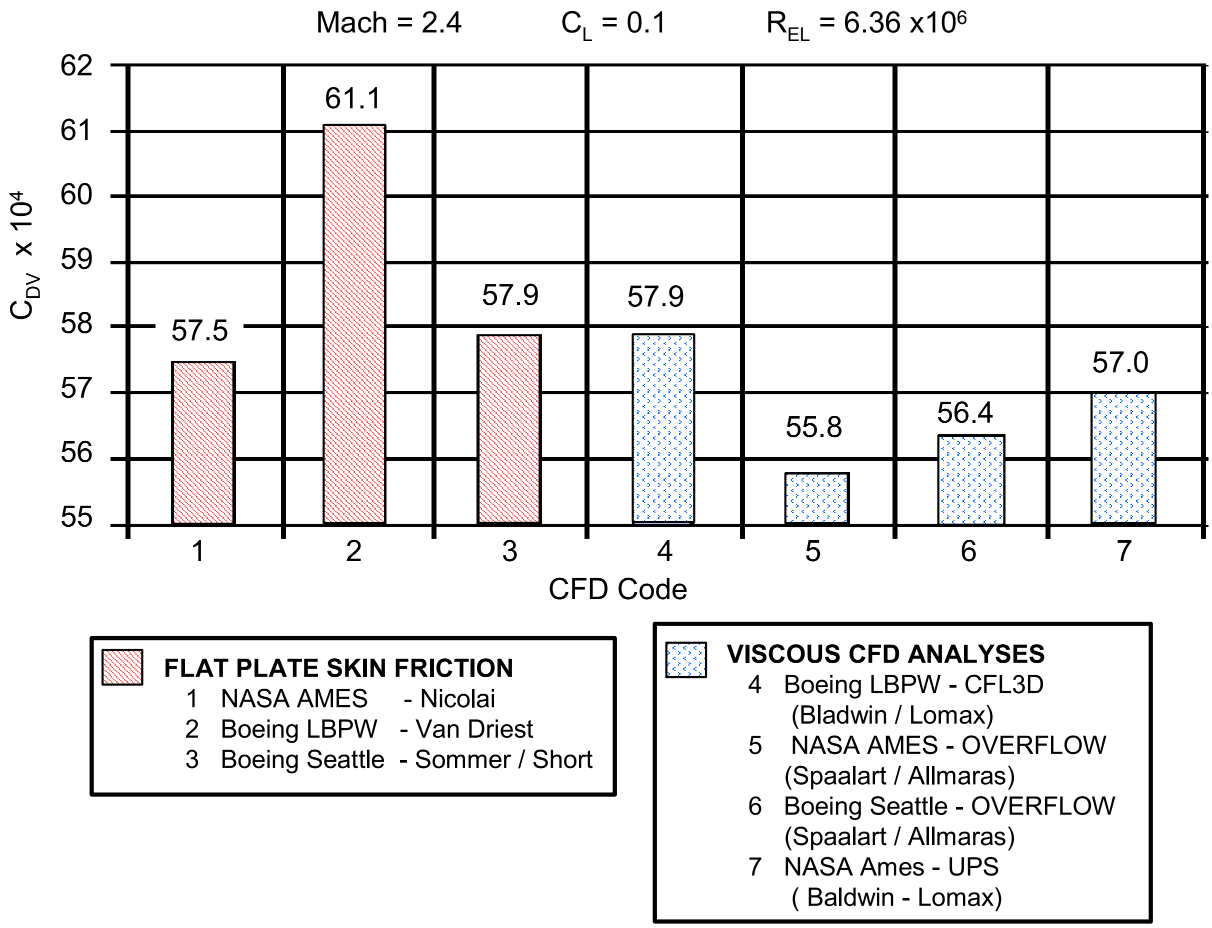
Either of the previously mentioned approaches to predict full scale characteristics of an HSCT leads to a number of fundamental Reynolds Number related questions:

- Are correct configuration decisions being made?
- Are the correct high lift systems and control surfaces being developed?
- When is testing at low Reynolds adequate?
- When is testing at high Reynolds number required?
- Can CFD codes, validated with low Reynolds number data, adequately predict forces, moments and flow characteristics at full-scale conditions?
- Can errors between measured and predicted drag levels mean incorrect representation of the flow physics?

High Reynolds number testing plus extensive code validation are very necessary to properly predict and understand full scale conditions.

The recent HSCT non-linear design activities utilized inviscid codes for the optimization. The viscous analyses of the inviscid optimized designs indicated a loss in potential performance of nearly 3 drag counts. This suggests that at full scale conditions that the full potential might be achievable. This would be equivalent to nearly a 30,000 lb reduction in MTOW.

Comparisons of Fully Turbulent Flow Viscous Drag Predictions ~ Typical HSCT Wing / Body

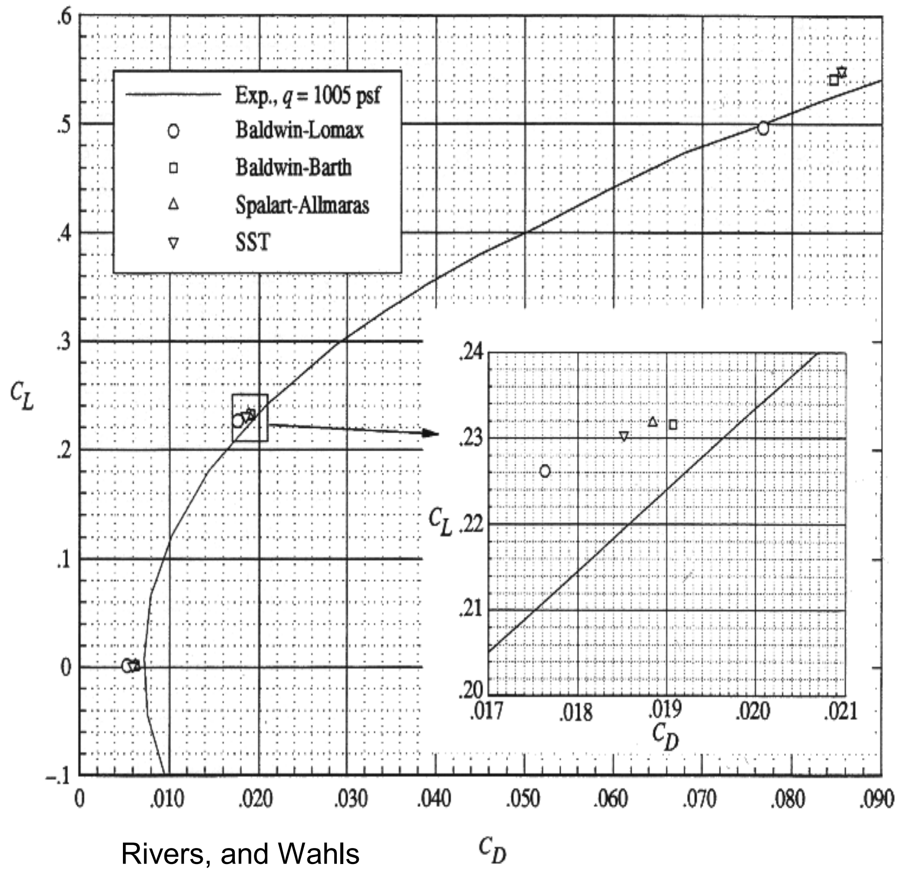


During Recent HSCT design studies significant variations in the viscous drag predictions were obtained by different organizations and with alternate turbulence models, as shown above, for an HSCT wind tunnel model wing plus body configuration.

There were substantial differences in flat plate theory predictions used in the inviscid CFD analyses and also between the CFD predictions obtained with the viscous analyses. This posed a concern since each organization was developing optimized configurations using their favored CFD tools. If the tools produced different answers on a common analysis configuration, how valid would comparisons be of different design options predicted by the different codes?

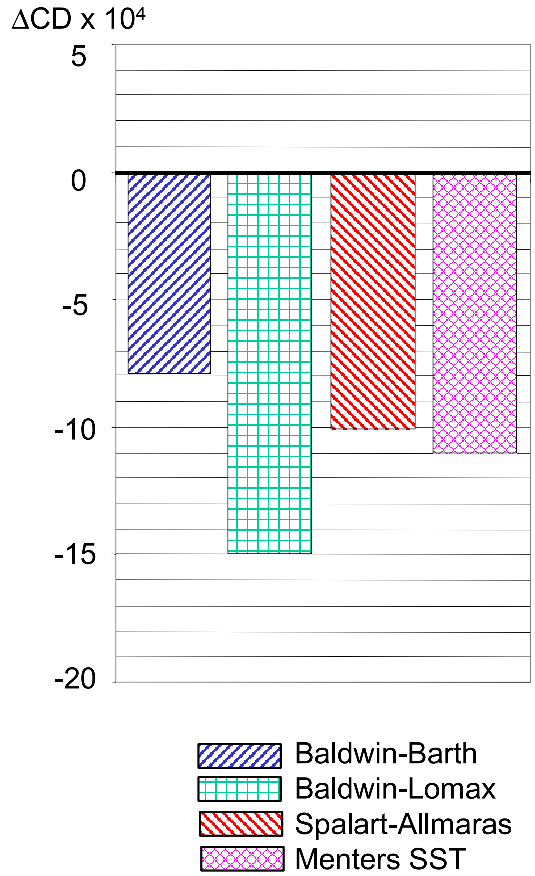
Drag Prediction With CFD Viscous Drag

Mach = 0.90 Rec = 30×10^6



Rivers, and Wahls

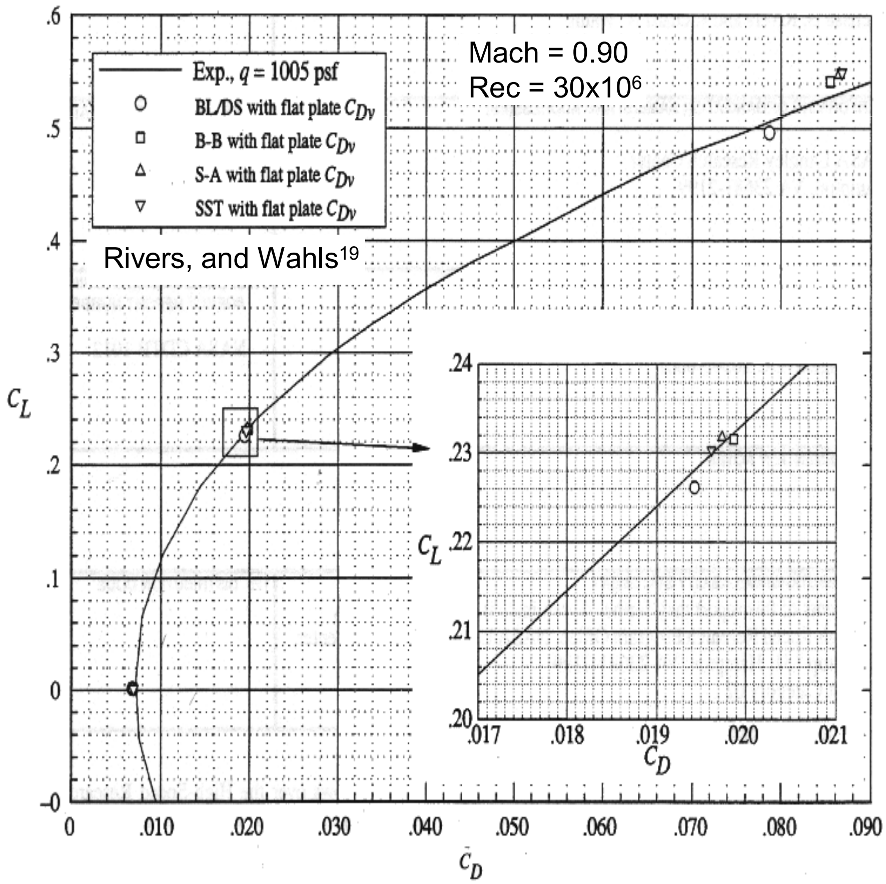
Test minus Theory Increment
α ~ 5 deg

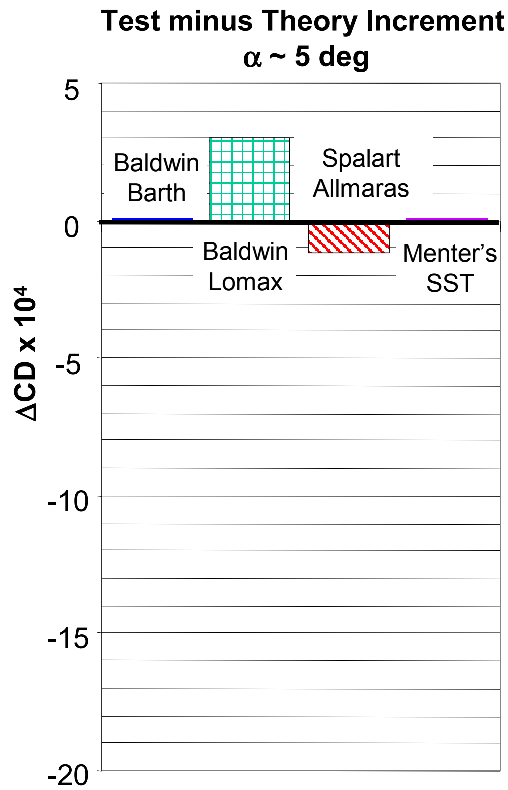


Similar differences between viscous drag predictions using different turbulence models and flat plate skin friction have been observed by Melissa Rivers and Richard Wahls[5]. This figure contains a comparison of an HSCT experimental wind tunnel model drag polar with CFD drag predictions using four different turbulence models.

The differences between the theoretical predictions and the measured drag level at an angle of attack of 5 degrees are also shown. The theoretical predictions were all substantially less then the test data. Theory under predicted the measured drag by 8 to 15 drag counts (-0.0008 to –0.0015).

Drag Prediction With Flat Plate Skin Friction Viscous Drag





Comparisons were made between the CFD predictions of the viscous drag for the model with estimates made using flat plate theory. The differences between the CFD predictions of the viscous drag and the flat plate viscous drag were found to be very similar to the observed test versus theory differences shown. The CFD predictions fall from 12.5% to 28.1% lower then the flat plate predictions of the viscous drag.

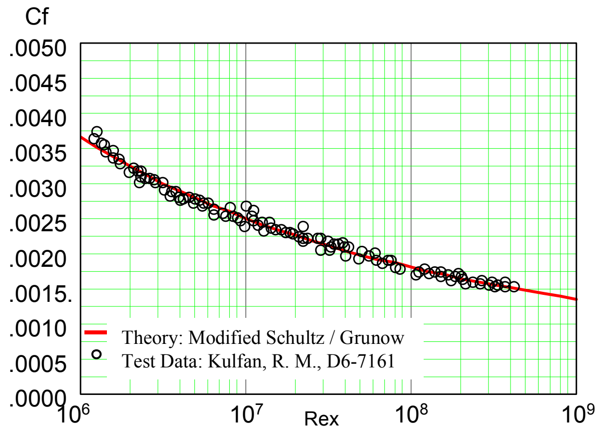
The drag polar predictions with the CFD viscous drag predictions replaced by the flat plat theory nearly match the test data very closly as shown in the Figure. There appears, therefore, a substantial and inconsistent error in the CFD viscous drag predictions.

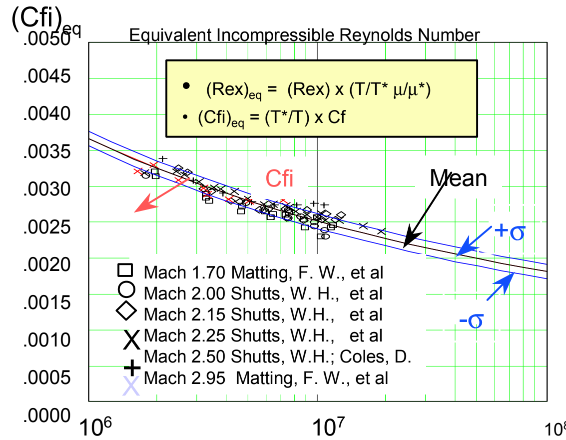
It was felt that an important element, in validating the viscous drag predictions of any Navier Stokes code, is to make sure that predictions of the local and average skin friction drag and boundary layer characteristics must match the "simple" flat plate measured skin friction test data over the range of Mach numbers and Reynolds for which the codes will be used. This process would help to evaluate the applicability of the various turbulence models. The validated codes and calculation schemes could then be applied to increasingly more sophisticated configuration geometries. A strategy was developed to help resolve the differences in the observed on the viscous drag predictions for an HSCT configuration. Results of first two phases were completed.

The first phase, involved the formulation of an experimental database[6] of fully turbulent flow skin friction measurements on flat plate adiabatic surfaces at subsonic through supersonic Mach numbers and for a wide range of Reynolds numbers.

In the second phase[7], CFD flat plate viscous drag predictions were made using a number of different Navier Stokes codes, analysis schemes and participating organizations. These included Boeing Phantom Works, Long Beach, (BPW-LB); NASA Ames Research Center, (ARC) and Boeing Commercial Airplane Group in Seattle, (BCAG).

Incompressible Local Skin Friction Data





- **The Mean Error Between Modified T* Skin Friction Equations and the Experimental Skin Friction Data measurements ~ 0.0 %**
- **Incompressible Experimental Cf Data: 1 σ = +/- 2.7%**
- **Supersonic Experimental Cf Data: 1 σ = +/- 3.8%**
- **Comparison with Modified Cf equations ~ Comparison with Mean of the Test data.**

Flat plate skin friction data was obtained from a number of experimental sources. These data cover a wide range of Mach numbers and Reynolds numbers. Comparisons were made with various flat plate theories to select the theory that most closely matched the test data. The results of these assessments are presented in the Reference 6

The flat plate theories are based on the reference temperature method. This method assumes that the incompressible skin friction equations apply to supersonic Mach numbers provided that the density and viscosity are calculate at some reference temperature that represents the variation of temperature across the boundary layer.

The left figure shows the comparison of the modified Shultz / Grunow equation with incompressible test data. Statistical analysis of the differences between the test data and corresponding Cf predictions shows that the mean of the differences is ΔCf = -.000000671 which corresponds to an average difference of 0.13% .The standard deviation of data about the mean is approximately 0.7 counts of drag (ΔCf = 0.000067) which corresponds to 2.8% of the corresponding predicted value.

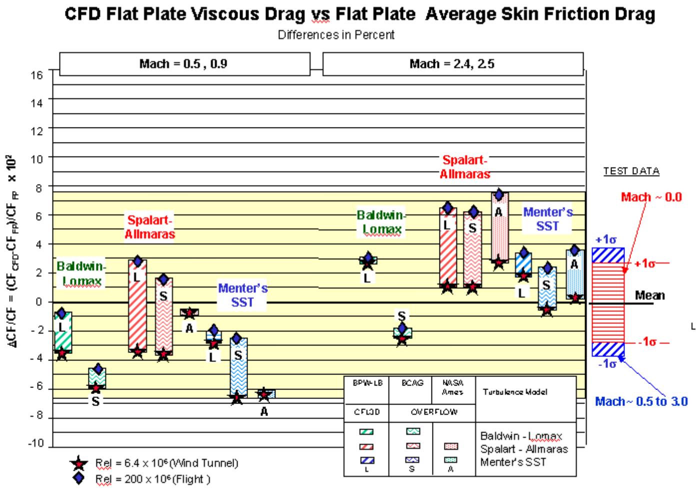
The modified Shultz / Grunow equation therefore appears to provide an accurate estimate of incompressible local skin friction coefficient over the entire range of Reynolds Numbers covered by the test data.

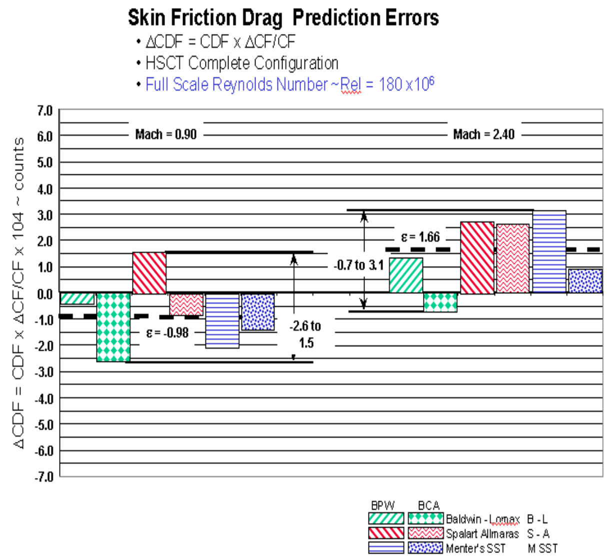
The figure on the right shows transformed experimental skin friction data for six different sets of test data obtained at Mach numbers from 1.7 to 2.95. The Kulfan T* equation[6], was used for the transformation process. The “mean” of the differences between the transformed skin friction data and the incompressible Cf predictions is essentially zero.

The “ scatter” of the test has a standard deviation of about 1 drag count (ΔCf ~ 0.0001). This corresponds to about a 3.8% scatter of the test data about the theoretical Cf predictions over the entire Reynolds number range and Mach number conditions represented by the test data.

The “scatter” in the compressible theoretical - experimental transformed skin friction increments are only slightly higher than the scatter in the incompressible data. (0.7 counts versus 1 count).

Results of CFD Flat Plate Viscous Drag Prediction Validation Study





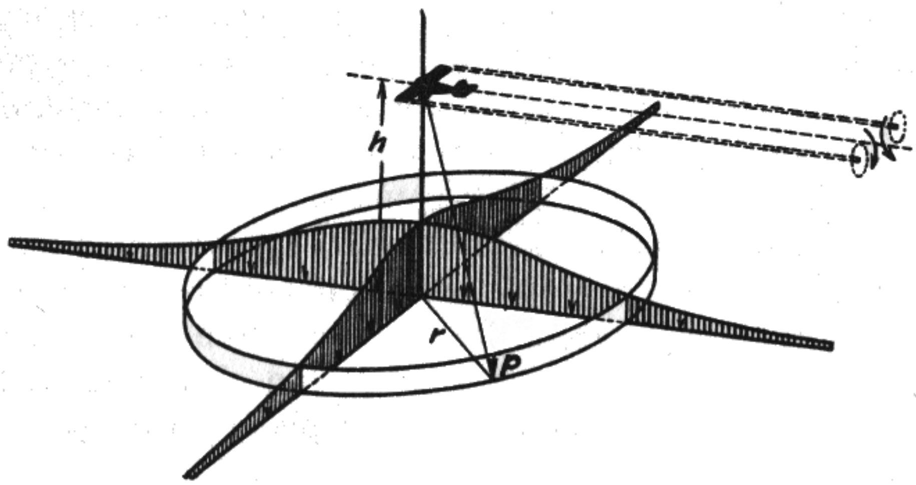
- The Differences in the CFD Predictions of Skin Friction Greatly Exceed the Scatter in the Test Data.
- The Uncertainty in the Friction Drag Predictions at Full Scale is Equivalent Reynolds (DCD ~ 0.00038) is Equivalent to an an Uncertainty in the MTOW of Nearly 40,000 lbs
- Carefully Coordinated Validation Test Program(s) are Desired, Involving CFD Development and Application Communities and the Experimental Community

The figure in the upper left contains a comparative summary of all of the CFD average skin friction predictions made in the study[8], relative to the flat plate theory and hence to the mean of the experimental flat plate. The comparisons shown are for Mach 0.5 or 0.9 and Mach 2.4 or 2.5.
The scatter band for the test data relative to the flat plate theory is also shown in the figure. It us seen that the variations in the CFD predictions far exceeds the scatter of the test data.
Viscous drag predictions for a commercial aircraft are typically used in three common applications

- Prediction of the drag of a scale model at wind tunnel conditions
- Prediction of the drag of an airplane at full-scale conditions
- Extrapolation of wind tunnel results to full-scale conditions

In order to understand the potential impact of the uncertainties in the viscous drag predictions, the differences between the CFD predictions and the flat plate theory have been converted into airplane drag counts. The equivalent drag counts are obtained by multiplying the average skin friction increments by the wetted area ratio, Awet/Sref, for a typical HSCT type configuration of approximately 3.5. The prediction errors at full scale conditions are shown in the figure on the right,
At the subsonic condition, the average error of all predictions is about 1 drag count low and the range of errors varies from – 2.6 to +1.5 drag counts.
The average error at Mach 2.4 is +1.66 drag counts with a range of errors from –0.7 to +3.1 drag counts.
As shown previously mentioned, a one count cruise drag error, (ΔCD ~ 0.0001) is equivalent to a structural weight error of about 2,000lbs and would impact the overall gross weight by nearly 10,000lbs. Hence, the impact of the uncertainties in the existing CFD predictions of the friction drag, are indeed very significant.
Resolution of this uncertainties in the CFD predictions will require a carefully coordinated test validation program involving those involved in testing, CFD development and CFD applications

Subsonic Airplane Ground Pressure Field



LIFT: $$L = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} p\,dx\,dy = \int_{r=0}^{\infty}\int_{\theta=0}^{2\pi} p\,dr \bullet r\,d\theta$$

$$p_{\max} = \frac{W}{2\pi h^2}$$

For: W = 400,000 lbs
h = 35,000 ft
p_{max} = 0.000052 lbs/ft^2

When an airplane is flying over the ground the weight of the airplane is transferred to the ground as an increased pressure field on the ground. For a low speed subsonic airplane, the increased pressure field has rotational symmetry with respect to the airplane and extends over a very large area. The increased pressure field travels at subsonic speeds with the airplane.

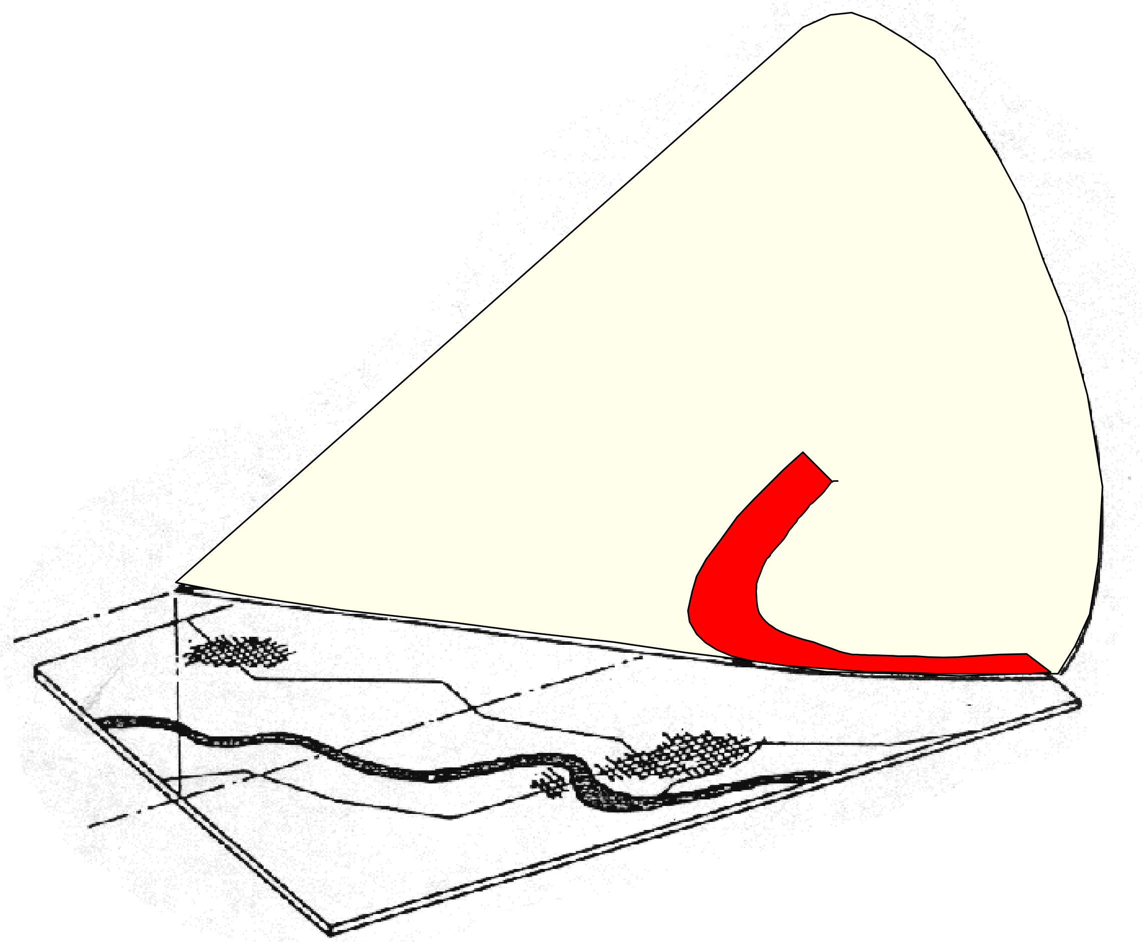
The center of pressure of the induced pressure field is directly below the airplane. The maximum pressure occurs at the center of pressure and is given by the expression:

$$p_{\max} = \frac{W}{2\pi h^2}$$

The maximum ground pressure is extremely small since it varies inversely with the height of the airplane squared.

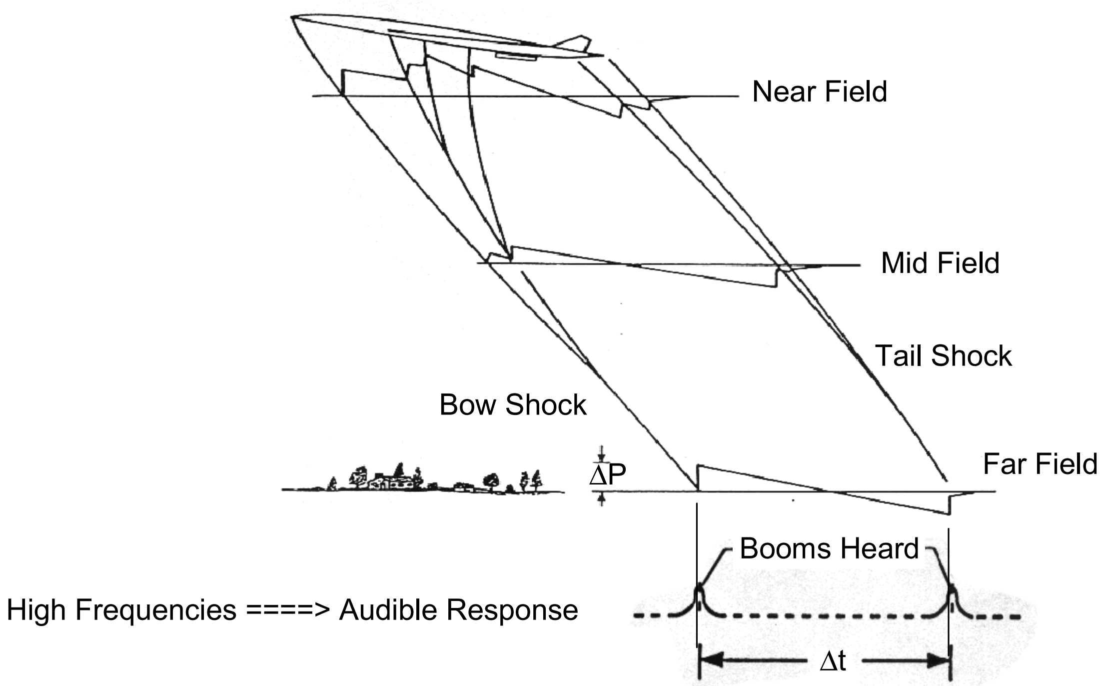
For the example given for a typical subsonic transport with a weight of 400,00 lbs at an altitude of 35,000 ft, the maximum pressure is an imperceptible level equal to 0.000052 lbs/ft^2

The Sonic Boom Pressure Field



The pressure field generated by a supersonic airplane is confined between two shock cones. One emanating from the nose of the airplane, called the bow shock cone, and a second emanating from the tail which is called the aft or tail shock cone. The intersections of the shock cones with the ground each delineates a hyperbola.

Pressure - Signature Propagation



A typical HSCT configuration typically generates an entire system of shock waves as shown in the near field close to the airplane [9,10].

At large distances from the airplane, as indicated by the mid field, the shock wave system tends to steepen and begin to coalesce.

At extremely large distances in the far field near the ground, the shock system will typically coalesce into a bow shock and a tail shock.

At the bow shock, a compression occurs in which the local pressure, p, rises rapidly to a value Δp, above the atmospheric pressure. Then a slow expansion occurs until some value below atmospheric pressure is reached, after which there is another rapid compression at the aft shock.

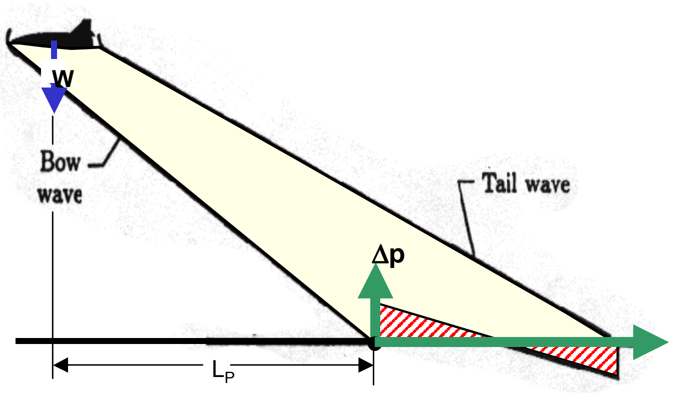
Generally the bow shock and the aft shock are of similar strengths, and the pressure varies linearly between the two shocks. This nominal sonic boom signature is called the “N” wave. This “N” wave moves at supersonic speeds with the aircraft.

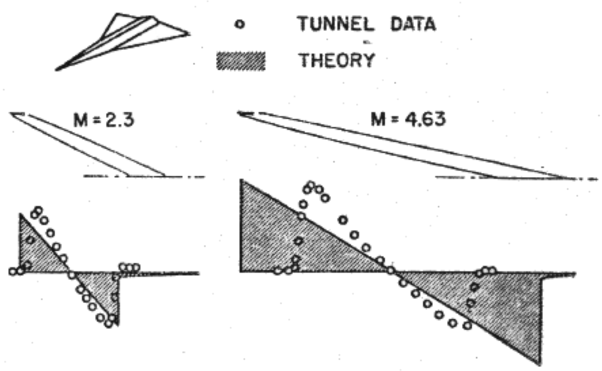
The region between the defined by the area between the intersections of the bow shock and the tail shock is known as the primary sonic boom carpet. Receivers in this carpet detect the sonic boom, that is the “N” wave as the airplane passes.

The primary carpet sweeping by a person outside on the ground would result in a audible response as shown in the figure. Since the ear detects changes in pressures only above a certain frequency, it will respond only to the steep parts of the pressure waves and not to the gradual pressure changes in between.

Typically the time between the front and rear shock is of the order of 0.1 sec or greater and the ear will probably detect two loud “booms”. The degree of indoor disturbance or structural damage attributed to the pressure signature is believed to be more dependent on the impulse (the integral of the positive portion) and the length of the signature.

Supersonic Airplane Ground Pressure Field





Pressure Supports the Airplane Weight $$W = \iint_{A_{CARPET}} \Delta p dx dy$$

Pressure Distribution Cancels the Airplane Moment : $$W \bullet L_P = -\iint_{A_{CARPET}} (x \bullet \Delta p) dx dy$$

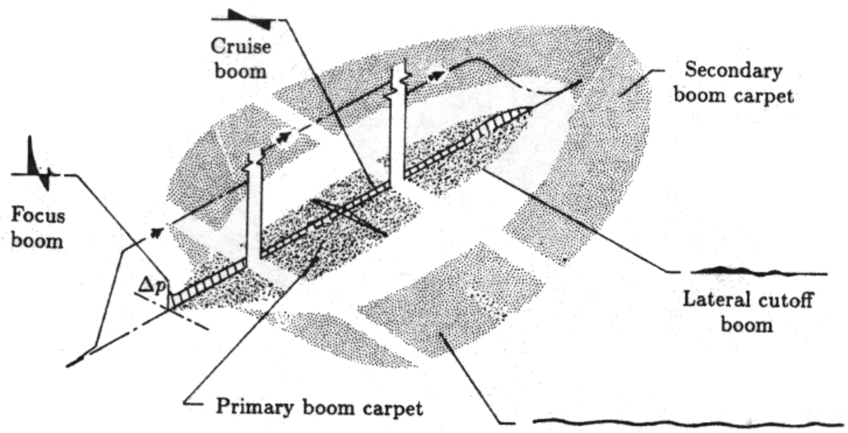
High Frequencies and Shock Strength (ΔP_{MAX}) → **Outdoor Disturbance**

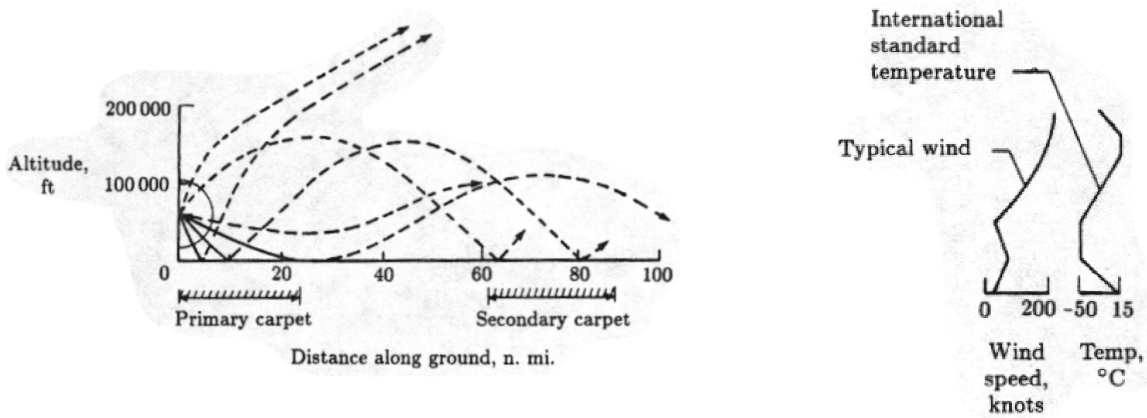
Low Frequencies and Shock Impulse → **Indoor Disturbance**

$$\int_{\Delta P > 0} \Delta P(x) dx$$

Just as in subsonic flight, the weight on a supersonic aircraft is supported by the pressure distribution on the ground that travels at the same ground speed as the aircraft. The supersonic ground pressure distribution, in addition must balance the moment of the airplane weight vector relative to the center of pressure on the ground.
The pressure signature must have both a positive pressure region and a negative pressure region in order to create the reacting moment. The magnitude of the positive pressure region force vector exceeds the magnitude of the negative pressure region force vector by the weight of the airplane.
The portion of the pressure distribution that supports the airplane weight acts on a much smaller region then the corresponding region for a subsonic airplane. Therefore, even this pressure distribution component is many times larger then that for a subsonic airplane.
Nearly all of the ground pressure distribution is due to the cancellation of the airplane weight moment. This results in the magnitude of the pressure distribution for a supersonic airplane being many orders of magnitude greater than that for a subsonic airplane even for flights at altitudes much higher then the cruise altitude for subsonic airplanes.
This also explains why the pressure signatures grow rapidly as the cruise Mach number is increased since the airplane weight vector moment increases as the Mach cones sweep further aft.
The formation of a sonic boom signature for high supersonic flights is therefore inevitable.
The high frequencies and the shock strength determine the perceived outdoor disturbance. The lower frequencies and the impulse associated with the positive pressures appear to determine the response to a person inside of a building.
The goals relative to sonic booms include understanding the factors affecting the nature of the pressure signature, determine both active and passive means to control the magnitude and shape of the signature and determine what magnitudes of the sonic boom will be considered environmentally acceptable.

Sonic Boom Ground Exposure Carpets





The upper figure shows schematically the nature of the sonic boom carpet for a flight such as the Concorde[11]. Two ground exposure patterns in which booms are observed, are shown. The primary boom carpet contains the normally observed sonic boom overpressures and results from wave propagation through only that part of the atmosphere below the configuration. The total width of the primary carpet is on the order of 25 miles on each side of the airplane.

A secondary boom carpet may also exist which involves that portion of the atmosphere both above and below the aircraft. The secondary carpet may extend between 60 yo 100 miles on each side of the airplane. Between the primary and secondary carpets exists a region in which no sonic booms are heard.

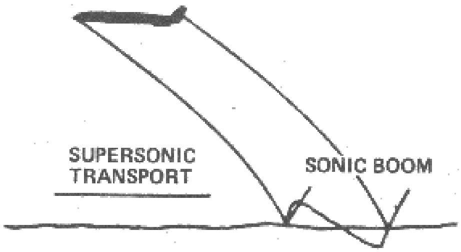
The wave forms vary dramatically in various areas of the carpet. The strongest pressures exist near the middle of the primary carpet and tend to degenerate into weak sound waves near the edges of the primary carpet. In the regions of the secondary carpet the disturbances tend to be rather weak in intensity but persist over longer times.

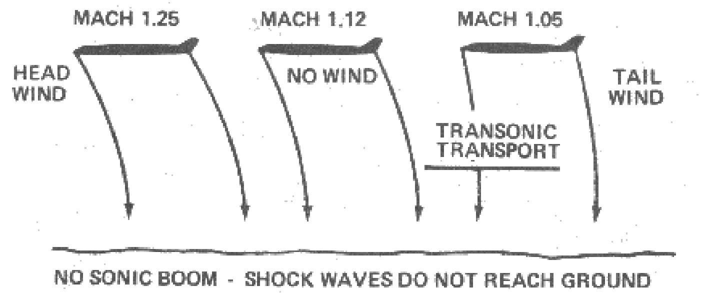
The lower figure shows the way in which the atmosphere is involved in developing the primary and secondary carpets. On the right side of the lower figure are shown the typical temperature and wind profiles.

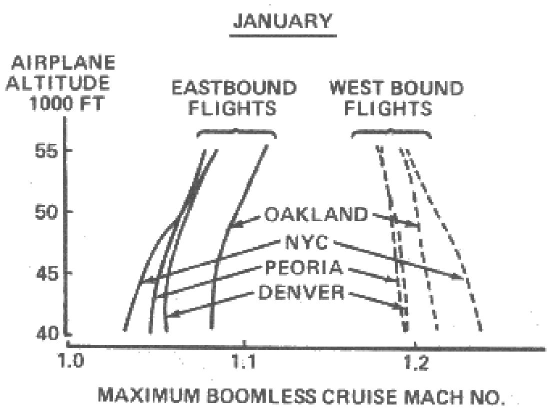
The downward propagating rays impact the ground to form the primary carpet. At some distance from the middle of the primary carpet, the rays refract from the ground and this defines the lateral extent of the primary carpet.

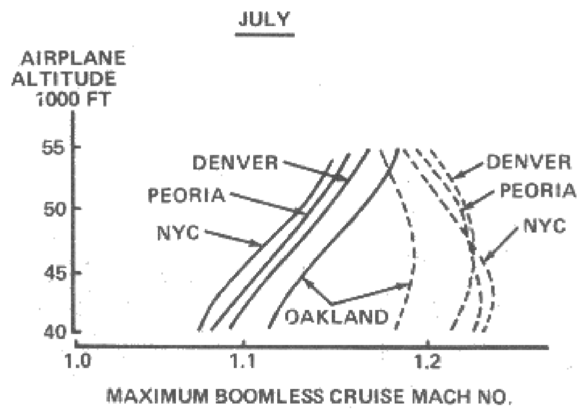
The rays in the secondary carpet may arrive in two ways. They may travel directly to the ground as a result of bending in the upper atmosphere, or they may first impinge in the primary carpet and then reflect upward from the service and then bend downward after traveling through a portion of the upper atmosphere.

Sonic Boom Free Supersonic Flight





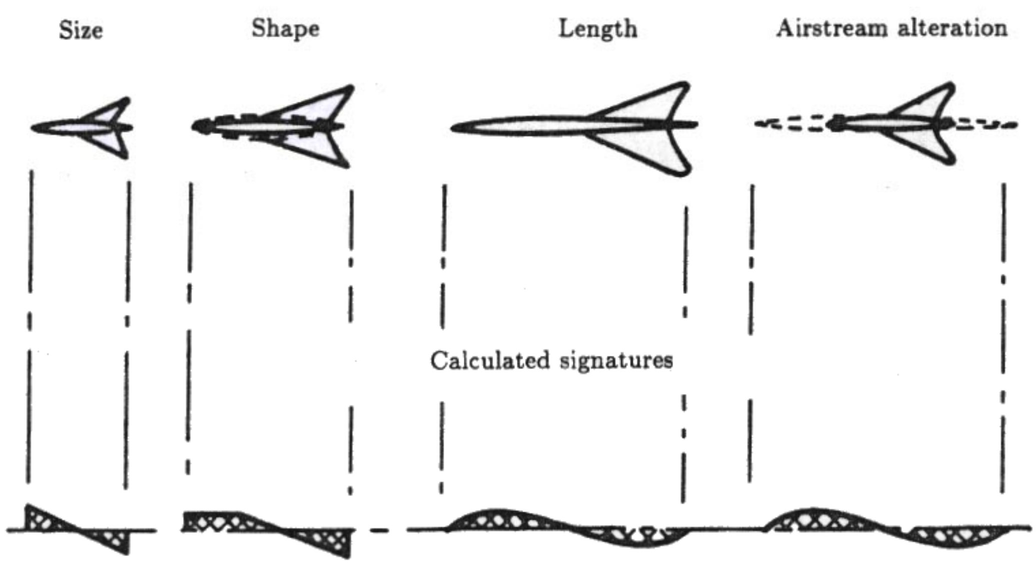


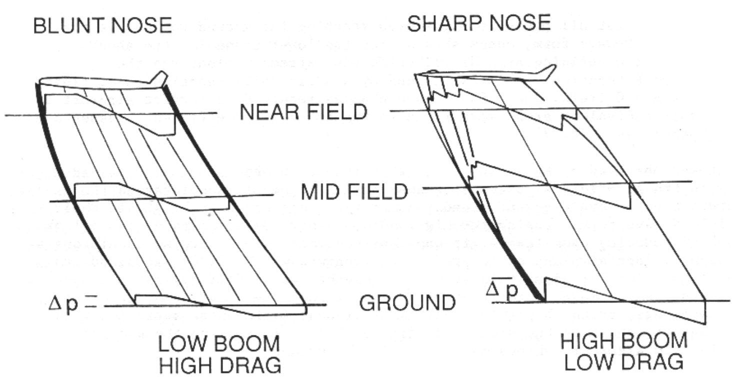


Boom free supersonic flight is possible as long as the ground speed is less then the speed of sound at the ground. Depending on the flight direction, season and airplane altitude, cruise Mach numbers in the range of 1.05 to 1.25 are allowed for east to west and west to east transcontinental US flights [12,13].

The use of advanced Gravitational Positioning Systems, should provide a continuous and accurate measure of the ground speed. This together with local information about the temperature and wind should allow the boom free flight conditions to be determined,

Sonic Boom Minimization





- **Sonic Minimization Efforts Have Focused on External Disturbance of the Sonic Boom**

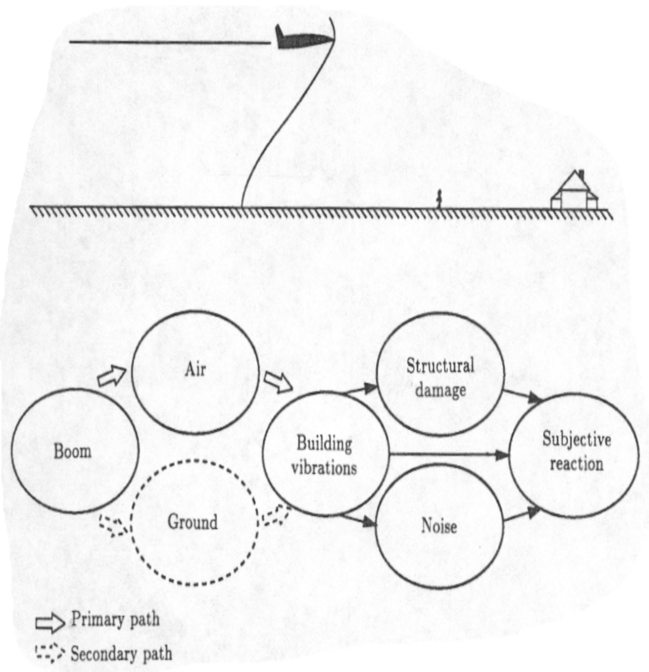
Minimizing sonic booms through aircraft design modifications has been investigated by many researchers and lower bounds have been established. Some of the approaches that have been considered are shown above [14].

These include reducing the size through reductions in gross weight, careful and skillful shaping of the configuration, increasing the aircraft length or perhaps using an energy source to effectively increase the apparent length of the airplane.

The lower portion of the figure shows the results for a blunt nose configuration that has low boom but high drag as compared to a sharp nose airplane that has lower drag but much higher stronger booms.

The primary focus of sonic boom minimization studies has been to reduce the external disturbances to an acceptable level. For a given airplane configuration and flight conditions, minimization processes that tend to reduce the shock level of the signature and the outdoor disturbance, tend to increase the impulse of the signature [14]. Therefore, efforts to minimize both situations may be extremely difficult or impossible to achieve.

Factors Involved in Boom Exposures



High Frequencies and Shock Strength (ΔP_{MAX}) → Outdoor Disturbance (Can be Reduced)

Low Frequencies and Shock Impulse $\int_{\Delta P>0} \Delta P(x)dx$ → Indoor Disturbance (Inevitable ?)

Research Needs in the Area of Sonic Boom Response

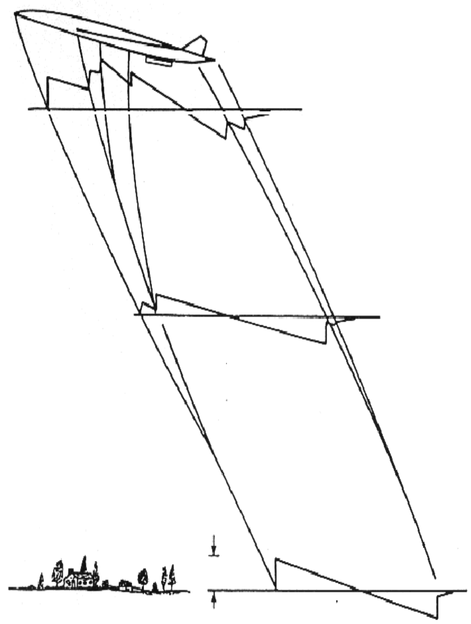
- Human Response
  - Loudness, Annoyance, and Startle
  - Infrasound, Cumulative and Temporal Effects
  - Indoor/Outdoor Effects on Impact Minimized Booms
  - Health ~ Epidemiological Studies, Sleep Disturbance
- Structural Response
  - Damage to Unconventional / Historic Structures
- Development of Acceptability Criteria
  - Human Response
  - Structural Damage
  - Politics and Ecomomics

One of the critical elements of sonic boom activities is determining the response to the sonic booms. There is considerable there is considerable concern about the manner in which people and structures respond to sonic booms and how such responses will affect the community acceptance of supersonic overland flight.the nature of the response problem is illustrated in the figure above.
The sketch suggests two different exposure situations for people.
In one case, the person is outdoors and is impinged on directly by the sonic boom.
In the other case the observer is inside the building and the waves impinge on the building. The building then acts as a filter which determines the nature of the exposure stimuli reaching the inside observer.the ingredients of the indoor stimulation is shown in the chain diagram.
The sonic boom induced excitation which causes the building to vibrate may arrive either through the ground or through the air. It is generally considered that the air path is the more significant one and is called the primary path. Building vibrations may be observed directly by the subject. The person may also sense the vibration induced noise. In extreme cases , superficial damage to the structure may occur.
Where as the outside exposure is related to the strength of the booms, the inside exposure is considered to be related to the impulse of the boom, which depends in the total positive pressure on the signature along with the exposure time.
The chart above lists some of the research needs in the very important area of sonic boom response design criteria.

Overland Sonic Boom Concerns

No Direct Control

1. Atmospheric Density and Wind (Large - Scale Variations With Altitude)
2. Atmospheric Absorption (Molecular Absorption of High Freq. Energy Affects Shock Wave Rise Time)
3. Low Altitude Turbulence (Random Variations in Shock Wave Intensity)
4. Secondary Booms (Low Intensity Noise Beyond the Primary Boom Carpet)



A. Configuration Feasibility (Special Aerodynamic Shaping May Result in Drag and Weight Penalties)

B. Climbout Boom (Higher Boom Intensity due to Low Altitude, Heavy Weight, and Acceleration Focus.

C. Human Response (Indoor and Outdoor)

D. Design Verification

Low Sonic Boom Research ==> Revolutionary Technology

- **Exploit the Possibility of Boom Free Flight**
- **Develop Appropriate Design Criteria Based Determining the Acceptable levels of Sonic Boom**
- **Is Minimization of Outdoor Disturbance Plus Internal Disturbance Possible ?**
- **Develop Configuration Concepts That Either Actively and / or Passively Reduce the Sonic Boom.**
- **Ultimately Reduced and/or Full Scale Flight Testing is Required**

This chart summarizes the overland sonic boom concerns. The list on the left include considerations over which we have no control. But it is very important to develop an understanding of each of these factors.
The list on the right lists things that we can do in the design arena or things that we need to develop an accurate understanding about.

The recommended categories of critical and needed research are also summarized above. These are the critical elements to allow the revolutionary concept of acceptable overland supersonic flight for a supersonic commercial airplane to become a reality.

Summary

In Summary, it has been shown that both evolutionary and revolutionary technology are significant and should included in any long term advanced technology program. An innovative technology program must also include both “idea driven and “product” driven development processes.

The development of a mature innovative technology most often takes a long time and may ultimately require flight validation. The development time for a new technology and the selection of the appropriate technology are both key factors in determining the impact on the market share for a new airplane.

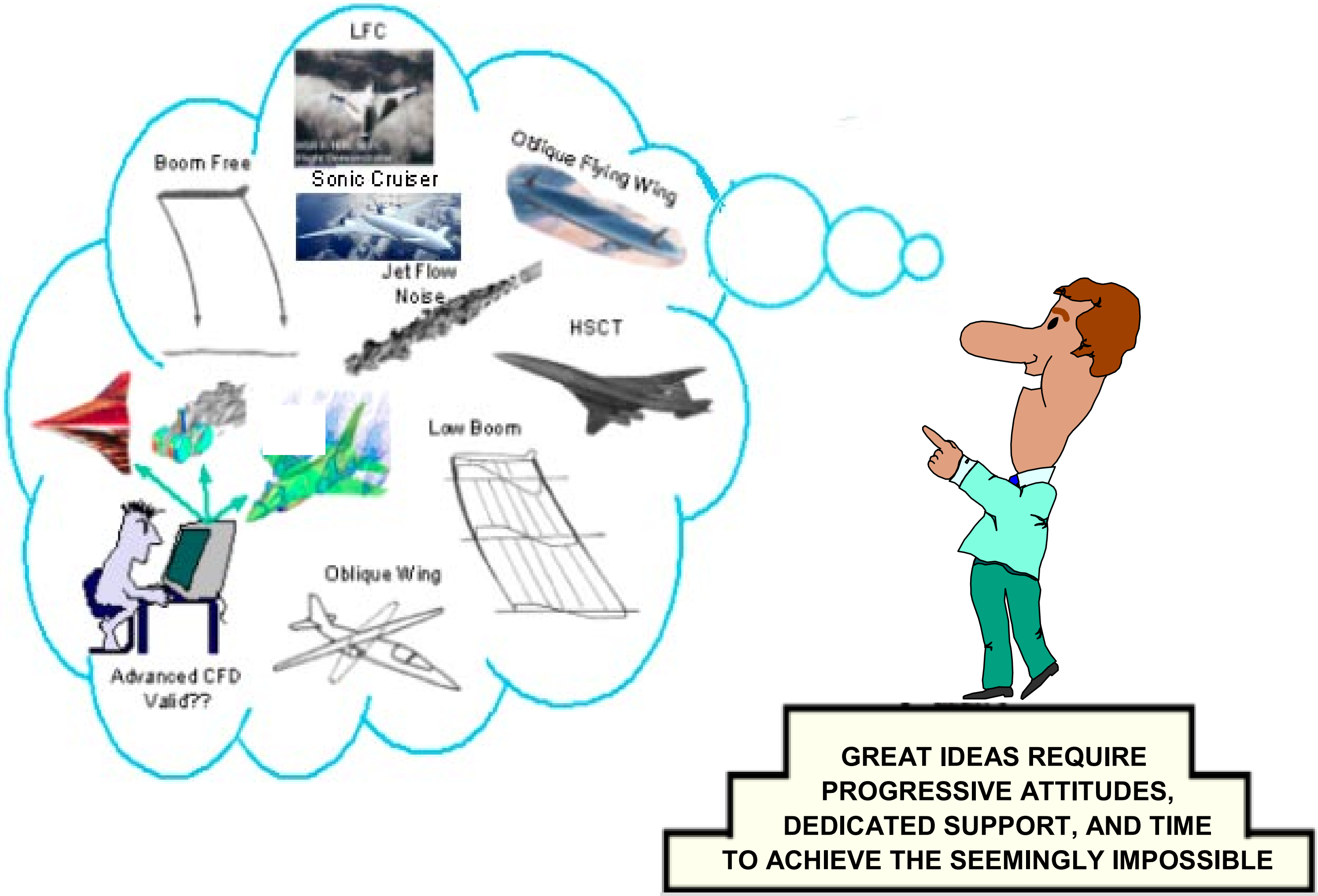
The recently completed HSCT studies used the “quantum” design strategy to explore a broad base of various technologies and design concepts in order identify the appropriate strategy for the development of a viable HSCT.

Some important specific areas for supersonic aerodynamic technology developments and activities include:

- Multi-point viscous non-linear design optimization
- Obtain high Reynolds number skin friction data for validation of CFD codes
- Validation of CFD codes for prediction of leading edge vortex formation on bulbous leading edges
- Fundamental Unconstrained Planform Studies
- Code development and validated for complicated separated flows, noise, forces, flow control

Specific areas for sonic boom technology development include

- Develop criteria to insure that sonic booms are acceptable.
- Determine the ultimate feasibility of boom free overland flight
- Explore and develop innovative active and passive boom minimization concepts
- Ultimately a scale configuration flight verification program will be necessary for performance validation and acceptability assessments.



All great ideas require progressive attitudes of “can do” together with dedicated financial and technical support of “will do” along with the required maturation “get done” time to achieve what might at one time have been conceived as the seemingly impossible “wow”.

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