HIGH SPEED CIVIL TRANSPORT OPPORTUNITIES,
CHALLENGES AND TECHNOLOGY NEEDS

Robert M. Kulfan
Boeing Commercial Airplane Group
Seattle, Washington 98124-2207, U.S.A.

ABSTRACT

Boeing market projections indicate a substantial potential demand for a High Speed Civil Transport (HSCT) to operate in the long-range international market, with service entry early in the next century. To maintain the leadership position in this market, Boeing has undertaken preliminary design and technology development to better understand the requirements and feasibility of this class of aircraft.

To date, marketing studies show that to penetrate the potential market for such an aircraft, the HSCT must be economically competitive with the subsonic fleet while meeting stringent environmental requirements. Our studies show that airplanes designed to fly between Mach 2.0 and 2.5, with 250- to 300-passenger capacity and range of at least 5,000 nautical miles, have the best chance of achieving both the economic and environmental objectives. The studies also indicate that present technology is inadequate to meet these requirements and that early, focused technology development is vital to the timing and ultimate success of the HSCT.

In this paper the reasons for the renewed interest in the HSCT and critical elements for a successful HSCT program will be reviewed. General technology development needs will be discussed primarily in the areas of structures, propulsion and aerodynamics. The greatest focus in this paper will be on the major aerodynamic issues and technology needs.

Key Words: HSCT (High Speed Civil Transport).

高速客運載具新契機，挑戰及科技需求

摘要

波音公司之市場評估顯示，在長程國際航運市場中正潛在地強烈需求一種高速客運載具，且可能在下世紀初期開始營運。為了保持在此一市場中之領導地位，波音公司正進行先期設計及技術研發，以明確此類飛機之必要規格及可行性。

目前市場分析指出，此種高速客運載具除在經濟效益上必須與現有之超音速機種競爭外，同時也得符合嚴格的環保規範，才能佔有潛在的市場。我們認為若能設計出具250至350人之載客量，航速在2.0至2.5馬赫間，而航程至少為5000浬之飛機便極可能同時達到經濟性及環保性的目標。研究中亦指出目前航空科技無法滿足上述需求，因此及早且專精的科技研發工作便成為高速客運載具問世時機及成功與否之重要關鍵。

本文將討論筆者重新考慮高速客運載具之原因及其成功之重要因素，另主要針對結構、推進與氣動力方面的科技研發需求亦在討論之列，而文中重點則放在主要氣動力議題及科技需求上。

關鍵詞：高速客運載具。
I. INTRODUCTION

The determination of The Boeing Company to maintain leadership in the commercial aircraft market requires the development of the most appropriate airplanes at the most opportune times to meet domestic and international air travel needs.

Population and economic growth, coupled with lower real travel costs and growing discretionary income, are increasing demand for additional air transport for the international market. At the same time the demand increases, the capability to produce the airplane is increasing as a result of the introduction of new design and manufacturing technology.

The market forecast, (Figure 1) based on major market area passenger flows, indicates that world air travel will grow at a rate of 5.9% per year through the year 2000. Studies of the long-range, largely overwater portion of this market indicate that the demand will be 615,000 passengers per day in the year 2005, growing to 1,120,000 per day in the year 2020. This increase in demand by the year 2020 could require (as shown in Figure 2) 1,000 to 1,500 HSCTs, certainly a sufficient number to justify studying the supersonic passenger airplane.

Based on encouraging market forecasts and study results, Boeing has increased its design efforts and has initiated the development of HSCT technologies in cooperation with NASA and our suppliers. Current efforts are aimed toward providing the technology and design information necessary for service introduction early in the next century.

II. BACKGROUND

The promise of high speed transport has been with us ever since the initiation of the commercial jet era, with the de Havilland Comet, the Boeing 707 and the Douglas DC-8. This technology of turbojet engines and swept-wing aerodynamics showed the world the advantages of long-range flights. Jet-speed convenience for the business and vacation travelers made international long distance flight very desirable. International non-stop flight times increased from 8, to 10 to 12 hours in length.

Design of commercial supersonic aircraft began in the early 1960s when U.S. companies coupled experience from military vehicles and commercial jetliner programs to design the prototype U.S. SST. Almost concurrently, the U.S.S.R. initiated its SST program which lead to the TU-144. A British and French consortium initiated work on the Concorde.

Boeing continued development of the U.S. SST, shown in Figure 3, until 1971, when the U.S. Government canceled the prototype program because of increasing concerns over its economic viability and environmental issues. No U.S. manufacturer was willing to continue the program because of the market risks associated with the unsolved problems of poor economics and possible environmental problems.

Although the Concorde has been a technical success, it has not proved to be economically attractive. Production was stopped after only 14 of 16 airplanes entered service.

Today, these airplanes are in service, catering to a small segment of the first-class market where high fares are necessary to support Concorde’s substantial operating costs.

III. MARKET FORECAST

The market forecast, based on major area passenger flows, projects that world air travel will nearly double by the year 2000. The scheduled international market is 23% of the total.

Portions of the international market appropriate to the HSCT include the longrange North America — Asia, North America-Europe, and Europe — Asia market. Markets shorter than 2,500 nmi have been eliminated from consideration. Markets mostly overland are not under consideration because of sonic boom concerns. Based on this projection, the demand in HSCT markets will be 615,000 passengers per day in the year 2005, growing to 1,120,000 in the year 2020 (Figure 4).

This is a potential market for up to 1,500 HSCTs and is sufficient to justify further study.
IV. HSCT Fleet Analysis

Since most subsonic jet transport airplanes fly between Mach 0.78 and 0.85, productivity (trips flown per year) is assumed to be equal among all competitors when evaluating subsonic airplanes. Productivity is a key attribute and must be included in the economic evaluation when comparing subsonic airplanes with the HSCT. A comparison has been made on a total fleet basis over a scheduled route system to evaluate productivity differences between an HSCT and a comparable subsonic airplane. The evaluation considered applicable routes, turn or through times, airport curfews, and waypoint routing. The markets exclude routes of less than 2,500 nmi, predominantly overland routes, and those where the demand is less than 300 passengers per day.

The route system used in the study included 51 cities and 234 city pairs, with about 2,300 flights per day. Subsonic flight over land and waypoint routing to minimize HSCT overland flying, as shown in Figure 5, were assumed.

The study results indicated that the average passenger-trip time savings is approximately 45%. HSCT productivity is approximately 1.8 times that of the subsonic airplane. Total miles flown are about 5% more for the HSCT than for the subsonic airplane because the HSCT will use waypoint routing to reduce subsonic operation.
IV. MARKET DRIVEN DESIGN REQUIREMENTS

Speed

Mach 2.4 provides a good balance in trip time benefit, technology risk, reducing environmental import, and overall system scheduling efficiency. This will be discussed in greater detail.

Design Range

An initial design range of 5,000 nmi was chosen for the initial baseline airplane in our studies and will serve more than 80% of the revenue passenger miles in the HSCT nonstop market. The speed of the HSCT will allow the longer range markets to be served on a one-stop basis with significant savings on trip time over a subsonic airplane.

As shown in Figure 6, 14-hr non-stop subsonic flight from Los Angeles to Sydney could be replaced by a 7.3 hr, one-stop HSCT flight, including a 1 hr stop in Honolulu. The 5,000 nmi range airplane will also serve important U.S. west coast—Japan markets non-stop.

A design range of almost 6,500 nmi would capture approximately 85% of the non-stop revenue passenger miles in the HSCT markets. However, an initial airplane with a 6,500 nmi range would be heavy and expensive. Downstream improvements in propulsion and structure technologies will allow the HSCT to "grow" into longer non-stop-range markets.

Seat Size

The airplane is nominally 300 seats tri-class. This capacity provides a balance between reduced seat-mile costs and a size that is consistent with the increased frequencies of the HSCT.

Airport Compatibility

The HSCT must be designed to operate from conventional airports. Surveys of the runway length for the candidate airports indicate that an 11,000-ft runway should be the target for maximum takeoff weight. Runway and taxiway pavement loading should be compatible with contemporary aircraft.

Comfort Level

Passengers should expect the same comfort levels currently experienced in the cabins of today’s subsonic fleet for flights of comparable duration.

VI. ENVIRONMENTAL REQUIREMENTS

Three environmental goals must be satisfied for an HSCT to be acceptable:

1. The HSCT must have no significant effect on the ozone layer.
2. HSCT community noise must meet the equivalent of current FAR 36 Stage 3 requirements.
3. There can be no perceptible boom over populated areas.

Atmospheric Effects

At 60,000 feet cruising altitude the HSCT is flying just below the highest concentration of ozone, as shown in Figure 7. No one knows for sure what impact this would have on the ozone layer.

Principal concerns about stratospheric ozone loss have arisen from the discovery that chlorofluorocarbons (CFC) undergo photochemical reactions when transported to the upper atmosphere. This process leads to the catalytic removal of ozone, which protects Earth’s atmosphere from potentially damaging ultraviolet light. Oxides of nitrogen, namely nitric oxide (NO) and nitrogen dioxide (NO₂), are also known to reduce stratospheric ozone by catalytic reaction. (These compounds are collectively described as NOₓ.)

Some earlier studies indicated that a fleet of SSTs might deplete the ozone layer by several percent. But
more recent studies, based on more complete models of atmospheric chemistry and low combustor emissions levels, indicate that the ozone layer impact would likely be much less. In fact, ozone levels could even increase.

In any case, early results of the low emissions combustor research are encouraging and it looks like very low NOx emissions levels might be possible. The question is, "Will they be low enough?"

As part of the High Speed Research Program, NASA has funded extensive research to assess the impact of oxides of nitrogen and other products of combustion on the atmosphere. Computer models of atmospheric chemistry and dynamics are being used in conjunction with atmospheric experimental research to predict the effects of supersonic aircraft on the ozone layer. The Atmospheric Advisory Committee, composed of Government and academic experts appointed by NASA, will review the program results and provide the assessment of the atmospheric effects from which emission rules can be developed.

Community Noise

The HSCT will be operated from existing international airports. The community noise it generates will meet the equivalent of current FAR 36 Stage 3 requirements.

Meeting these stringent noise limits is difficult with engines that are required for supersonic flight. These engines produce high velocity jet exhaust flow and are inherently noisy. Engine and nozzle systems that can entrain and mix ambient air with the engine exhaust flow to reduce the peak flow velocities must be developed. The key objectives are to provide rapid flow mixing within an acoustically treated section while minimizing weight and thrust loss. Research is being conducted by Boeing, the engine companies, and NASA to develop the required technology.

Sonic Boom

Supersonic operation over land would naturally be beneficial to the economics of an HSCT. However, at supersonic speeds, as shown in Figure 8, the aircraft produces shock waves that can propagate to the ground, creating sudden pressure changes that can sound loud and offensive to the ear. Aerodynamic theory suggests that the magnitude of the sonic boom levels can be minimized by careful treatment of the aerodynamic design of the aircraft. Nevertheless, the low-boom design process has not been fully validated, and the levels of acceptability have yet to be established.

NASA is conducting human-response studies to establish criteria for sonic boom acceptability. Until clear standards have been established and more confidence has been placed in the low-boom design process, design analysis of our baseline design will assume subsonic overland flight, and the economics of the aircraft will be assessed on that basis. We will continue to research, in conjunction with NASA, the technology of reducing sonic boom effects.

VII. TECHNICAL AND ECONOMIC VIABILITY

In order for the next SST/HSCT to enter service, it must contain technologies known to be economically viable.

An HSCT aircraft program launched today would, by necessity, be made of aluminum and be limited to Mach 2.0 and would not be an economic success. If we delivered the airplane in the year 2000, it would probably be titanium and fly at Mach 2.4. We still need significant advances in technology to produce an economically viable product as shown in Figure 9.

![Sonic Boom Pressure Field](image)

Fig. 8. Sonic Boom Pressure Field

![Technology Impact on HSCT](image)

Fig. 9. Technology Impact on HSCT
Cruise Speed Studies

Boeing studies conducted under a NASA contract evaluated 21 configurations designed for Mach number between 2.4 and 10.0. A screening process was used to evaluate the concepts on the basis of risk versus benefit. Of the 21 configurations, the 6 shown in Figure 10 were further developed and analyzed. These analyses showed that speeds above Mach 3.2 will be impractical. Subsequent studies narrowed the speed range studies to Mach 2.4 to 3.2 for economic commercial vehicles.

Aircraft size and complexity increase significantly with increasing Mach number. The practical upper airplane weight limit for turn of the century runways was assumed to be around 900,000 lb. The results shown in Figure 11 indicates that the region bounded by Mach 2.0 and 2.5 would be optimum for an HSCT. This speed region is further supported by the relationship between the system's average Mach number and cruise Mach number as shown in Figure 12. Constraints on the operation of higher speed airplanes, such as airport curfews, and the added impact of subsonic flight over land prac-
720 000 lb (326 592 kg) max. takeoff weight
7700 ft² (715.33 m²) wing area
309 passenger three-class interior

Designed for 5000 nmi range at Mach 2.4 cruise

Baseline Airplane Design

A baseline airplane is continually developed as the logical outgrowth of design studies and technology developments. The baseline is used as the basis for design development, technology development and testing, and evaluation of HSCT operations, economics, and environmental impact.

The current baseline (Figure 13), is the result of 4 years of design evolution and meets the market-driven design requirements of 5,000-nmi range and Mach 2.4 cruise speed.

Interiors

Interior arrangement of an arearuled body creates a challenge different from that of a constant-sectionin fuselage (Figure 14). The baseline interior, shown in Figure 15, is tri-class with 2 to 6 abreast seating, depending on the location.
Economic Viability Assessment

For an airplane to be economically viable, it must offer a value to the airline that is equal to or more than the price charged by the manufacturer to cover manufacturing costs. Economic viability occurs when a market size justifies the investment and risk that both the manufacturer and an airline undertake when deciding to develop or purchase an airplane (Figure 16).

While our goal is for the HSCT to operate profitably on the same fare base as the subsonic fleet, configuration assessments show that some increase in fare may be necessary.

The willingness to pay a fare premium is subject to a great deal of uncertainty. Nevertheless, airline surveys (Figure 17), have shown that, from a passenger point of view, the time savings offered by an HSCT can justify a fare premium.

Optimistic assessments show that if fare premiums for HSCT flights averaged 20% over the fares of subsonic flights, nearly 65% of the potential HSCT market could be obtained, and if fares averaged only 10% over, nearly 85% of the market could be obtained. Conservative assessments at the same fare premium levels yield respective market share estimates of 25% and 50%.

Technology Development

Successful development of the HSCT is dependent on advanced technology. Relative to the Concorde (Figure 18) a viable HSCT must increase cruise speed by 20%, double the range, triple the payload, reduce the community noise by orders of magnitude and cut the operating cost by a factor of eight. This presents a formidable technical challenge.
The highest near-term priorities for technology development are low-emission engine combustors, engine noise suppressors, variable-cycle engines, high-temperature composite structural materials, high-lift aerodynamics, and high-temperature metals. Other efforts in technology development include high-speed aerodynamics, supersonic engine inlets, aircraft systems, avionics, and flight deck requirements. Component service life will have to be similar to the service life of our most economical subsonic, long-range jet aircraft. Engines must have an on-wing life of 15,000 hours. Structure life will have to be 60,000 hours. Fluids and seals and other components, everything associated with the second generation SST, will have to have operational lives similar to or better than today's aircraft.

Fig. 21. HSCT Aerodynamic Research Needs

Fig. 22. Aerodynamic Design Tools
High temperature organic composites produce much superior weight performance for reduced airplane costs. The downside includes potentially high development costs and technical risks. Advanced metallics are another possibility for primary structure and are being studied in parallel. They will produce a heavier, and possible slower, vehicle but represent less risk as their durability and cost performance are better understood. It will be a while before the choice of materials is clear, but it will probably be a mix of composites and metallics.

VIII. AERODYNAMIC TECHNOLOGY DEVELOPMENT

Cruise Aerodynamics

The cruise aerodynamic efficiency (lift/drag) can have a significant effect on the economic viability of a HSCT. A one percent reduction in cruise will save 4,900 pounds of fuel and reduce the mission sized maximum takeoff weight by approximately 7,700 lbs.

As shown in Figure 19, an aerodynamically efficient design is a highly integrated configuration subject to many structural, systems and off design performance constraints.

The current aerodynamic design methodology is based on 1970 technology. New emerging advanced computational fluid dynamic (CFD) methods and improved wind tunnel testing facilities and techniques offer the opportunity for significant improvement in lift/drag ratio as shown in Figure 20.

General HSCT Aerodynamics Research needs are summarized in Figure 21. Resolving these aerodynamic needs will require fine tuning and utilization of the aerodynamic design tools shown in Figure 22.

Advances in CDF will allow us to improve our aerodynamic design capability beyond the current linear potential flow methods. CFD, together with the wind tunnel, is an essential part of the design process. We cannot design a viable HSCT without CFD. There are still many areas in the aerodynamic design process where CFD is not adequate as shown in Figure 23.

We are currently in the process of validating our CFD design and analysis tools with test data to establish the applicability and limitations of these methods. Figures 24 and 25 are examples of this work.

Historically, the development of any viable aircraft configuration has required many wind tunnel tests to develop and validate the design concepts, Figure 26. Wind tunnel testing can provide a fundamental understanding of the fundamental flow physics over an HSCT as shown in Figure 27.

Wind tunnel testing provides data for our CFD validation work but is also critical in our concept develop-
Low Speed Aerodynamics

The slender wing planform configurations typically used for HSCT configurations are designed to achieve attached flow over the wing surface at cruise conditions. As shown in Figure 29, these slender, thin wings tend to develop leading-edge vortices at subsonic off-design conditions. We need to suppress or control these leading edge vortices, (Figure 30), to improve low-speed performance of increasing lift-to-drag ratio during takeoff and climb. This will lower community noise levels by making a steeper climb possible or by allowing the engines to be operated at lower thrust settings. Optimum L/D will be maintained after lift-off throughout takeoff and again during landing by continually optimizing flap position.

Conversely, as shown in Figure 31, it may be desired to increase lift coefficient and pitching moment by intensifying the vortex formation during takeoff rotation or during descent to reduce approach speed.
energy and lower drag. A strong vortex forming over the wing causes suction pressures that add to the lifting force. Amplifying or suppressing the vortex will be controlled by changing flap deflection.

Boeing-NASA Supersonic Laminar Flow Control Studies

An HSCT has greater sensitivity to aerodynamic drag that its subsonic counterparts. Any reduction in aerodynamic drag leads directly to reduction in airplane size and fuel requirements.

Skin friction drag accounts for approximately 40% of the total aerodynamic drag on an HSCT at cruise. In regions where laminar flow is maintained, skin friction drag is reduced as much as 80% to 90%. Laminar flow is achieved by sucking away a small amount of flow
through tiny holes on the wing surface. Maintaining laminar flow over a large area of the wing surface by this method is currently being studied by Boeing.

To assess net performance and economics, the benefits of aerodynamic drag reduction must be balanced against the weight, fuel displacement, and cost penalties of laminar flow control (LFC) system installation. Systems studies (Figure 33) have shown a potential for significant benefits of LFC implementation on HSCTs.

Low Sonic Boom Studies

Supersonic operation overland would have a beneficial impact on fleet economics. The level of sonic...
boom acceptable to the public is as yet unknown. NASA is conducting human-response studies to establish criteria for sonic boom acceptability.

Sonic boom may be reduced by precise shaping of the fuselage and the wing as illustrated in Figure 34 and 35. The design process is complex and has not yet been completely validated. In addition, there are a number of unknowns, such as the effects of variations in wind shear, turbulence, temperature gradients, water vapor, and ground surface conditions, that can strongly affect the perceived noise level.

Boeing is working with NASA to develop low sonic boom technology that will incorporate emerging analysis methods and wind tunnel testing to see whether a satisfactory low sonic boom aircraft design is achievable. In addition, we are conducting detailed airplane systems studies to assess the economic viability and technical feasibility of our lowboom design concepts. Clearly, the HSCT must not become an unacceptable source of noise. If low sonic boom technology does not achieve expectations, overland flight will be limited to subsonic speeds over heavily populated areas. It may still be possible to operate at reduced boom levels over some of the underpopulated regions in the world. This will still require a significant reduction in boom levels and will require international agreements, but could result in important economic benefits without undue environmental hardship.

VIII. PROPULSION TECHNOLOGY DEVELOPMENT

Emission — Low NOx Combustors

To ensure that the emissions from the engines will not harm the ozone layer, the engine combustor will be designed for low production of NOx (oxides of nitrogen — NO and NO2). Both Pratt & Whitney and General Electric have identified combustor concepts that appear to have the potential to reduce the NOx levels by 80% to 90%.

The low NOx combustor of the future will achieve low emission levels through precise control of the burning process and the combustion time during each stage of the process. One candidate is shown in Figure 36. The combustion occurs in two stages: first in a fuel-rich zone, then in a fuel-lean zone. This avoids the high rate of NOx production that occurs when the fuel burns in one stage. All combustion air is either premixed with the fuel on entering the first-stage fuel-rich zone or introduced into the intermediate quench zone. The fuel-rich condition is accomplished by not permitting cooling air through the combustion zone walls as in conventional combustors.

Without this cooling air, the combustor liner must be designed to work at higher temperatures, requiring application of new, higher temperature materials. The achievement of an emissions index (gm equivalent NOx/kg fuel) of 5 is estimated to have an impact of less than 1% of the atmospheric ozone depletion as shown in Figure 37.

Noise

The HSCT must be a good neighbor around airports. Accordingly, it will be designed to meet the equivalent of current FAR 36 Stage 3 noise requirements. Advanced-technology ejector-suppressor nozzles will be required to reduce the two main contributors to jet noise — mixing and shock cell noise — which result from the very high jet velocities characteristic of supersonic engines. High-velocity jet mixing noise can be reduced by mixing the propulsive jet with large amounts of entrained outside air within an acoustically lined nozzle duct. Shock cell noise can be reduced by properly controlling the rate of expansion of the high-pressure jet prior to mixing with the aspirated air.

A low-bypass-ratio turbofan and turbojet are the leading HSCT propulsion candidates today because of their good supersonic and subsonic performance. These engines require a noise suppression nozzle that will provide a reduction of at least 18 decibels in jet noise with little loss in thrust as shown in Figure 38, a significant advance in suppressor technology will be required.

Current studies suggest that meeting the noise goals will be a difficult but achievable task that will require innovation and technology advancements in engines, noise suppressors, aircraft design, and flightpath management.

Research at Boeing has focused on ejector suppressor development, shown in Figure 39, where injection of secondary (freestream) air is used to mix the hot exhaust jet and reduce the nozzle exit velocity from 3,000 ft/sec to 1,600 ft/sec while attenuating the mixing noise and at the same time, without significant thrust loss. This, coupled with advanced noise abatement procedures and a highly capable high-lift system (to reduce climbout thrust requirements), should allow us to meet Stage 3 levels.

Early acoustic wind tunnel scale model tests as shown in Figure 40, of suppressor ejectors show promise. Secondary flow requirements are high — about equal to engine flow. And the mixing process itself produces noise which must be reduced with acoustic lining materials. In these parametric tests, varying amounts of asymmetric lining were added and the results showed that it might be possible to meet Stage 3 requirements if enough lining could be designed into the nozzle. Separate acoustic lining tests have confirmed that flightworthy lining designs could provide the required noise reductions.

Although achieving Stage 3 noise levels is possible, it will require much effort and have significant but acceptable penalties in aircraft weight, complexity and economics. Expecting an HSCT to conform to future, more restrictive noise regulations (Stage 4?) may not be realistic as they could drive the economic penalties to a point where the new HSCT would not be viable.
Variable-Cycle Engines

Considerable effort has been devoted to improvement of engine specific fuel consumption (SFC) at subsonic conditions over the past 20 years. The U.S. SST has very poor subsonic SFC. Poor subsonic SFC penalizes the mission performance by reducing the efficiency during subsonic mission legs and by requiring larger amounts of reserve fuel. The key to good subsonic and supersonic SFC is a variable-cycle engine. The major objective for a future HSCT application is to provide some degree of engine cycle variability that will not significantly increase the cost, the maintenance requirements, or the overall complexity of the engine. The variable-cycle engine must have a good economic payoff for the airline while still providing more mission flexibility and reducing the reserve fuel requirements so that more payload can be carried.

In the past, variable-cycle engines were designed with large variations in bypass ratio to provide jet noise reduction. However, these types were complicated and did not perform well. Today, the trend is toward turbojets or low-bypass engines that have the ability to improve off-design performance by adjustment of compressor bleed or by relatively small variation in bypass ratio (Figure 41). The current engine offerings from Pratt & Whitney and General Electric fall into this category. These engines will require an effective jet noise suppressor.
Rolls-Royce / SNECMA favors other approaches. One is a tandem fan that operates as a turbojet cycle for cruise but opens a bypass inlet and nozzle for higher flow at subsonic speeds. A second approach is to increase the bypass ratio by incorporating an additional fan and turbine stream into the flow path at subsonic speeds.

Supersonic Inlet Design

At supersonic flight speeds, the air to the engine must be slowed to subsonic speeds before entering the engine. The flow must be supplied efficiently to obtain optimum engine operation. An inlet is required that can vary the geometry of the air supply duct to accelerate the flow during takeoff and low-speed flight and decelerate the flow during transonic and supersonic flight. A digital electronic control system is required to provide stable operation at all flight conditions. An example of a variable geometry inlet concept is shown in Figure 42.

Extensive analyses (using modern computational fluid dynamic methods as shown in Figure 43) and test programs are continuing to show that such an inlet system can be designed with the high-performance, reliability, and stability characteristics required on a commercial airplane.

Other inlet concepts with different characteristics are also being studied. Installed aerodynamic efficiency and stability, weight, initial costs, and operating costs will be the basis for selecting the final inlet design.

X. SYSTEMS TECHNOLOGY DEVELOPMENT

When compared with those existing on today’s subsonic commercial airplanes, the mechanical, electrical, and avionic flight systems for the HSCT will require substantial development. Some systems will require change to cater to the greater range in flight speeds and altitudes and to the corresponding increases in operating temperature. Other systems will require development to address the higher levels of system complexity and automation required to optimize the performance and hence the economics of this type of airplane. Advanced flight systems and avionics required for an HSCT are summarized in Figure 44.

Landing Gear

A typical mechanical system requiring development is the landing gear. Factors influencing main landing gear designs include runway loading requirements, spatial separation of the gear elements from the engine inlets to prevent ingestion of foreign objects, and critical requirements for stowing gear elements efficiently in the thin, supersonic wing contours.

Conceptual design studies, such as shown in Figure 45, are addressing all these problem issues. Technology advances in wheels, tires, and brakes will aid in providing minimum weight and minimum volume gear designs compatible with the stowage requirements.
XI. STRUCTURES TECHNOLOGY DEVELOPMENT

Probably the most critical technology challenge is in the development of lightweight, cost-effective primary structure capable of operating in the high temperature environment of Mach 2.4 cruise flight (Figure 46). Our current baseline aircraft projects extensive use of composite structure as shown in Figure 47. High temperature organic composites produce much superior weight performance promising reduced airplane costs. The downside includes potentially high development costs and, at least at present, high technical risk. Advanced metallics are another obvious possibility for primary structure and are being studied in parallel. They will produce a heavier, and possibly slower, vehicle but represent less risk as their durability and cost performance are better understood. It will be a while before the best choice of materials is clear and it is probable that a mix of composites and metallics will be included in the final design. If the airplane struc-

![Diagram of aircraft with shock waves and engine face](image)

**Fig. 42. Variable Geometry Inlet Concept**

![Diagram of CFD Mach 2.4 Inlet Analysis](image)

**Fig. 43. CFD Mach 2.4 Inlet Analysis**

![Diagram of advanced flight systems and avionics](image)

**Fig. 44. Advanced Flight Systems and Avionics**

![Diagram of landing gear design](image)

**Fig. 45. Landing Gear Design**
ture is to be composite however, we must get an early start in the materials development process and our composite structure program at Boeing is well underway.

Any material used in HSCT primary structure must be safe, damage tolerant and maintainable for at least 60,000 hours of supersonic operation — that's about seven continuous years of real time testing for validation and so one of the important research activities is the development of an accelerated aging process such as shown in Figure 48 to shorten the materials evaluation process. This will have to be backed up with real time testing, of course, but if such a process can be designed and validated it may allow rapid evaluation of emerging materials.

Extensive materials screening at Boeing has narrowed the current field of candidates to around five materials but more advanced materials are required and expected.

Structural designs must be developed to take advantage of the materials properties. The process of substituting composites for metals in conventional metallic designs — what we call "black-aluminum" — won't cut it on HSCT primary structure. The design must play to the strengths (and weaknesses) of the basic materials — strength, stiffness, toughness and damage tolerance.

Design study trades are in progress where conventional designs are being compared to innovative structural concepts, as shown in Figure 40 and 50.

To satisfy strength and stiffness requirements for proposed airplane configurations, structural sizing is being conducted through the application of finite-element analysis and high-speed computers. Results are incorporated into airplane sizing and performance predictions.

Major structural design features, such as landing gear support, engine location, and wing-to-body intersection, will undergo in-depth studies to achieve optimum performance with maximum reliability.

XII. MANUFACTURING TECHNOLOGY DEVELOPMENT
The HSCT will require development of many new designs, materials, and processes. Manufacturing Research and Development in the HSCT program is providing manufacturing, tooling, and assembly support as the development of the design progresses. The manufacturing processes must be compatible with the materials. In addition to meeting the technical requirements manufacturing cost effectiveness is of extreme importance.

The only way all these requirements can be met simultaneously is through a highly integrated team approach Figure 51. That’s what we’re doing at Boeing Engineering, Manufacturing Technology and Cost Estimating work together through out the design processes. This design-build team approach will ensure that the materials and structural design will result in an efficient, producible, cost-effective aircraft.

Typical body structural panels such as shown in Figure 52 are being produced using new manufacturing process technologies to establish the producibility of the design and to assess process costs.

XIII. HSCT OPERATIONS

The addition of a new supersonic aircraft type with markedly different operating characteristics will require changes in the Air Traffic Control (ATC) infrastructure. Current National Airspace System plans will provide for worldwide navigation and communication coverage, automatic data linking, and strategic control. The problems foreseen are the control and efficient use of airspace, transition operations, and the impact of HSCT airplanes on airport capacity. Planned changes made for a future subsonic fleet will cover most of the needs of a supersonic fleet. HSCT takeoff and approach speeds are similar to those of the 747 and will not have a significant impact on ATC operations.

The HSCT will takeoff and land on existing international airport runways. Runway strengths will be adequate if they now can accommodate the high-gross-weight 747s. Some attention to taxi operations and taxiway design and, in many cases, new gates and servicing ar-
rangements will be required because of the extreme length of the HSCT (Figure 53).

XIII. SUMMARY

A successful Supersonic Transport program will have to integrate technology development, aircraft design, manufacturing research, and airline requirements.

Boeing is teamed with NASA, engine manufacturers, and many other suppliers in assessing the commercial and environmental viability of such an aircraft and to develop the technology that will allow Boeing to be a leader in this market if the HSCT proves feasible.

Technology development is aimed at protecting the ability to launch an HSCT early next century.

All of us, the scientists, manufacturers, vendors, and airline companies have the challenge of understanding and then correctly applying what we have learned about supersonic commercial air transport. How much new technology will supersonic commercial flight require? How must the operating infrastructure change to accommodate this new airplane? How will costs be affected?

There are many questions. All of them must be answered thoroughly so that the next supersonic transport will be a financial as well as a technological success.