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TECHNOLOGY READINESS AND DEVELOPMENT RISKS OF THE NEW SUPersonic TRANSPORT

By Yorgo E. Saounatsos

ABSTRACT: Realistic specifications for the new supersonic transport call for a 2.2 Mach, 270 passenger, 5,500 NM range aircraft, requiring $15–20 billion for research and development. Nonlinear aerodynamic analysis methods promise an enhanced lift-to-drag ratio of about 45% in subsonic cruise and 25% in supersonic cruise. Adequate sonic-boom suppression does not appear feasible. The resized increment in weight reduction due to the elimination of the droop nose is estimated at 4,500 kg. Considerable progress has been made in meeting FAR-36/Stage-3 noise requirements through the use of a mixed-flow turbopod with ejector or a mid-tandem fan variable cycle engine. A 5–15% lower specific fuel consumption is projected, while the dominant combustion philosophies are the lean-premixed-prevaporized and the rich-burn/quick-quench/lean-burn processes. Research is aimed at a nitrogen oxide emission index of 5, resulting in less than 1% annual ozone depletion. The estimated market needs of about 550 units by 2020 justify a satisfactory return on investment (~12%) for only one manufacturer. A well-structured international consortium could reduce development risks, time, and expenditures through technology transfer and the sharing minimization of nonrecurring costs. The date of entry into service can be placed between 2010 and 2015.

INTRODUCTION

The launch of any large commercial airplane program involves a high-stakes gamble, because uncertainty always exists on whether enough units will be produced and sold to provide a positive return on investment. With the next generation supersonic transport this uncertainty is magnified to unprecedented levels due to the increased technical challenges. Estimates by both American and European manufacturers suggest that nonrecurring costs for this program could be 15–20 billion US$ (Bunin et al. 1994). Technology readiness and the understanding of the risk factors involved are key elements in the successful development of the next generation supersonic transport.

In April 1994, Aerospatiale, British Aerospace, and Deutsche Aerospace (DASA) signed a memorandum of understanding, creating a joint European supersonic research program and expecting the aircraft to reach operational status by 2010. In parallel, Snecma, Rolls-Royce, MTU, and Fiat have been working together to develop a propulsion system since 1991. Investing no more than $12 million per year (Sparaco 1997), mainly of company-funded research, the program covers materials, aerodynamics, systems, and engine integration for a reference configuration by 1999. The European supersonic research program exploratory studies are based on a 2.0 Mach, 250 seat, 5,500 NM (nautical mi.) range aircraft. Canards are incorporated to improve low-speed performance and handling, as shown in Fig. 1.

In the Pacific region, the Japan Aircraft Development Corporation (JADC) coordinates the efforts of Mitsubishi, Kawasaki, and Fuji Heavy Industries in their research on the next generation supersonic transport (SST). Currently JADC is making efforts to expand their activity to $20 million per year, according to Hiroshi Mizuno, General Manager of JADC (personal communication 1996). At the same time, Alexander Pukhov, Tupolev's chief designer, maintains that through the flight tests conducted on a Tu-144 in collaboration with NASA, Russia's research and development of a second generation supersonic transport (Tu-244) is revived. Revealed at the Paris Air Show in 1993, the Tu-244 is a 2.05 Mach, 300 passenger, 5,100 NM range aircraft powered by four 323.8 kN (72,800 lbf) engines and having a maximum take-off weight of 349,000 kg (770,000 lb). Although because of the current political and economic instability, Russia does not seem to be a major player in the SST development, its scientific input cannot be ignored.

In the United States, as a first step in assessing the market and technology needs for a viable supersonic transport, contracts were awarded in 1986 to Boeing and Douglas Aircraft companies to conduct feasibility studies. In 1990, NASA initiated an intensive high-speed research program, a thorough first-order assessment of the performance benefits associated with technology improvements. The program has been since moving along with steady support of team leader Boeing and some 50 other U.S. subcontractors (Ott 1997). Advanced technologies in the areas of aerodynamics, structures, propulsion, and flight deck systems were applied to a representative 2.4 Mach vehicle concept, called reference H. In autumn 1995, engineers from NASA, Boeing, McDonnell Douglas, General Electric, Pratt & Whitney, and Honeywell produced a new planform, the technology-concept airplane or TCA. The TCA calls for a 2.4 Mach aircraft with a capacity of 300 passengers, a range of more than 5,000 NM and a maximum take-off weight of under 340,000 kg (750,000 lb). NASA is currently spending a quarter of its annual $1 billion aeronautics budget for high-speed research. By 2002, after having spent nearly $2 billion on it high-speed research program (Zurker 1995), NASA hopes to have developed with U.S. industry the required technology for a technically feasible and economically viable supersonic transport. This future SST may resemble the characteristics depicted in Fig. 2, as envisioned by the Boeing

![Aerospatiale's Supersonic Transport Concept](image)

**FIG. 1.** Aerospatiale's Supersonic Transport Concept

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Note. Discussion open until December 1, 1998. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on June 10, 1997. This paper is part of the *Journal of Aerospace Engineering*, Vol. 11, No. 3, July, 1998. ©ASCE, ISSN 0893-1312/98/0003-0095—0104/$8.00 + $.50 per page. Paper No. 15969.
for an increase in L/D of 0.8 (25%) at supersonic speeds and 2.0 (45%) at subsonic speeds (Ozoroski et al. 1993). Characteristically, Aerospatiale obtained an L/D increase equivalent to 1.5 times of payload during Mach 2.0 wind tunnel experiments (Collard 1990). This was achieved by creating a larger laminar flow region over the wing through the optimization of its camber, sweep, and twist angle. Likewise, scientists at the U.K. Defence & Research Agency have produced a wing shape with an increase in L/D ratio of 24% at supersonic and 58% at transonic conditions relative to the Concorde (Hayes 1997). High-lift leading and trailing edge wing devices can also be used to decrease the required thrust for take-off, climbout, and landing, reducing in parallel community noise (Wesoky et al. 1990). These advanced high-lift concepts, when combined with modern landing and takeoff procedures such as automatic flap and throttle settings, can give an aircraft more than double the low-speed L/D ratio of the Concorde (Darden et al. 1993; Wilhitte et al. 1997).

Supersonic laminar flow control can also have significant aerodynamic benefits (increased L/D) by reducing skin friction drag on SST configurations. NASA is investigating the implementation of SLFC through a series of flight tests on an F-16XL. The objective of this project is to achieve laminar flow over 40–50% of the wing chord in SST cruise conditions of Mach 2.4 at 60,000 ft (Smith 1995). Program officials believe that the application of laminar flow control on SST through active suction has the potential of reducing drag by 7–9%, resulting in a considerable decrease in fuel consumption (NASA 1992; Smith 1995). Moreover, supersonic laminar flow could lower the skin surface temperature by about 95°C, allowing to push up the speed of the aircraft and still use kerosene (Jet A) as a heat sink (Strack 1990). Nevertheless, active suction, which is accomplished through millions of nearly microscopic holes laser-drilled in the wing skin, is viewed as a “high-risk” technology. It has been suggested that 4–5% of the cruise engine power might have to be absorbed in order to drive the system (NASA 1996). Moreover, because of the weight penalty and the structure complexity the supersonic laminar flow control system introduces, the benefits of laminar flow may become marginal. It has, however, the potential of becoming the enabling technology for future supersonic and subsonic aircraft if it is partially applied on aerodynamically critical areas (Smith 1995).

Another issue that is being considered is the elimination of the droop-nose configuration. This will considerably decrease complexity and cost, as well as drag and weight penalties, through the removal of mechanisms, guide rails, hinge joints, and jacks for drooping and returning the nose and visor in place. The total resized increment in drag and weight reduction for the larger next generation SST is estimated at 4,500 kg (10,000 lb), which translates to as many as 50 additional passengers (Swink et al. 1992).

Without a droop-nose, however, forward external visibility is negated during take-off and landing guidance, and control must be vested in synthetic-vision systems. The next generation SST may have a de facto Category III all-weather operation capability autonomous of the landing aids of the airports. That would dramatically increase the dispatch reliability and on-time arrivals, enhancing operating economics, and contributing to passenger satisfaction and sizable increases in cost savings across a fleet. A cost/benefit model developed by the Douglas Aircraft Corporation, for assessing the impacts of such enhanced operating flexibility across a typical airline fleet, estimated average annual cost savings of approximately $188 million due to the avoidance of weather-related delays (Swink et al. 1992). Additionally, there would be an added benefit of reduced fuel reserve requirements due to the implementation of inherent Category III landing capabilities, which
could be used as additional payload or simply decrease the take-off gross weight. One of the major U.S. carriers, for example, has estimated that an extra 4,500 kg (10,000 lb) of fuel is loaded on-board on oceanic routes across the Pacific, of which 2,700 kg (6,000 lb) is never burned. NASA has completed preliminary flight tests of a synthetic-vision landing system with very encouraging feedback from the pilots (Norris 1996). The tests were conducted on subsonic transport aircraft equipped with infrared sensors, video cameras, and X-band radar, as well as a digital-data system capable of generating a 3D ground scene. According to NASA, an integrated synthetic-vision system will be tested before 2001.

The new generation SST flight deck environment will also include two-way air/ground data linking, precision satellite-based navigation and automatic surveillance. The satellite navigation will be based on a differential global positioning (GPS) system, coupled with a digitized map database, providing flight profile information and drawing the airport runways on the display screen (Ott 1997; Wilhite et al. 1997). Automated surveillance will comprise the traffic collision avoidance system and an on-board radar for active protection from aircraft not equipped with the system. These will give SST the capability to operate within a “free-flight” air traffic environment as envisioned by the FAA and Eurocontrol.

SONIC BOOM ISSUE

The availability of high-speed overland corridors would have a major impact on the capability of SST to penetrate specific city-pairs markets, involving significant overland components in the aircraft routing for which there is no effective overwater rerouting option. Therefore, the obtained reductions in trip-times and operating costs would substantially boost the commercial success of the new SST. This leads to the essential issue of overland flight, which is the “Achilles’ heel” of supersonic transports; they are prohibited from such operations due to their sonic boom loudness level. It is well-known that conventional supersonic aircraft have a sharp nose to reduce wave drag, generating a weak bow shock. Nevertheless, strong and multiple secondary shocks are formed. The sonic boom phenomenon is generated by the coalescence of these shock waves in the process of propagation from aircraft to the ground (Yoshida et al. 1994). The parameters that characterize the pressure waveform (N-wave) are the peak pressure (overpressure $\Delta P$), duration and rise time ($\Delta t$). The sonic boom intensity is proportional to overpressure ($\Delta P$), so when the peak pressure decreases, the sonic boom loudness decreases. In parallel, it has been established that extension of the rise time ($\Delta t$) decreases the high frequency component, which is more severe for human hearing than low frequency (Archer et al. 1996; Yoshida et al. 1994). Therefore, when the rise time becomes longer, for any given peak pressure, humans hear a “softer” boom noise. The perceived loudness also depends on atmospheric conditions, because atmospheric gradients introduce refraction of the propagating waves, which can create superbooms or double-booms.

The concept of boom minimization is based on suppressing the coalescence of multiple secondary shock waves caused by the SST in supersonic flight, so that the overpressure ($\Delta P$) at ground level is reduced. This can be achieved through the manipulation of aircraft’s design characteristics, resulting in an optimized N-wave pressure signature with significant sonic boom loudness attenuation (Fig. 3). Conventional supersonic designs generate a non-optimized N-wave signature at ground level for all flight altitudes above 40,000 ft (Wesoky et al. 1991). This implies that reduced sonic boom loudness can only be achieved below this specific altitude, which is not efficient for the operation of SSTs from a fuel consumption standpoint. In contrast, low boom configurations produce a non-optimized

![FIG. 3. N-wave Properties and Optimized Characteristics (Exaggerated for Clarity)](image)

N-wave only when the aircraft altitude exceeds 60,000 ft, suggesting a larger operational flexibility as far as the altitude is concerned. The main characteristic of a typical, inexpensive, low-boom aircraft configuration is a blunt nose, which can decrease the overpressure by more than 50% (Yoshida et al. 1994). Such an aircraft shape, however, generates stronger bow shock waves and more wave drag than a conventional sharp-nosed configuration, leading to the “low-boom high-drag paradox.” As a result, the performance of the airplane is reduced, implying that the blunt-nose aircraft has a shorter range than a sharp-nosed SST aircraft of the same weight or greater weight.

Alternatively, advanced low-boom configurations can be achieved by a more uniform lift distribution stretched over a longer length, so that the sonic boom maintains its weaker midfield features with lower bow shock. However, to obtain adequate boom loudness suppression, the area distribution of an aircraft must be carefully determined aerodynamically (Vachal 1990). Such advanced low-boom designs induce a drag penalty, tending toward lightly loaded but larger wing surfaces (Darden et al. 1993). Studies conducted by JADC and Kawasaki Heavy Industries indicate that low-boom SST aircraft configurations, designed to cruise at Mach 2.2, would have an economic advantage only if the percent of overland distance is above 20% (Yoshida et al. 1994). In any other case the induced lower L/D ratio would have a pronounced negative effect on aircraft performance, undermining the commercial viability of the SST. Because of the current status in the development of the required technologies, the prognosis for a practical design in this area does not appear promising at this time (Wilhite et al. 1997; Williams 1994). For this reason, parallel studies are focusing on the potential of overland operations at somewhat reduced speeds or altitude, or over remote land areas which are either completely uninhabited or very sparsely populated.

On the legal side, the sonic boom loudness level allowed overland has yet to be clearly defined. This seems to be more of a political than a technical issue; a “favorable” definition could offer one half of the solution to the sonic boom problem. Meanwhile, the operational experience of British Airways with the Concorde has established that for proper secondary boom control, the aircraft should maintain subsonic cruise within 105 NM from the coast during the months of unfavorable upper atmospheric conditions (Macdonald 1989). Nonetheless, further investigation is required on the potential effects on both maritime mammals and maritime shipping from the overwater sonic booms of a large fleet of SSTs.

PROPELLION TECHNOLOGY

In contrast to other aircraft projects, in which the engine development usually leads the airframe by two or three years, in the SST program the propulsion system and the airframe
come to life at about the same time. The fact that almost 45% of the take-off gross weight is fuel and the propulsion system itself is about 20% of the operating empty weight points out the importance of the propulsion system to the economic viability of SST. The challenge is to have a fuel-efficient and lightweight engine while keeping emissions acceptably low and incorporating noise suppression devices to meet current (FAR-36/Stage-3) and future airport noise requirements. A successful SST engine should feature:

- Thrust of more than 223 kN (50,000 lbf)
- A 10–15% lower fuel consumption than that of the Concorde
- Lightweight construction
- High-temperature resistance and high reliability
- Meet Stage-3 noise requirements
- Have low NOx emission levels

The primary requirement, however, for the propulsion system of the future supersonic transport is better specific fuel consumption than that of the Concorde’s Olympus 593 engine. A relatively small improvement of 5–10% is expected in supersonic cruise fuel consumption due to the possibility of further increase in thermal efficiency. This is a result of the progress made in the field of materials, allowing higher compressor and combustor outlet temperatures than Olympus 593 (Habrand 1989). In subsonic operations a larger reduction in specific fuel consumption (10–15%) can be achieved, allowing to cover long enough distances in subsonic conditions.

However, engineers face a major design dilemma since the optimum aerothermodynamic cycle at subsonic speeds is naturally different from the optimum cycle at supersonic speeds. The first requires high propulsion efficiency, the latter, high specific thrust (Hiroyaka et al. 1994; Hodder 1994). In terms of performance, the engine nacelle and air inlet should generate minimum drag, suggesting that the frontal area of the engine has to be as small as possible. Theoretically, such a requirement prevents the achievement of high propulsion efficiency in subsonic cruise, since a small inlet area leads to a smaller mass flow rate through the engine. At the same time, the need to obtain high specific thrust in supersonic operations introduces high exhaust velocity during subsonic cruise, which is also detrimental to propulsive efficiency. The high exhaust velocity can reach a maximum of 900 m/s. It has been well established that the exhaust jet velocity should be on the order of 400 m/s, at a mean temperature of 600–800 K, to guarantee an acceptable noise level and meet the take-off and approach sideline noise requirements as depicted in Fig. 4 (Habrand 1989; Hodder 1994; M. J. T. Smith 1990).

These conflicting design requirements are summarized as follows:

- For supersonic cruise, a high specific thrust cycle is desirable to meet performance requirements.
- For subsonic cruise, high propulsion efficiency (i.e., low specific thrust) is needed for lower SFC and reduced noise (exhaust jet speed <400 m/s).

The difficulty, therefore, consists in finding a “flow multiplier” device, which at take-off and during subsonic operation can significantly increase the air flow adjusted for operation at supersonic speeds.

Two general solutions to this design dilemma have evolved. The first method aims at optimizing the engine’s supersonic cruise and control take-off noise by incorporating a silencer such as an ejector. This creates the problem of designing an exhaust system that gives significant noise attenuation, but with minimal thrust and weight penalty. The best noise-sup-

![Fig. 4. Impact of Exhaust Jet Velocity on Noise](image)

![Fig. 5. Mid-Tandem Fan (MTF) and Turbofan with Ejector (TwE) Concepts](image)
2 (Lowrie et al. 1990; Proctor et al. 1994). This double flow path, which provides low specific fuel consumption and moderate ejection speeds of about 400 m/s, meets noise regulations. During supersonic cruise, the lateral inlets are closed and the variable-pitch guide vanes of the mid-fan reduce the frontal airflow into the bypass duct. This decreases the bypass ratio to 0.7, which is favorable under supersonic conditions (Proctor et al. 1994). Jet speed at the nozzle outlet is then about 650 m/s. The innovation in this design is the insertion of the fan downstream of the low-pressure compressor, where the primary air flow is already compressed in a duct of a moderate (from a drag standpoint) diameter of about 2 m (Poisson 1994). The mid-fan therefore plays the dual role of supplying the bypass flow in its external section and compressing the air in the primary circuit (between the low and high pressure compressors) in its inner section. The mid-tandem fan has marginally better mission performance than the mixed-flow turbofan, but also has a more complex design and a slightly higher weight (Hodder 1994).

On the other hand, the mixed-flow turbofan is a simpler and easier system to develop, but its main design difficulty is its long mixer-ejector nozzle, which may generate installation problems. This type of nozzle is essential because it entrains outside free-stream air that is mixed with the core jet exhaust, resulting in a slower, cooler exhaust jet that reduces noise by about 16 dB (Wilhite et al. 1997).

Rolls-Royce intends to complete its studies on propulsion by 2001, according to A. Newby, Chief of Advanced Propulsion Systems at Rolls-Royce (personal communication 1996). On the American side, a full-scale technology demonstrator engine, incorporating the materials needed for a production engine, is expected between 2001 and 2006. The baseline design for the SST propulsion demonstrator currently relies on a mixed-flow turbofan rather than a variable cycle engine (Kandebo 1997; Norris 1996). Meanwhile, if the current rate of U.S. research expenditure is maintained, there is a good chance of successfully attaining the entry-into-service year of 2007, as A. Newby asserts (personal communication 1996).

**ATMOSPHERIC EMISSIONS**

In addition to the technical challenges encountered in the development of a new propulsion system, several critical environmental issues are involved. Engine exhaust gas emissions constitute major problem requiring special attention. Important emissions from SSTs include water vapor, carbon dioxide (CO₂), nitrogen oxides (NOₓ), sulfur oxides (SOₓ), carbon monoxide (CO), hydrocarbons (HCs), and soot (NASA 1995). These emissions are directly involved in the radiative balance of the atmosphere, making climate changes possible. Furthermore, SSTs are expected to cruise at high altitudes of 55,000–70,000 ft, which correspond closely to the region of maximum ozone density. Stratospheric ozone change will take place, since SST emissions will directly affect photochemical processes that control the ozone abundance. It has been established that photochemical loss of ozone is dominated by catalytic reactions involving nitrogen oxides (NOₓ), hydrogen oxides (HOₓ), halogen radicals, and bromine oxides. Nitrogen oxides catalytically destroy stratospheric ozone, but also inhibit ozone destruction by HOₓ and halogen radical catalytic cycles through the formation of more stable gases (NASA 1995). The net effect, therefore, of adding NOₓ to the atmosphere is sensitive to the balance of these two effects. Recent studies conducted by both NASA (1995) and the German Institute of Atmospheric Physics (Schumann 1994) verified that heterogeneous reactions on stratospheric aerosol particles also play an important role by reducing the ozone loss due to NOₓ and increasing the loss due to HOₓ and halogens. Atmospheric circulation will affect the distribution of exhaust gases emitted by a fleet of supersonic vehicles, increasing the time the gases spend in regions of photochemical loss, or heterogeneous reactions, and possibly enhancing their detrimental effect.

These critical emission levels depend on the engine injection and combustion system performance—the quality of the air/fuel mixture, its distribution in the combustor primary zone, and the corresponding temperatures. The reduction of NOₓ emissions remains of primary concern, because NOₓ has the largest emission index (grams of emission produced per kilogram of fuel consumed) among the substances responsible for the ozone layer depletion. The high level of NOₓ emissions from current combustors is due to the burning of fuel at near stoichiometric air/fuel ratios (Wilhite et al. 1997). Therefore, the key in reducing NOₓ production is to burn either fuel-rich or lean (Fig. 6).

Two combustion processes are being examined: the two-stage richburn/quick-quench/lean-burn (RQL) process and the lean premixed vaporized (LPP) process. In the RQL system, combustion takes place in three distinct zones: the fuel-rich, the rapid quench, and the fuel-lean zones. Initially, the fuel is injected into the fuel-rich zone with a low rate of oxides formation due to insufficient oxygen (M. G. Smith 1990). After the fuel is mixed rapidly with large quantities of air in the quick quench zone, the reaction is completed in the lean zone. In the lean zone the temperature is sufficiently high to carry out the reactions, but does not reach the higher levels at which formation of nitrogen oxides can be accelerated. Thus, the RQL approach operates at higher fuel/air ratios than normal stoichiometric combustion, inhibiting NOₓ formation due to the lack of available oxygen. In the alternative LPP approach, fuel is vaporized and injected into the air in a premixing passage, delivering a uniform droplet-free mixture to the combustion zone. The fuel/air ratio is set as low as possible, but above stability or inefficiency thresholds.

For both combustors, liner material is a challenge in the 1,900° C (3,500° F) environment, because active cooling (with air) changes the mixing and chemistry critical to maintaining low NOₓ levels (Wilhite et al. 1997). A mighty advantage of the LPP method is the capability of the liner to operate with small amounts of cooling air, giving additional design flexibility (Stephens et al. 1993).

Although extensive full-scale experiments on these two concepts have not been concluded, preliminary measurements by NASA and its industry partners indicate a reduced NOₓ emission index of 5 (Zurer 1995). Pratt & Whitney is focusing on the RQL concept, which is capable of producing an eightfold decrease in NOₓ levels relative to current engines (Proctor et al. 1994). General Electric is examining LPP technologies. The final selection of a combustor concept is scheduled by the American team for 1998 (Kandebo 1997). Meanwhile, a successful LPP combustor developed by Rolls-Royce has demonstrated ultra-low NOₓ emission levels, one-tenth the levels produced by current conventional subsonic technology (Singh 1996). Experiments were carried out at Cranfield University, U.K., under a $1.68 million Rolls-Royce research project. In

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**FIG. 6. LPP and RQL Combustion Philosophies**

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simulated real combustion conditions, the results indicated extremely low NOx levels, close to an emissions index of 1, according to Prof. R. Singh of Cranfield University (personal communication). Nevertheless, transforming the combustor success to date into fully operational engines remains a difficult challenge in the development of the new SST. It is yet to be shown that the experimental combustor technologies can be used at full-scale, operating across the entire range of the speed required by supersonic transport, and still produce low NOx emissions.

In an attempt to evaluate the amount of engine emissions from a fleet of SSTs, several scenarios have been examined. Using a gas chemistry model, which included the effects of both homogenous and heterogeneous reactions, the German Institute of Atmospheric Physics concluded that the global percentage change in ozone by 2015 would be insignificant (Schumann 1994). Similar results obtained by NASA indicate that the ozone decrease would be less than 1% for the ground rules depicted in Fig. 7 and a NOx emission index of 5 (NASA 1995, 1996; Poisson 1994; Zurer 1995).

Most of these calculations, however, were performed with 2-D models, which do not address the 3-D emission distribution, the stronger variability of temperature and humidity in a 3-D atmosphere, and the details of 3-D atmospheric dynamics. Moreover, these models do not fully account for future climate changes due to the increase of greenhouse gases such as CO₂ or methane. Uncertainties are involved. Therefore, one cannot yet positively conclude that a fleet of supersonic transport aircraft will have insignificant effects on the stratospheric ozone.

Another issue under investigation is exposure to high-altitude radiation of galactic or solar origin. Galactic cosmic rays are heavy, high-energy ions that penetrate deep into the Earth's atmosphere, unlike solar cosmic rays, which are less penetrating but can be very intense for short periods of time as they are produced by solar flares. Biological damage may therefore occur depending on the radiation dosage. At supersonic cruise altitudes, the radiation dose is double that in a subsonic airliner flying at 40,000 ft, but because the trip time is halved, the total radiation dosage for passengers is roughly the same. The main concern, therefore, is for the exposure levels of flight crew members, which can be managed only partially by crew rotation scheduling based on validated radiation prediction methods (Wilhite et al. 1997). Uncertainties also exist in our knowledge of the radiation in the upper atmosphere and at various latitudes. Research is therefore being undertaken to attempt to map the solar cycle effects and the maximum radiation environment.

**STRUCTURAL REQUIREMENTS**

Optimum balance between structural performance and cost must be attained if the aircraft is to be profitable for both manufacturers and airlines. Weight effectiveness is of prime importance in designing SST structures due to the extremely high influence of structural mass on the maximum take-off weight. Critical issues arise in view of the extremely severe operating conditions:

- High altitude operations, which imply a cabin pressure differential 25% higher than in subsonic aircraft
- A temperature range from –50°C (–58°F) to 150°C (302°F) for the main structure, as well as thermal cycling under moisture and radiation impact
- High productivity, because supersonic aircraft must yield twice as many seat-miles per year to compete with subsonic aircraft

The high productivity requirement suggests high utilization and high dispatch reliability along an economic service life of over 20 years and a 60,000 hour durability standard (Ott 1997). The need for an extended service-life of the future SST is outlined in the requirement for a total of 25,000 flight cycles, compared to the Concord's estimated 7,500 flight cycles (Ernmann 1994).

Many lightweight, high-temperature materials are under development, including advanced aluminum and titanium alloys, polymer matrix composites, metallic/intermetallic matrix composites, high-temperature adhesives, and high-temperature sealant. DASA believes that the intermediate modulus carbon fiber may represent a satisfactory compromise between performance and costs, while toughened epoxy-resins, bismaleimides, and thermoplastics have been selected for screening tests (Ernmann 1994). In NASA's HSR program, analytical methods are being advanced for optimizing structural designs, such as sandwich, honeycomb, and superplastic-formed, diffusion-bonded designs (Stephens et al. 1993). Polymide carbon fiber matrix composites are also being developed to lighten the fuselage, outboard wing strake, and empennage (Wilhite et al. 1997).

However, engineers confront increasing difficulty arising from high engine temperatures. The structural total life requirement for the SST propulsion system is 30,000 hours, the same as in subsonic commercial engines. Nevertheless, subsonic aircraft engines spend less than 10% of their mission time at the most severe engine conditions. In contrast, SST engines will spend about 60% of the mission time under the most severe combination of component stress levels and high temperatures. The challenge is to utilize advanced materials to cope with the high temperatures without incurring excessive weight and cost penalties. This requires significant improvements in turbomachinery, combustion, and exhaust nozzle materials.

Turbomachinery materials enhancements will increase life at temperatures and stresses found in today's subsonic aircraft engines. Titanium-based metallic matrix composites and nickel-based superalloys are under consideration for compressor and turbine applications. Researchers believe that they will deliver suitable materials for SST turbine blades and disks, which will probably be twice the size of those used in current subsonic transports (Kandebo 1997). Development of viable combustors, having a long life goal of 18,000 hours, depends on the development and demonstration of a new class of high-temperature ceramic matrix composites not previously used in commercial practice. A silicon carbide—silicon carbide (SiC-SiC) ceramic matrix composite seems to be the leading contender for use in the combustor, due to its excellent conductivity and thermal stress characteristics (Kandebo 1997). At the same time, lightweight, high-strength, and high-stiffness metallic, intermetallic, and ceramic composite materials are being examined for the exhaust nozzle design to meet engine noise and weight requirements. These include gamma titanium aluminides and thin wall castings of superalloys.

In general, large complex configurations must be manufac-

![Fig. 7. Annual Percentage of Estimated Ozone Depletion](image-url)
tured economically and demonstrate long life under adverse operating conditions. However, the behavior and related manufacturing processes of such materials are beyond current operating experience and little information is available (Barbaux 1994; Stephens et al. 1993). Through intensive testing and analysis, scientists are attempting to establish long-term performance of these materials under SST conditions, as well as their reliability and economic performance. Although cost prediction is a complex issue due to the difficulty in providing enough data at this stage, preliminary studies by DASA and NASA indicate that SST structures can be produced at an acceptable cost (Ermanni 1994; NASA 1992).

Maintenance costs are an integral part of the overall commercial viability analysis of supersonic transports. The labor-hours required per flight for SST airframe and engine maintenance, as experienced in Concorde maintenance, are almost five to six times more than in subsonic aircraft maintenance (Douglas Corp. 1989). Nonetheless, supersonic aircraft achieve twice the productivity of subsonic jets, resulting in a much lower labor cost per seat-mile. A promising message for further reduction in labor comes from British Airways, which has already achieved progress in Concorde maintenance. Increased component reliability allowed them to escalate service checks to 150 hours from 75, and intermediate checks to 1,100 hours from 750. Additionally, major checks are conducted every 12,000 hours with a down-time of three months (Macdonald 1989). This notable improvement on maintenance time indicates that a significant cutback in labor-hours on the future SST is feasible.

DEVELOPMENT CHALLENGES

An aircraft becomes economically viable only when the market size justifies the investment and risks that both manufacturers and airlines undertake by deciding to develop or purchase it. Apparently, the level of the investment exposure for the development of a supersonic transport is substantially larger than for a subsonic aircraft. The development time of the SST will be longer, the amount of negative cash flow will be two to three times greater, and a break-even point will be reached later, as illustrated in Fig. 8 (Bunin et al. 1994). Thus, the project becomes vulnerable to time-dependent parameters such as market size and needs, the impact of political economic and ecological developments, fuel price, and the securing of uninterrupted financing sources.

The dominant criterion, therefore, for the commercial viability of the SST is the completion of the cost-price-market loop, which translates into having the aircraft at the right time and offering it at the right price:

- On the cost side, manufacturers will require assurance that risks can be reduced to an acceptable level, so that they can proceed with the program and expect a reasonable return, of about 12%, on their investment (Boeing 1989; Mizuno 1994). This can be achieved by manufacturers who not only possess the "know-how" but also employ innovative ways of minimizing the design and manufacturing costs.

- On the price side, airlines will demand an aircraft having economic performance and total ownership costs that enable them to make a profit, while still offering attractive ticket prices to their customers. This, in turn, will determine market share, because the challenge from the traveling public is to have a ticket price affordable for everyone, not just wealthy or business travelers.

- A surcharge should be selected based on how much passengers value time-savings and how much extra they are prepared to pay for it. Some preliminary elasticity demand curves constructed indicate that for a time-savings of

![Fig. 8. Investment Exposure Comparison: Subsonic versus Supersonic](image)

50%, a surcharge of 20% could establish a long-haul market share of about 45%, whereas a 30% surcharge would reduce market share to about 30% (Boeing 1989; Odell 1994).

Closing the cost-price-market loop results in the design and construction of a product that is actually commercially useful, rather than one that is merely technologically feasible and super. The Concorde is a characteristic example of an aircraft that did not follow this principle. While it certainly proved the technical feasibility of high-speed commercial flight, it was not affordable for the general public or the airlines. Furthermore, the tripling of fuel prices during 1973 and the exciting developments in subsonic aircraft economics, best represented by the low cost per seat-mile of wide-bodied jets, gave the coup de grâce to the first supersonic airliner.

Competition from direct or indirect sources may become a threat in the development of the future SST. Direct competition could arise if two or more parallel SST programs are developed. Indirect competition involves improvements in telecommunications, such as teleconferences or the Internet, and the concept of a very large aircraft (VLA) with a capacity of more than 500 passengers and great economic advantages over long-haul routes (Donoghue 1997). The remarkable advancements in electronic communications are likely to affect only business travel, which may decline by about 5% (Boeing 1995). The coexistence of very large subsonic aircraft and supersonic aircraft over long-haul intercontinental traffic is plausible, because these two aircraft families will correspond to different passenger needs. Nonetheless, the superior operating economics of VLAs, as outlined in the 15–20% reduction in DOCs from B747-400 levels (Moxon 1997) and its advantage of a much larger range than the SST, should not be underrated. However, Boeing anticipates a potential market for just 500 VLAs over the next 20 years (Doyle 1996). Surprisingly, the average projected market needs for SSTs in 20 years from now call for about 550 aircraft (Boeing 1989; Fischer 1994; Mizuno 1994; Mizuno et al. 1991; Nuesser et al. 1994), close to Boeing's estimated number of VLAs required. The number of SSTs also corresponds to the maximum achievable rate of production within a 10-year period, as determined by Boeing, considering 2010 as the entry-into-service year (NASA CR-4719 1996). This number of aircraft justifies a satisfactory return on investment (~12%) for only one manufacturer (Boeing 1989; Bunin et al. 1994), indicating no room for direct competition.

Today's global political and economic stability promises results very different from those obtained in the past. The pace of change in the aviation marketplace is remarkable: new products, new management philosophies, shifting customer expectations, and mergers that surpass national boundaries. The liberalization of the airline industry and passengers' demand for
convenience have been the driving factors for the recent market fragmentation (Dennis 1997). New ultra-long-range airliners (Boeing 777-300/200X, Airbus 340-500/600) are being developed to satisfy the increased need for convenient nonstop long-haul service, making possible new city-pair routes and markets. The world is becoming a "global village," generating the need for increased rapid transit. Potential global cooperation in the supersonic transport project appears more realistic, reflecting the political, economic, and cultural unification of the world. As Daniel Goldin (1993) of NASA contends, now is the time to make the dream of a commercially successful SST reality.

CASE FOR GLOBAL COOPERATION

The likelihood of a globally cooperative effort to develop a next generation supersonic commercial transport depends entirely on the benefits realized by the participants in such a venture. These are:

- **Technology transfer and combined strengths.** The experience and capabilities accumulated in aircraft design, manufacturing processes, and testing from individual leading aerospace companies are formidable. The combined technical abilities of highly trained and experienced engineering staff will reduce the risk and cost associated with the development and application of new technology. Furthermore, each of the participants is presumed to have a large base of the world's leading suppliers of commercial aircraft structures, equipment, and systems. Through the combination of all of these available resources and capabilities in an internationally cooperative venture, the technical feasibility of an SST program could be enhanced.

- **Reduced development time and costs.** A cooperative program could reduce expenditures through the sharing of nonrecurring costs, which might otherwise be duplicated by manufacturers (Bunin et al. 1994). The synergistic capabilities of the participating companies could also reduce the amount of time required for development and production. This may be particularly true in the case of sharing existing capital equipment and facilities. Furthermore, because a market for just a single supersonic aircraft model exists, cooperation could lessen the risk of multiple manufacturers pursuing independent programs with an insufficient market for economic viability. This would eliminate direct competition and let the partners constructively focus on indirect sources of rivalry.

- **Establishment of common environmental standards and certification rules.** International standards associated with issues such as aircraft emissions and noise must be proposed and established. Broad, international participation and interest in an SST program could increase cooperation between scientific communities conducting research on key environmental issues, and enhance the harmonization of proposed standards between national regulatory agencies. It could also expedite the rule-making processes associated with environmental and regulatory issues such as aircraft certification. Furthermore, an international cooperative program could secure the global market access that will be needed in order to operate in Asia, America, and Europe.

The participant countries would also benefit from the jobs created by the program as well as from the increased commerce and trade that would result by a cooperative effort and the subsequent use of supersonic transports. A study by the society of Japanese Aerospace Companies, estimated that the potential economic benefits for Japan, in the manufacturing, trade, and tourism related industries, would be $30 billion by 2020 (Iwaki et al. 1994).

Considerable knowledge has been gained on organizational and administrative needs of multinational consortiums. Europe's long experience in cooperating on large projects offers good lessons about what should be done or avoided. For instance, the "two-headed" organization of the Concorde project and its unnecessary duplication resulted in extra costs and delays that had a negative effect on the outcome of the program (Poisson 1994). The acquired experience, however, led to the successful Airbus Industries, Panavia, and the Euro-Fighter project, which assisted in the modernization of Europe's main aeronautical research centers and in the production of excellent flying machines. Transcontinental collaboration has also been proved prosperous by CFM International, the successful U.S.-French engine manufacturer formed by General Electric and Snecma, which has established an average 60% market share on single-aisle aircraft engine orders over the last few years.

At the same time, an international consortium would have to overcome several barriers related to the efficiency of the management structure for the joint venture, the decision-making process, the engineering design and development approach, the location of the final assembly line, the form of the legal entity, the process for establishing shares in the program, the allocation of work packages, and the sales and support mechanism. Exchange rates, antitrust constraints, and government bureaucracy may also restrict technology transfer. Therefore, the key element for success in an international consortium should be a flexible management structure through an effective business setup, which may take the form of a "limited liability company" or a "lead company with subcontractors." The five largest aircraft manufacturers (McDonnell Douglas, Boeing, Aerospatiale, British Aerospace and Deutsche Aerospace), at a common presentation during the 7th European Aerospace Conference, agreed that if an international program were put forth, it would follow the phasing depicted in Table 1 (Bunin et al. 1994).

At present, activities are focused on the review of common interest and on coordinated studies of the market, technical, and business aspects of the project (Swadling 1992). Competition among design offices in preliminary project phases is vital, to generate new ideas and sharpen the creativity that is indispensable in the successful completion of ambitious projects. Therefore, independent research and development of critical SST technologies is taking place, to determine whether the tough design and mission targets of the SST can be materialized. After the bulk of this "risk reduction" work is completed, the aerospace industry will have a reasonably clear understanding of whether the project is technically and environmentally feasible. They will be able to accurately evaluate the aircraft's commercial potential, so that the program can be launched by 2002. Through the potential development and production stages presented in Table 1, the first flight could be made possible as early as 2007. Accounting for po-

<table>
<thead>
<tr>
<th>Phase</th>
<th>Duration</th>
<th>Cost</th>
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<tr>
<td>(a) Commitment to Partnership</td>
<td></td>
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<tr>
<td>II. Preliminary design and development</td>
<td>1998–2002</td>
<td>$1.5–3 billion</td>
</tr>
<tr>
<td>(b) Program Launch</td>
<td></td>
<td></td>
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<tr>
<td>III. Development and production</td>
<td>7 years to certification</td>
<td>~$15 billion</td>
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<tr>
<td>Specification (1)</td>
<td>Projected Value (2)</td>
<td>Realistic Value (3)</td>
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<tr>
<td>Average speed</td>
<td>2.4 Mach 270–300 Pax</td>
<td>2.2 Mach 270 Pax</td>
</tr>
<tr>
<td>Capacity Range</td>
<td>4,500–6,500 NM</td>
<td>&gt;223 kN (50,000 lbf)</td>
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<tr>
<td>Engine thrust</td>
<td>Reduced by 10–15% of</td>
<td>Reduced by 10–15% of</td>
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<tr>
<td>SFC (Subsonic)</td>
<td>Olympus 593</td>
<td>Olympus 593</td>
</tr>
<tr>
<td>SFC (Supersonic)</td>
<td>Reduced by 5–10% of</td>
<td>Reduced by 5–10% of</td>
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<tr>
<td>Aircraft length</td>
<td>Olympus 593</td>
<td>Olympus 593</td>
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<tr>
<td>Aircraft span</td>
<td>41–43 m</td>
<td>41–43 m</td>
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<tr>
<td>MTOW</td>
<td>~340,000 kg (750,000</td>
<td>~340,000 kg (750,000</td>
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<td></td>
<td>lbs)</td>
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<td>NOx, E1 Noise</td>
<td>&lt;5</td>
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<td>Level</td>
<td>Far-36 ≠ Stage = 3</td>
<td>Far-36 ≠ Stage = 3</td>
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Potential delays associated with the development of such a demanding project, a more realistic entry-into-service date could be between 2010 and 2015.

CONCLUSIONS

The following SST specifications could be supported by the anticipated technology availability in the next decade (Table 2):

- Nonlinear aerodynamic analysis methods point toward an enhanced L/D ratio of about 45% at subsonic, 58% at transonic, and 25% at supersonic speeds. Current results from supersonic laminar flow control experiments indicate that this technology will not be extensively used in the SST, although it may be applied to aerodynamically critical areas. No practical solution is foreseen for a sufficient reduction in sonic boom loudness. Research on low-boom aircraft configurations suggests that some low-boom characteristics, such as optimized lift redistribution, will be incorporated into the next generation SST.

- Synthetic vision systems will be installed in the new SST, eliminating the heavier and more complex droop-nose configuration. The total resized increment in drag and weight reduction for the larger next generation SST is estimated at 4,500 kg (10,000 lb), which translates to as many as 50 additional passengers. Category III all-weather operation capability, autonomous of the landing aids of the airports, will be obtained. This will dramatically increase the dispatch reliability and on-time arrivals, enhancing operating economics and passenger satisfaction. The outcome of recent tests suggests that a successful synthetic vision system can be available for use after 2001.

- The mixed-flow turbofan (with ejector) has been indicated by Americans as a more likely propulsion system than the equally advantageous variable cycle mid-tandem fan system explored by Rolls Royce. The level of noise suppression is coupled to the exhaust jet velocity of the engine, and FAR-36/Stage-3 noise requirements can be met through the use of a silencer or variable geometry components. The mid-tandem fan has a mission performance marginally better than that of the mixed-flow turbofan, but it has a more complex design and a higher weight. The final selection of the propulsion system by the American team is expected between 1998 and 1999. If the current rate of research expenditure is maintained, there is a good chance of successfully attaining an entry-into-service date of 2007.

- Results from preliminary analyses indicate that low nitrogen oxides emission levels (an emission index of 5) can be achieved, contributing to a negligible annual ozone layer depletion of less than 1%. The dominant combustion processes to be used are the rich-burn/quick-quinch/lean-burn and the lean premixed prevaporized processes. It is yet to be shown that the combustor technologies can be used at full-scale, operating across the entire range of the speed required by a supersonic transport, and still produce low NOx emissions. Further studies of more detailed 3-D atmospheric models must also be conducted to validate the low ozone depletion results originally obtained.

- The extremely severe combination of component stress levels and high temperature operating conditions, as well as the requirement for an extended 25,000 cycle service life, introduce the challenge of utilizing advanced materials without incurring excessive weight and cost penalties. The behavior and related manufacturing processes of such materials are beyond current commercial experience and little information is available. Polymer matrix composites, advanced aluminum and titanium alloys, metallic matrix composites, intermetallic matrix composites, and ceramic matrix composites are being examined in order to establish their long-term performance and reliability under SST conditions, as well as their production cost.

- The long development period of 7–10 years makes the SST project vulnerable to time-dependent parameters such as political and economic instability. The average projected market requirements for about 550 SST aircraft by 2020 justifies a satisfactory return on investment (~12%) for only one manufacturer, implying that there is no room for direct competition. A well-structured international consortium could minimize the risks and uncertainties involved, by reducing the development time and total expenditures through technology transfer and the sharing of nonrecurring costs. The establishment of common environmental standards and certification rules would secure global market access and acceptance for the new supersonic transport.

APPENDIX. REFERENCES


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