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THE IMPACT OF EMERGING TECHNOLOGIES ON AN ADVANCED SUPERSONIC TRANSPORT

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Abstract

The cancellation of the US National SST Program in 1971 seriously hampered technical progress in supersonic cruise research. However, the momentum gained from the quarter century of focussed effort in supersonic cruise research that preceded the national program along with progress in numerous military programs and, of course, the SCR Program that came afterward, identified significant advances in every technology area. The impact of these emerging technology advances in propulsion, structures and materials, aerodynamics, and systems is more than three times as powerful on an SST as on a subsonic transport.

Highly efficient propulsion systems having variable geometry elements, long-life hot core, axisymmetric variable-geometry inlets, and low-noise nozzle and reversers are the major advances to propulsion. Advanced structural concepts, long-life damage-tolerant structures, advanced material development, aeroelastic tailoring, and low-cost fabrication reflect the structures and materials advances. Blended arrow-wing configurations, laminar flow technology, and nacelle/airframe integration highlight the aerodynamics advances. Finally, the advances in primary flight controls, integrated avionics systems, and aircraft subsystems reflect the strides made in systems technology. Application of these emerging technologies, both individually and synergistically, result in an AST having significant improvement in range/payload, a sharp reduction in aircraft gross weight and empty weight, and a significant improvement in airport-community noise.

I. Introduction

The timing of a new airplane program is driven by a number of key ingredients including cost, market, economics, financing, and, of course, technology readiness. Launching a new airplane program requires the proper blending of these ingredients. Thus far, the recipe for success has applied singularly to subsonic airplanes. Whether our future air transportation system will continue to be dominated by these subsonic airplanes will, of course, depend upon the leverage each of these ingredients exerts in the future, especially on very long-range routes where time becomes another important factor in the recipe.

This paper will focus primarily on the technology ingredients in a new recipe for supersonic travel. It will begin with a review of past SST activities and present a significantly new and unique capability that will result from the synergistic integration of the enabling technologies in propulsion, structures and materials, aerodynamics, and systems. Such a vehicle, which will also be environmentally acceptable, shows enormous promise of an efficient and highly productive SST that could serve an ever-expanding market, especially in the Pacific Basin.

II. Brief Review of the Past

The United States Government and industry have a substantial investment in the technology necessary for a successful SST. A billion dollars were invested in the National Program from 1962 through 1971 (Fig. 1). The NASA Supersonic Cruise Program, started after the National Program specifically to provide a focused effort on the problems identified in the National Program, lasted nearly 10 years and invested another 130-million dollars.(1) More than 1,300 technical reports resulted from the NASA effort.(2-4)

It is difficult to believe that 24 years have passed since the initiation of the National Program by President Kennedy in 1962, or, that 15 years have passed since the program was cancelled by Congress in 1971. During this period, the Concorde entered commercial service and has accumulated more than 100,000 hours at M = 2.0 (Fig. 2). More civilians have flown at Mach 2.0 since the introduction of the Concorde into commerical service than all the military pilots in the world. It should be recognized that a Concorde built with the technologies described in this paper would do the same mission at half its current weight and less than half its fuel consumption. The Boeing 2707 of 1971 was to carry 290 passengers 3,500 nautical miles at a takeoff gross weight of 750,000 pounds. With the technologies to be discussed in this paper, 290 passengers could be carried 3,500 nautical miles for a gross weight of 307,000 pounds.

III. Potential Configuration

Many of the technology advances being adopted in the subsonic area have direct application to an SST. When combined with the results of the SCR (Supersonic Cruise Research) Program and military engine improvements, a drastically different airplane than the one cancelled by Congress in 1971 can be envisaged (Fig. 3).

This exciting 2-engine, 250-passenger, M = 2.7 configuration would have an arrow wing, SPF/DB (superplastically formed and diffusion bonded) titanium metal-matrix structure, variable-cycle engines, an advanced 2-man cockpit, a flight management system, and fly-by-wire relaxed static stability.

This advanced airplane would have a takeoff gross weight of 361,400 pounds which would provide a range of 5,500 nautical miles. This would enable Los Angeles-Tokyo capability in a little over 3 hours while achieving a seat-mile per gallon capability of almost 50. If the airplane was configured for all first-class in initial service, it would carry 135 passengers from New York to Tokyo in a little more than 5 hours (Fig. 4). If laminar flow can be achieved, the takeoff gross weight would be reduced nearly 100,000 pounds and the seat-miles per gallon would be about 80. Conversely, at the same gross weight of 361,400 pounds, the range would be increased from 5,500 nautical miles to 7,500 nautical miles. Either of these potential AST's (Advanced Supersonic Transports) substantially outperform the Concorde or the 1971 US SST by such a large margin that renewed interest in SST development is inevitable.

IV. Enabling Technologies

It is appropriate at this time to examine the enabling technologies that, when carefully put together in a synergistic manner, can provide for such an AST. They include significant improvement in propulsion, structures, aerodynamics, and systems.

Propulsion

Propulsion systems, whether for subsonic or supersonic aircraft, are always counted on to provide great gains. Two areas of supersonic propulsion are different than in the subsonic applications. Propulsion efficiency, unlike aerodynamic efficiency, tends to increase with increasing Mach number and because of the lower payload fraction of supersonic aircraft compared to subsonic aircraft, supersonic aircraft are more sensitive to propulsion system weight.

Concepts of variable-cycle engines arose from the SCR Program of the 1970's.(5) Considerable analysis and validation of these "variable-flow" engines were conducted including full-scale demonstration testing. Since then (Fig. 5), considerable further progress has been made on cycle designs, materials, cooling, and hot-section technologies, all of which combine to permit higher turbine temperature, lower weights, and fewer parts. The technology incorporated in the compressors and turbines of the subsonic engines, which has driven the specific fuel consumption down by half in 15 years while reducing the total part count, can also be applied to the supersonic engines. In addition, the military interest in very high thrust-to-weight ratio engines for use in highly maneuverable fighters has produced high-temperature technology transferable to the SST engine.

It is interesting to compare the overall propulsion efficiency of supersonic power plants with subsonic power plants (Fig. 6). The Olympus engine in the Concorde was a very good engine for its time period and has a higher overall efficiency than the early high-bypass turbofans. It operates at an overall pressure ratio (OPR) of 15.5, a turbine inlet temperature (TIT) of 1,970°F, and attains an overall efficiency (η_o) of .41. The GE-4 engine of the United States SST program achieved an overall efficiency of .42. A reasonable goal for a future SST engine is an overall efficiency of .55 or greater.

Obviously, engine thrust-to-weight ratio plays a significant role. The subsonic engines have historically traded much of this weight improvement for higher engine bypass ratio. Sustained supersonic operations, however, whether for military or commercial vehicles, require very low-bypass ratio engines. The significant improvements in engine T/W ratio, therefore, which have gone from about 8.0 to about 12 for today's military systems (Fig. 7), can now be reflected in reduced engine weight. A new engine, designed for a cruise Mach number of 2.62, would have an overall pressure ratio (OPR) of about 20, and a turbine inlet temperature (TIT) of at least 2,850°F, a bare engine thrust-weight (T/W) ratio of 8.0, and half the part count of the Concorde's Olympus engine (Fig. 8). When combined, these propulsion advances alone would reduce the airplane gross takeoff weight by more than 100,000 pounds.

Structures and Materials

Significant progress has been made since the mid-sixties in the structures and materials relative to design methods, metallic and nonmetallic materials, and processing (Fig. 9). For example, increased computer modeling capability and better understanding of the airloads at off-design conditions have made important contributions to the understanding of the flexible shape of the airplane, both on the aerodynamic center shift impact on trim drag, and to the design for prevention and control of flutter of the wing (Fig. 10). The analysis time of a major structural change in the airplane can now be evaluated in 2 days; whereas in the late 60's, it took as long as 6 weeks.

The particular material selected for the SST will, of course, be dependent upon the cruise Mach number selected for the aircraft. At the present time, candidate materials include new aluminum alloys, titanium, thermoplastics, and different types of composites in nonmetallic and metallic matrices, the latter being very attractive from a sandwich material aspect.

The retention of high specific strength of these materials to very high temperatures is also a requirement in terms of their applicability to the supersonic flight regime. Since there are very large increases in strength-to-density ratio of many of these new materials as compared to conventional titanium, it is not difficult to imagine the potential for savings in terms of innovative structures that could result from such processes as superplastic forming of titanium and sandwich construction using metallic matrices (Fig. 11).

Superplastic forming and diffusion bonding (SPF/DB) is one of the most significant advances to occur in metal processing in recent years, particularly for high Mach number, high-temperature application.(6) A technique pursued by the Douglas Division of McDonnell Douglas(7) in the SCR Program (Fig. 12) is a process in which four flat titanium sheets are placed in a mold and heated to plastic metal temperatures, blown into shape, and diffusion-bonded together. The resulting bonds exhibit parent metal strength. The process provides the capability to form and fabricate structural configurations not previously possible using titanium. The substitution of a metal-matrix face sheet further improves the designer's ability to realize large weight savings. Reduction in part-count and fasteners have contributed to the weight and cost reduction. Sandwich cover panels for the wing made in this manner, combined with similar methods for the wing internal structure, have reduced the wing structural weight by about 30%, and a change in the fuselage structure from skin-stringer titanium to a SPF/DB sandwich construction reduced the fuselage weight nearly 50% (Fig. 13). Tests have shown that these large diffusion-bonded panels have excellent fatigue resistance, and design guides are being developed for their use.(8) Studies have shown a reduction of total airplane structural cost approaching 50%.

Aerodynamics

Advancements in the field of aerodynamics suggest some exciting possibilities that could bring tremendous advantages to an AST (Fig. 14). Nonlinear aerodynamic design methods, highly effective vortex flaps, digital flight electronics, and the possibility of supersonic laminar flow project a 40% to 60% improvement in L/D, better takeoff and landing performance, and lower gross weight by as much as 100,000 pounds.

The increases in the supersonic aerodynamic cruise efficiency (lift/drag ratio) since the Concorde have been significant. The computer has made it possible to optimize the wave drag and drag due to lift of these configurations, and the gains have been proven gradually through complete configuration wind-tunnel tests.(7) Fuselage shaping, wing-body blending, planform optimization for minimum drag due to lift, and favorable interference of the propulsion package and vertical tails have all contributed to the increased level of lift-drag ratio from slightly more than 7 to nearly 11 at a Mach number of 2.2. Values near 10 have been obtained at Mach 2.7 (Fig. 15).

Of course, even with these significant gains, supersonic L/D's are no match for those available to subsonic airplanes. However, in the same fashion that laminar flow control can contribute substantially to improving the L/D of the subsonic aircraft, it can have an equally profound influence on supersonic cruise efficiency. Application of supersonic LFC, at say, $M = 2.7$, could increase L/D from 10 to nearly 17. This improvement alone would reduce the gross weight by about 20% and double the seat-miles per gallon. In addition, the reduced surface temperatures (about 160°F) associated with LFC will reduce the weight penalty for high-temperature structures. Programs to understand supersonic laminar flow on highly-swept arrow wings have been initiated.

One of the problems in accepting these higher sweep supersonic wing planforms had been the low level of aerodynamic performance and pitch-up at takeoff and landing conditions. Significant progress has been made in solving these low-speed problems through a combination of wind-tunnel and theoretical approaches.(9-10) The results (Fig. 16) indicate that the highly-swept arrow wing, with superior high-speed performance is now slightly better than the delta-wing configurations during takeoff and landing. The same devices that provide improved L/D also keep the pitching moments linear thus controlling the pitch-up.

Systems

Significant gains will result from the tremendous progress being made in the systems area, particularly those areas which are usually not identified, by some researchers at least, as having a very high payoff (Fig. 17). However, new seat designs that are 50% lighter than earlier designs can add up to a lot of weight savings for a 250-passenger airplane. Use of carbon brakes, which are lighter and longer lasting than present brakes, along with radial tires that are tougher, more effective, and longer lasting than the current bias-ply tires, can add the benefits of 40% and 30% weight savings, respectively, in those subsystems. It is estimated that new design galleys will be 30% lighter than current ones and new lavatories will also be 10% lighter. These items are either well in hand or already in use to some extent. Aircraft actuation systems with 8,000 psi hydraulics or electromagnetic actuators can be another 10% to 20% lighter than previous systems.

Electronics/avionics is considered to be the discipline integrator which will permit us to fully realize the anticipated benefits of advances in aerodynamics, structures, and propulsion. Future AST's would have an all fly-by-wire capability, an all-electric secondary power system, and a flight management system which integrates, optimizes, and controls the airframe-propulsion functions including active controls for load alleviation and airplane relaxed static stability to reduce trim drag.

The impressive advances in electronics-avionics being realized on subsonic aircraft will find their way into supersonic transports. When combined with the significant weight savings within the airplane secondary systems such as seats, galleys, lavatories, tires, brakes, etc., the payoff to the SST will be twice as effective as on subsonic airplanes (Fig. 18). The important fact, which is often overlooked, results from the growth factor of an SST which is double that of a subsonic aircraft.

V. Environmental Concerns

There were major issues relating to environmental concerns over the US SST program; namely, engine emissions relative to urban pollution in the vicinity of airports and pollution of the stratosphere, airport-community noise, and sonic booms. Each of these demanded, and received, considerable attention and research.

Engine Emissions

The principal urban pollutants were carbon monoxide and unburned hydrocarbons during idle and toxic and oxides of nitrogen and smoke during takeoff and climb. Attention has been given in the advanced burner area to these emissions(11) and important gains have been accomplished

(Fig. 19). The oxides of nitrogen during high-altitude cruise flight relative to the upper atmosphere pollution area has been addressed by the Climatic Impact Assessment Program (CIAP) and the High Altitude Pollution Program (HAPP). The results, as of the recent findings of January 1984,(12) indicate that the NO_x impact on the ozone is not a problem as it was stated to be in the early 1970's (Fig. 19) and that impact of the supersonic transport on the ozone layer is very small and probably can be considered insignificant.

Airport-Community Noise

Marked progress has been made in reducing airport-community noise through reduction of the noise at the source combined with advanced operating procedures.(13) Government and industry have exerted considerable research and technology efforts(5) toward developing an understanding of jet noise generation, concepts for its reduction, and practical means for suppressor implementation (Fig. 20). Coannular nozzles, mechanical suppressors, and thermal acoustic shields have been explored as part of noise reduction research. Use of the unique inlets associated with SST's has the potential for very large reductions in forward radiated noise through inlet choking. Wind tunnel tests have shown that this can be done at minimal penalties.(14) In addition, advanced operating procedures that have the potential to reduce airport-community noise have been developed and evaluated.(15-16) The results of these noise programs, when traded in terms of performance and cost and combined with the previously discussed enabling technologies that will permit a lighter-weight better-performing vehicle, will allow the designer to attain the desired noise goals at much less cost. In fact, noise exposure levels for supersonic cruise vehicles can be comparable to those of its equivalent weight subsonic counterpart.

Sonic Boom

The third in the trio of environmental concerns is the sonic boom. Although progress on emissions and noise are evident, the same cannot be said for the sonic boom. As a result, overland supersonic operations are still out of reach to the commercial SST.

A great deal of knowledge exists regarding the generation, propagation, and prediction of sonic booms, particularly for the "primary" carpet booms. In comparison, very little information exists relative to the "secondary" or "over-the-top" booms.(17) Good correlation exists between measured and predicted values of sonic boom for aircraft cases and Shuttle Orbiter during reentry (Fig. 21). The sonic boom levels, in general, increased with increasing aircraft size and decreased with increasing altitude.

The measured sonic boom signatures associated with some of these vehicles (Fig. 22) such as those from the Shuttle Orbiter on reentry and Concorde and SR-71 during cruise flight exhibit an N-wave shape. In-house NASA studies have indicated that even with the application of laminar flow to reduce the gross weight to 302,600 pounds, a similar N-wave signature will result even when the fuel is off-loaded (OL) for a 2,500 nautical-mile range (Fig. 23). These studies also show that a very low-boom design (DES) of a domestic version of this AST can result from the application of the aforementioned enabling technologies in propulsion, materials, and aerodynamics. This aircraft is shaped to produce a "flat top" signature and the boom level is reduced to less than 1 psf (about half expected from the US SST). Previous studies(18) have suggested that each of these changes is in the direction of increased community acceptability. However, little if any information exists on reaction to booms of 1 psf or less. Further research is urgently needed on the community acceptance of sonic booms levels of less than 1.0 pound per square foot.

Further improvements in boom overpressure may result from the application of supersonic laminar flow since it exerts a very powerful influence on reducing airplane gross weight and increasing altitude--each of which result in lower boom levels.

VI. Market Potential

Some current market analyses project that the number of aircraft in operation will triple by the end of the century, resulting in the need for over 4,000 new aircraft in the next 15 years. Most of the demand will probably continue to be in the domestic size and range classes, but a substantial amount will be in the larger over-ocean category. The projected increases in population, commerce, and tourism are expected to result in significant increases in long-distance transoceanic travel between various points in the developed and developing countries (Fig. 24). It appears, therefore, that if a greatly improved AST can be developed, a greatly enlarged traveling public will utilize it. The technology benefits that can be applied to an AST are so potent as to provide the performance improvement margin necessary to end the subsonsic jet dominance of the long-haul over-water passenger market. Advanced SST's could displace subsonic jets on these routes just like the subsonic jets displaced the propeller airplanes.

Summary Remarks

As mentioned in the introduction, there are a number of ingredients critical to the emergence of an AST; readiness of the key technologies is one. The overwhelming influence that the previously discussed enabling technologies have upon the AST and the growing need for highly productive transportation between far-distant population centers is so apparent that serious consideration must now be given to the maturing of these technologies in propulsion, structure and materials, aerodynamics, and systems. In particular, work is needed in engine noise suppression trades, titanium metal matrix structure, low-speed vortex flaps, and high-speed laminar flow for highly swept arrow wings and on sonic boom tolerance levels and sonic boom shaping.

Once these technologies are matured, the other ingredients in the AST recipe, including development costs and method of financing, will balance out to provide the air transportation system with a new and viable high-speed capability.

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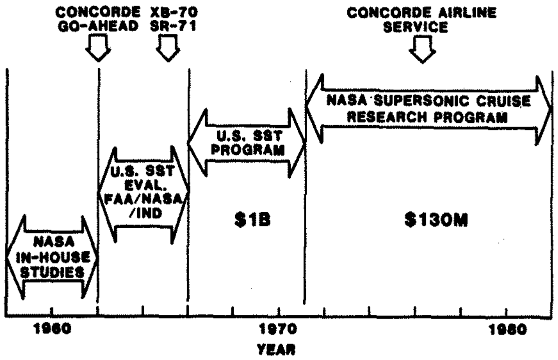


FIGURE 1. Evolution of US SST Effort

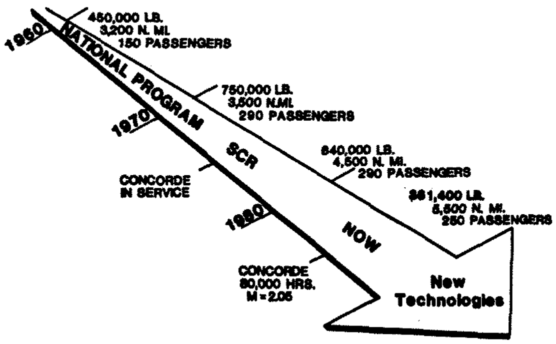


FIGURE 2. Supersonic Perspective

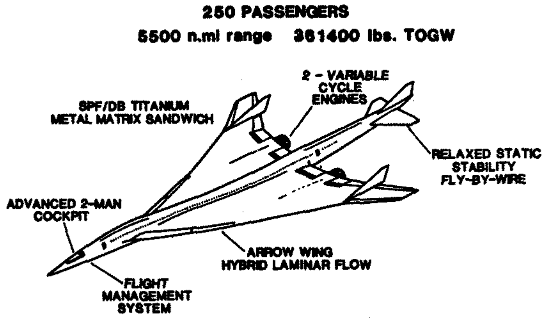


FIGURE 3. Emerging Technology Configuration

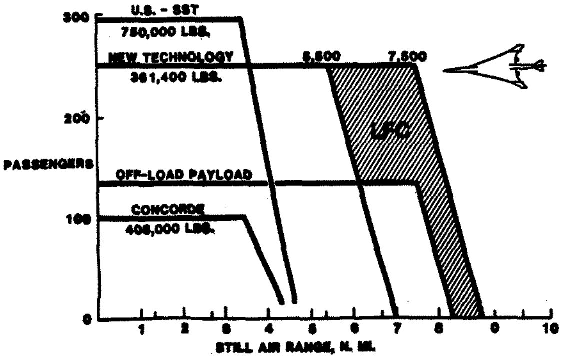


FIGURE 4. AST Capabilities

- IMPROVED ALLOYS
- IMPROVED COOLING/COATING
- HIGHER STAGE LOADING
- IMPROVED INTERNAL FLOW
- BETTER CYCLE OPTIMIZATION
- DIGITAL CONTROLS

} CET - 500 °F

} BETTER SFC

NET PAYOFF

- T/W FROM 4 TO 8
- LOWER SFC BY 20%
- REDUCED PART COUNT BY 50%

FIGURE 5. Enabling Technologies in Propulsion

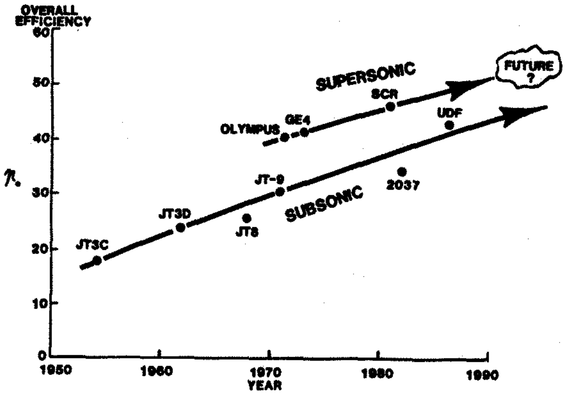


FIGURE 6. Projected Overall Efficiency in Commercial Engines

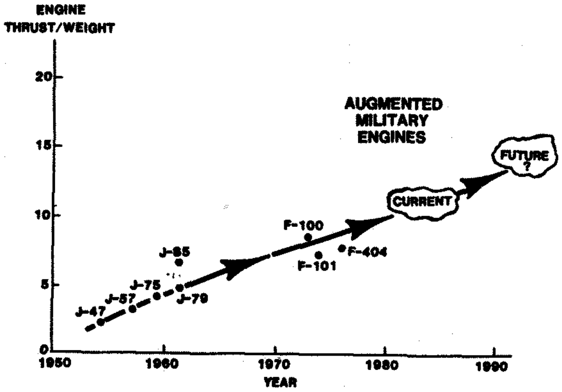
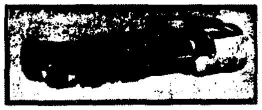


FIGURE 7. Improvements in Engine Thrust/Weight



NOW		FUTURE
7465 lb	Weight	~4500 lb
15.5	OPR	20+
1970°F	TIT	2800 - 3000°F
14	No. Compressor Stages	6
0.41	η_o	0.5 - 0.55
1.19	SFC	~.95
	Part Count	~1/2 of Concorde's Olympus Engine

FIGURE 8. SST Propulsion Potential

- **METAL MATRIX SPF/DB**
- **HIGH TEMPERATURE COMPOSITES**
- **REDUCED TEMPERATURE via LFC**
- **DESIGN METHODS**

NET PAYOFF

- **SANDWICH FUSELAGE - 50% WT.**
- **SANDWICH WING-NACELLE - 30% WT.**

FIGURE 9. Enabling Technologies in Structures and Materials

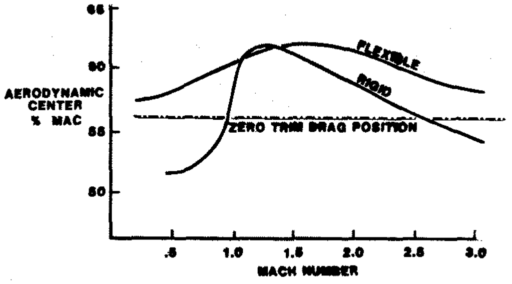


FIGURE 10. Arrow-Wing Aerodynamic Center Position

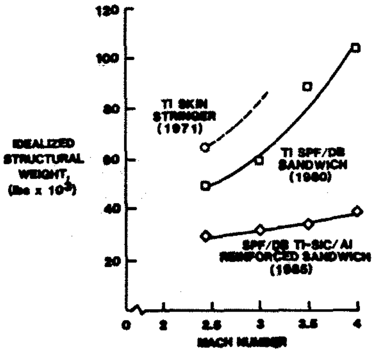


FIGURE 11. SST Structural Weight Progress

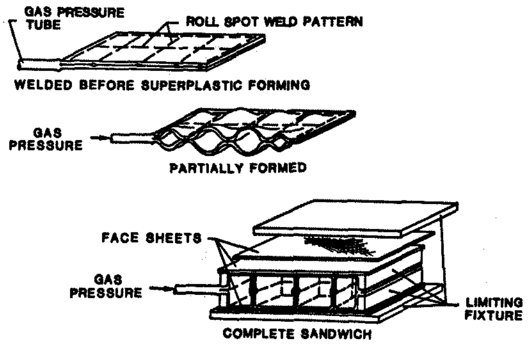


FIGURE 12. Superplastic Forming/Diffusion Bonding Process

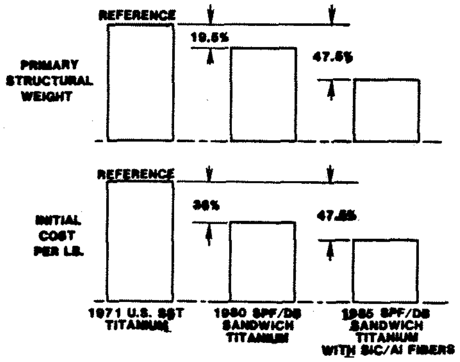


FIGURE 13. Weight and Cost Benefits of Ti SPF/DB

- **DESIGN METHODS**
- **VORTEX FLAPS**
- **LAMINAR FLOW CONTROL**
- **DIGITAL FLIGHT ELECTRONICS**

NET PAYOFF

- **IMPROVED L/D - 40% TO 60%**
- **IMPROVED TO/LTG PERFORMANCE**
- **LFC REDUCES TOGW BY 100,000#**

FIGURE 14. Enabling Technologies in Aerodynamics

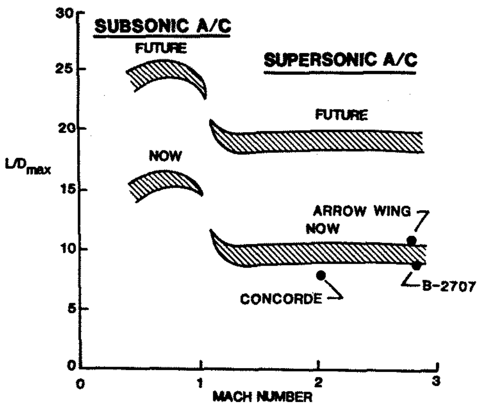


FIGURE 15. Aerodynamic Efficiency Potential

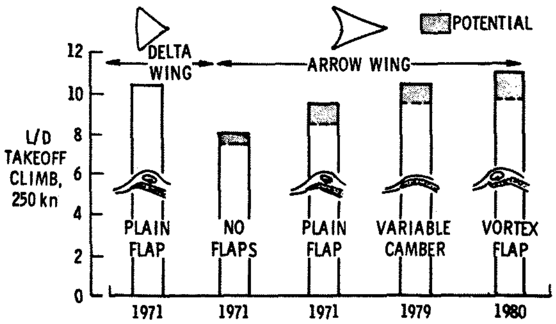


FIGURE 16. Arrow Wing Low-Speed Aerodynamic Progress

LIGHTWEIGHT SEATS & INTERIORS	**30%**
CARBON BRAKES	**40%**
RADIAL TIRES	**30%**
ELECTRONICS	**50%**
ELECTRONIC FLIGHT CONTROLS	**40%**

FIGURE 17. Enabling Technologies in Systems

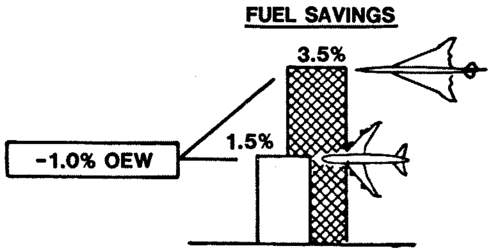


FIGURE 18. Weight Payoff - SST Versus Subsonic

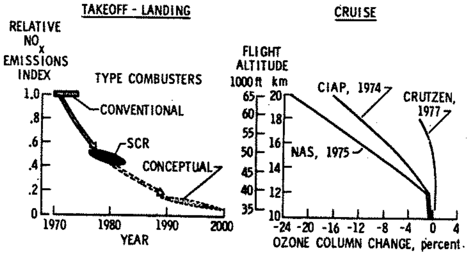


FIGURE 19. Emissions Progress

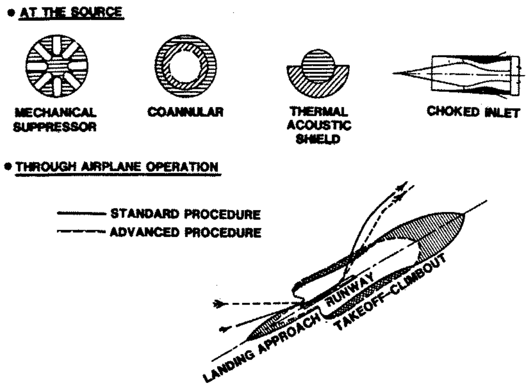


FIGURE 20. Concepts for Reducing Airport Community Noise

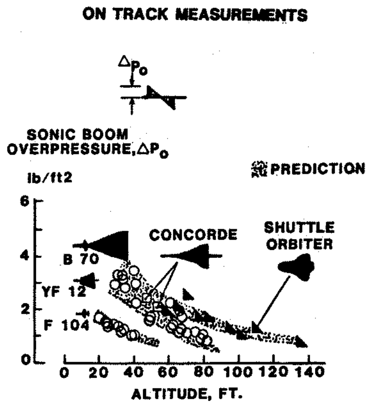


FIGURE 21. Measured and Predicted Primary Sonic Booms

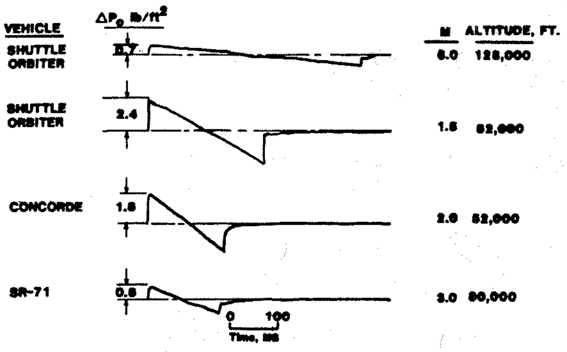


FIGURE 22. Primary Boom Signature Characteristics

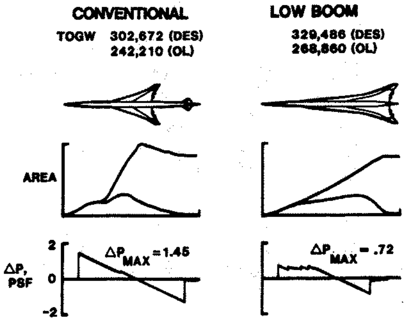


FIGURE 23. Low Sonic-Boom Design Study

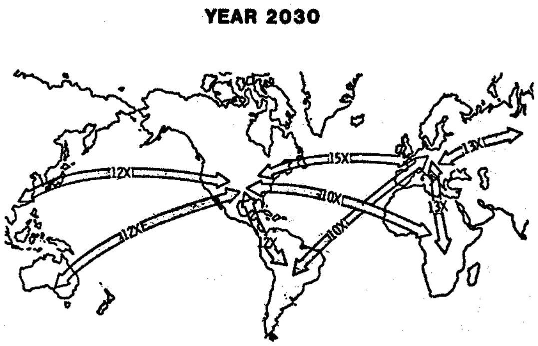


FIGURE 24. Increased Worldwide Travel